Technology landscape report and business case for the recycling of Li-ion batteries in South Africa

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MINTEK
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Technology landscape report and business case for the recycling of Li-ion batteries in South Africa

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EXECUTIVE SUMMARY

The outcomes of a study to assess whether there is a business case for the establishment of a lithium ion battery (LIB) processing plant in South Africa are discussed in this report. The objectives of the study were three-fold:

- To provide an overview of the current state of the LIB recycling industry in South Africa.
- To assess commercial recycling technologies that are currently available and evaluate the extent to which these technologies can be adapted to suit the South African situation.
- To conduct a techno-economic study to investigate the business case for the establishment of a LIB recycling plant in South Africa.

A desktop review was performed to establish the broad trends and dynamics impacting the LIB industry locally and globally, the scope of LIB recycling in various parts of the world, end user markets for LIB fractions and the nature and availability of technologies used in the recycling of LIBs.

A sharp increase in global consumption of LIBs was observed in recent years, mainly due to the growing market for electric vehicles (EVs). Currently, China, Japan and South Korea collectively account for around 80% of global LIB production. A large portion of international LIB recycling takes place in close proximity to these LIB manufacturing facilities, since closed-loop systems with recycling at the end-of-life provide a source of recycled battery materials that can be used by the manufacturers for the production of new batteries. Without a local LIB manufacturing sector, the local demand for resources recovered from LIB waste will also be lower. Although the quantities of LIBs being recycled globally are still small, the anticipated large amounts of spent lithium-ion batteries joining the waste stream in the next decade, is currently driving the establishment of new recycling facilities, especially in the Northern hemisphere and it is anticipated that North American and Asian regions will lead the growth in LIB recycling activities between 2020 and 2030.

Currently there are three recycling process options available for the processing of waste LIBs; pyrometallurgy, hydrometallurgy and direct recycling. Pyro- and hydrometallurgical technologies have been commercialised, whereas direct recycling is still in the research stage. These different processes can be combined in different flowsheet configurations, depending on factors such as quantity and characteristics of the material available and quantity and value of the materials that can be recovered. The hydrometallurgical route is favoured for new installations in China, the United States and Northern Europe.

Historically, the main objective of Li-ion battery recycling has been recovery of high value metals such as cobalt and nickel. However, as the cobalt content in batteries decreases and mandatory recycling regulations are globally coming into effect, interest is growing in recovery of additional components such as lithium, graphite and electrolyte. Technology development is a very dynamic area and further progress can be expected in the coming years, especially in the face of ongoing battery development, such as changing battery chemistries and varied design types. The ongoing developments are making it difficult to establish robust, versatile and cost competitive recycling processes.

Due to the complex process chains, a number of new operations have recently started to follow the route of partnership formation, in which companies do not cover all process steps, but typically pre-treatment, metallurgy, refining and cathode material production are operated by different companies.

Locally, interviews conducted with various stakeholders indicated that very low volumes (between 6-10 tonnes) of LIB waste are annually collected in South Africa. This represents around 1% of the estimated LIB waste annually generated in South Africa. The waste originates mainly from the consumer electronics and ICT equipment sectors. The low volumes are insufficient to support a local recycling facility and as a result the current LIB waste in South Africa is either stockpiled, landfilled or shipped to recycling facilities abroad.

A techno-economic study was performed to investigate the business case for the establishment of a LIB recycling industry in South Africa. Three generic flowsheets, pyrometallurgical, hydrometallurgical and physical processing to produce a black cathode powder (black mass) were analysed. Based on the analysis, the most profitable recycling route is the production of black mass, which can be sold to metal refineries, followed by the hydrometallurgical and pyrometallurgical routes. The analysis shows that recycling only becomes economical at a LIB feed rate of round 500 tpa for high-value batteries, while for lower value batteries, the process becomes economical at much larger capacities. Profitability is very sensitive to the feed composition, specifically the Co, Ni and Cu content. If battery manufacturers are successful in developing battery chemistries containing less cobalt, the revenue from recycling is likely to decrease.

At the current low collection rates, there is not a business case for establishing a commercially viable LIB recycling plant in South Africa. The biggest driver for the establishment of such a facility would be the anticipated growth in the EV market and the use of these batteries in renewable energy storage applications. The impending implementation of the Extended Producer Responsibility (EPR) regulations by the Department of Environment, Forestry and Fisheries (DEFF), the approaching ban on the landfilling of battery waste coming into effect during August 2021 and the environmental and safety risks (fires caused by LIBs stored in materials recovery facilities and landfills) associated with storage and landfilling of LIBs are additional drivers for considering the development of a local LIB processing facility in South Africa.

Globally, the EV revolution is anticipated to happen over the next 10 years, however South Africa is lagging behind, and the impact of large volumes of end-of-life batteries entering the waste stream will probably only be experienced in the next 10 to 20 years. Until such time, it is recommended that:

- Strategies to increase the collection of LIBs be implemented.
- Government encourages the uptake of EVs in South Africa through acceleration of the implementation of South Africa's Green Transport Strategy, implementation of fiscal incentives to make EVs more cost-competitive and stimulate market penetration, and addressing issues related to the availability of charging stations, reliable electricity supply and possibly setting manufacturing and sales targets as is being done elsewhere.

Until local volumes increase sufficiently to merit a local recycling facility, it is recommended that processes be implemented to treat LIBs to a stable/safe state, after which they can be exported to international recycling facilities.

Longer-term recommendations include:

- Once collection rates around 500 tpa are reached, a small-scale mechanical plant for the pre-processing of the LIB waste to produce black mass could be implemented. The black mass can be treated locally through partnerships with metallurgical operations or exported to international refineries for metal recovery.
- Once a reliable supply, of large enough LIB waste volumes, is collected a hydrometallurgical plant can be considered for the treatment of LIBs to produce either metal precipitates or high purity battery materials.
- The LIB waste volumes available for local treatment can be increased by accepting regional or international LIB waste through creation of a favorable economic and regulatory environment for battery recycling. It is, however, questionable if we could be competitive in a market currently dominated by China.

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Abbreviations

Abbreviation	Definition
CAGR	Compounded Annual Growth Rate
Capex	Capital expenditure
Co	Cobalt
Cu	Copper
DEFF	Department of Environment, Forestry and Fisheries
DOE	Department of Energy
DoT	Department of Transport
DRC	Democratic Republic of the Congo
DSI	Department of Science and Innovation
Dtic	Department of Trade, Industry and Competition
EEE	Electrical and Electronic Equipment
EoL	End of Life
EPA	Environmental Protection Agency
EPR	Extended Producer Responsibility
EU	European Union
EV	Electric vehicle
eWASA	E-waste Association of South Africa
E-waste	Electronic Waste
EPCM	Engineering, procurement and construction
Fe	Iron
G	Gram
ICASA	Independent Communications Authority of South Africa
ICT	Information and Communication Technology
ICE	Internal Combustion Engine
IEA	International Energy Agency
IRR	Internal rate of return
IT	Information Technology
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
LIB	Lithium Ion Battery
Li	Lithium
LMO	Lithium Manganese Oxide
Mn	Manganese
MWh	Megawatt-hour
NCA	Nickel Cobalt Aluminium
Ni	Nickel
NiCd	Nickel Cadmium
NiMH	Nickel Metal Halide
NMC	Nickel Manganese Cobalt
OEM	Original Equipment Manufacturer
PCB	Printed Circuit Board
SADC	Southern African Development Community
SOE	State Owned Enterprise
USGS	United States Geological Survey
t	Tonnes
tpa	Tonnes per Annum
USA	United States of America
USD	United States Dollar
WEEE	Waste Electrical and Electronic Equipment

1 Introduction

1.1 Background

Lithium ion batteries (LIBs) are important electrochemical energy storage devices because of their unique characteristics, which include their high energy capacity, long lifespan, compact design, better resistance to self-discharge, higher resistance to elevated temperatures and higher voltage output when compared with other types of batteries such as nickel metal hydride (NiMH) and lead (Pb) acid batteries (Martinez et al., 2019).

The global consumption of LIBs has increased sharply in recent years in line with the increasing use of electrical, electronic, industrial and mobility equipment to improve people's lives. The automotive and transportation sectors are poised to become the single largest and fastest growing segment of the global LIB market, reaching 8.6TWh by 2030 (Table 1). This segment of the global LIB market is estimated to grow by a compounded annual growth rate (CAGR) of 21% between 2020 and 2030 (IHS Market Insight, 2020).

Table 1. Expected growth in energy demand in different market segments (HIS Market Insight, 2020)

Segment	Expected demand	Expected compound annual growth rate (CAGR)
Automotive and transport	8.6TWh	+21%
Energy storage	418GWh	+16%
Portable electronics	604GWh	+3%

The increased demand for LIBs, combined with improvements in battery technologies, has stimulated LIB production. This has led to an 85% decline in LIB prices (Figure 1), which is having a positive effect on electric vehicle sales and application of LIBs in stationary energy storage. This increase in LIB applications will, however, translate in higher volumes of LIBs joining the waste stream in the next 10 years. Consequently, policy makers throughout the world are shifting their focus to end-of-life management of LIBs to reduce their environmental impacts, as well as recovering and re-using the secondary resources contained in the batteries (Zhang et al., 2018).

Only limited quantities of LIBs undergo recycling at the end of their useful lives, with the majority being held in storage in households, government departments and company warehouses before ultimately being landfilled. Aside from the environmental benefits of redirecting waste LIBs, their processing in recycling plants represents an important source of secondary metal supply, particularly for critical and strategic high-value, hard-to-access metals including copper, cobalt, nickel, aluminum and lithium (Martinez et al., 2019). In addition to the recovery of strategic metals in LIBs, the collection, dismantling and pre-processing of LIB containing waste electrical and electronic equipment presents a significant opportunity to expand and diversify the small and medium-sized business sector, particularly in developing countries (World Bank, 2020).

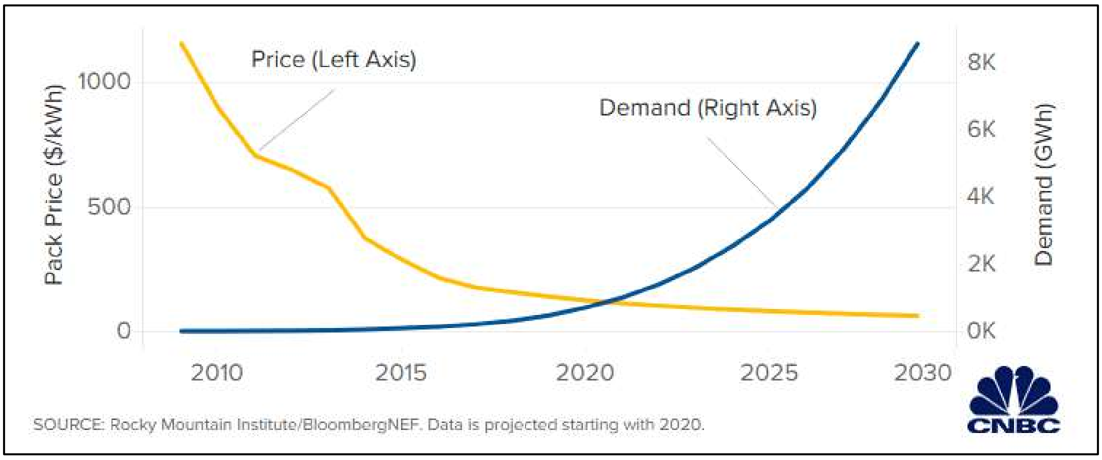


Figure 1. Li-ion battery market development for electric vehicles

Despite these advantages, LIB recycling processes are still under development in most countries, whilst the technologies that are being used are not yet fully optimized. This is due to a variety of reasons including the non-availability of sufficient recycling volumes (lack of economies of scale), inefficiencies in LIB collection, the complexities in different LIB designs and the numerous battery chemistries involved.

Unlike for LIBs, Pb-acid batteries, through various iterations have become standardized and easy to recycle with approximately 95% of the material found in Pb-acid batteries being recovered and re-used (Thompson et al., 2020). Stakeholders in the automotive industry have developed dedicated collection channels for the Pb-acid battery and manufacturers of Pb-acid batteries use the recovered material in the manufacturing of their products, which makes recycling comparatively simple, capable of attaining sufficient recycling volumes and profitable. Conversely, LIBs are made from a variety of materials and this material complexity makes it difficult to implement standard recycling processes.

In addition, the collection of LIBs for recycling has remained low in many parts of the world. Detachable LIBs found in small consumer electronics equipment such as mobile phones are lost or thrown away when the equipment becomes obsolete. LIBs used in electric vehicles have an average useful life of 10 years. These batteries find their way to automotive OEMs and their dealer networks, but the collection strategies are not yet fully developed, since the electric vehicle market is in its infancy and still very small in many countries.

South Africa does not currently have processing facilities for complex waste fractions such as printed circuit boards (PCBs) and LIBs, resulting in these fractions being exported in their raw form or landfilled after dismantling. The country is facing a number of challenges in the collection, transportation, treatment and proper disposal of waste due to an expanding population, higher levels of urbanisation and increasing waste generation volumes. Although South Africa has an extensive waste management and regulatory framework supporting sound waste management practices, landfilling still remains the most preferred waste management solution for most municipalities and other stakeholders in the waste sector. The country is estimated to be landfilling approximately 90% of all waste generated due to the limited use of technology in the dismantling, pre-processing and processing of waste and the relatively underdeveloped domestic markets for waste fractions (DST, 2013).

While the South African government recognizes the importance of implementing alternative waste treatment technologies as a way of diverting waste from landfill sites and create value addition opportunities in the waste sector, business entities and municipalities have been slow in making this transition. A number of reasons, including the lack of customized and fit for purpose technology solutions, reluctance in adopting proven technologies and non-availability of repair and maintenance solutions explain why companies in South Africa's waste sector have been slow in implementing treatment technologies (DST, 2013).

In addition, waste management companies have also cited the lack of sufficient feed material supply to ensure commercially viable recycling operations and lack of end markets for fractions they produce as some of the key challenges they experience in implementing alternative waste treatment technologies. One such waste stream that has been affected by the challenges cited above are LIBs, which are mainly recovered from the consumer electronics and information communication technology (ICT) equipment waste stream in South Africa.

In South Africa, there is no reliable data on the quantities of the waste LIB material that are potentially available for recycling, neither are the origins (sources), the flows, intermediate and final markets of LIB fractions very well understood. Such information is critical in informing the decisions on technology selection as well as determining the economics of the process. To date, the focus of waste electrical and electronic equipment (WEEE) recycling activities, from which LIBs are mainly recovered, has largely been on the recovery of ferrous, non-ferrous metal and printed circuit board (PCB) fractions. This is mainly due the well-developed state of the downstream metals recycling sector in South Africa and export markets respectively.

Although some studies have previously been conducted on the LIB value chain in South Africa, no study has been undertaken to evaluate the technology landscape and assess the business case and economics of establishing a LIB processing plant in the country. From a business perspective, this assessment is a critical first step that will inform the decisions that will be made about technology selection as well as the economic and financial viability of the chosen technology, while from a policy perspective this assessment will be critical in determining the interventions required to unlock potential business opportunities in the LIB sector.

In 2020, the DSI/CSIR's Waste RDI Roadmap awarded Mintek funding to evaluate the technology landscape and assess whether there is sufficient LIB waste that can support the establishment of a commercially viable LIB processing plant in South Africa. This study fulfills the Waste RDI Roadmap's objective of diverting waste from landfill, towards value adding opportunities and optimized extraction of value from reuse and recycling of waste.

1.2 Aims and objectives of the study

The overall aim of this research was to evaluate the technology landscape and assess whether there is a business case for the establishment of an LIB processing plant in South Africa.

Specifically, the objectives are three-fold and are as follows:

- Provide an overview of the current state of the LIB recycling industry in South Africa by identifying the companies involved in the LIB recycling value chain, volumes of waste LIB material collected, markets that LIB fractions are sold to and the future outlook of the industry in the next 5-10 years.
- To identify and assess commercial recycling technologies that are currently available, evaluate the extent to which these technologies can be adapted to suit the South African situation (volumes handled, synergies with other waste streams, cost implications) and to identify the gaps in technology solutions.
- To develop a business case for the establishment of a LIB processing plant in South Africa, which will support the diversion of LIB waste from landfill sites as well as the development of a local secondary resource economy that provides maximum local social and economic benefit to the country.

1.3 Research approach

A three-pronged approach was applied in collecting and validating the data used in this study:

- **Primary data collection** – A total of 15 primary interviews were conducted with WEEE recyclers, information communication technology (ICT) and automotive original equipment manufacturers (OEMs), state owned entities (SOEs) and telecommunications companies, battery storage researchers and national government departments in order to understand the origins (sources), the flows, intermediate and final markets for LIB fractions and determine the quantities of the waste LIB material that is potentially available for recycling in South Africa (Annexure 1). Participants in the study were selected on basis of the role they play in the LIB value chain in the country.
- **Secondary research** – A desktop review of publicly-available local and international reports on LIB recycling was conducted to establish the broad trends and dynamics impacting on the LIB industry locally and globally, the scope and nature of LIB recycling in various parts of the world, end-user markets for LIB fractions and the nature and availability of technology used in the dismantling, pre-processing and processing of LIBs.
- **Leveraging off existing internal expertise** – Mintek scientists and engineers have gained very broad experience and exposure in designing and evaluating the economic viability of pyrometallurgical and hydrometallurgical processing plants in different commodity sectors and across many countries in the world through a variety of research and consulting projects. In the recycling sector, Mintek is involved in the development of technologies for the treatment of complex waste streams including PCBs and WEEE plastics. In the battery chemicals and energy storage sector, the South African government appointed Mintek to be a technical partner to Eskom's World Bank funded 'Energy Storage' project.

1.4 Parameters and delimitations

1.4.1 Value chain parameters

In South Africa, the LIB recycling value chain is inextricably linked to the WEEE value chain since LIBs are integral components that power EEE including laptops and mobile phones. Therefore, the LIB value chain consists of four stages – collection, dismantling, pre-processing and processing (Figure 2).

Figure 2. The four stages of the LIB recycling value chain

Whilst the objective of this study was to consider whether there is a business case for the establishment of a LIB recycling facility in South Africa, it nonetheless touched on the full LIB value chain in order to determine the quantities of waste LIB material potentially available for recycling in the country as well as understanding the sources, flows and markets of the material.

Although there is an intricate web of informal LIB trade characterising the WEEE recycling sector in South Africa, particularly with Asian and North African countries, only formal activities were reviewed in this study.

1.4.2 Geographic scope

From a geographic perspective, the scope of the study was limited to collection, dismantling, pre-processing and processing of LIBs in three provinces – Gauteng, Western Cape and KwaZulu-Natal (KZN). This is due to the concentration economic and recycling activities in these three provinces in South Africa.

1.4.3 Definition of lithium ion batteries

LIBs comprise a wide range of electro-chemical energy storage devices that are made from a variety of anode and cathode materials, different electrolytes and other components. Currently there are different types of LIBs available, with a variety of chemical compositions and suitable for different applications. Typically, consumer electronics equipment are powered by relatively smaller LIBs that discharge very quickly and should be recharged every day, whilst electric vehicle batteries have higher level of power and energy density to enable the vehicles to accelerate, gain speed and drive long distances (Danino-Peraud, 2020).

From a product perspective, the study focused on the following LIB categories (Table 2).

Table 2. Lithium Ion Battery Categories

LIB Category	Applications
Lithium nickel cobalt aluminium oxide – NCA ($LiNiCoAlO_2$)	Electric vehicles & renewable energy storage applications
Lithium nickel manganese cobalt oxide – NMC ($LiNiMnCoO_2$)	Electric vehicles, power tools, home energy storage & medical applications
Lithium cobalt oxide – LCO ($LiCoO_2$)	Smart phones, lap tops, tablets & cameras
Lithium iron phosphate – LFP ($LiFePO_4$)	Renewable energy storage applications, e-bikes, electric vehicles & medical devices
Lithium manganese oxide – LMO ($LiMn_20_4$)	Hybrid electric vehicles, power tools, cell phones, laptops & medical devices
Lithium titanate – LTA ($Li_4Ti_5O_{12}$)	Electric vehicles, renewable energy storage applications, & buses

1.4.4 Data availability and disclosure challenges

In developed parts of the world, such as the European Union (EU), the installed capacity of electrical and electronic equipment (EEE) and LIBs put on the market, electric vehicle sales, their useful economic lives, the collection, refurbishment and recycling volumes for LIB waste are readily available from national statistical bodies. In the EU, region-wide battery recycling targets, take back channels and recycling best practices are very well established.

Although there is growing interest and acknowledgement of the waste LIB challenge in developing countries including South Africa, the recycling industry in most of these countries is still in its infancy and there is no central repository or database of quantitative data pertaining to the volumes of LIB generated, held in storage, the lifespan of obsolete goods, intermediate and final sinks (markets) for LIB waste. The installed capacity of laptops in South Africa, from which LIBs are derived is not known and cannot be independently verified.

Aggregated sales data from retailers regarding electronic goods sales is largely unavailable and recycling companies are not required by law to disclose the quantities and the markets that WEEE fractions are sold to. In addition, the rollout of LIBs for automotive and energy applications is still in its infancy with the majority of the batteries in these applications not expected to reach the end of their life for another 10-15 years.

In an effort to address these challenges, Mintek supplemented the data it gathered from interviews through approximations derived from its previous projects on LIBs and energy storage, as well as engagements with energy storage researchers in universities, science councils and state owned enterprises (SOEs).

1.4.5 Report structure

The report commences with a brief review of the global LIB recycling value chain, which provides contextual overview of LIB supply and demand flows and processing routes (Chapter 2).
Chapter 3 discusses the structure and dynamics in South Africa’s LIB recycling industry and presents the findings from the primary data gathering process.
Chapter 4 gives an overview of established and emerging recycling technologies for the treatment of LIB waste material.
Chapter 5 discusses the findings from a desktop techno-economic study performed to evaluate the feasibility of LIB recycling.
Chapter 6 concludes with a discussion of the main findings from the study and a list of recommendations.

2 The Global Lithium Ion Battery Recycling Industry

A number of supply, demand, cost and sustainability factors are expected to drive the rapid expansion of the global LIB recycling industry, resulting in it tripling its capacity by 2030. The increasing volume of end-of-life batteries from the consumer electronics and electric vehicle sector will create a sizeable repository of recyclable material and this will increase the profitability of LIB recycling activities. Industry analysts anticipate that, globally, more than 500 000 tonnes of LIBs reached the end of their useful economic life in 2019. That figure is forecasted to increase to 1.2 million tonnes in 2025 and will reach 3.5 million tonnes in 2030. Large scale LIB recycling infrastructure is therefore required to ensure that this LIB waste is processed in an environmentally sustainable manner (IHS Markit, 2020).

Accurate data regarding the production and installed capacity of LIBs in EEE and electric vehicle sector per each segment or region of the market, useful economic lives, rate of disposal, flows and markets for fractions and the quantities of LIB waste material potentially available for recycling in each country is globally not readily available. Although government agencies, industry analysts and researchers have made approximations of LIB production quantities, their installed capacity in EEE and the volumes of LIB waste potentially available for recycling, these estimates vary greatly and in most cases can not be independently verified.

A confluence of factors are expected to fundamentally change the dynamics and trends in the global recycling industry within the next 5 years – 10 years. Tightening environmental legislation, the increasing popularity of electric vehicles and renewable energy applications are expected to drive the growth in consumption of LIBs world-wide, whilst inefficiencies in LIB waste collection systems and material complexity of LIBs will hold back the growth of the downstream LIB recycling industry.

