BatteryStewardshipCouncil

Battery Life Cycle Analysis

The environmental impacts of battery recycling in Australia

October 2023

A B-cycle benchmarking project conducted by UTS

UTS Institute for Sustainable Futures

B-cycle Battery Recycling

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About the authors

The Institute for Sustainable Futures (ISF) is an interdisciplinary research and consulting organisation at the University of Technology Sydney. ISF has been setting global benchmarks since 1997 in helping governments, organisations, businesses, and communities achieve change towards sustainable futures.

For further information visit: www.isf.uts.edu.au.

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Glossary of terms

LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
GWP	Global Warming Potential
Li-ion	Lithium-ion
NiCd	Nickel Cadmium
NiMH	Nickel Metal Hydride
SLAB	Sealed Lead Acid Battery
LAB	Lead Acid Battery
EoL	End-of-Life
Primary Materials	Materials sourced from mining and extraction
Secondary Materials	Materials sourced from recycled products

1. Executive summary

> **"Placing highly purified recycled materials from batteries onto the materials market has the potential to offset the CO^2e emissions of battery materials supply by around 50%."**

1.1. Overview

This technical report presents the findings from a benchmarking project commissioned by the Battery Stewardship Council (BSC), undertaken by the Institute for Sustainable Futures (ISF) at the University of Technology Sydney. The research will inform future performance evaluation of the BSC B-cycle Scheme.

This research comprises a Life Cycle Assessment (LCA) to quantify the environmental impacts of battery recycling in Australia. A separate Market Analysis and Fate Mapping study was performed to establish a benchmark of battery collections and recycling in Australia in 2021. Information from the 'Market Analysis' and 'Fate Mapping' study on battery collections, processing, and material fates informs this LCA.

1.2. Goal and scope definition

A LCA was performed to understand the consequential life cycle impacts and benefits associated with the BSC's B-cycle Scheme, for the year 2021.

The analysis followed a four-stage process that is common to most LCA studies.

1. **Goal and scope setting** – to understand the purpose and boundaries of the assessment.
2. **Life Cycle Inventory** (LCI) development – to estimate the flows and exchanges of Materials, Energy, Resources and Emissions between the product system and the environment.
3. **Life Cycle Impact Assessment** (LCIA) – to translate inventory items into quantified measures of environmental impact.
4. **Results analysis and interpretation** – to make judgements on the meaningfulness of results, their usefulness for communication or decision making, and to understand their limitations given the study design, available data sources, and modelling approaches employed.

Results have been expressed in relation to a common functional unit to enable fair, like-for-like comparisons to be made between different production systems.

> **The functional unit used for the study was "the collection and waste management of 1kg of batteries in Australia via B-cycle".**

The goal of the study was to understand the consequential benefits of material recovery from recycled batteries in Australia, therefore the study has been designed to quantify the impacts of producing highly purified materials from recycled batteries and this impact is assumed to offset an equivalent 'basket of goods'[1] from the global market (estimated to be mostly from primary sources).

The LCA study focuses in on results relating to Global Warming Potential (GWP), however the complete list of impact categories assessed include Acidification, Climate Change, Eutrophication, Freshwater Ecotoxicity, Human Toxicity, Ionising Radiation, Photochemical Ozone Depletion, Particulate Matter Formation, Ozone Layer Depletion, Resource Depletion (Minerals and Fossil Fuels), and Water Scarcity.

1.3. Results

Based on the results of the LCA the following observations are reiterated here regarding the impacts of recycling batteries in Australia, and the potential offset impact that recycled materials from batteries could have on a global materials market is explored[2].