This chapter provides an overview of global LIB production trends, current recycling trends, estimates of the installed capacity of LIBs in EEE and electric vehicles, drivers and challenges to LIB recycling and the current technology landscape for LIB recycling.

2.1 Global production of LIBs

It is estimated that the total global LIB manufacturing capacity was 189 762 MWh for all end market applications in 2019, with the bulk of this manufacturing capacity concentrated in China, the USA, Japan, and South Korea (Mayyas et al., 2020). Asian countries (China, Japan and South Korea) collectively accounted for 84 % of global LIB production capacity for all applications during the same year (Table 3). At country level, China is the world's largest LIB manufacturer, accounting for 62.3 % of global LIB manufacturing capacity in 2019, while the USA and Japan ranked second and third, accounting for 13.1 % and 11.8 % of global LIB manufacturing capacity respectively (Mayyas et al., 2020).

Japan's LIB manufacturing cluster grew steadily from sustained investments in LIB manufacturing technology made by consumer electronics companies in the 1980s and 1990s as well as the Japanese government's funding of R&D activities in the consumer electronics sector to build the country's competitive advantage in that sector (Mayyas et al., 2020).

Table 3. Lithium Ion Battery Manufacturing Capacities in 2019

Country	Total Capacity (MWh)	Share of Total Capacity (%)	Automotive Capacity (MWh)
China	118 234	62.3	50 670
Japan	22 479	11.8	19 414
South Korea	18 547	9.8	17 874
USA	24 766	13.1	22 016
EU	2 626	1.4	2 400
Rest of the World	3 110	1.6	2 110
Total	**189 762**	**100**	**114 484**

China replicated and surpassed Japan's success in the consumer electronics and LIB manufacturing sectors by subsidizing the LIB industry, offering R&D and concessionary funding facilities, tax and investment incentives, imposing export restraints and domestic content requirements to the industry.

The South Korean LIB manufacturing cluster was built through partnerships between the government and the consumer electronics manufacturing sector. Although the USA currently accounts for only 13.1% of global LIB manufacturing capacity, this is expected to grow rapidly in the near to medium term in response to the anticipated boom in the electric vehicle sector. Tesla, is for example, building a LIB manufacturing plant in Nevada, USA to power its electric vehicles (Mayyas et al., 2020).

While many European auto manufacturers are marketing their electric vehicles in the global markets, LIB manufacturing capacity in the EU is only 1.4% (2 626 MWh) of the total global production. However, the low LIB manufacturing capacity could stimulate European automotive manufacturers to develop regional supply chains for LIBs and related components in the region. To this end, Daimler invested $610 million to build a LIB plant in Germany in 2018, whilst 16 other LIB manufacturing plants are planned for Sweden, Hungary and Poland in the near to medium term (Mayyas et al., 2020).

Going forward, LIB manufacturing is expected to increase significantly in line with the continuous improvements of battery chemistries, growing electric vehicle fleets and the growing demand for EEE in both developed and developing countries.

2.2 Installed capacity of LIBs

The global LIB manufacturing industry is estimated to have produced 7 billion units of LIBs for various market applications and was worth $44.2 billion in 2020 (Table 4). The batteries for consumer electronics products (laptops, mobile phones, cameras and notebooks) are typically small, weighing an average of 20 - 30 g and have useful economic lives of between 2 - 3 years. Electric vehicle LIBs are large, weighing an average of 200kgs - 300kgs and have a useful economic life of between 5 to 10 years (Mossali et al*.,* 2020).

Table 4. Global LIB installed capacities

LIB Market	2010-2020	2020-2030
Units sold	7 billion (2020)	>15 billion (2030 estimate)
Market size	$44.2 billion (2020)	$100 billion (2030)
EV LIB unit sales	>5 million	180 million (2030)
Major LIB types	NMC (31%), LCO 14%, LFP (38%)	NMC (68%), Li-S (10%), LCO (10%)
Price	$150-$300/KWh	>$100/KWh
LIB waste projections	500 000 tonnes	3 500 000 tonnes

Spurred by rising demand electric vehicles and the burgeoning consumer electronics sector, the global LIB production is forecasted to increase to approximately 15 billion units that are estimated to be worth $100 billion by 2030. The world's electric vehicle fleet is forecasted to increase from less than 5 million vehicles currently to approximately 180 million by 2030.

The NMC batteries which currently account for 31% of global LIB sales will increase their share of the market to approximately 68% by 2030. In addition, LIBs which currently cost between $150-$300/KWh are forecasted to cost less than $100KWh by 2030 (Mossali et al., 2020). It is estimated that, particularly the projected increase in EV sales over the ten years, will result in a seven-fold increase in the LIB waste produced, which will put strain on the global LIB recycling capacity.

2.3 Global LIB recycling trends

Globally, the quantities of LIB waste potentially available for recycling and the actual recycled volumes are not very well documented. This is mainly due to the absence of dedicated LIB collection systems, lack of LIB processing plants in many parts of the world and the material complexity of LIBs that makes it difficult to recycle in standardised recycling plants (Danino-Perraud*,* 2020).

Eric Melin, a world renowned LIB life cycle management expert, estimates that approximately 500 000 tonnes of LIB waste was generated and available for recycling in 2019, from which only 110 000 tonnes were recycled (Mayyas et al., 2020). Research undertaken by the European Commission's Joint Research Centre, established that an estimated 47% of the global LIB recycling capacity is located in Asia, while European countries accounted for 32%. The USA is far behind Europe and Asia, accounting for less than 5% of global LIB recycling capacity. This is partly due to the fact that, the consumer electronics sector, which has been at the forefront of LIB manufacturing and recycling technology development in Asia and Europe in the past decade, is very small in the USA. However, this situation is poised to change dramatically in line with the increasing popularity of electric vehicles powered by LIBs in the USA market (Danino-Perraud*,* 2020).

The bulk of LIB recycling activities during 2019 was concentrated in China and South Korea, which also dominate the world's LIB manufacturing activities. China and South Korea are estimated to have recycled 67 000 tonnes and 18 000 tonnes of LIB waste respectively in 2019. A modest 15 000 tonnes of LIB waste is estimated to have been recycled in Europe during the same year (Mayyas et al., 2020).

Australia is estimated to have generated around 3 300 tonnes of LIB waste in 2017 from which between 66t - 99 t (2%-3%) was collected and exported for offshore recycling during that year. Research work undertaken by environmental scientists indicate that Australian LIB waste is growing at approximately 20% per annum and LIB waste generation is forecasted to reach between 100 000 tonnes – 188 000 tonnes by 2036 in line with the anticipated increase in the uptake of electric vehicles and use of LIBs in renewable energy storage applications (King et al., 2018).

Unlike elsewhere in the world, Australia is yet to formalise its policies and regulations around product stewardship for LIB waste. Consequently, the recycling of waste batteries has been intermittent and patchy at best, with the majority of small recycling schemes relying on scrap metal recyclers to break down the waste for export as there is no dedicated infrastructure or technology available to process and recover the value from the waste locally. The majority of this waste is disposed at landfill sites, which has undesirable environmental and human health implications (Randell et al., 2015).

As already indicated, the recycling of LIB waste in the USA is not very well developed, with an estimated 95% of LIB waste that was collected in the country being landfilled in 2017. To date, LIB recycling has not been proven to be profitable in the USA and the country has much lower recycling capacity than China, the EU, Japan and South Korea. In addition, the rate of recycling varies considerably between the three primary types of consumer electronics equipment. In 2017, mobile phones accounted for approximately 21% of the mass of consumer electronics sold, but only 9% were recycled when they became obsolete. Laptops made up about 72% of the mass of consumer electronics equipment sold in the USA in 2017 and were recycled at a much higher rate of approximately 40%. Overall, the recycling rate for consumer electronics in the USA was approximately 30% by mass, but the rate of recovery of the batteries in these devices appears to be much lower (Randell et al., 2015). However there are a number of recycling start-up companies that are at various stages of construction, which when completed will radically transform the LIB recycling landscape in the USA. Li-Cycle, a Canadian company is in the process of developing a 25 000 tpa LIB recycling plant in New York State, which when completed will become the largest LIB recycling facility in North America.

China's LIB recycling industry is very well developed and it is supported by strong backward linkages with companies involved in the upstream collection, dismantling and pre-processing of LIB waste as well as forward linkages with the downstream consumer electronics manufacturing sector that buy the valuable metals for the manufacturing of new EEE. This has resulted in China having the largest LIB recycling capacity in the world (Mayyas et al., 2020).

2.4 Global LIB recycling industry size and outlook

Markets and Markets, a United States based market research house, estimated the global LIB recycling industry to have been worth approximately $1.5 billion in 2019 and is projected to grow at a compound annual growth rate (CAGR) of 8.2% between 2020 and 2030. The global recycling industry's value will reach $12.2 billion in 2025 before growing further to reach $18.1 billion in 2030 (Figure 3). The rising global LIB production, increasing global concern about the harmful environmental impacts of battery waste disposal together with the anticipated rapid increase in the world electric vehicle fleet are expected to remain the key drivers of growth of the LIB recycling industry during the forecast period (Markets and Markets, 2020).

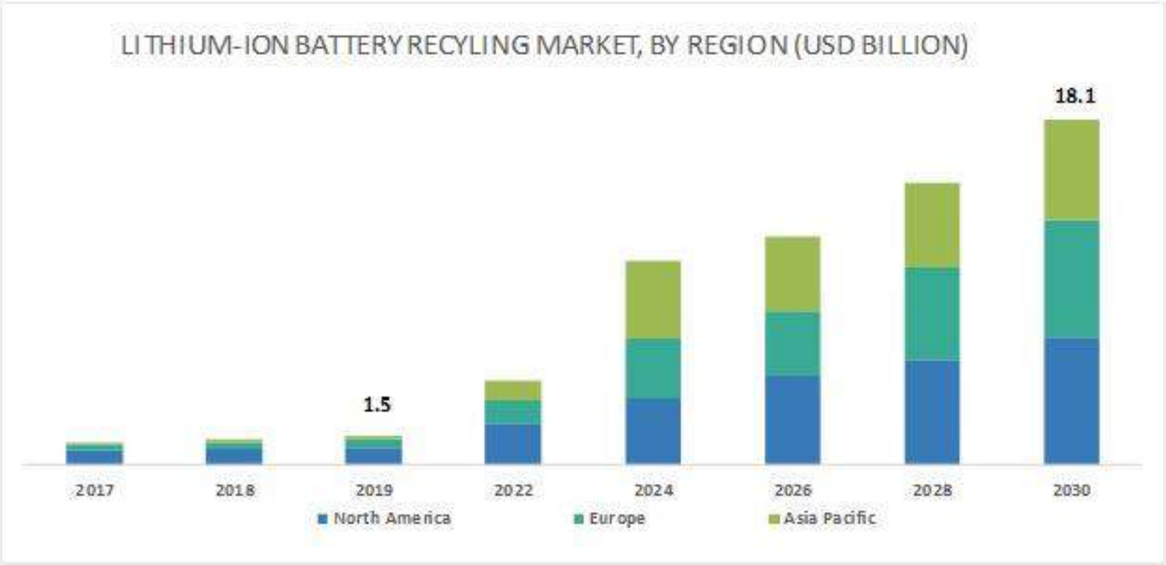


Figure 3. Global LIB recycling industry growth trends (2019 -2030)

The North American region is projected to lead the LIB recycling industry growth between 2020 to 2030 in terms of both value and volume. This is attributed to the increasing popularity of electric vehicles in the North American market, implementation of the stringent environmental regulations by the Environmental Protection Agency (EPA) and the additional LIB manufacturing and recycling plants under construction in both the USA and Canada. LIB recycling activities in both Asia and the EU regions are also set to grow in line with the anticipated increase in battery collections and expansion of existing recycling capacities (Table 3).

A series of mergers and acquisitions, strategic alliances, geographic expansions, divestments and joint venture have left the LIB recycling industry concentrated in the hands of a few large scale players with considerable market power (Markets and Markets, 2020). Umicore (Belgium), Accurec (Germany), Redux (Germany and Austria) International Metals Reclamation Company, LLC /INMETCO (USA), Retriev Technologies (USA), Akkuser and Boliden (Finland) are currently dominant players in the global recycling industry.

2.5 Global drivers of LIB recycling

Globally, LIB waste is now considered a strategic waste stream with significant metallic value that can be targeted for recovery. A complex interplay of factors have been driving the growth of the global LIB recycling industry in the past decade. These include:

- **Rising commodity prices** - Lithium, cobalt and nickel prices have risen significantly in the past decade in response to rising demand for battery metals from the consumer electronics and electric vehicles manufacturing sectors on one hand amid constrained sources of supply on the other. Although, historically, recycling has not been a significant secondary source of lithium, cobalt and nickel supply, this has changed significantly in recent years owing to the growth in volumes of recyclable material available and rising commodity prices.

  Lithium is the least recycled of the three battery metals. Currently less than 1% of the lithium used in consumer electronics products is recycled and this is partly due to the relatively large above the ground stocks of lithium when compared to cobalt, as well as the cost of recovering lithium through recycling (Benchmark Mineral Intelligence, 2019).

  The Democratic Republic of Congo (DRC), which accounts for over 50% of global new mine supply of cobalt, is an unstable mining jurisdiction fraught with armed conflicts, unpredictable mining regulatory regime and seizure of mining assets. This has resulted in cobalt prices increasing by 300% between 2013 and 2019 to reach $95 000/tonne. The nickel market was in deficit in the past 5 years in response to constrained supply from major producing countries, Indonesia’s ban on ore export and burgeoning demand for nickel from the Chinese stainless steel manufacturing sector. Battery grade nickel price averaged $15 000/t in 2020 and it is projected to be on the upward trend between 2021 and 2025.

  Lithium prices have been increasing since 2000 owing to increasing demand from automotive and EEE manufacturers in the USA and China amid supply side constraints, particularly in Australia (USGS, 2019). Depending on the type of lithium compound (lithium carbonate and lithium hydroxide) and the grade, prices can range between $15 000/t and $30 000/t. According to Benchmark Mineral Intelligence (2019) spot lithium carbonate prices ranged between $20 000/t – $25 000/t in China in 2017 owing to tight supply of imported spodumene from Australia. Comparatively, lithium hydroxide prices in China ranged between $25,000/t – $30 000/t. In the United States, lithium prices for all grades ranged between $13 500/t and $16 000/t in 2019 (Benchmark Mineral Intelligence, 2019).

  Research in the EU indicated that LMO (without cobalt) and LCO batteries contained valuable metals worth approximately $860/t and $8 900/t respectively. Globally, many of the existing industrial scale recycling plants target LCO and NMC battery chemistries because of high cobalt content which translate to higher profits. Conversely LMO and LFP which contain little or no precious metals are not widely recycled due to the low possibility of making profits out of the recycling operations (Danino-Peraud, 2020).

Research undertaken by Australia’s Commonwealth Scientific and Industrial Research Organisation (CSIRO) estimated LIB waste material to be containing valuable metals worth between \$3 600/t - \$13 900/t in that country (King and Boxall, 2019).

- **Reducing reliance on primary mining activities**

According to several lifecycle analysis (LCA) studies, rising consumer electronics and electric vehicle manufacturing since 2000 has induced a greater reliance on mineral resources such as cobalt, nickel, lithium, manganese, which are non-renewable, than in the 1980s and 1990s when the use of consumer electronics technology and electric vehicles was low.

Benchmark Mineral Intelligence (2019) estimates that the consumption of lithium and nickel in battery manufacturing will increase from 150 000 tonnes and 82 000 t in 2018 to 1.89 million tonnes and 1.09 million tonnes respectively in 2028 owing to strong demand from the electric vehicle manufacturing industry (Figure 4). In addition, cobalt and graphite consumption in battery manufacturing will increase from 58 000 tonnes and 170 000 tonnes in 2018 to 320 000 tonnes and 2.05 million tonnes respectively in 2028 (Benchmark Mineral Intelligence, 2019).

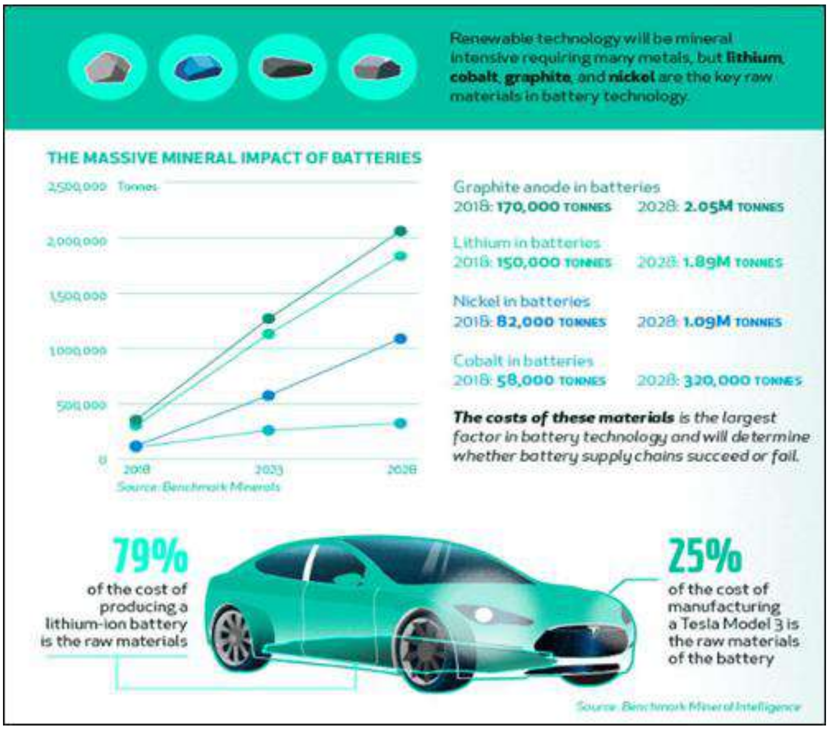


Figure 4. Impact of battery manufacturing on mineral demand

While many industry analysts maintain that the mining industry will be able to meet this anticipated increase in demand, as evidenced by the many lithium, nickel and manganese development projects throughout the world, it is preferable to minimize reliability on mineral extraction and processing because of the adverse environmental impacts (Beaudet et al.,2020).

The recycling of mineral bearing waste which is commonly referred to as 'urban mining' is clearly a part of the solution in this regard. LIB waste recycling could significantly reduce the demand for battery metals and the adverse impacts of resource utilization. A study performed in the USA estimated that approximately 65% of the cobalt necessary to satisfy automotive sector demand in the US can be met from recycling activities. Research in Europe indicated that between $485 million - $606 million worth of metals (at current prices) can be recovered from waste material throughout the EU region's urban mines by 2030. In addition, the World Economic Forum (WEF) estimate that obsolete electric vehicles could become the single largest stock of critical battery metals by 2050 (Beaudet et al., 2020).

- **Compliance with environmental regulations and policies** – The recycling of LIB waste and development of technology for the recovery of valuable secondary materials from battery waste in many parts of the world has largely been driven by the need to comply with environmental regulations that prohibit the disposal of both hazardous and non-hazardous waste from landfill site (King and Boxall, 2019).

  The EU's Battery Directive 2006/66/EC is one such environmental policy that has led to the development of the LIB recycling industry in the EU region. It has led to the development of LIB recycling infrastructure throughout the EU and has set achievable targets for the recovery of resources from battery waste (European Commission., 2014). These targets are driven by supporting regulations which compel manufacturers and distributors of batteries to take them back from users at the end of their useful life and to ensure that a certain percentage of the total battery materials used in the manufacturing of new batteries comes from battery waste.

  Japan and South Korea which are among the largest manufacturers, distributors and consumers of LIBs in the world, have environmental policies and regulations in place that ensure the recovery of valuable metals from battery waste as well limiting its adverse impacts on the environment. The USA and Canada implemented co-regulatory or voluntary product stewardship schemes to manage the environmental impacts associated with improper handling and disposal of LIB wastes (King and Boxall, 2019).

  Although the development of environmental regulations, policy and product responsibility schemes are still in their infancy in many developing countries, they are nonetheless an important milestone that will enable them to meet their obligations under international treaties such as the Paris Accord.

- **Increasing consumer education and social awareness of the waste problem** – Generally, the collection, sorting and pre-processing of waste are the most significant challenges associated with the recycling of waste, since this relies on the consumer to undertake most of the work at home and at no identifiable remuneration to them. Many studies have highlighted that consumer behaviour impacts significantly on the profitability of recycling activities and as such consumer awareness and education programmes are critical in achieving higher resource recovery from waste (King and Boxall, 2019).

Research studies in developed countries have indicated the consumer awareness about the metallic content of LIBs, their harmful impacts on the environment and their willingness to recycle LIB waste is considerably higher than it is for other WEEE categories such as small and large household goods. A study in Australia indicated that the landfilling of obsolete mobile phones declined from 9% in 2005 to 2% in 2015 with the bulk of these mobile phones being re-directed to the recycling value chain. Obsolete LIBs recovered from electric vehicles are highly likely to join the recycling value chain since these will be handed back to the automotive OEMs and their dealer networks (King and Boxall, 2019).

- **Increasing efficiency in recycling technologies** - Battery recycling and standard minerals processing share technologies drawn from hydrometallurgy, pyrometallurgy, comminution and material classification, all of which are all very well developed globally. Recent improvements and development of processes such as direct recycling and biohydrometallurgy have made it possible to recover valuable metals from complex waste streams such as PCBs and LIBs as well as reducing the environmental impacts of the processing of waste (King and Boxall, 2019).

- **Generation of local economic activities** – In line with the increasing use of consumer electronics and uptake of electrical vehicles throughout the world, the recycling of LIBs has potential to become a significant industrial niche of the future, generating billions of dollars in revenue, tax income, clean and sustainable jobs, many of which would be in countries and regions that currently do not benefit from battery-related manufacturing activities. Due to the high cost of transporting used battery packs, there are strong incentives for localizing some components of the recycling infrastructure (Beaudet et al., 2020).

2.6 Challenges to LIB recycling

The world is forecasted to have generated approximately 500 000 tonnes of LIB waste in 2019 but only around 20% of this was successfully recycled for the recovery of high value metals. This can be attributed to a number of challenges including:

- **Low LIB waste collection volumes** – Globally, the low LIB waste collection volumes is the single largest challenge the global LIB recycling industry is facing. Sufficient quantities of LIB waste have to be collected at an optimal and consistent scale to achieve profitability of recycling operations. Globally, many LIB collection systems are deficient, thereby making it difficult for recycling companies to be achieve economies of scale and be profitable. The collection of LIB waste for recycling is still in its infancy and faced with many hurdles including the lack of dedicated LIB collection infrastructure, high storage rates for EEE, cherry picking and lack of domestic markets for LIB waste (Danino-Perraud, 2020).

- **Difficulties in storage and transportation of LIBs** – In many countries, LIBs are classified as hazardous waste due to their unstable thermal and electrical properties. The high fire risk associated with LIBs does not only limit their collection from generators of waste to processing facilities but also make their storage in warehouses and transportation to markets very challenging and this increases operating costs of many recyclers.

- **Material complexity of LIB waste streams** – LIBs, unlike lead-acid batteries, are made from a wide range of materials and this material complexity makes it difficult to disassemble and recover valuable materials using standard recycling processes. However, there is scope to implement the lessons learnt from Pb-acid recycling, once LIB product design and the materials used in their processing are standardized. Existing research indicates that between 95%-98% of the material found in a Pb-acid battery can successfully be recovered and reused because of their standard product design and common raw materials (Thompson et al., 2020).

- **Limited information on the profitability of LIB waste recycling** – Although a number of research studies established that the low LIB waste collection volumes is a primary challenge facing the LIB recycling industry, the limited availability of information on the economics and profitability of LIB recycling was found to be significant factors limiting investment by entrepreneurs in this industry. (Mayyas et al., 2020).

3 South Africa's Lithium Ion Battery Recycling Industry

The South African LIB recycling industry landscape is in transition. Thus far, LIB waste has either been send to landfill or exported to overseas refineries for processing, with little or no emphasis on local beneficiation and the retention of the value contained in LIB waste in the country. However, the impending implementation of the Extended Producer Responsibility (EPR) regulations by DEFF, the approaching ban on the landfilling of battery waste beginning August 2021 and the anticipated increase in the generation of LIB waste from the EV sector are all drivers for considering the development of a local LIB processing facility in South Africa.

This section provides a background on the installed capacity of EEE and EVs, which are the major source of waste streams for LIB waste, in South Africa. It also presents the key findings of the questionnaire survey and interviews conducted with WEEE recyclers, ICT OEMs, battery storage researchers and other stakeholders in South Africa's LIB recycling industry.

3.1 Background and overview of the South African LIB Recycling Industry

As discussed in Chapter 1, the availability of data on the installed capacity of ICT equipment and electric vehicles, the useful economic lives together with the levels of LIB waste generated from these, are major challenges in South Africa. There is no centralized database providing information on the installed capacity of EEE, imports of such equipment into the country every year, electric vehicle sales, LIBs put on the market, their useful economic lives, their collection, refurbishment and recycling volumes.

While approximations have been made by international organisations, national government departments and independent researchers, these estimates vary widely and they are not easily verifiable. The background data used in this section of the report is drawn from various national government and stakeholder publications such as the Department of Trade, Industry and Competition (the dtic), the Department of Transport (DOT), Electronic Waste Association of South Africa (EWASA), Independent Communications Authority of South Africa (ICASA), uYilo e-Mobility Programme and specialist reports by participant firms and consulting companies.

3.2 Information and communication technology market indicators

South Africa is a developing, upper-middle income economy that imports significant quantities of ICT products such as desktop computers, laptops, notebooks, servers and computer accessories including cables, batteries and uninterrupted power supply units from Europe, Asia and North America. All major global ICT OEMs such as Hewlett Packard (HP), Apple, Lenovo and Dell have strong local presence and they use their South African base to service the Sub-Saharan African ICT market.

Brand South Africa and Flicker Leap, a digital solutions company based in Johannesburg, in its 'Digital Statistics for South Africa' publication, indicates that, approximately 11% (6.5million) of the country's population of 59.6 million people owned personal computers (PCs), laptops and notebooks in 2020. This presents a significant increase from 5.5 million personal computers that the International Data Corporation (IDC) estimated were installed in South Africa in 2013 (Brand South Africa, 2020).

Another study that was undertaken by World Wide Worx (2014) entitled 'PC Users in South Africa' estimated that the number of personal computers in use in the country passed the 5 million for the first time in 2006, up from the 4.5 million mark reached in 2005.

The same study established that, in South Africa, PCs have an average life span ranging between 3 years and 6 years, while laptops last for 3 years only. However, many PCs and laptops remain in use for longer than their average useful lives partly due to tighter infrastructure budgets, longer replacement cycles, the need within corporates to extract maximum value out of PCs as well as the difficulties companies experience in keeping up with changes in hardware and software trends (World Wide Worx, 2014).

Notable ICT market indicators for South Africa are indicated in Table 5.

Table 5. ICT market indicators (2020)

Key Performance Description	Indicator
Personal Computers, laptops & notebooks)	6 556 000
Mobile phones	54 355 000
Average life span of PC, laptop & notebook	3 – 6 years
Average life span of mobile phone	2 - 3 years
Average computer imports (units) into South Africa per annum	300 000 – 500 000

The Independent Communications Authority of South Africa's (ICASA) State of the ICT Sector (2020) report, indicates that the country's smartphone penetration reached 91.2% in 2019, up from 81.7% in 2018 with the average useful life of a smart phone estimated at between 2 years – 3 years. The same report indicates that the use of social media, online shopping, online learning and the provision of digital services such as online banking, application for civic documents (birth certificates, identification cards & passports) and the ordering meals from restaurants online will continue expanding the ownership of mobile phones by South Africa (ICASA, 2020).

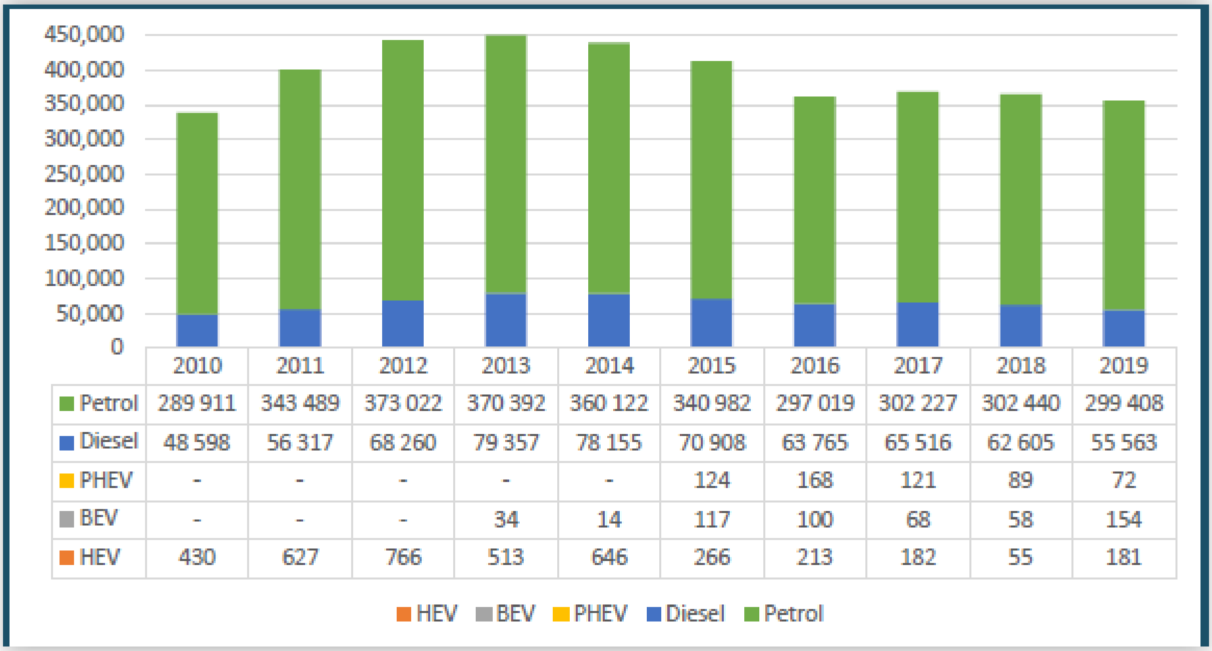
Going forward, the demand for computers in South Africa, particularly laptops and notebooks and mobile phones is expected to remain very strong in line with the need for connectivity and mobility benefits, competitive prices for ICT products, rising consumer disposable incomes and highly aspirational consumers in the country.

3.3 Installed capacity of electric vehicles

Only four fully electric vehicle models (the BMW i3, MINI SE, Porsche Taycan and the Jaguar I-PACE) are available for sale in South Africa (Neves, 2021) in contrast to the 162 models available world-wide in 2020. Although the Nissan Leaf was the second EV to enter the South African market in 2013 after the Joule, which made its debut in 2004, the model has since been discontinued. Nissan planned to launch an upgraded version of the Leaf in 2020, with a 62-kWh battery and 384km range. The Mercedes -Benz EQC, which was expected to be launched in South Africa in 2020 was poised to become the sixth EV model on the local market (Engineering News, 2019).

The exact size of South Africa's EV fleet is not known. However the automotive industry estimates the country's EV fleet to have been approximately 1 000 in 2019, with the majority of these found in the Western Cape and Gauteng provinces. South Africa's annual EV sales have been somewhat unstable (Figure 5). EV sales increased from 34 cars sold in 2013 to 117 cars sold in 2015 before declining to 58 cars in 2018. However, the country's EV sales grew to reach 154 cars in 2019, but this was still significantly less than 1% of the 355 378 new vehicles sold in South Africa during that year (Montmasson-Clair et al., 2020).

The International Energy Agency (EIA) data indicates that, a total of 2.1 million EVs were sold worldwide in 2019, representing 2.6% of global new vehicle sales during that year (International Energy Agency., 2020).



	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
🟩 Petrol	289 911	343 489	373 022	370 392	360 122	340 982	297 019	302 227	302 440	299 408
🟦 Diesel	48 598	56 317	68 260	79 357	78 155	70 908	63 765	65 516	62 605	55 563
🟨 PHEV	-	-	-	-	-	124	168	121	89	72
▨ BEV	-	-	-	34	14	117	100	68	58	154
🟧 HEV	430	627	766	513	646	266	213	182	55	181

Figure 5. South Africa's vehicle sales (2010-2019)

South Africa's EV fleet size is relatively small when compared with the USA and China, which in 2019 had about 450 000 and 300 000 EVs on the roads respectively. Japan and Norway had 150 000 and 100 000 EVs on their roads respectively in 2019 (Daily Maverick, 2020). At the existing national EV fleet size and annual uptake rates, the demand for EVs remains marginal and is not sufficient to stimulate local production of EVs and related components including LIBs in South Africa.

Although the global adoption of EVs is increasing at a rapid pace with the EV fleet exceeding 5.1 million in 2020, the adoption of EVs in South Africa has been very slow, due to high EV prices, high import taxes (25% import tariff for EVs versus 18% for the internal combustion engine (ICE)), the unstable electricity grid, limited charging facilities in cities and along the country's major highways, limited range per single battery charge and the absence of local production of EVs. Of the factors listed above, the high EV prices appear to be the single and largest deterrent to the growth of the local EV market. In 2020, the BMW i3 and the MINI SE were the cheapest and most affordable EVs on the local market and retailed for R640 000 and R642 000 respectively. The Jaguar I-PACE had a starting price of R1 942 600 and offers a range of 470km. The Porsche Taycan is available in 3 models and these were retailing for between R2 537 000 – R3 977 000.

Autotrader, South Africa's leading automotive sales and marketing company's Electric Vehicle Car Buyer Survey (2020) indicated that consumers are ready to buy EVs, but they are willing to do so in the next five years during which time they anticipate EV prices would have declined substantially and the existing EV charging infrastructure in the country would have improved significantly. In addition, South African consumers want vehicles that cost less than R500 000, they want more range and faster charging than what is currently the case with existing EVs. Out of the 3100 respondents identified in the Autotrader survey, only 2% indicated to be owning an EV, while only 13% had previously driven one (Autotrader, 2020). The existing EV models compete in the higher end to niche segments of the markets, excluding the entry level to mid-tier segments of the local EV market.

3.4 Future outlook for the electric vehicle market in South Africa

Globally, technological developments are enabling the diversification of drivetrains, away from traditional internal combustion engines towards cleaner forms of mobility including EVs. South Africa is home to a vibrant automotive manufacturing value chain. The Government, through the Department of Trade, Industry and Competition (the dtic) is working closely with automotive OEMs to position the local automotive value chain as a key player in the mobility of the future. This is critical to ensure a just transition to e-mobility. To this end a number of policy options to develop the EV value chain in South Africa, both from a market and industrial development perspective are being explored. This includes the development of a local LIB value chain that will harness the country's mineral resource endowment in the manufacturing of LIB components (Montmasson - Clair et al., 2020).

The Department of Transport's (DOT) Green Transport Strategy (2018-2050) seeks to radically grow the uptake of EVs in South Africa by incentivizing both the manufacturing and consumption of affordable EVs, setting annual uptake targets for EVs for national government departments and provinces, retrofitting old technology vehicles with EV technology (Department of Transport., 2018). Comparatively, the vast majority of EU countries offer subsidies and tax rebates of between €4 000 - €7 000 upon purchase of an EV. In the DOT's view, greater local production of a wider variety of models at various price points would help to stimulate the local market and result in increased uptake of EVs in South Africa.

In addition, the government will provide incentives for the manufacturing of EV components, including LIBs using local resources in line with the Industrial Action Policy Plan (IPAP) and the country's Mineral Beneficiation Strategy. The DOT maintains that with increased production and demand, coupled with the advancements in battery technology, the high up-front costs for EVs will decline sharply resulting in rapid uptake of the EVs in the country (Department of Transport, 2018).

Furthermore, rising customer awareness about the carbon footprint of the ICE will result in EV sales increasing for the foreseeable future in South Africa. A study undertaken by Eskom (Chapman 2019) forecasts South Africa's EV fleet to increase exponentially, reaching 233 672 by 2040 as more affordable EV models enter the local automotive market and the existing barriers to entry are removed (Figure 6).

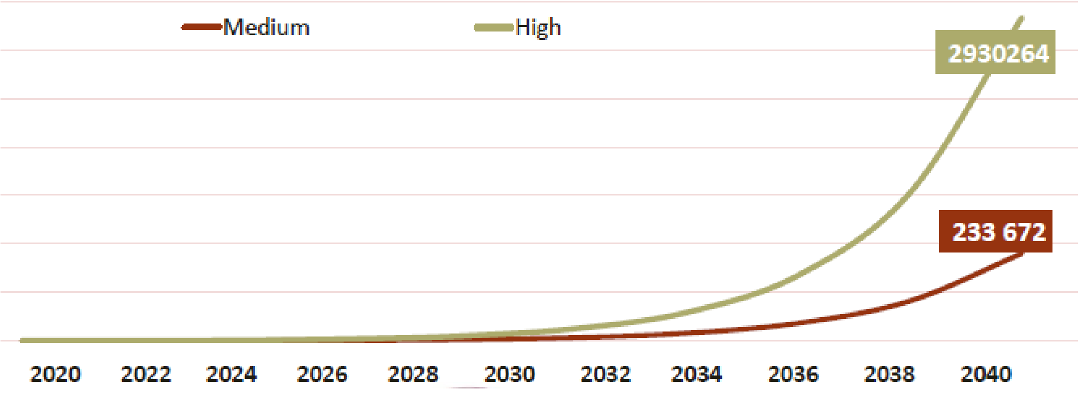


Figure 6. South Africa EV sales forecasts (2020-2040)

3.5 Installed LIB capacity

As indicated earlier, the availability of verifiable data on the installed capacity of EEE, their useful economic lives, LIB consumption and waste generation volumes are major challenges in South Africa. The installed base of LIBs in South Africa is not very well understood. Nonetheless, this is an important metric in assessing whether there is a sufficient stock pile of LIB waste, which when discarded, will become feed material for a LIB processing plant developed in the country.

The installed capacity of PCs and mobile phones can be used to develop a reasonable indication of the LIBs currently in use in South Africa and the waste that can potentially be generated therefrom when the LIBs become obsolete.

Table 6. LIBs in use in South Africa (2020)

Equipment	Installed Capacity	Average Battery Weight	LIBs in Use (t)
Personal Computers	6 556 000	400 g	2 622
Mobile phones	54 355 000	40 g	2 174
Electric vehicles	1 000	250 kg	250
Total			**5 046**

It can reasonably be inferred that, although useful economic lifespans vary, at current installed capacity and the average battery weight of personal computers, mobile phones and EVs, that South Africa had approximately 5 046 tonnes of LIBs in use in 2020 (Table 6).

Based on the information presented in Tables 5 and 6, the potential waste flows from the current installed capacity were estimated as follows:

(i) If it is assumed that the average lifespan of a mobile phone is 3 years, around 700 tpa of LIBs will become available for recycling.

(ii) Similarly, if we assume the average lifespan of a laptop is 5 years, around 500 tpa of LIB waste will join the waste stream.

(iii) At a collection rate of 10%, around 120 tpa LIB waste will be available for recycling.

These numbers do not take into account the undefined inventory of obsolete LIBs stored in households, government departments and company warehouses. A targeted drive to increase the collection rate might see these obsolete LIBs joining the waste stream. This will, however, not provide a sustainable volume of waste LIBs available for recycling in the long-term.

A study conducted by CM Solutions in 2015 forecasted that South Africa would have 9 578 tonnes of LIBs in use by 2020. According to CM Solutions' forecasts, approximately 89% of these LIBs would be installed in the automotive sector, while the consumer electronics sector would account for the remaining 11% (Knights and Salojee, 2015).

3.6 Key findings of the Mintek market study

In order to formulate a picture of the structure, dynamism and trends in the South African LIB recycling industry, the researchers asked WEEE recyclers, ICT OEMs, battery storage researchers and other stakeholders in South Africa's LIB industry a series of questions regarding the scope of their activities in the LIB recycling value chain, the source material for LIB waste they handle, the flows, intermediate and final markets of LIB waste fractions.

The discussions and responses obtained therefrom enabled the researchers not only to formulate a picture of the South African LIB industry, but also determine the quantities of LIB waste material that is currently and potentially available for recycling in the country. Such information is critical for the development of the business case for the establishment of an LIB processing plant in South Africa.

The key findings of this study include the following:

- **Low LIB collection volumes** – South Africa's WEEE recycling industry is estimated to have collected between 6 tonnes – 10 tonnes of LIB waste for recycling purposes in 2019. Although LIB waste collection volumes are likely to increase following the banning of the landfilling of battery waste beginning August 2021, the low LIB waste collection volumes make the recycling of such material not commercially viable. At current LIB waste collection volumes, South Africa cannot provide adequate feed material to sustain the operations of a commercially viable LIB processing plant. Large scale WEEE recyclers indicated that, in their targeted LIB collection campaigns, it can take between 3 – 5 years to fill a 20 tonne container with LIB waste, which is the minimum weight per consignment accepted by European refineries.

- **Potential for South Africa to become an LIB processing hub for the Southern African Development Community (SADC) and Sub-Saharan Africa regions** – Standard mineral processing and battery waste recycling share technologies that are drawn from hydrometallurgy, pyrometallurgy, material classification and comminution, which are all very well developed in South Africa. There is potential for South Africa to import LIB waste, subject to the provisions of the Basel Convention, from neighbouring countries and harness its well-developed mineral processing expertise to process the LIB waste locally. This will not only augment the existing stocks of LIB waste available locally and improve the economic feasibility of establishing a LIB processing plant, but will enable the country to become a processing hub for LIB waste for the SADC and Sub-Saharan Africa regions.

- **Laptops and mobile phones are the major sources of LIB waste collected for recycling in South Africa** – While it is apparent that LIBs are used to power a diverse range of consumer electronics, industrial equipment and EVs in South Africa, laptops and mobile phones account for the bulk of LIB waste collected for recycling in the country. This is because there are formal and organized collection channels for LIB waste from consumer electronics and ICT equipment for recycling purposes throughout the country. In South Africa's WEEE recycling sector, consumer electronics and ICT equipment account for an average of 80% of the e-waste materials collected for recycling by recycling companies each year. Data collected in this survey indicated that the quantities of LIBs used in industrial equipment such as forklifts are negligible and LIB waste material emanating from forklifts is lost to the recycling value chain when these are shredded in the downstream metals sector.

- **Storage and transportation of LIB waste are major operational challenges for recyclers** – The storage of LIB waste to accumulate sufficient volumes onsite and transportation of the material to the markets are major operational challenges for recycling companies in South Africa due to the highly flammable nature of LIB waste and the low volumes currently being collected. In South Africa, LIB waste is classified as hazardous waste due to its inherent toxicological, chemical and physical characteristics. Specialised storage and transportation facilities are required for the movement of such waste. In addition, in terms of the South African waste regulations, LIB waste can only be landfilled at designated hazardous landfill sites, which translates to higher operational costs for recyclers.

- **Non-existent or undeveloped market for LIB waste in South Africa** – Unlike PCBs, ferrous and non-ferrous metal fractions that can be easily sold to overseas precious metals refineries and the domestic steel fabrication industries respectively, the domestic market for LIB waste in South Africa is non-existent or undeveloped. The stringent weight, safety and environmental standards imposed by the European precious metal refineries on LIB waste consignments from South African WEEE recyclers have deterred the growth of the local market for LIB waste. European refineries only accept LIB waste consignments from South Africa if each consignment weighs a minimum of 20 tonnes - 22 tonnes and is mixed with sand to avoid fires and explosions during shipment.

- **LIBs are predominantly being landfilled as hazardous waste** – The lack of both domestic and overseas markets for LIB waste have resulted in this waste fraction being primarily landfilled in hazardous landfill sites and at a significant cost to the recyclers. However, this practice will change following the banning of the landfilling of battery waste beginning August, 2021. The landfilling cost, in addition to the high dismantling cost have made LIBs negative value products in the recycling value chain. The latest generation of laptops and smart phones come with embedded (non-removable) LIBs, which are not easy to dismantle and this increases recycling costs.

- **LIB re-use market is very small and negligible in SA**
  The re-use market for LIBs is very small and negligible in South Africa. This is due to the relatively smaller size of the computer refurbishment market when compared with the recycling market. Many WEEE recyclers throughout the country give away LIBs to backyard engineers (mostly young university graduates) for free as part of their corporate social and community responsibilities.

- **Merchants from North Africa, Middle East and Asia buying LIBs from SA** – As is the case with WEEE plastics and PCBs, there is evidence of some merchants from North Africa, the Middle East and Asia that buy LIBs from South Africa for onward sale to their clients in China, South Korea and Thailand, but their purchasing patterns are erratic and unpredictable. It is therefore difficult to estimate the size of this external market for LIBs.

- **Electric vehicles expected to be the game changer in South Africa's LIB recycling industry** – While EVs are anticipated to be the game changer in SA's LIB recycling industry, providing significant volumes of waste material for processing, there are currently no end of life LIBs from EVs joining the recycling value chain in South Africa. It can reasonably be inferred that LIBs from EVs that entered South Africa in 2005 should have joined the waste stream between 2015 and 2020, assuming a 10 years – 15 years life span for the LIBs. However, WEEE recyclers also cautioned that the higher EV battery weight of between 250kgs – 600kgs can result in higher storage, material handling, packaging and transportation costs for the recyclers.

- **Implementation of the extended producer responsibility (EPR) regulations set to radically**

transform South Africa's LIB recycling industry – The South African LIB recycling industry is facing a number of challenges, ranging from low LIB waste collection volumes, non-existent or underdeveloped markets for LIB fractions, to the non-availability of a local processing plant for LIB waste. Although the implementation of an EPR scheme is not the panacea for all these challenges, compelling automotive and ICT OEMs to take ownership of their products from 'cradle to grave' can result in the development of dedicated LIB collection infrastructure, increase in LIB collection volumes and the development of a LIB processing plant in the country. Under EPR schemes, OEMs and distributors of consumer electronics and ICT products are physically or financially responsible for the collection of their products in their end of life stage and divert such waste from landfill sites. OEMs can set aside financial budgets to develop dedicated LIB collection infrastructure, work with retailers and distributors to expand existing e-waste and LIB collection sites, embark on consumer awareness campaigns, develop an LIB waste processing facility for the country and finance the recycling of negative value products.

4 LIB recycling technology landscape

4.1 Recycling technologies

This chapter focuses on the different processes currently available for the recycling of LIBs. The various stages in the recycling process can be broadly classified into pre-processing and mechanical processes, followed by hydrometallurgical or pyrometallurgical technologies as shown in Figure 1. All these process routes are characterized by long and complex process chains and in some cases using combinations of pyro- and hydrometallurgical operations. Lithium-ion batteries are complex products and designs and materials are still evolving. In recent years, extensive research has focused on the development of a process for the direct recycling of cathode materials (Gaines 2018).

Pyro- and hydrometallurgical technologies have been commercialised, whereas the third option of direct recycling is still in research stage.

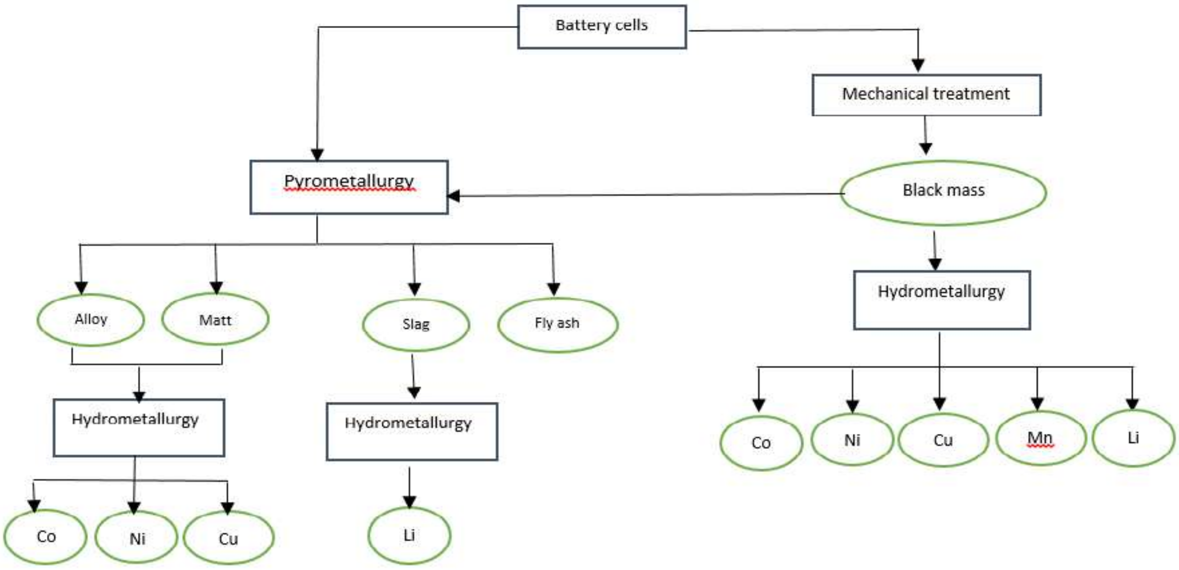


Figure 7. Possible process routes in the recycling of lithium-ion batteries (Adapted from Brückner et al., 2020)

4.1.1 Pre-processing and mechanical processing

Pre-processing is considered to be any process which does not alter the structure of LIB cells. Because EV batteries come in a large variety of formats and chemistries, the first step in recycling is to sort and identify battery chemistries based on visual inspection and/or shipping information, after which the battery packs are disassembled to the cell or module level (Kelleher and Millette 2019).

Mechanical processing involves the use of different techniques to liberate and concentrate fractions without altering their chemistry. Mechanical processes are used to safely remove the electrolyte and break the EV battery components apart to concentrate the metals and make them easier to process.

These techniques operate based on relative differences in the physical properties of materials, for instance density, shape and size and occur generally before stages which involve chemical reactions (Danino-Perraud, 2020).

In many recycling process flowsheets, the spent batteries are dismantled, and the parts containing the electrodes, such as battery cells, get crushed or shredded to produce a powdery fraction referred to as "black mass." The black mass requires further processing to recover valuable elements such as cobalt, nickel, manganese and lithium salts.

After mechanical processing, the material fractions obtained are refined by pyrometallurgy, hydrometallurgy or a combination of both.

4.1.2 Pyrometallurgy

Pyrometallurgy uses high temperatures (~1500 °C) to smelt the batteries and burn all carbon-based compounds. A Co-, Cu-, and Ni-containing alloy (metallic phase), an Al-, Mn- and Li-containing slag, and a fly ash are typically produced (Brückner et al., 2020). The valuable metals end up in the alloy, which can be further treated by a hydrometallurgical process to recover individual elements.

This type of process affords the advantage of reducing the handling of spent batteries by avoiding the crushing stage and other pre-treatment steps (Table 7). By doing so, however, other battery components, such as electrolyte, graphite, steel, aluminum and lithium are not recovered and are lost as slags or off-gas. In principle, the recovery of these substances from slag is technically feasible via hydrometallurgical processes but not economically. The slag is currently used as filler material, e.g. in road construction or in concrete, or alternatively deposited in landfills. The major disadvantages of pyrometallurgy include the considerably expensive gas effluent treatment facilities required to avoid the release of toxic compounds in air. Moreover, this process makes it impossible to gain any value from processing low-cost LIBs (e.g., $LiFePO_4$, $LiMnO_2$, or $LiTiO_4$) because these elements end up in the slag (Beaudet, 2020, Werner et al. 2020).

4.1.3 Hydrometallurgy

Hydrometallurgy exploits the high solubility of transition metals and lithium in acid. In such a process, the batteries must be crushed and components have to be sorted using various mechanical methods to allow the recovery of steel, copper foil, and aluminum foil, which account for approximately one quarter of the overall value. Hydrometallurgical processing is mainly applied for the metals coated on the cathode. Once dissolved, the metals are extracted from the solvent by liquid–liquid extraction, ion exchange, or chemical precipitation. If the resulting metal salts meet the quality requirements of the corresponding raw materials, subsequent recovery can be forgone. Otherwise, further precipitation, crystallization, or electrochemical processes such as electrowinning are used to refine the metals. Moreover, it may be possible to recover electrolytes, although this requires more expensive and complex recovery processes, and only a few studies have been performed on this topic.

The significant advantage of hydrometallurgy over pyrometallurgy is the potential for lithium recovery (Table 7). This is usually performed by Li_2CO_3 precipitation after leaching solution purification. In view of this, hydrometallurgical processes are generally perceived as the most promising approach for battery recycling when a circular economy approach is adopted. This is reflected in the scientific literature, where according to Melin (2019), more than 75% of research papers on LIB recycling primarily address hydrometallurgical processes.

Table 7. Comparison of advantages and disadvantages of the different recycling routes (Lv et al., 2017, Mayyas et al., 2018, Beaudet 2020)

Recycling process	Advantages	Disadvantages
Pyrometallurgy	Flexible, robust process which can treat any battery chemistry and configuration	Does not recover Li, Al and organics
	No sorting or other mechanical pre-treatment required	Cannot treat LFP batteries
	High recovery of metals such as Co, Ni and Cu	Extensive gas cleanup required to avoid toxic air emissions
	Proven technology which can be implemented using existing pyrometallurgical facilities	Capital intensive and profitability is dependent on scale
	Batteries contain enough energy to run the process	Further refinement is necessary to recover metals from metal alloys produced in the smelting process
Hydrometallurgy	Applicable to any battery chemistry and configuration	Battery cells must be crushed before treatment
	Flexible in separation and recovery processes to target specific metals	Acid breaks down cathode structure
	High recovery rates of metals including lithium	High volume of process effluents to be treated and recycled or disposed
	High purity products, suitable for cathode precursors	Requires input of chemicals. Large consumption of acids/bases required to dissolve low value elements
	Energy efficient	Not economical for LFP batteries
	Low off-gas	High operating cost
	Can be built on smaller scale than pyrometallurgical plants	
Direct recycling	Retains valuable cathode structure	Complex mechanical pre-treatment and separation required
	Practically all battery materials can be recovered, including anode, electrolyte and foils	Recovered materials may not perform as well as virgin material or become obsolete by the time it is introduced to the market

	Suitable for LFP batteries	Mixing cathode materials could reduce the value of the recycled product
	Energy efficient	Regeneration processes yet to be developed
	Convenient for recycling manufacturing scraps	Not scaled up to industrial level, still in development stage

4.1.4 Direct recycling

Direct recycling aims to restore the initial properties and electrochemical capacity of cathodic active materials without decomposing into substituent elements, which can then be directly reused for manufacturing new LIBs. This is performed by means of mechanical, thermal, chemical, and electrochemical processes. The end product is to be reused in new battery manufacturing. Although recent progress shows promise for improved efficiency, thus far, the potential for fully restoring the initial cathode capacity is yet to be proven. In terms of economics, direct recycling can create added-value products, but extremely complex battery sorting and pre-treatment steps are necessary. Another key problem is that the recovered material may be obsolete by the time it is introduced to the market (up to 15 years after the original battery is manufactured) as battery technology continuously evolves (Beaudet, 2020).

These different technologies can be combined and applied in different flowsheets, depending on factors such as quantity and characteristics of the material available and quantity and value of the materials that can be recovered. Besides utilisation of specialised battery recycling processes the addition of spent batteries to existing large-scale processes, which are not dedicated to battery recycling (for example extractive cobalt or nickel metallurgy) is common practice and very often an economical advantage. An indication of the advantages and disadvantages of the different process options is summarised in Table 7.

4.2 Commercial recycling processes

The LIB recycling landscape is in a state of dynamic change. At present, there is a proven suite of established technologies for LIB recycling available, a number of emerging technologies in piloting and early market stages, and 'new' technologies still in the research stage. In traditional LIB recycling, up to 40% of the materials are not recovered. The new and emerging technologies (none yet at scale) aim to recover up to 90% of the battery materials without using pyrometallurgical processes (Kelleher and Millette 2019).

The processes included and described in this investigation have been selected based on the following criteria:

- Processes at commercial scale
- Processes which accept LIBs as a secondary feed

- Emerging technologies which have been demonstrated on pilot plant scale or are in the process of being commercialized

The recycling processes were analysed using the following guidelines:

- What type of battery feed does the plant accept?
- Which processes (pyro- or hydrometallurgy) are used?
- What are the main materials recovered?
- What is the annual throughput of the plant?
- Where is the plant located?

Numerous commercial recycling companies worldwide treat spent LIBs of different types. The recycling technologies differ according to the used process stages and unit processes as well as the generated final products. This is due to the historical development of the individual companies, the environmental conditions and regulations, as well as the relevant market situation (Werner et al., 2020).

Two technologies—used alone or in combination—are currently employed commercially for recycling of LIBs, namely pyrometallurgy and hydrometallurgy. Avoiding high investments for dedicated process equipment, spent LIBs are also fed as secondary feed in existing metallurgical plants. The flowsheets of the majority of these processes have been described in detail in literature and will not form part of this report (Lv et al., 2017, Li et al., 2018, Velázquez-Martínez et al., 2019, Brückner et al., 2020, Danino-Perraud 2020, Werner et al., 2020).

4.2.1 Commercial pyrometallurgical plants

Examples of commercially applied pyrometallurgical technologies are presented in Table 8. In processes dominated by pyrometallurgy, the expected product is a metallic alloy. The industrially implemented process routes for LIB recycling typically combine pyrometallurgical unit operations with hydrometallurgical operations for treatment of the alloys.

The processes can be divided into:

- Co-processing of LIBs in existing primary or secondary Co, Cu, and Ni smelters and
- Dedicated plants specifically designed for LIB recycling

4.2.1.1 Co-Processing in Co-, Cu-, Ni-Smelters

Due to the high Al, Li, F and organic content, LIBs are a difficult feed for conventional Co, Cu, and Ni smelters with respect to corrosion, slag properties, energy, and mass balance. Fluorine and Li can severely attack the refractories, and the first one is also an issue in the off-gas treatment. Al increases the viscosity of the slag and is therefore only acceptable to a certain extent, which depends on the applied slag system and operating temperature of the furnace. Furthermore, in addition to the organic and graphite content, its participation in redox reactions adds a high amount of energy to the system, which also needs to be considered (Brückner et al., 2020).

Nevertheless, some smelters accept a certain amount of LIBs as feed material. Examples are Glencore (Canada), INMETCO (USA), Batrec (Switzerland), Nickelhütte Aue Gmbh (Germany) and Dowa (Japan) (Lv et al., 2017, Velázquez-Martínez et al., 2019, Sattar et al., 2020). In all cases the metals are recovered from the metal alloy produced in the smelter using hydrometallurgical processes.

4.2.1.2 Dedicated facilities

In contrast to co-processing, dedicated pyrometallurgical processes for LIB recycling are specifically developed for the treatment of LIBs. The processes enable the enrichment of Li in the slag, and the furnaces are designed to handle the highly corrosive feed material. Nevertheless, also in dedicated processes, LIBs are often co-processed with other feed materials and different types of batteries, in order to meet a suitable energy and mass balance as well as to enable sufficient plant utilization in this emerging market (Brückner et al., 2020).

One of the most prominent examples is Umicore SA (Belgium), which operates a furnace at Hoboken (Belgium) with a capacity of 7000 t/year (Lv *et al*., 2017, Velazques *et al*., 2019, Brückner *et al*., 2020). The plant processes LIB and NiMH battery materials, which include consumer battery material, automotive battery material, storage battery material and battery manufacturing scrap. Umicore announced an increase of its recycling capacity by a factor of approximately 10 by the mid-2020s (Manthey 2018). A combination of pyrometallurgy (patented technology) and hydrometallurgy is used to recover rare earth elements, cobalt, nickel, and copper from spent batteries (Kelleher and Millette 2019)

Another example is the Sony process, with a capacity of 150 tpa, which was developed through a cooperation between Sony Electronics and Sumitomo Metal Mining (Lv et al., 2017, Winslow et al., 2018, Velázquez-Martínez et al., 2019) and was reportedly designed for the recycling of only LIBs. The process leads to the recovery of a metallic alloy consisting of Co and Ni, while the Li is lost in the slag. The Co is subsequently extracted from the alloy by a leaching process. Similarly, Ni-based and Li-ion batteries are treated pyrometallurgically by SNAM in a 300 tpa plant in France. The alloys and black mass produced are sold to metallurgical companies (Li et al., 2018, Danino-Perraud 2020, Larouche et al., 2020, Sattar et al., 2020).

Table 8. Summary of industrial-scale pyrometallurgical recycling processes

Technology	Feed	Process	Materials recovered	Capacity (tpa)	Country	References
Umicore ValEas^{TM} (UHT Technology)	LIB, Li-polymer, nickel-metal hydride (NiMH)	Pre-processing: Dismantling Pyrometallurgical processing Cu, Co, Ni, Cu recovered from the alloy by dissolution and precipitation using hydrometallurgy	Co-Ni-Cu alloy Fe, Al and Li with the slag, which is used as low-cost by-product in the construction industry	7 000	Belgium	King et al., 2018, Li et al., 2018, Manthey 2018, Velázquez-Martínez et al., 2019
Sumitamo-Sony	LIB	Pre-processing: Sorting and dismantling. Pyrometallurgical treatment (high temperature calcination) Alloy - hydrometallurgical treatment	Co-Ni-Fe alloy	150	Japan	Lv et al., 2017, Winslow et al., 2018, Velázquez-Martínez et al., 2019
SNAM	NiCd, NiMH, LIB	Pyrometallurgical Refining (hydrometallurgical)	Black mass (Co, Cu, Ni) – sold to refiners. Ni-Fe and Co-Fe alloys sold metallurgical companies	300	France	Li et al., 2018, Danino-Perraud 2020, Larouche et al., 2020, Sattar et al., 2020
Glencore	Primary feed - sulphide ores. Secondary feed - Li and Ni-based batteries	Batteries broken into smaller fractions Pyrometallurgical process (rotary kiln). Matte shipped to Glencore facility in Norway for hydrometallurgical treatment	Mainly recover Co, Cu and Ni Other battery components are slagged or used as energy source or reducing agent in the process	550 000 (total smelter capacity)	Canada	Lv et al., 2017, Pinegar and Smith 2019, Velázquez-Martínez et al., 2019, Brückner et al., 2020, Kelleher and Millette 2020
Accurec GmbH (EcoBatRec process)	Various including LIB. Originally developed for Ni-Cd batteries	Combination of mechanical treatment (sorting, dismantling), pyrometallurgical (electric furnace) and hydrometallurgical processes	Li_2CO_3, LiCl, Co-Ni-Mn alloy, Fe, Ni, Al, steel, plastics.	6 000	Germany (batch industrial scale)	King et al., 2018, Velázquez-Martínez et al., 2019, Danino-Perraud 2020
Batrec Industrie AG	Developed for Zn and Hg recovery from alkaline and Zn-C batteries.	Stored and shredded under CO_2 atmosphere. Mechanical, followed by pyro- and hydrometallurgical treatment	Ni, Co, Cu alloys Different material fractions are sold and represent feedstock materials in other processes	200	Switzerland	Lv et al., 2017, Velázquez-Martínez et al., 2019, Larouche et al., 2020
The International Metals Reclamation	Not originally designed for LIB Li and Ni-based batteries is secondary feed to plant.	Pyrometallurgical (Rotary hearth furnace, further refined in electric furnace)	Co-Ni-Fe alloy. Other material e.g. Al and Li report to the slag and organic materials are burned and used as reducing agents	6 000	USA	Lv et al., 2017, Chen et al., 2019, Kelleher and Millette 2019, Velázquez-Martínez et al., 2019, Pinegar and Smith 2019

Technology	Feed	Process	Materials recovered	Capacity (tpa)	Country	References
Company (INMETCO)	Do not take EV batteries					
Dowa Eco-System	All lithium batteries	Pyrometallurgical	Fe, Al, Cu, Co-Ni mixture	1 000	Japan	Larouche et al., 2020
Nickelhütte Aue Gmbh	Secondary raw materials such as Co-, Cu-, and Ni-bearing spent catalysts, electroplating sludges, filter dusts and ashes. LIB is a secondary feed to plant.	Pyrometallurgical, followed by acid leaching	Co, Ni, Mn	20 000	Germany	Brückner et al., 2020, Larouche et al., 2020

4.2.2 Commercial hydrometallurgical plants

Examples of commercially applied hydrometallurgical technologies are presented in Table 9. Established technologies include Retriev (previously Toxco), who are operating plants in Canada and the USA at capacities of 4 500 4 000 tpa respectively, Recupyl, a French battery recycling company with pilot facilities (110 tpa) in France and a commercial installation in Singapore (320 tpa) and Duesenfeld who is operating a plant with a capacity of 3 000 tpa in Germany.

These processes typically involve deactivation of the batteries, followed by mechanical pre-treatment and acid leaching. Further purification of the metals could happen on site using well-known metal purification processes such as selective precipitation or electrowinning.

It is important to note that the majority of new commercial installations are focusing on hydrometallurgical processing, especially in China. Large-scale recycling operations in China include Hunan Brunp and GEM in China. These facilities are linked to the manufacturing industry and the materials recovered are used by the manufacturers in the production of new batteries. The capacity of these plants are significant, with annual throughputs up to 100 000 tpa planned by Chinese recyclers such as Hunan Brunp. Very little information is available on the flowsheets and operational conditions of these plants.

4.2.1 Mechanical processing plants

Examples of processes utilising only mechanical processing include the Akkuser technology which has been successfully implemented in Finland. The 4 000 plant treats NiMH, LIB, nickel-cadmium, and alkaline batteries using dry technology (crushing followed by magnetic and mechanical separation) to produce Cu and black mass, which is sent to a chemical company for use in new Li-ion products. Nickel recovered goes to Boliden's smelter and Norilsk's nickel plant where metallic Ni is produced (Kelleher and Millette 2019, Velázquez-Martínez *et al.*, 2019, Danino-Perraud 2020, Larouche *et al.*, 2020, Sattar *et al.*, 2020).

Another example is Onto Technology's operation in the USA, treating primary Li and Li-ion batteries. The process involves direct recycling (discharge and dismantling). Supercritical fluid is used to separate the different materials. The electrolyte can be recovered in this process, but the process has not been adopted on industrial scale due to the high cost (Lv *et al.*, 2017, Chen *et al.*, 2019, Velázquez-Martínez *et al.*, 2019).

Table 9. Summary of industrial-scale hydrometallurgical recycling processes

Technology	Feed	Process	Materials recovered	Capacity (tpa)	Country	References
Retriev Technologies (previously TOXCO)	All types, including primary and secondary LIBs, LIB scrap and Pb-acid batteries	Liquid nitrogen deactivation Physical processing include manual disassembly and hammer mill, screening followed by hydrometallurgical treatment	Metal solids rich in Cu, Al and Co. Liquid rich in Li send off-site to Glencore for Co and Ni recovery	4 500 4 000	Canada USA	King et al., 2018, Li et al., 2018, Chen et al., 2019, Velázquez-Martínez et al., 2019, Larouche et al., 2020
Recupyl Valibat	Primary or secondary LIBs and zinc-based batteries	Inert gas protection Physical processing (crushing, vibrating screen, secondary screen, magnetic separator, densimetric table) followed by hydrometallurgical treatment (selective precipitation)	Li_2CO_3, $LiCO_2$, Li_3PO_4, Cu, Al, $Co(OH)_2$	110 (pilot) 320 (commercial)	Pilot plant: France Commercial plant: Singapore (TesAMM)	Lv et al., 2017, King et al., 2018, Li et al., 2018, Velázquez-Martínez et al., 2019, Sattar et al., 2020
Duesenfeld (Lithorec based)	LIB	Mechanical and hydrometallurgical	Black mass after shredding and sorting. Active materials (Co, Ni, Mn) send to Albemarle Germany (GmbH) for hydrometallurgical acid treatment. Cu, Ni, Mn, Li for re-use in battery industry	3 000	Germany	Chen et al., 2019, Velázquez-Martínez et al., 2019, Danino-Perraud 2020, Willuhn 2020
Euro Dieuze	LIB	Hydrometallurgical treatment		200	France	Mayyas et al., 2018
Green Eco-Manufacture (GEM)	Originally a battery and white goods recycling company	Mechanical pre-treatment and hydrometallurgical. Very limited information available on the process.	Ni, Co and other metals transforming them into materials used by battery producers like Samsung.	300 000 (LIB and waste Co Ni materials)	China (16 recycling industrial parks in China)	Li et al., 2018, Willuhn 2020, Zou, 2019

Technology	Feed	Process	Materials recovered	Capacity (tpa)	Country	References
Hunan Brunp Recycling Technology (largest LIB recycling company in China)	Various, including LIB, NiMH	Hydrometallurgical leaching in acid (limited information available on flowsheet)	Metal hydroxides utilized for cathode fabrication by manufacturers such as LG, Xiawu.	Currently 30 000 tpa. Plant which will produce 100,000 tpa of LIB scrap under construction in Hunan province.	China	Li et al., 2018, Chen et al., 2019
Shenzhen Green Eco-manufacture Hi-Tech Co	LIB, NiMH	Hydrometallurgical	Co powder	20 000	China	Lv et al., 2017, Mayyas et al., 2018
Bngpu Ni/Co Hi-Tech Co	LIB	Hydrometallurgical	Cathode material and Co_3O_4	3 600	China	Lv et al., 2017
SungEel HiTech	LIB	Hydrometallurgical	Ni, Mn, Co, Li, and Cu (metal sulfate and lithium phosphate) which are supplied to LIB manufacturers.		South Korea	Chen et al., 2019
JX Nippon Mining and Metals	LIB	Focus on cathode materials. Leaching in acid, followed by solvent extraction. Metal recovery: Cu and Ni: Electrowinning Mn and Li: carbonate precipitation	Initial focus on cathode material. Due to difficulty collecting cathode material, focus shifted to include LIB scrap.	Pilot plant (2010)	Japan (Tsuruga plant)	Haga et al., 2018
AEA Technology	Li	Remove electrolyte, solvent and binder with organic solvent. Leaching of cathode material.	LiOH, CoO	Unknown	UK	Lv et al, 2017, Danino-Perraud 2020
Battery Resourcers	LIB	Mechanical (Discharge, shredding, magnetic separation) followed by hydrometallurgical leaching and precipitation.	Li_2CO_3, $NMC(OH)_2$, ferrous metals	Unknown	USA	Velázquez-Martínez et al., 2019, Chen et al, 2019

4.2.2 Emerging technologies and operators

A number of emerging technologies are currently being piloted and commercial implementation considered.

Noteworthy developments are presented in Table 10 and include:

- American Manganese's patented technology claims 100% recovery of Co, Ni, Mn, Al and Li. Pilot plant testing is currently underway at a rate of 1kg/h and commercial plant construction is scheduled to start once the pilot plant testing is concluded. The commercial plant's planned processing capacity would be 1 200 tpa of scrap cathode material (Kelleher and Millette 2019).

- Another prominent emerging technology has been developed by Neometals Ltd., an Australian lithium mining and refining company, who made a strategic decision to become involved in recovering metals and other materials from lithium batteries through recycling. Process design sheets were developed to recover multiple critical metals from LCO, NMC and NCA batteries. The process does not address LFP batteries. Neometals carried out a li-ion battery pilot in collaboration with SGS and a commercial plant is planned in collaboration with a German partner (Arnott 2019, Kelleher and Millette 2019).

- Li-Cycle, a Canadian company has a vision of recovering 80% to 100% of material from EV batteries through recycling. No details are available on the technologies used in the Li-Cycle process, but the process has been piloted and it is known that the materials recovered include lithium as lithium carbonate, Cu, graphite and a Ni-Co-Mn hydroxide cake, which will be sent to a smelter in South Korea for now, but future processes will recover cobalt sulphate and nickel sulphate as separate streams. Construction has apparently started on a 5 000 tpa plant in Rochester, New York (Kelleher and Millette 2019, Movchin 2020).

Due to the complex process chains, a number of new operations have recently started to follow the route of partnership formation. This means that companies do not cover all process steps, but typically pre-treatment, metallurgy, refining, and cathode material production are operated by different companies. Especially in the metallurgical processing, co-processing is pursued at various stages to take advantage of large-scale installations and to homogenize the feed material.

An example of such an initiative is the Hydro Volt joint venture between Northvolt and Hydro, who plans to launch a recycling pilot plant in Norway in 2021, followed by the establishment of a full-scale recycling plant at the Northvolt's gigafactory for lithium-ion batteries in Skellefteå, Sweden in 2022 (Murray 2020). The focus will be on the recycling of both battery materials and aluminum from Norway's electric vehicle sector. Material output from the recycling processes in Norway will include aluminium and black mass containing Co, Mn and Li. The material will then be transported to Northvolt's and Hydro's recycling plants (Frangoul 2020).

Table 10. Emerging operations for LIB recycling

Technology	Process	Materials recovered	Capacity (tpa)	Country	References
Neometals	Mechanical (shred, remove steel casing and plastic). Upgrade Li, Co, Ni, Cu into black mass followed by 2-stage hydrometallurgical process. Refine to battery material grade.	Co, Ni, Cu, Li, Gr for re-use in the battery supply chain	Pilot plant (100 kg/d)	Pilot plant in collaboration with SGS Canada. Joint venture between Neometals and SMS Group (Primobius GmbH) to demonstrate the technology in Germany (20 000 tpa)	Arnott 2019, Kelleher and Millette 2019, Danino-Perraud 2020
LiCycle Corp	Mechanical size reduction technology processing cathode and anode materials. Hydrometallurgical metal recovery (Rochester plant)	Black mass containing Co, Ni, Li and Mn (80-100% recovery)	Mechanical processing (5000tpa) Hydrometallurgical plant (365tpa)	Demonstration facility: Canada Commercial scale plant plant planned: New York State (25 000)	Colthorpe 2020, Kelleher and Millette (2020), Mochin 2020, Kumagai 2021
American Manganese (RecycLiCo™)	Hydrometallurgical treatment of LIB chemistries, LCO, NMC, NCA	Lithium-ion cathode materials incl. Co, Ni, Mn, Li and Al	3 t/d LIB Cathode recycling plant in conceptual phase	USA (pilot plant)	Kelleher and Millette 2019
Fortum (Crisolteq technology)	Mechanical and hydrometallurgical treatment of mainly NMC	Removal of Cu, Al, plastics followed by metal (Li, Co and Mn) recovery from black mass		Finland	Calthorpe 2019, Kelleher and Millette 2019
Northvolt (gigafactory) and Norsk	Mechanical (automated process) Black mass refined hydrometallurgically at Northvolt facility.	Black mass	Pilot: 8 000 Commercial plant at Gigafactory: 25 000	Norway (pilot) Sweden (refining and commercial plant)	Frangoul 2020, Murray 2020
SungEel MCC Americas (SMCC)	Hydrometallurgical		5 000	USA Joint venture partner is SungEel HiTech who has similar facility in South Korea.	Taylor 2018
Argonne laboratories (ReCell centre)	Direct cathode recycling	Cathode materials	Lab-scale, piloting planned	USA	Gaines 2018

Similarly, a number of car manufacturers, such as Volkswagen and BMW, are planning installation of pilot plants in Europe.

- The BMW Group formed a consortium with Northvolt and Umicore to produce and recycle vehicle batteries at a pilot plant in Germany, which will be commissioned in 2022 (Manthey 2018).

- The Volkswagen Group is putting up a 1 500 tpa plant in Germany. The process involves mechanical shredding and black mass production. The black mass will be send to refineries for metal recovery (Vellequette, 2019).
- Although they have not yet received significant numbers of batteries for recycling, Tesla is developing a unique battery recycling system at their Gigafactory in Nevada, USA, which will process both battery manufacturing scrap and end-of-life batteries. Through this system, the recovery of critical minerals such as lithium and cobalt will be maximized along with the recovery of all metals used in the battery cell, such as copper, aluminum and steel. All of these materials will be recovered in forms optimized for new battery material production (Lambert, 2019).

Meanwhile, the US Department of Energy’s ReCell team at Argonne laboratories, is pursuing direct recycling methods for recovering and reusing battery materials without costly processing. One approach involves removal of the electrolyte with supercritical carbon dioxide, then crushing the cell and separating the components physically on the basis of, for example, density differences. In principle, nearly all the components can be reused after processing. The process is, however, still in research phase (Gaines 2018).

4.2.3 Location of the LIB recycling plants

The production of LIBs has so far taken place almost exclusively in China, South Korea, and Japan (Mayyas et al., 2018, Werner et al., 2020). It is acknowledged that recycling activities are typically aligned with an active manufacturing industry, therefore industrial scale battery recycling operations, capable of recycling LIBs, are mainly located in Asia and to a lesser extent in Europe and North America as indicated in Figure 8.

The majority of current commercial installations in Europe make use of pyrometallurgical technologies, in many cases existing smelters accept a certain amount of LIBs as feed material. New installations in the USA are mostly using hydrometallurgical technologies for metal recovery. As in Europe, some large smelter facilities do accept LIBs as secondary feed. In China, hydrometallurgical processes are favoured and very large operations are already in operation or are in the planning phase.

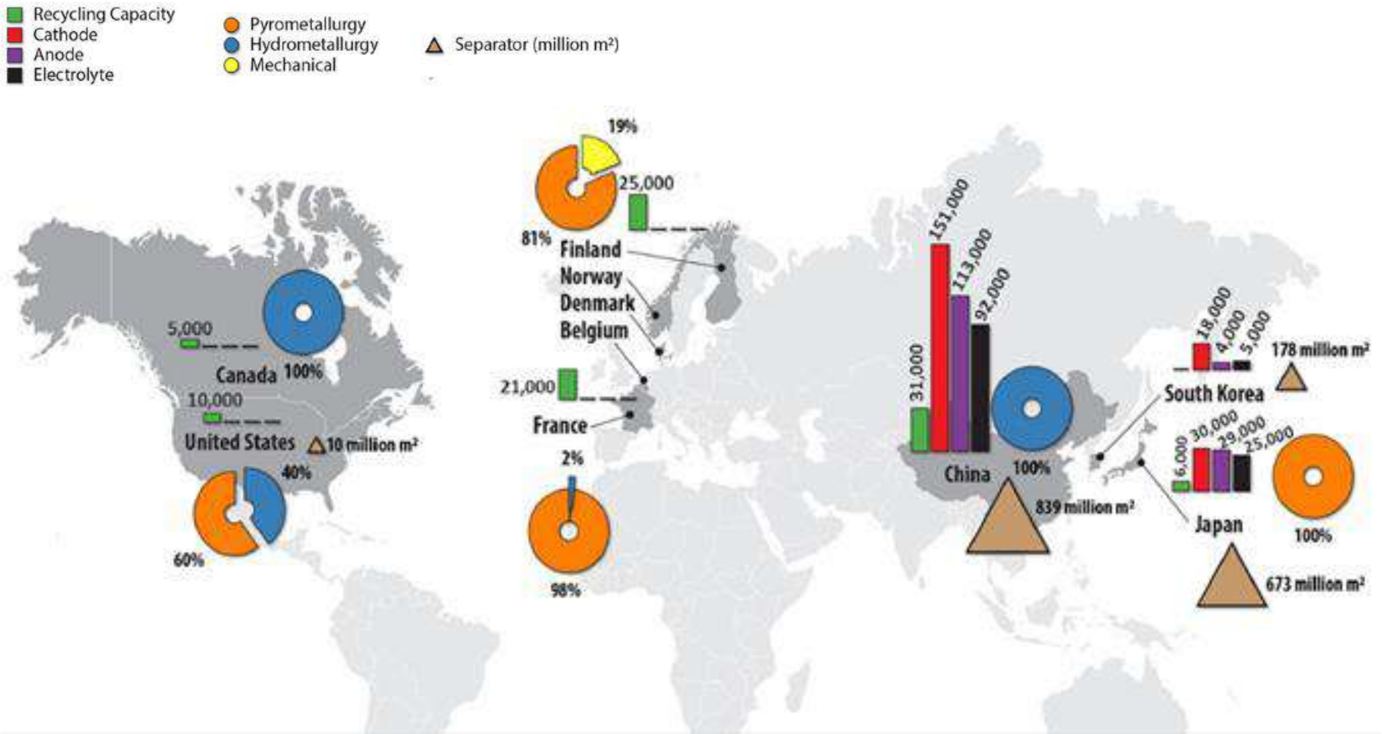


Figure 8. Recycling capacities of the spent batteries (Mayyas et al., 2018)

4.3 Challenges for technology implementation

Lithium-ion batteries are complex products, and designs and materials are still evolving, which makes planning for future recovery more challenging. Current recycling operations mainly recover high value metals from cathodes and disregard anodes and other pack components. A number of battery recycling technologies currently under development aim to recover up to 90% of the battery materials. However, most of these are still in laboratory or small-scale pilot stages.

One of the primary challenges for LIB recycling in the short-term include the lack of a viable collection mechanism for spent batteries, leading to low volumes of LIBs available for recycling. There is also very limited information available on the economics of LIB recycling.

Long-term challenges for LIB recycling mainly revolve around uncertainty regarding the future composition of LIBs. The materials in each cell are not standardized and are constantly evolving and if current efforts to decrease the cobalt content of LIB are successful, the economic viability of LIB recycling could be threatened. Highly specialized recycling processes could be rendered obsolete or ineffective if battery chemistries change significantly or if LIBs are replaced with alternatives such as flow batteries, solid state batteries or ultra-capacitors.

The recycling process could be further simplified if all the packs and modules were similar, facilitating sorting and possibly enable cell disassembly instead of size reduction. However, automakers resist standardisation for competitive reasons and it is acknowledged that currently experimenting with different battery types and designs helps drive economic and technical innovations in EV development, and is expected to be ongoing for the foreseeable future (Kelleher and Millette 2019).

The first generation of EV batteries were designed with energy and power density, weight, performance, reliability and safety in mind. However, not enough thought was given to their reuse and recycling and the way in which an EV battery is designed can limit the ability to recover the raw materials. Much effort is currently put into "design for recycling" (Gaines 2018).

5 Techno-economic analysis

A techno-economic study was performed to investigate the business case for the establishment of a LIB recycling industry in South Africa. Mintek's extensive in-house flowsheet and costing models were used in the study. Since there are numerous process flowsheet options described in literature (Velázquez-Martinez et al., 2019; Naberezhnykh et al., 2013), a decision was made to focus on three generic flowsheets: pyrometallurgical, hydrometallurgical and physical processing for the production of black mass. Variables investigated include battery chemistry and plant capacity. Capital and operating costs were calculated for all three options and were benchmarked against similar published studies. Profitability was assessed by comparing internal rates of return over a 10 year period.

The compositions of the five LIB battery types considered in this study are provided in Table 11 (Kelleher Environmental, 2019). The main types are Nickel Cobalt Aluminium (NCA), Lithium Manganese Oxide (LMO), Nickel Manganese Cobalt (NMC), Lithium Cobalt Oxide (LCO) and Lithium Iron Phosphate (LFP). Also indicated in Table 11 is an estimated global market share of each battery type, called the "Blend" (Boxall et al., 2018).

Table 11. Battery compositions (Kelleher Environmental, 2019)

Battery type		**NCA**	**LMO**	**NMC**	**LCO**	**LFP**	Blend [**]
Global market share		0.072	0.214	0.29	0.372	0.052	
		Nickel Cobalt Aluminium	Lithium Manganese Oxide	Nickel Manganese Cobalt	Lithium Cobalt Oxide	Lithium Iron Phosphate	
Al	%	21.9	21.7	22.72	5.2	6.5	15.1
Co	%	2.3	0.0	8.45	17.3	0.00	9.1
Cu	%	13.3	13.5	16.6	7.3	8.2	11.8
Fe	%	0.1	0.1	8.79	16.5	43.2	11.0
Li	%	1.9	1.4	1.28	2.0	1.2	1.6
Mn	%	0.0	10.7	5.86	0	0	4.0
Ni	%	12.1	0.0	14.84	1.2	0	5.6
Binder	%	3.8	3.7	1.39	2.4	0.9	2.4
C (non-graphite)	%	2.4	2.3	3.47	6.0	2.3	4.0
Eletrolyte + solvent	%	11.7	11.8	1.66	14.0	14.9	9.8
Fluoride	%	-	-	4.99	-	-	1.4
Graphite	%	16.5	16.3	-	23.1	13.0	13.9
Thermal insulation	%	1.3	1.4	-	-	-	0.4
Oxygen	%	8.3	12.4	4.52	-	-	4.6
Phosphorous	%	-	-	2.04	0	5.4	0.9
Plastics	%	4.4	4.7	3.4	5	4.4	4.4
		100	100	100	100	100	100

[**] Blend according to global market share ratios

There is substantial variation in the valuable metal components of the different battery types. The total contained value in the LIB feed, based on current metal prices (March 2021) was estimated to be between 1008 $ / t (LFP) and 7032 $ / t (NMC), with most of the value contained in the Co, Ni and Cu. More valuable battery types such as the NMC and LCO contain high levels of Co and Ni, whereas the least valuable battery types such as the LMO and LFP contain no Co or Ni. For the purposes of the study, a hypothetical "blend" feed was also calculated, according the market share ratio of the five battery types.

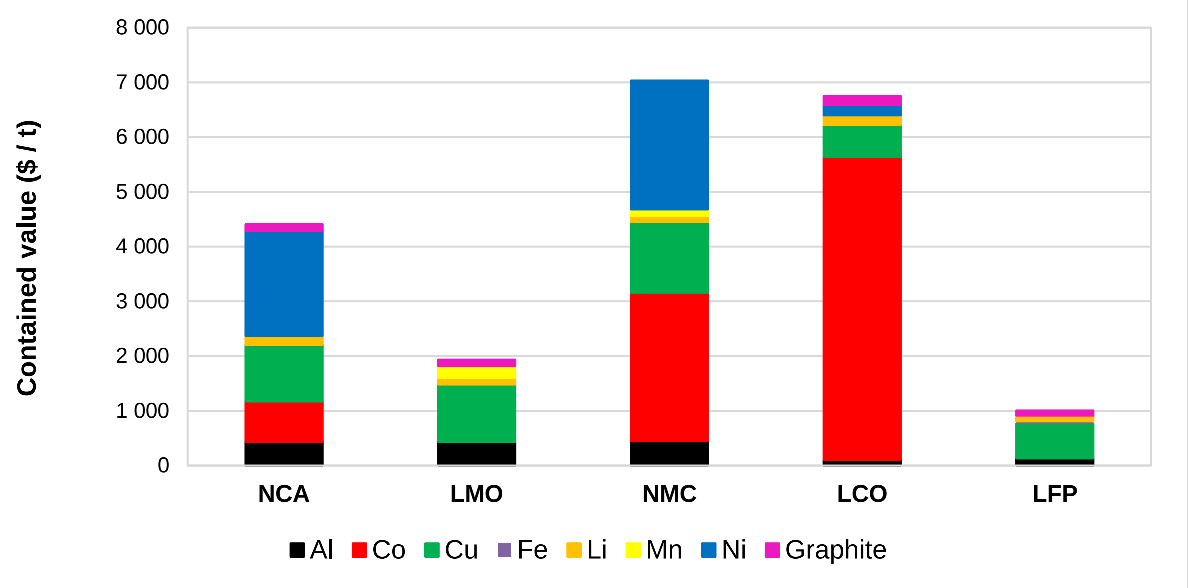


Figure 9. Contained value per tonne of LIB

Table 12. Metal prices (March 2021) used in the techno-economic study

Metal	Price (USD / kg)
Al	1.9
Co	34
Cu	7.7
Fe	0.1
Li (as Li_2CO_3)	8.75
Ni	15.8
Mn	2.0
Slag	27.5

Figure 9 provides a summary of the metal values contained in each battery type, assuming metal prices as provided in Table 12. The NMC and LCO battery types contain the most value, primarily as Ni, Co and Cu. The LFP and LMO battery types contain no Ni or Co and have the lowest value. Since there is a significant difference in value, changes in battery feed composition or type may significantly alter the profitability of the recycling process.

5.1 Flowsheet selection

Three generic flowsheets were derived for the costing model. The hydrometallurgical flowsheet (Figure 10) comprises shredding, crushing, screening and physical separation, followed by acid leaching and metal precipitation. The metal casings, steel and plastic are separated out of the coarser (+3 mm) fraction. The high-value black mass reports to the finer (-0.5 mm) fraction and is fed to the hydrometallurgical treatment plant. Li, Cu, Co and Ni are dissolved in the leach tanks. Cu is cemented out with steel shot and the other metals are precipitated as salts. The Ni and Co salts are sold to a refinery and refining charges (in this case 20% of the contained metal value) was assigned to these intermediate products.

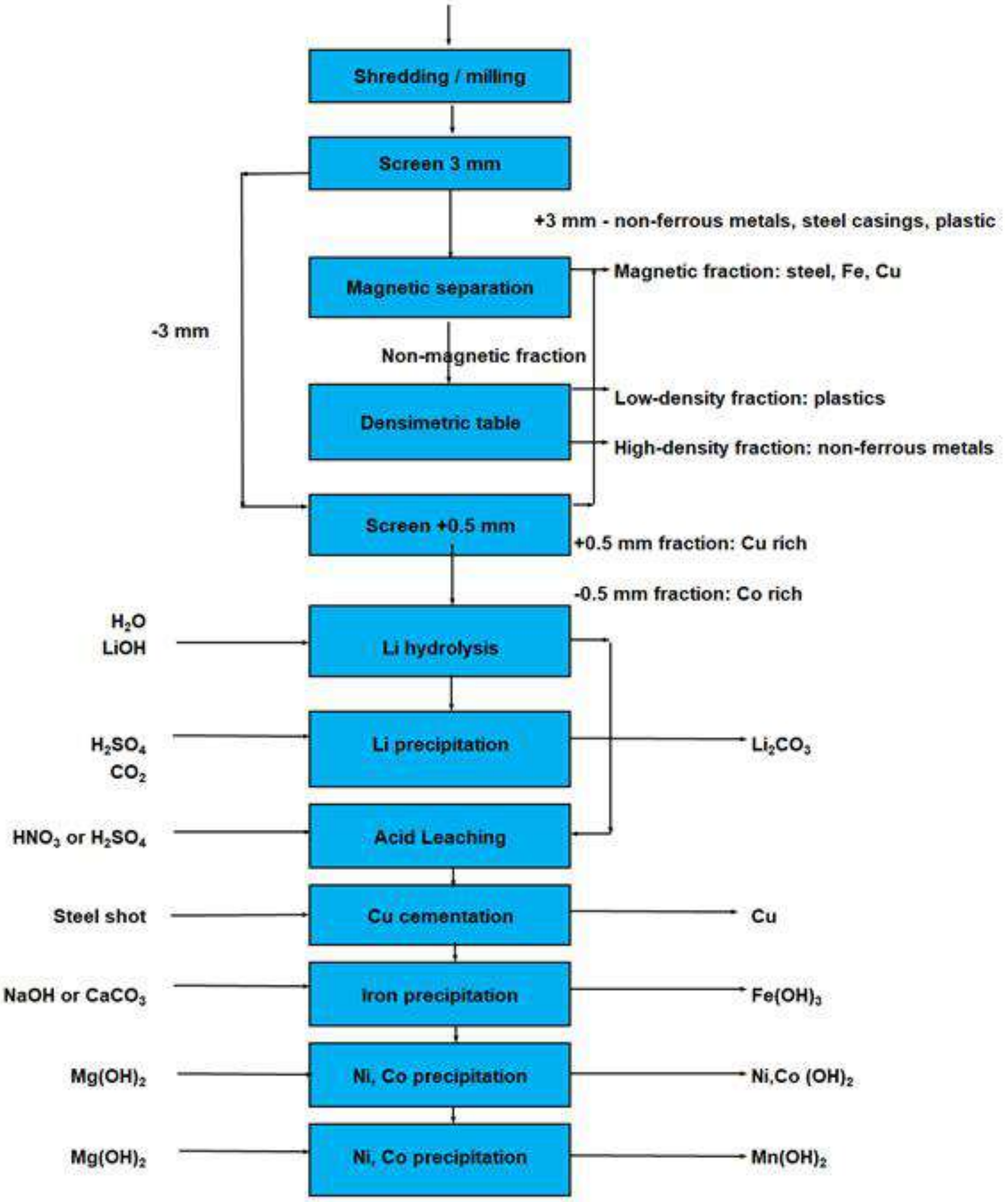


Figure 10. Hydrometallurgical flowsheet

The pyrometallurgical flowsheet (Figure 11) comprises a shaft furnace, into which the battery components is fed together with coke and slag formers. The shaft furnace consists of three main reaction zones: a 300°C zone where the electrolyte is evaporated, a 700°C zone where plastics pyrolysis takes place, and a high temperature zone (1450°C) where the metals are reduced. Heat is generated internally by the combustion of the feed materials. The furnace produces a slag and an alloy. The alloy contains most of the valuable metals and is further treated by hydrometallurgical process steps to recover the valuable metals such as Cu, Ni and Co.

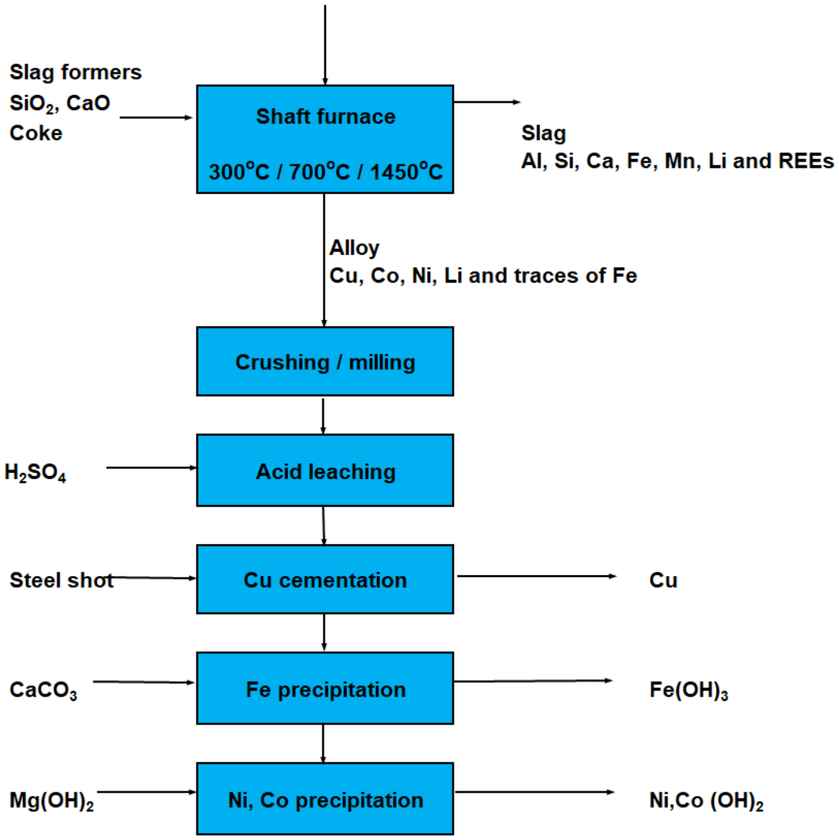


Figure 11. Pyrometallurgical flowsheet

The third process flowsheet (Figure 12) consists of shredding, crushing, screening and physical separation. Typical products of the mechanical process are ferrous and non-ferrous metal concentrates including Al and Cu concentrates as well as a fraction containing the active electrode materials, which is called black mass. The black mass can be either fed in pyrometallurgy or treated directly in hydrometallurgy. Depending on the overall process design, the black mass requires a thermal treatment prior to hydrometallurgy to remove the organic components and to concentrate the metal content to produce a black mass intermediate and does not include hydrometallurgical refining. This process is essentially similar to the first stages of the hydrometallurgical flowsheet (Figure 12). The black mass can either be fed into pyrometallurgical routes or directly treated by hydrometallurgical methods. Both approaches are pursued industrially (Brückner et al., 2020).

Currently, the production of high-grade products from black mass and similar production waste only takes place in Asia due to the sufficient amount of available feed material, especially production wastes, as most battery producers are located in Asia. Nevertheless, several European companies work on comparable processes, as European battery cell production is expected to increase significantly within the next years (Brückner et al., 2020). By assigning a refining charge to the black mass (in this case 60% of the metal value), this process represents the lowest investment risk, provided a suitable buyer can be found for the black mass.

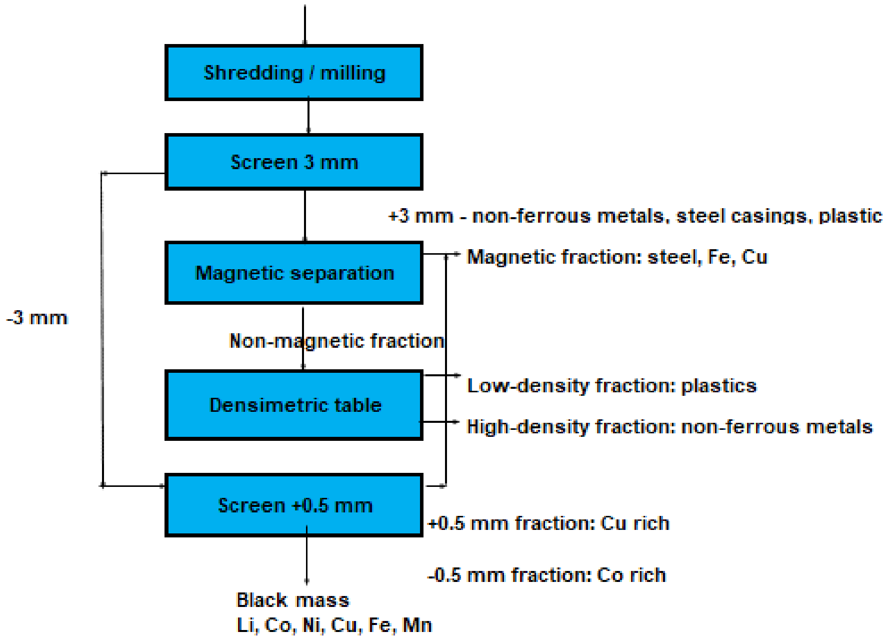


Figure 12. Black mass flowsheet

5.2 Operating costs

The breakdown of operating costs calculated for the treatment of a 1000 tpa LIB feed “blend” using the different process options are summarised in Figures 13, 14 and 15 and Annexure 2. Transport costs were assumed to be 29% of the operating cost in line with estimates published by Sattar et al., (2020). The cost of purchasing the feed material was estimated at 15% of the contained metal value. Reagent costs are summarised in Table 13. The operating cost breakdown for the hydrometallurgical process in Figure 5 comprises 29% for transport costs and 29% for purchasing of feed materials, which is in agreement with the work of Sattar et al. (2020).

Table 13. Reagent costs

Reagent	Price (USD / t)
H_2SO_4	200
Scrap iron	195
$CaCO_3$	200
$Mg(OH)_2$	400
SiO_2	71
CaO	71
Electricity	54 USD / MWh

The operating cost for the hydro- and pyrometallurgical processes were similar and varied between 7523 $ / t and 1460 $ / t for the hydrometallurgical route and between 7485 $ / t and 1511 $ / t for the pyrometallurgical route. The operating cost for the black mass route was lower at between 4000 $ / t and 1154 $ /t. The calculations indicated that the operating costs (USD/t) decreased substantially with increasing feed rate.

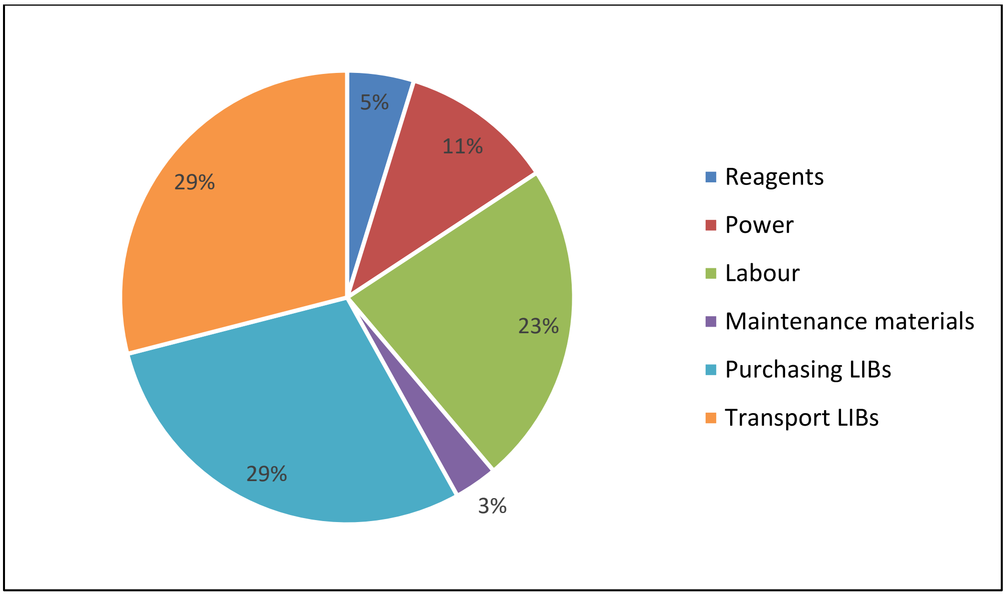


Figure 13. Hydrometallurgical route: Operating cost breakdown (blend, 1000 tpa)

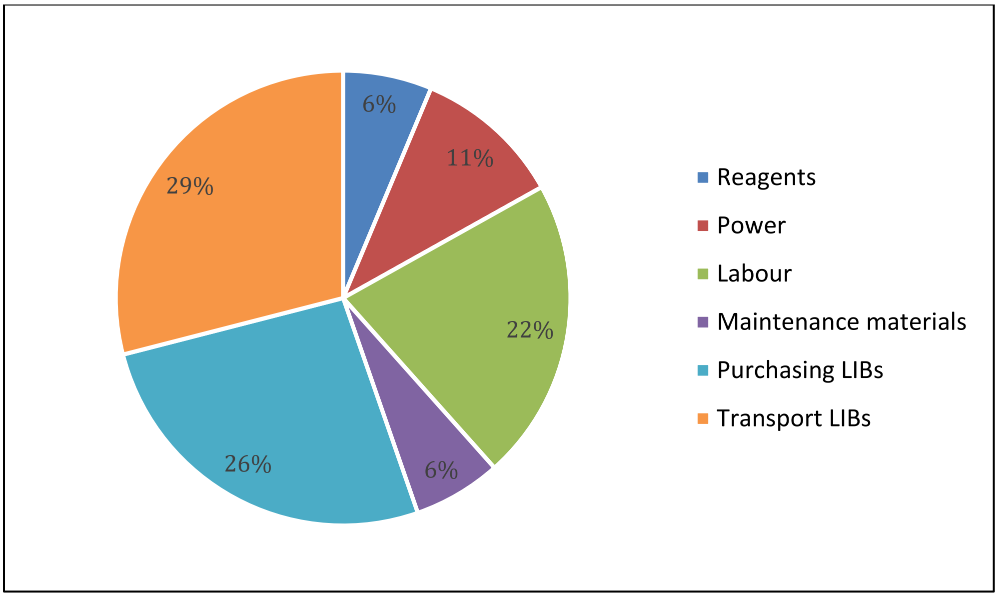


Figure 14. Pyrometallurgical route: Operating cost breakdown (blend, 1000 tpa)

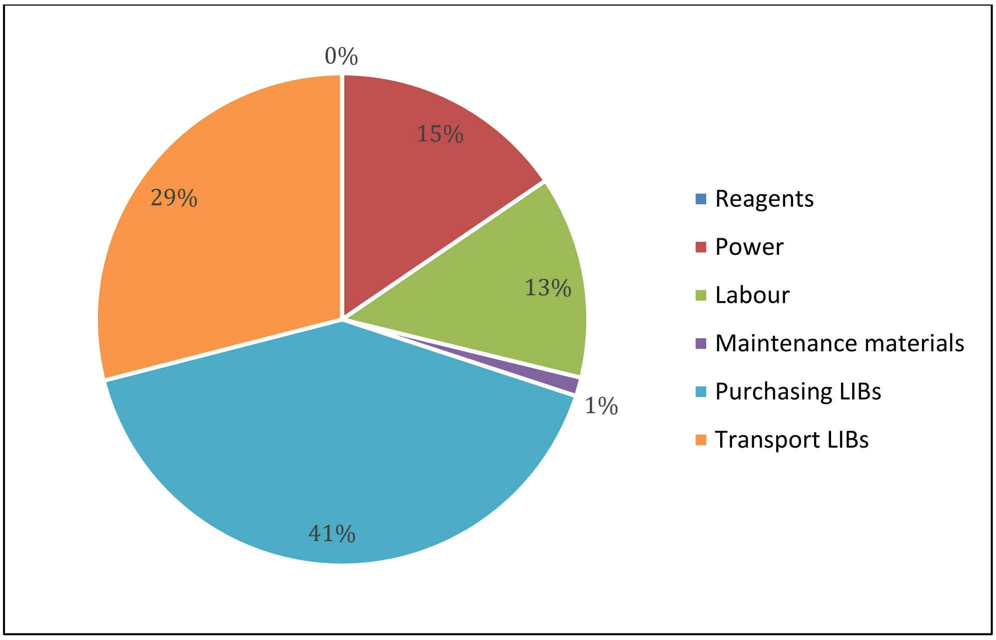


Figure 15. Black mass route: operating cost breakdown (blend, 1000 tpa)

Figure 16 shows the operating costs for the “blend” at various feed rates, bench-marked against the values calculated for hydrometallurgical processes by Sattar et al. (2020) and Nicely et al., (2020). The Mintek values compare well with the published values. It also shows that the process becomes more economical at higher feed rates, since the operating cost per tonne of feed material decreases with increasing throughput.

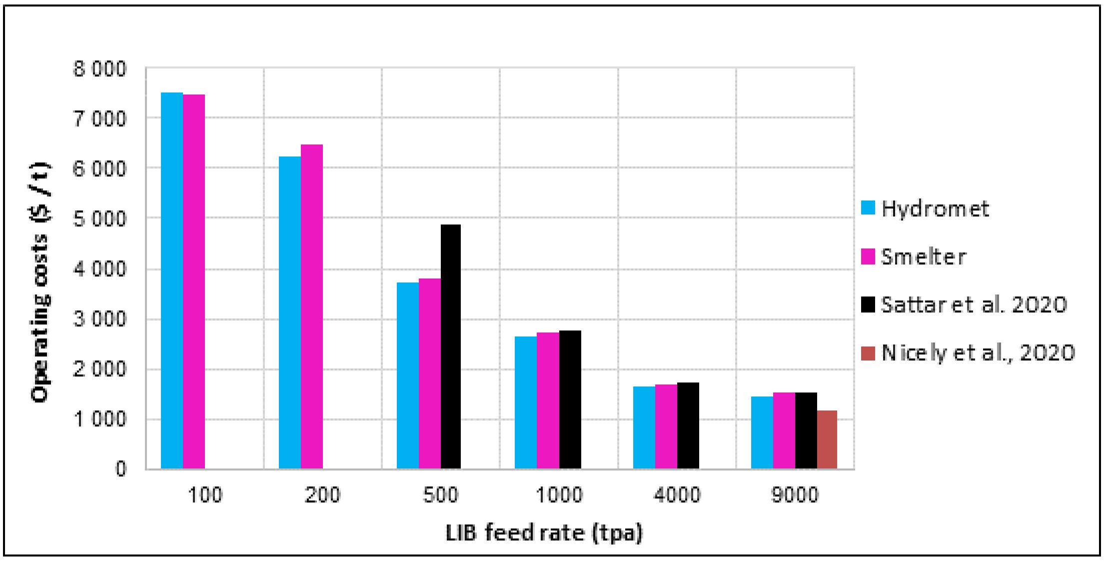


Figure 16. Operating cost comparison for the feed "blend"

5.3 Gross margin minus operating costs

The sensitivity analysis for the profitability based on the gross margin (revenue) minus operating costs (not including depreciation and tax) is summarised in Figures 17, 18 and 19 for the various feed compositions and feed rates. For the more valuable battery types (LCO, NMC and the blend) the process only becomes economical at feed rates of 500 tpa and above. The less valuable battery types such as LMO and LFP become economical at even higher feed rates. The hydrometallurgical route (Figure 17) and pyrometallurgical route (Figure 18) yielded similar gross margins, since in both cases most of the Co and Ni (containing most of the value) were recovered.

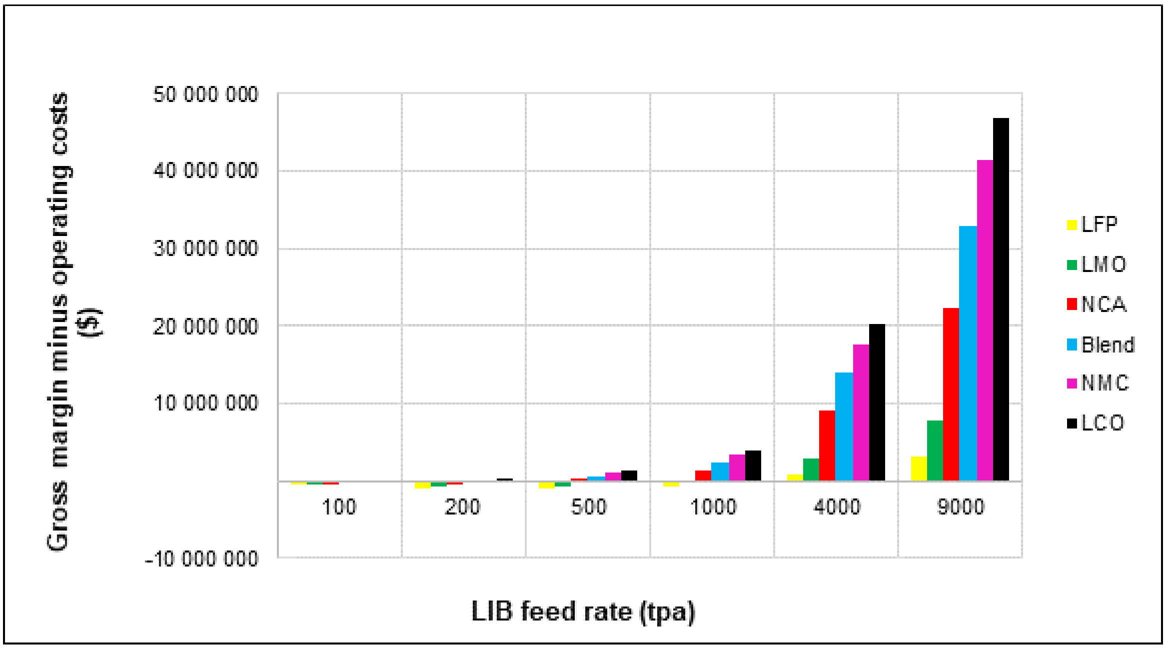


Figure 17. Hydrometallurgical route: Gross margin minus operating costs

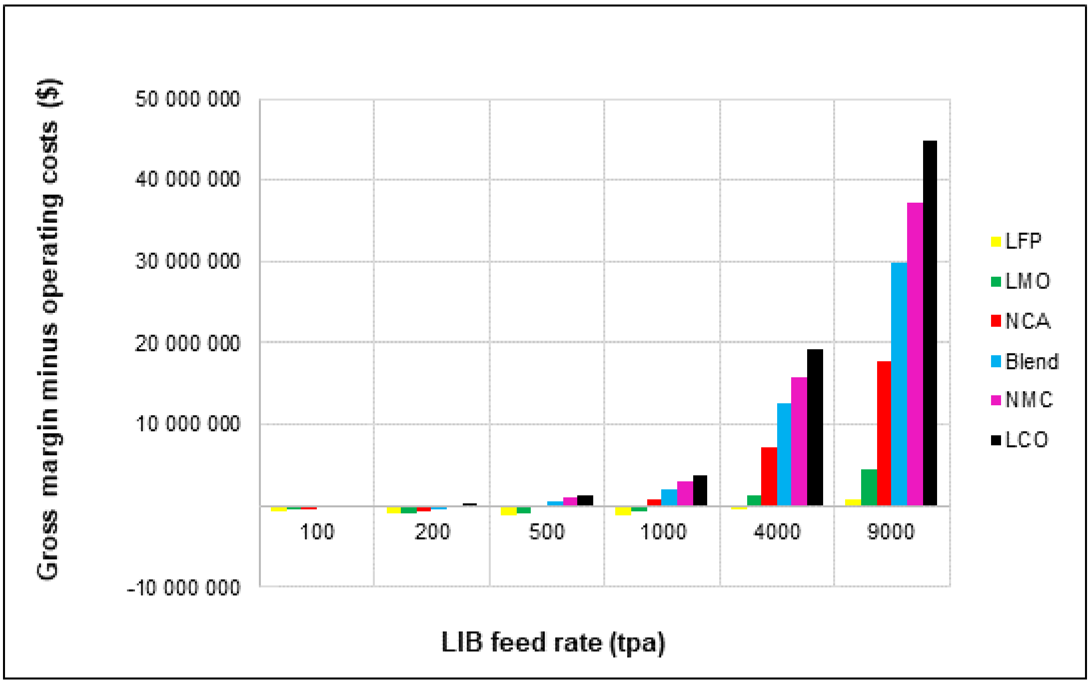


Figure 18. Pyrometallurgical route: Gross margin minus operating costs

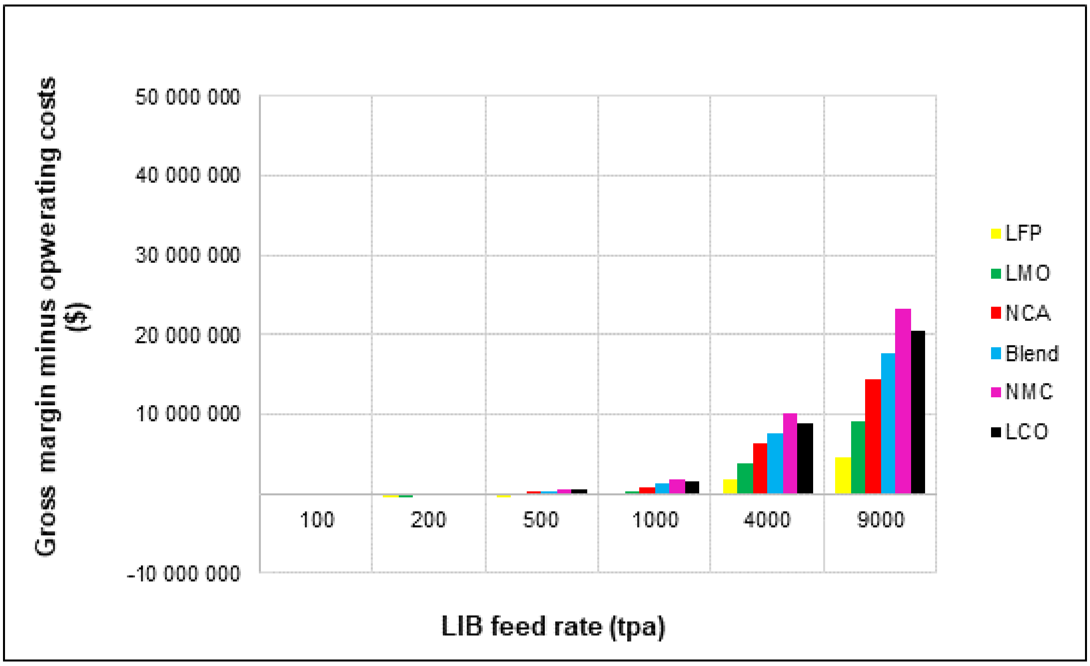


Figure 19. Black mass route: Gross margin minus operating cost

5.4 Capital costs

Capital costs for the three process options are summarised in Figures 20, 21 and 22 and Annexure 3.

The capital costs calculations include:

- Costs of major equipment items such as leach tanks, agitators, filters and feed pumps, adjusted to 2020 prices
- An installation factor of 3 was added to the equipment costs, which takes into account civils, piping and instrumentation
- Services and utilities (20% of direct capital costs)
- Infrastructure (15% of direct capital costs)
- Engineering, procurement and construction (EPCM) (11% of total direct costs)
- Site temporary facilities (2% of total direct costs)
- Owner’s cost (7.5% of total direct costs)
- Contingency (10% of total indirect costs)

The calculations indicated that the capital costs for the pyrometallurgical route was the highest, followed by the hydrometallurgical route and the black mass route. Total project capital costs varied between 0.66 $ million (100 tpa) and 12.3 $ million (9000 tpa) for the hydrometallurgical flowsheet, between 1.06 $ million (100 tpa) and 20.7 $ millon (9000 tpa) for the pyrometallurgical route and between 0.18 $ million (100 tpa) and 3.5 $ million (9000 tpa) for the black mass flowsheet

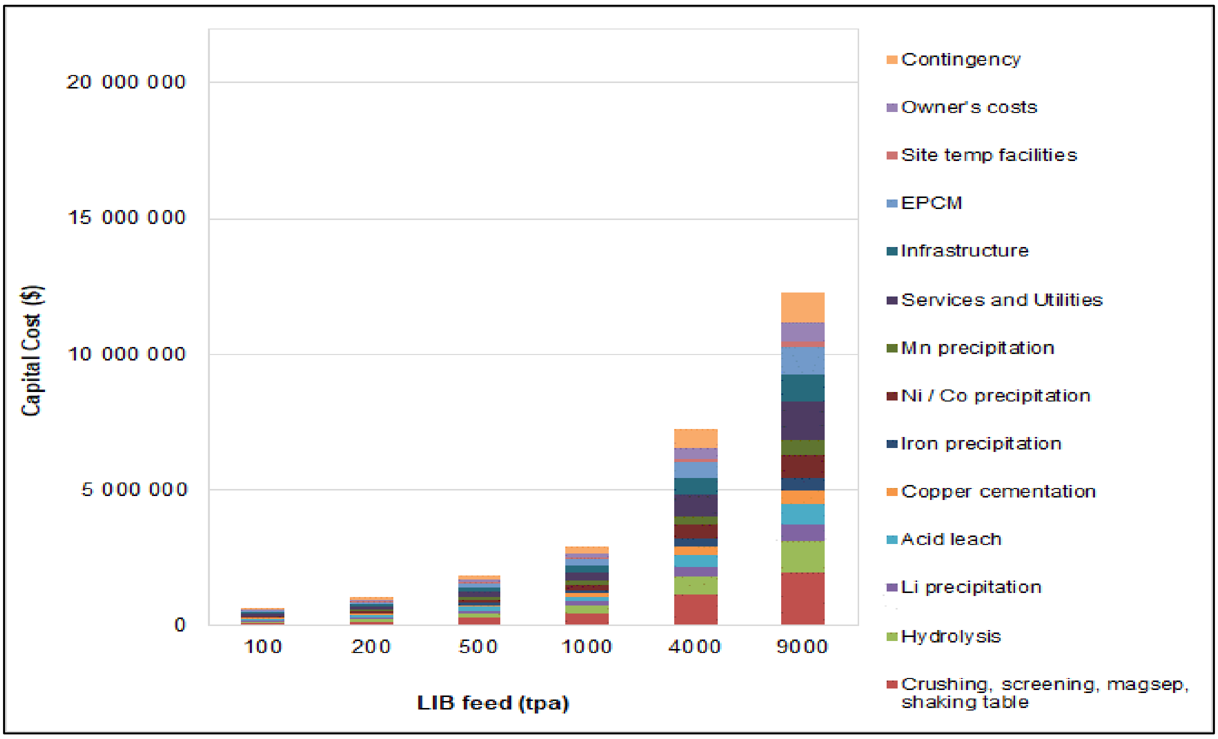


Figure 20. Hydrometallurgical route: Capital costs “blend”

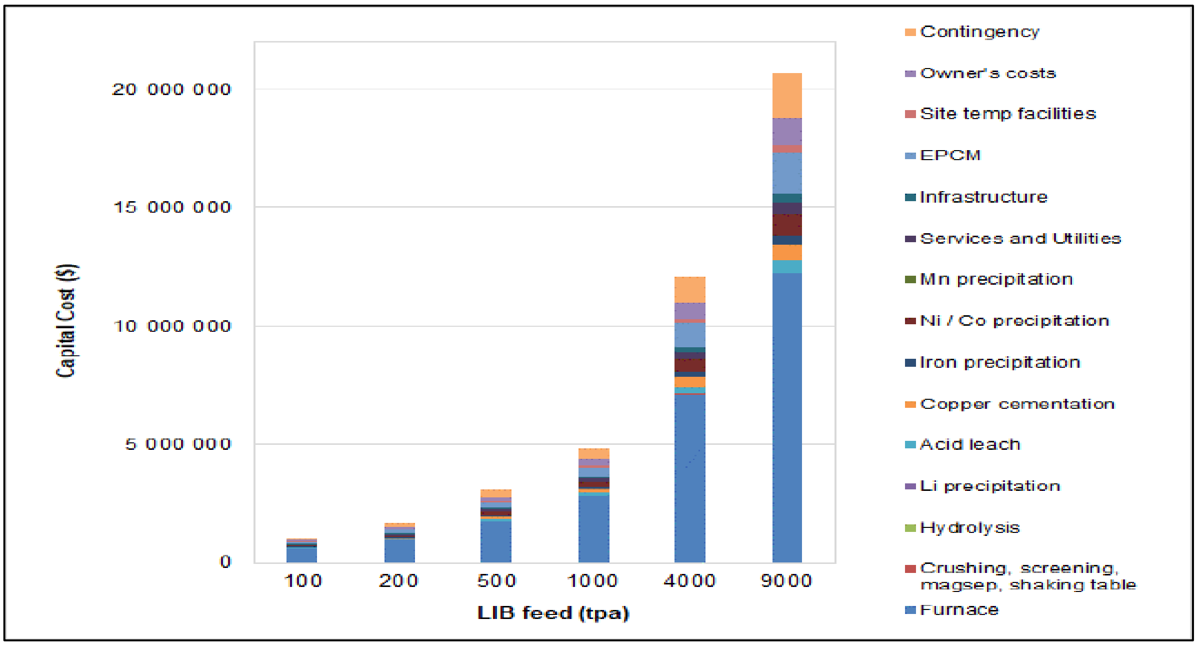


Figure 21. Pyrometallugical route: Capital costs "blend"

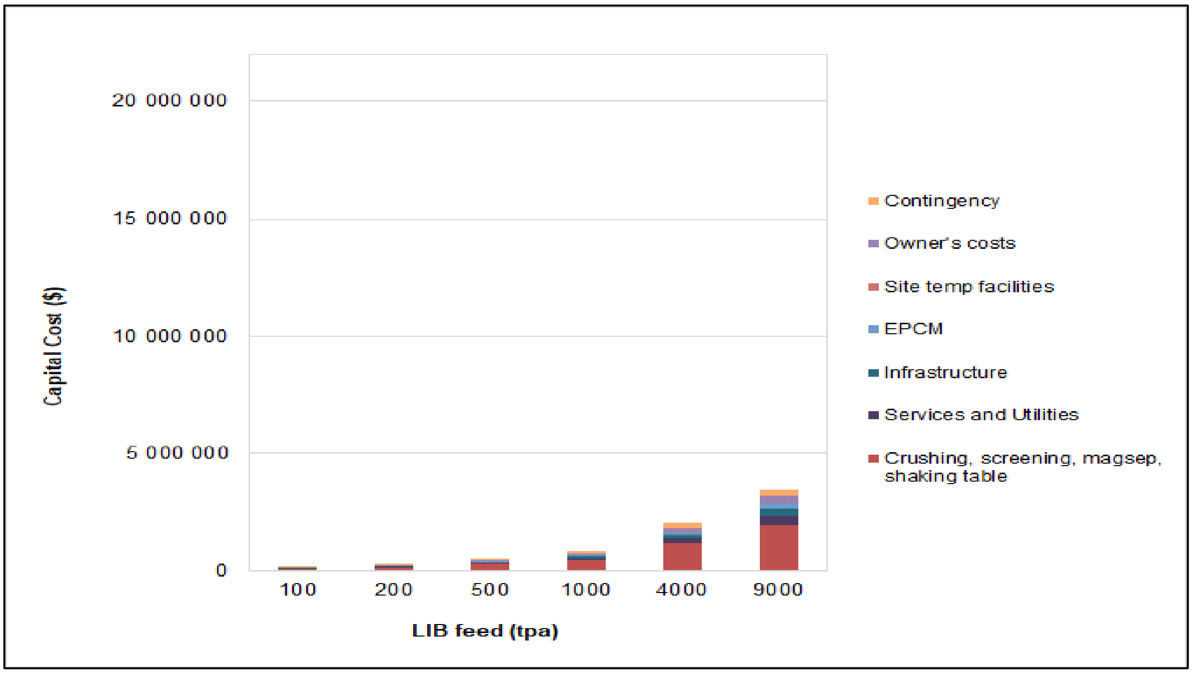


Figure 22. Black mass route: Capital costs "blend"

The capital costs for the feed "blend" is presented in Figure 23 and compared with published data for hydrometallurgical plants including American Manganese Inc. (2018), Li-cycle (Kelleher and Millette, 2020), Hydrovolt (Colthorpe, 2021), Neometals (2019), Hayman and Denton (2018), CM solutions (Knights and Salojee, 2015) and Nicely et al. (2020). The Mintek calculated costs fall within the range of published data, with the exception of Li-cycle and Neometals, where capital costs were substantially higher.

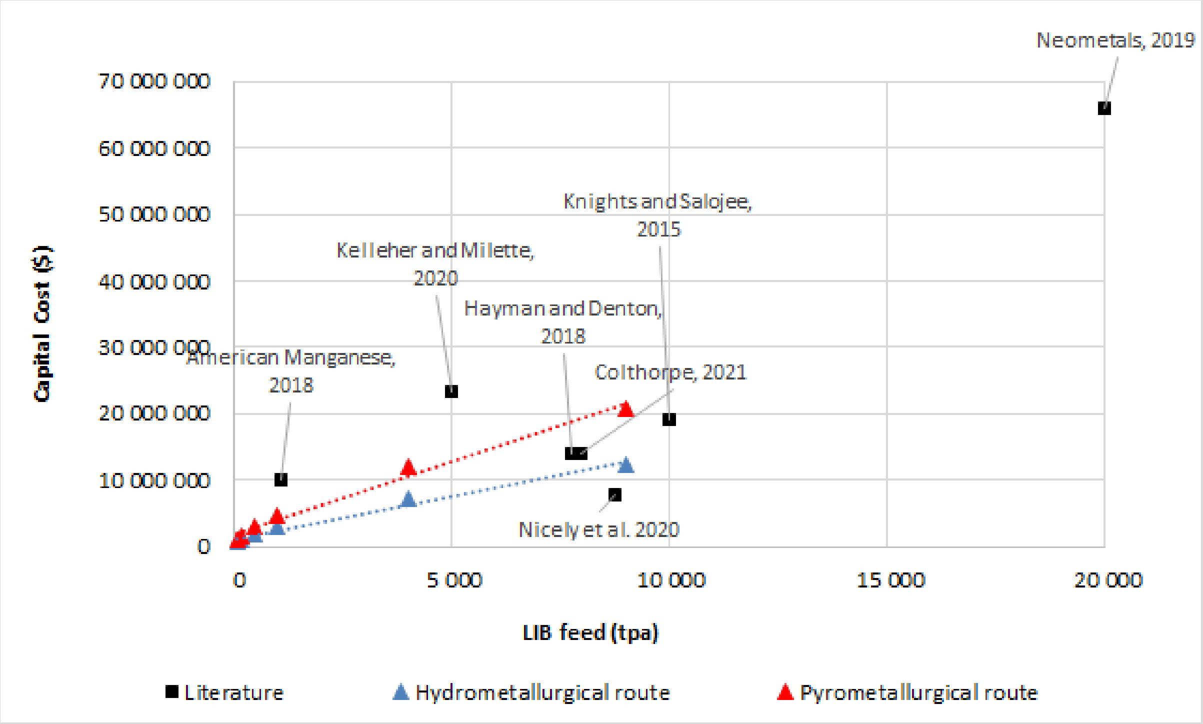


Figure 23. Capital cost comparison "blend"

5.5 Internal rate of return

The internal rate of return (IRR) was calculated for the various feed compositions, feed rates and flowsheets (Figures 24, 25 and 26). The black mass flowsheet yielded the highest IRRs. Positive IRRs were obtained for the more valuable battery types (LCO, NMC and blend) at feed rates of 500 tpa and above. The lower value battery types (LMO and LFP) yielded positive IRRs at even higher feed rates. The IRRs of all three flowsheets are highly dependent on the Ni and Co prices, as well as the refining charges. In this model, refining charges equal to 20% of metal value was assumed for hydroxide salts and 60% of contained metal value for black mass.

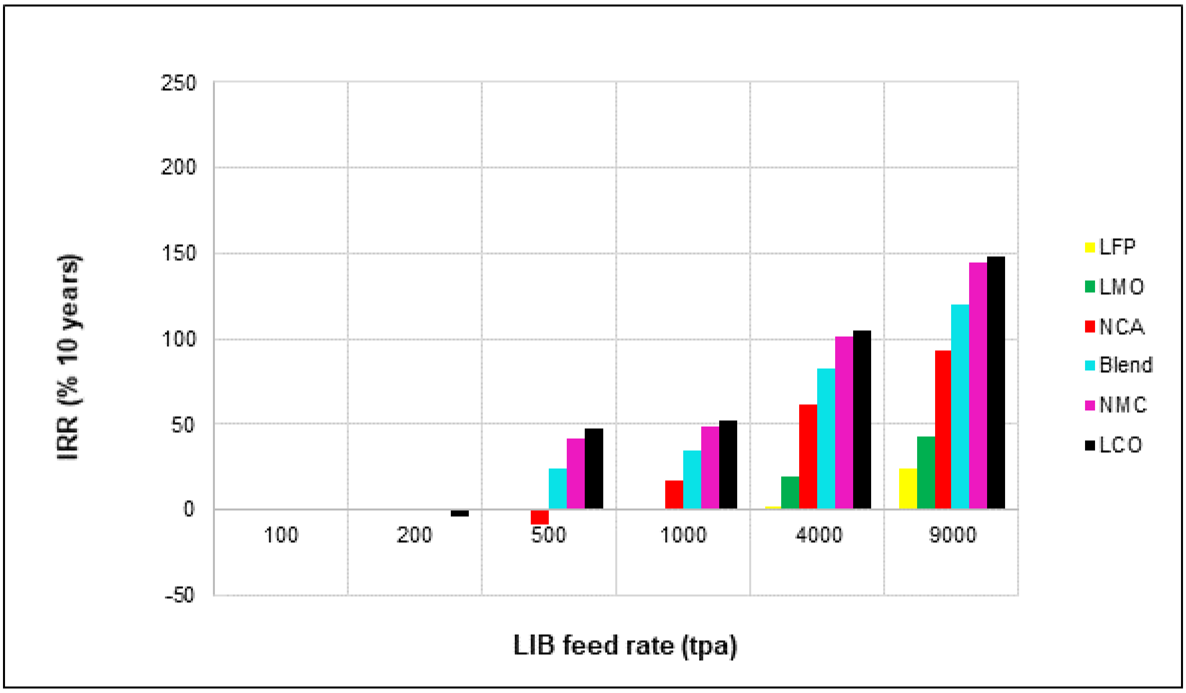


Figure 24. Hydrometallurgical route: IRR 10 years

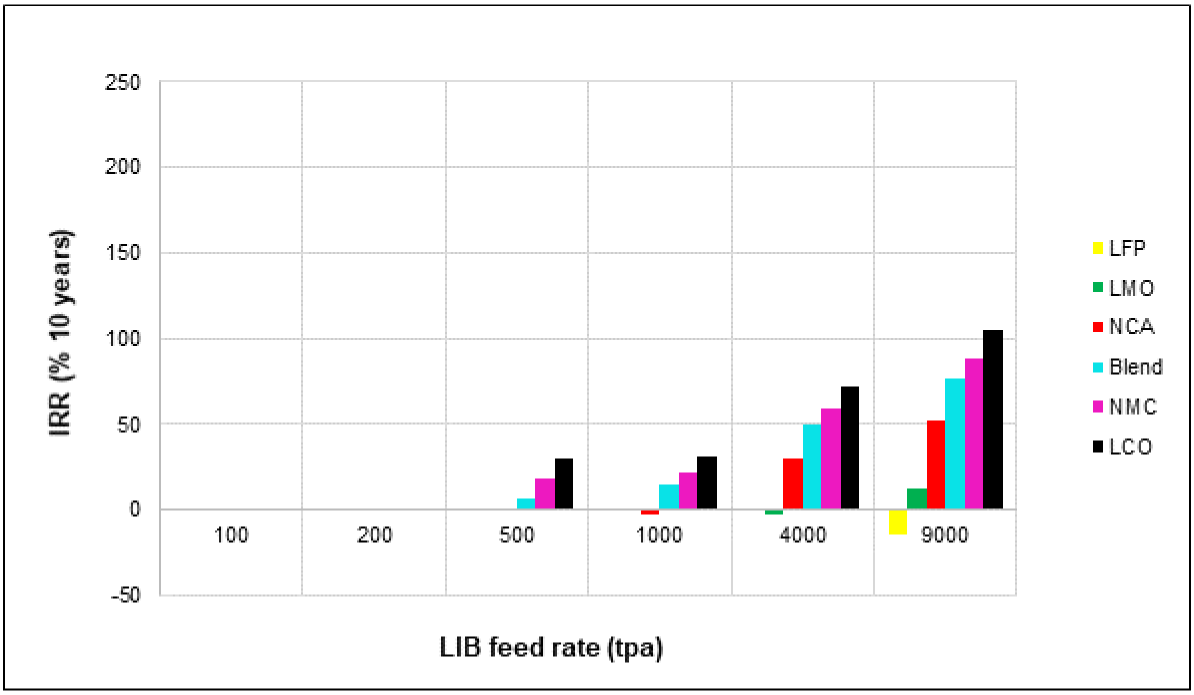


Figure 25. Pyrometallurgical route: IRR 10 years

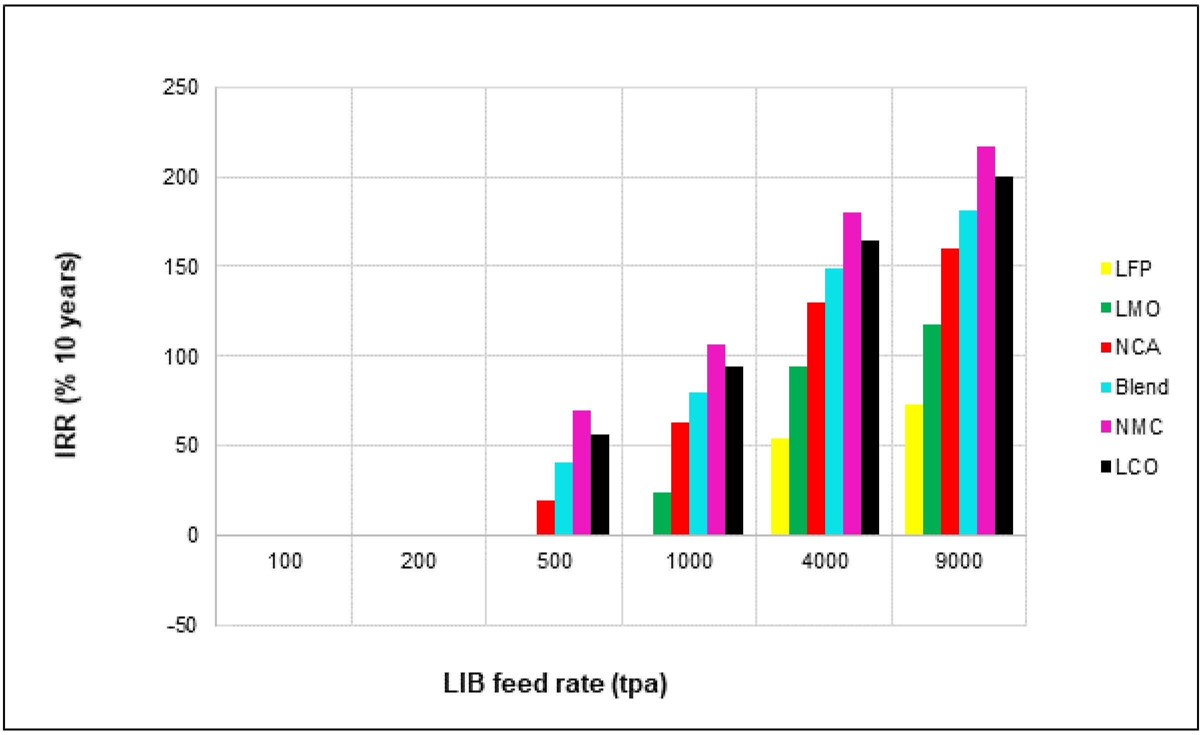


Figure 26. Black mass route: IRR 10 years

5.6 Main outcomes of the techno-economic analysis

- The LIB-recycling process only becomes economical at feed rates of about 500 tpa for the more valuable battery types. For less valuable batteries even higher feed rates are required for the process to become economical.
- The profitability is sensitive to the battery feed composition, specifically the Co, Ni and Cu content. Any changes in battery feed composition, therefore has the potential to significantly alter the economic viability of the process.
- Capital costs of the pyrometallurgical route are substantially higher without providing better recovery of metal values compared with the hydrometallurgical route.
- It appears most pyrometallurgical operations are modifications to existing plants and LIBs comprise only a portion of the feed. Most new proposed plants are based on the hydrometallurgical flowsheet.
- The hydrometallurgical route is complex with various product-streams.
- Based on a calculation of IRR, the pyrometallurgical route is the least profitable, followed by the hydrometallurgical route and the black mass route.
- Production of black mass presents the lowest risk, but depends on finding a suitable buyer and subject to refining charges (estimate 40% of contained metal value is paid out).

6 Conclusions and Recommendations

Global situation

The global consumption of LIBs has increased sharply in recent years in line with the increasing use of electrical, electronic, industrial and mobility equipment. The market for electric vehicles especially, is growing exponentially and as the demand for EVs grows, so is the demand for batteries.

China, Japan and South Korea collectively accounted for around 84% of global LIB production capacity for all applications during 2019. This is mirrored by the majority of the LIB recycling activity occurring in Asia, followed by Europe.

The quantities of LIBs currently being recycled globally remains small. This is due to a variety of reasons including the non-availability of sufficient recycling volumes (lack of economies of scale), inefficiencies in LIB collection, the complexities in different LIB designs and the numerous battery chemistries involved. However, the anticipated large quantities of spent lithium-ion batteries joining the waste stream, are currently driving the establishment of new recycling facilities, especially in the Northern hemisphere. The North American and Asian regions are anticipated to lead the growth in LIB recycling activities between 2020 and 2030.

South African situation

It is estimated that the current installed LIB capacity in South Africa is around 5000 tpa, with around 1200 tpa available for recycling. Very low volumes of waste LIB (between 6-10 tonnes per year), mainly from consumer electronics and ICT equipment, are currently collected. This represents around 1% of the estimated LIB waste annually generated in South Africa. The low volumes are insufficient to support a local recycling facility and as a result the current LIB waste in South Africa is either stockpiled, landfilled or shipped to available facilities around the globe.

The biggest driver for the establishment of a recycling facility in South Africa would be the anticipated growth in the EV market. Electric car sales in South Africa are however marginal and most EV batteries in the market have not yet reached the end of their lives.

While the existing stock of LIB waste in the country is currently insufficient to support a commercially viable processing plant, the anticipated increased uptake of electric vehicles, which are powered by various types of LIBs and use of these batteries in renewable energy storage applications is poised to generate significant quantities of waste LIB material in the near future. The ongoing process of establishing an EPR scheme for batteries sold in the country, enforced through regulation, could provide the impetus for the establishment of a recycling facility in the medium term.

Commercially available technologies

Currently there are three basic recycling process options available for the recycling of LIBs, namely pyrometallurgy, hydrometallurgy and direct recycling. Pyro- and hydrometallurgical technologies have been commercialised, whereas direct recycling is still in the research stage. These different processes can be combined in different flowsheet configurations, depending on factors such as quantity and characteristics of the material available and quantity and value of the materials that can be recovered.

Industrial scale battery recycling operations which are capable of recycling LIBs are mainly located in Asia and to a lesser extent in Europe and North America. The hydrometallurgical route is favoured for new installations, mainly in China, USA and Northern Europe.

Historically, the main objective of Li-ion battery recycling has been recovery of valuable metals such as cobalt and Ni, because of its high value and everything else has been secondary. There is also currently not an economic process for the recovery of lithium phosphate batteries available. However, as the cobalt content in batteries decreases and mandatory recycling regulations come into effect globally, interest is growing in recovery of additional materials such as Li, graphite and the electrolyte. A solution for efficient recovery of these materials could be a competitive advantage, especially in the case of battery chemistries with no or low Co and/or Ni contents.

There is still scope for process development and optimization, especially in the face of ongoing battery development, such as changing battery chemistries and varied types each with its own distinct design and component features, which is making it difficult to establish robust, versatile and cost competitive recycling processes. The developments are very dynamic, and further progress can be expected in the coming years.

Due to the complex process chains, a number of new operations have recently started to follow the route of partnership formation. This means that companies do not cover all process steps, but typically pre-treatment, metallurgy, refining, and cathode material production are operated by different companies. Especially in the metallurgical processing, co-processing is pursued at various stages to take advantage of large-scale installations and to homogenize the feed material. A further advantage of using established process routes is an easier entry of recycling material into the loop, as no additional certification of the products is necessary.

Techno-economic analysis

A techno-economic study was performed to investigate the business case for the establishment of a LIB recycling industry in South Africa. Three generic flowsheets, pyrometallurgical, hydrometallurgical and physical processing to produce a black mass were used to perform a techno-economic analysis. Based on our analysis, the most profitable recycling route is the production and sale of black mass, followed by the hydrometallurgical and pyrometallurgical routes.

The analysis shows that recycling only becomes economical at a LIB feed rate of round 500 tpa for high-value batteries. For lower value batteries, the process only becomes economical at much larger capacities. Profitability is very sensitive to the feed composition, specifically the Co, Ni and Cu content. If car manufacturers are successful in developing battery chemistries containing less cobalt, the revenue from recycling is likely to decrease.

Recycling facilities are often linked to battery manufacturing facilities, allowing re-use of the recycled materials in the manufacturing of new batteries. Establishment of a local battery manufacturing capacity could result in higher volumes of spent batteries being available for recycling. Such a facility could also lead to joint ventures and partnerships, similar to those emerging elsewhere in the world. It, however, still remains to be proven whether a local manufacturing facility would be competitive.

The introduction of EPR regulations in South Africa, expected to be implemented towards the end of 2021, is expected to assist with financing battery management. Once the details of the EPR scheme, related to recycling of LIBs are known, the techno-economic analysis can be fine-tuned.

Recommendations

At the current low collection rates of batteries, there is not a business case for establishing a LIB recycling plant in South Africa. Strategies to increase the collection of LIBs are required in the following areas:

- Improvement of collection infrastructure
- Increased consumer awareness of the importance of recycling batteries
- Disincentivising or banning of disposal to landfill

There needs to be political will to encourage the uptake of EVs in South Africa. These could include:

- Acceleration of the implementation of South Africa's Green Transport Strategy
- Adoption of green public transport
- Implementation of fiscal incentives to make EVs more cost-competitive and stimulate market penetration.
- Addressing issues related to the availability of charging stations, reliable electricity supply and possibly setting manufacturing and sales targets as is being done elsewhere.

Globally, the EV revolution is anticipated to happen over the next 10 years, however South Africa is lagging behind, and the impact of large volumes of end-of-life batteries entering the waste stream will probably only be experienced in the next 10 to 20 years. Until such time as local volumes increase sufficiently to merit a local recycling facility, it is recommended that processes be implemented to treat LIBs to a stable state, after which it can be exported to international recycling facilities.

Longer-term recommendations include:

- Once collection rates around 500 tpa are reached, a small-scale mechanical plant for the pre-processing of the LIB waste to produce black mass could be implemented. The black mass can be treated locally through partnerships with metallurgical operations or exported to international refineries for metal recovery.
- Once a reliable supply, of large enough LIB waste volumes, is collected a hydrometallurgical plant can be considered for the treatment of LIBs to produce either metal precipitates or high purity battery materials.
- The LIB waste volumes available for local treatment can be increased by accepting regional or international LIB waste by creating a favorable economic and regulatory environment for

battery recycling. It is, however, questionable if we could be competitive in a market currently dominated by China.

There is much interest locally in the topic of LIB recycling and it is recommended that a forum of stakeholders, including recyclers, OEMs, relevant government departments, research councils and universities be established to ensure that information on LIB waste remains relevant, gaps in technology development are identified and that research efforts are not duplicated.

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ANNEXURE 1

SURVEY QUESTIONNAIRE

MINTEK
A global leader in mineral and metallurgical innovation

ISO 9001 QUALITY MANAGEMENT SYSTEM
ISO 17025 TESTING AND CALIBRATION LABORATORY
ISO 14001 ENVIRONMENTAL MANAGEMENT SYSTEM
OHSAS 18001 OCCUPATIONAL HEALTH AND SAFETY MANAGEMENT SYSTEM

Technology Landscape and Business Case for the Recycling of Lithium Ion Batteries in South Africa

☐ I have been informed about the purposes of this study as stated in the cover letter and I/my organisation participates voluntarily

If this questionnaire has been incorrectly sent to your organisation and you are not involved in lithium ion battery recycling in any way, please tick the adjacent box and return to Mintek via email (Email: wondern@mintek.co.za) Please tick ☐

NO COMPANY-SPECIFIC INFORMATION WILL BE RELEASED. ALL INFORMATION PROVIDED IS STRICTLY CONFIDENTIAL AND WILL BE SUMMARISED AND COLLATED TO PROVIDE AN OVERALL PERSPECTIVE OF THE STATE OF THE SOUTH AFRICAN LITHIUM ION BATTERY RECYCLING INDUSTRY

I. Background

Interviewer:	Date of interview:	Company:

Interviewee:	Position:

Contact details:

Overview of activities:
Years in operation:
Number of staff:
Geographical footprint:

II. WEEE Recycling Market Trends

1. How many tonnes of waste electrical and electronic equipment (WEEE) did your company collect for recycling in 2019?
2. What is the approximate percentage split (%) of the waste streams (ICT & consumer electronics, large and small household goods, lamps etc) for the WEEE your company collected in 2019?
3. How has your company's collection of the WEEE streams identified above changed over the past five years?
4. What do you consider to be the key factors *(local, regional or global)* that are likely to influence trends in the WEEEE recycling industry and your particular niche over the next 5-10 years?

III. Lithium Ion Battery Recycling Processes

1. How many tonnes (t) of lithium ion batteries (LIBs) did your company collect for recycling in 2019?
2. How have the LIB collection trends for your company changed over the past 5 years? Please explain the factors underlying the trends identified above*?*
3. What were the major source WEEE material (laptops and tablets, mobile phones, hand tools etc) for LIBs your company collected for recycling in 2019? *Indicate, the percentage (%) contribution of these WEEE streams to total LIB collections in 2019?*
4. What are the major LIB types and/or chemistries (LiCo, Li-P etc) your company get from the source WEEE streams identified above?
5. Can you please take us through the dismantling, pre-processing, storage and packaging process for LIBs that your company follows? Are there any environmental and safety precautions your company observe in undertaking the above processes?
6. Do you have any plans to expand your LIB recycling operations in future? Please motivate your answer.

7. What were the main end markets for LIB fractions produced by your company in 2019?
8. How big (in percentage terms) was the re-use (second hand) market for LIBs for your company when expressed as a proportion (share) of the total market in 2019?
9. How the price (R/t) your company has received for LIB fractions from end markets identified above changed in the past 5 years?
10. What technology interventions do you think WEEE recyclers in South Africa will require to unlock further growth opportunities in LIB recycling in the medium to long term?
11. The latest generation of smart phones (Samsung, Huawei, i-phone etc) come with embedded (non-removable) LIBs. In your view, what impacts will this have on the collection and recycling of LIBs in South Africa?
12. What are the main future growth opportunities for the LIB recycling sector in South Africa?

Please return to completed questionnaire to Mr Wonder Nyanjowa, Senior Mineral Economist, Mineral Economics & Strategy Unit (MESU), Mintek: wondern@mintek.co.za

ANNEXURE 2

SUMMARY OF OPERATING COSTS

	Hydrometallurical route						Pyrometallurgical route						Black powder route					
Feed rate, tpa	100	200	500	1000	4000	9000	100	200	500	1000	4000	9000	100	200	500	1000	4000	9000
Reagents, $/a	$ 12 559	$ 25 119	$ 62 797	$ 125 595	$ 502 379	$ 1 130 352	$ 17 333	$ 34 666	$ 86 666	$ 173 331	$ 693 325	$ 1 559 980	-	-	-	-	-	-
Power, $/a	$ 6 481	$ 260 561	$ 268 441	$ 289 766	$ 54 188	$ 102 217	$ 4 484	$ 260 561	$ 268 441	$ 289 766	$ 27 148	$ 50 059	$ 2 901	$ 260 561	$ 268 441	$ 289 766	$ 9 160	$ 16 692
Labour, $/a	$ 420 000	$ 420 000	$ 560 000	$ 610 000	$ 790 000	$ 850 000	$ 400 000	$ 420 000	$ 520 000	$ 590 000	$ 730 000	$ 810 000	$ 200 000	$ 200 000	$ 200 000	$ 250 000	$ 290 000	$ 350 000
Maintenance materials (5% of TIC)	$ 18 344	$ 28 706	$ 52 005	$ 81 635	$ 201 772	$ 343 094	$ 37 448	$ 59 252	$ 108 562	$ 171 739	$ 430 305	$ 736 860	$ 5 022	$ 7 931	$ 14 517	$ 22 940	$ 57 315	$ 97 946
Purchasing LIBs (15% of metal value)	$ 76 737	$ 153 473	$ 383 683	$ 767 367	$ 3 069 466	$ 6 906 299	$ 72 174	$ 144 348	$ 360 871	$ 721 742	$ 2 886 968	$ 6 495 678	$ 76 737	$ 153 473	$ 383 683	$ 767 367	$ 3 069 466	$ 6 906 299
Transport of LIBs (29% of Opex)	$ 218 162	$ 362 647	$ 541 984	$ 765 584	$ 1 886 145	$ 3 811 646	$ 217 067	$ 375 296	$ 549 178	$ 795 081	$ 1 947 389	$ 3 942 602	$ 116 269	$ 254 042	$ 353 980	$ 543 269	$ 1 399 328	$ 3 010 664
Total operating costs $/a	$ 752 282	$ 1 250 506	$ 1 868 910	$ 2 639 946	$ 6 503 950	$ 13 143 608	$ 748 507	$ 1 294 123	$ 1 893 719	$ 2 741 659	$ 6 715 134	$ 13 595 179	$ 400 928	$ 876 007	$ 1 220 622	$ 1 873 342	$ 4 825 268	$ 10 381 600
Total operationg costs $/t	$ 7 523	$ 6 253	$ 3 738	$ 2 640	$ 1 626	$ 1 460	$ 7 485	$ 6 471	$ 3 787	$ 2 742	$ 1 679	$ 1 511	$ 4 009	$ 4 380	$ 2 441	$ 1 873	$ 1 206	$ 1 154
Gross margin minus operating costs - blend	-$ 240 705	-$ 227 351	$ 688 978	$ 2 475 830	$ 13 959 158	$ 32 898 384	-$ 267 345	-$ 331 801	$ 512 088	$ 2 069 955	$ 12 531 319	$ 29 709 340	-$ 90 270	-$ 254 690	$ 332 671	$ 1 233 243	$ 7 601 071	$ 17 577 663
Gross margin minus operating costs - NCA	-$ 358 630	-$ 463 299	$ 98 391	$ 1 293 828	$ 9 225 035	$ 22 242 720	-$ 400 268	-$ 597 099	-$ 150 748	$ 744 734	$ 7 229 550	$ 17 783 209	-$ 124 253	-$ 322 646	$ 162 799	$ 893 520	$ 6 242 276	$ 14 520 495
Gross margin minus operating costs - LMO	-$ 518 284	-$ 782 808	-$ 700 923	-$ 305 421	$ 2 824 324	$ 7 837 958	-$ 546 116	-$ 890 862	-$ 887 813	-$ 732 401	$ 1 312 925	$ 4 454 046	-$ 183 111	-$ 440 363	-$ 131 494	$ 304 933	$ 3 887 926	$ 9 223 204
Gross margin minus operating costs - NMC	-$ 144 751	-$ 36 515	$ 1 164 727	$ 3 425 804	$ 17 754 610	$ 41 429 469	-$ 186 276	-$ 167 726	$ 924 271	$ 2 896 562	$ 15 839 991	$ 37 166 890	-$ 28 471	-$ 131 107	$ 641 600	$ 1 851 069	$ 10 072 213	$ 23 137 533
Gross margin minus operating costs - LCO	-$ 86 130	$ 83 005	$ 1 466 081	$ 4 031 410	$ 20 183 513	$ 46 911 394	-$ 98 715	$ 4 692	$ 1 352 429	$ 3 749 631	$ 19 247 960	$ 44 816 060	-$ 58 216	-$ 190 568	$ 493 001	$ 1 553 933	$ 8 883 972	$ 20 464 366
Gross margin minus operating costs - LFP	-$ 563 369	-$ 879 759	-$ 950 181	-$ 811 716	$ 785 528	$ 3 204 139	-$ 585 735	-$ 972 734	-$ 1 095 283	-$ 1 150 457	-$ 364 503	$ 661 744	-$ 235 084	-$ 544 390	-$ 391 711	-$ 215 677	$ 1 804 636	$ 4 534 764

ANNEXURE 3

SUMMARY OF CAPITAL COSTS

		Hydromet - Capital Cost, USD					
		100	200	500	1000	4000	9000
Furnace		-	-	-	-	-	-
Crushing, screening, magsep, shaking table		$ 100 433	$ 158 619	$ 290 340	$ 458 808	$1 146 292	$1 958 918
Hydrolysis		$ 59 717	$ 93 982	$ 171 246	$ 269 715	$ 669 684	$1 140 616
Li precipitation		$ 32 438	$ 51 067	$ 93 106	$ 146 725	$ 364 807	$ 621 934
Acid leach		$ 45 063	$ 69 016	$ 122 045	$ 188 659	$ 455 030	$ 765 218
Copper cementation		$ 31 276	$ 47 231	$ 82 162	$ 125 640	$ 297 693	$ 496 516
Iron precipitation		$ 23 084	$ 36 291	$ 66 061	$ 103 998	$ 258 155	$ 439 807
Ni / Co precipitation		$ 45 377	$ 71 516	$ 130 550	$ 205 896	$ 512 561	$ 874 284
Mn precipitation		$ 29 486	$ 46 407	$ 84 581	$ 133 262	$ 331 217	$ 564 582
Services and Utilities		$ 73 374	$ 114 826	$ 208 018	$ 326 541	$ 807 088	$1 372 375
Infrastructure		$ 55 031	$ 86 119	$ 156 014	$ 244 905	$ 605 316	$1 029 281
Total Direct Costs		**$ 495 277**	**$ 775 073**	**$1 404 123**	**$2 204 149**	**$5 447 842**	**$9 263 532**
EPCM		$ 54 480	$ 85 258	$ 154 454	$ 242 456	$ 599 263	$1 018 988
Site temp facilities		$ 9 906	$ 15 501	$ 28 082	$ 44 083	$ 108 957	$ 185 271
Owner's costs		$ 37 146	$ 58 130	$ 105 309	$ 165 311	$ 408 588	$ 694 765
Total Indirect Costs		**$ 596 808**	**$ 933 963**	**$1 691 969**	**$2 655 999**	**$6 564 650**	**$11 162 556**
Contingency		$ 59 681	$ 93 396	$ 169 197	$ 265 600	$ 656 465	$1 116 256
Total Project Capital Costs	**Blend**	**$ 656 489**	**$1 027 360**	**$1 861 166**	**$2 921 599**	**$7 221 115**	**$12 278 811**
Total Project Capital Costs	**NCA**	**$ 639 152**	**$ 999 869**	**$1 810 643**	**$2 841 582**	**$7 020 642**	**$11 935 955**
Total Project Capital Costs	**LMO**	**$ 626 133**	**$ 979 280**	**$1 772 915**	**$2 781 938**	**$6 871 612**	**$11 681 356**
Total Project Capital Costs	**NMC**	**$ 624 682**	**$ 977 423**	**$1 770 380**	**$2 778 771**	**$6 866 852**	**$11 675 453**
Total Project Capital Costs	**LCO**	**$ 685 124**	**$1 072 170**	**$1 942 343**	**$3 049 029**	**$7 536 115**	**$12 814 536**
Total Project Capital Costs	**LFP**	**$ 464 169**	**$ 726 102**	**$1 314 842**	**$2 063 444**	**$5 097 871**	**$8 666 627**
IRR - 10 years	**Blend**			**24.1**	**34.4**	**82.1**	**119.7**
IRR - 10 years	**NCA**			**-9.12**	**16.68**	**61.11**	**93.12**
IRR - 10 years	**LMO**					**19.85**	**42.69**
IRR - 10 years	**NMC**			**41.97**	**48.83**	**101.78**	**144.65**
IRR - 10 years	**LCO**		**-4.07**	**47.23**	**51.97**	**104.42**	**147.68**
IRR - 10 years	**LFP**					**1.58**	**24.03**

		Smelter - Capital Cost, USD					
		100	200	500	1000	4000	9000
Furnace		$ 608 294	$ 965 562	$1 778 471	$2 823 016	$7 112 897	$12 212 692
Crushing, screening, magsep, shaking table		$ 550	$ 2 547	$ 4 439	$ 6 756	$ 15 650	$ 25 583
Hydrolysis		-	-	-	-	-	-
Li precipitation		-	-	-	-	-	-
Acid leach		$ 32 502	$ 49 303	$ 86 216	$ 132 301	$ 315 285	$ 527 263
Copper cementation		$ 40 838	$ 62 475	$ 110 332	$ 170 405	$ 410 417	$ 689 732
Iron precipitation		$ 21 400	$ 33 643	$ 61 240	$ 96 406	$ 239 290	$ 407 643
Ni / Co precipitation		$ 45 377	$ 71 516	$ 130 550	$ 205 896	$ 512 561	$ 874 284
Mn precipitation		-	-	-	-	-	-
Services and Utilities		$ 28 133	$ 43 897	$ 78 555	$ 122 353	$ 298 641	$ 504 901
Infrastructure		$ 21 100	$ 32 922	$ 58 916	$ 91 764	$ 223 980	$ 378 676
Total Direct Costs		**$ 798 193**	**$1 261 864**	**$2 308 719**	**$3 648 896**	**$9 128 722**	**$15 620 773**
EPCM		$ 87 801	$ 138 805	$ 253 959	$ 401 379	$1 004 159	$1 718 285
Site temp facilities		$ 15 964	$ 25 237	$ 46 174	$ 72 978	$ 182 574	$ 312 415
Owner's costs		$ 59 864	$ 94 640	$ 173 154	$ 273 667	$ 684 654	$1 171 558
Total Indirect Costs		**$ 961 823**	**$1 520 546**	**$2 782 007**	**$4 396 920**	**$11 000 109**	**$18 823 032**
Contingency		$ 96 182	$ 152 055	$ 278 201	$ 439 692	$1 100 011	$1 882 303
Total Project Capital Costs	**Blend**	**$1 058 005**	**$1 672 601**	**$3 060 207**	**$4 836 612**	**$12 100 120**	**$20 705 335**
Total Project Capital Costs	**NCA**	**$1 067 223**	**$1 687 009**	**$3 085 818**	**$4 876 332**	**$12 196 434**	**$20 867 718**
Total Project Capital Costs	**LMO**	**$1 005 026**	**$1 589 156**	**$2 908 719**	**$4 598 499**	**$11 510 416**	**$19 701 776**
Total Project Capital Costs	**NMC**	**$1 104 188**	**$1 745 162**	**$3 190 883**	**$5 040 982**	**$12 602 301**	**$21 557 012**
Total Project Capital Costs	**LCO**	**$1 037 247**	**$1 639 959**	**$3 001 257**	**$4 744 256**	**$11 872 569**	**$20 318 981**
Total Project Capital Costs	**LFP**	**$ 940 935**	**$1 488 812**	**$2 728 740**	**$4 317 752**	**$10 823 393**	**$18 538 726**
IRR - 10 years	**Blend**			**7.1**	**15.1**	**50.3**	**77.3**
IRR - 10 years	**NCA**				**-2.29**	**29.88**	**52.24**
IRR - 10 years	**LMO**					**-2.85**	**12.67**
IRR - 10 years	**NMC**			**18.01**	**22.34**	**58.87**	**88.14**
IRR - 10 years	**LCO**			**29.57**	**31.77**	**71.74**	**104.76**
IRR - 10 years	**LFP**						**-14.43**

		Black powder - Capital Cost, USD					
		100	200	500	1000	4000	9000
Furnace		-	-	-	-	-	-
Crushing, screening, magsep, shaking table		$ 100 433	$ 158 619	$ 290 340	$ 458 808	$1 146 292	$1 958 918
Hydrolysis		-	-	-	-	-	-
Li precipitation		-	-	-	-	-	-
Acid leach		-	-	-	-	-	-
Copper cementation		-	-	-	-	-	-
Iron precipitation		-	-	-	-	-	-
Ni / Co precipitation		-	-	-	-	-	-
Mn precipitation		-	-	-	-	-	-
Services and Utilities		$ 20 087	$ 31 724	$ 58 068	$ 91 762	$ 229 258	$ 391 784
Infrastructure		$ 15 065	$ 23 793	$ 43 551	$ 68 821	$ 171 944	$ 293 838
Total Direct Costs		**$ 135 585**	**$ 214 135**	**$ 391 959**	**$ 619 390**	**$1 547 494**	**$2 644 539**
EPCM		$ 14 914	$ 23 555	$ 43 115	$ 68 133	$ 170 224	$ 290 899
Site temp facilities		$ 2 712	$ 4 283	$ 7 839	$ 12 388	$ 30 950	$ 52 891
Owner's costs		$ 10 169	$ 16 060	$ 29 397	$ 46 454	$ 116 062	$ 198 340
Total Indirect Costs		**$ 163 380**	**$ 258 033**	**$ 472 310**	**$ 746 365**	**$1 864 730**	**$3 186 669**
Contingency		$ 16 338	$ 25 803	$ 47 231	$ 74 637	$ 186 473	$ 318 667
Total Project Capital Costs	**Blend**	**$ 179 718**	**$ 283 836**	**$ 519 541**	**$ 821 002**	**$2 051 203**	**$3 505 336**
Total Project Capital Costs	**NCA**	**$ 180 149**	**$ 284 538**	**$ 520 867**	**$ 823 136**	**$2 056 693**	**$3 514 844**
Total Project Capital Costs	**LMO**	**$ 180 135**	**$ 284 514**	**$ 520 822**	**$ 823 064**	**$2 056 508**	**$3 514 522**
Total Project Capital Costs	**NMC**	**$ 179 015**	**$ 282 695**	**$ 517 393**	**$ 817 548**	**$2 042 335**	**$3 489 994**
Total Project Capital Costs	**LCO**	**$ 180 343**	**$ 284 854**	**$ 521 464**	**$ 824 098**	**$2 059 171**	**$3 519 136**
Total Project Capital Costs	**LFP**	**$ 176 412**	**$ 278 495**	**$ 509 524**	**$ 804 932**	**$2 010 090**	**$3 434 306**
IRR - 10 years	**Blend**			**41.0**	**79.9**	**148.9**	**181.5**
IRR - 10 years	**NCA**			**19.81**	**62.89**	**130.29**	**159.94**
IRR - 10 years	**LMO**				**24.09**	**94.07**	**118.06**
IRR - 10 years	**NMC**			**69.44**	**106.68**	**179.51**	**216.91**
IRR - 10 years	**LCO**			**56.62**	**93.90**	**164.55**	**199.57**
IRR - 10 years	**LFP**					**54.41**	**72.72**

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