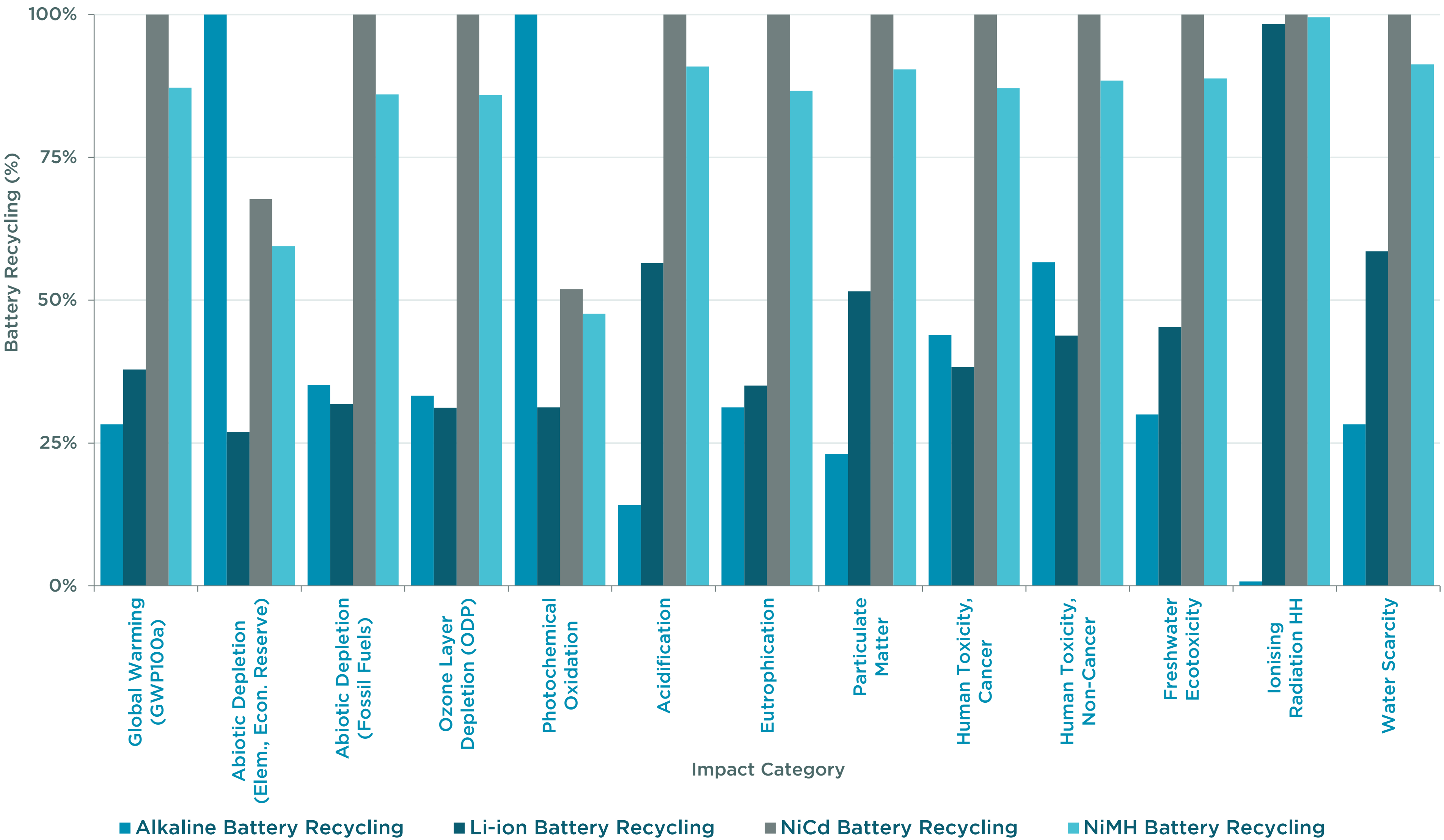
The total impacts of battery recycling across all impact categories are shown in Figure 1 on the following page. This figure presents recycling impacts relatively across battery chemistries. For example, the recycling of Nickel Cadmium (NiCd) batteries has the highest GWP impact, in comparison, Alkaline battery recycling is more than 70% less in terms of GWP impact. Based on the results of the impact assessment, the following can be observed:

+ Batteries with the highest recycling impact across all categories are NiCd batteries and Nickel Metal Hydride (NiMH) batteries. In comparison, alkaline battery recycling featured between 40% and 95% lower impact across other impact categories except for abiotic depletion and photochemical oxidation.
+ Processing and refining of materials from Lithium-ion (Li-ion) batteries, such as cobalt, manganese, and nickel resulted in high impacts in the areas of Acidification, Particulate Matter, Freshwater Ecotoxicity and Water Scarcity.
+ Extracting nickel from NiMH batteries resulted in a very high impact on Acidification, Particulate Matter, and Water Scarcity.

[1] 'Basket of goods' describes the equivalent mass balance of materials that would need to be sourced from the global materials market in the absence of recycled battery materials. Also known as a 'bill of quantities'. The 'basket of goods' differs depending on the battery type being recycled.

[2] Significant data gaps resulted in the use of secondary data (LCA literature, sources elaborated in the main section, combined with assumptions on industry practices) to represent Australian industry inputs, outputs, and unit processes. It is recommended that due care is used when relying on the results of the LCA, to understand the inherent uncertainties contained within results, as the results presented rely predominantly on secondary data. It is also recommended that future efforts are made to improve the reliability of LCA results by collecting more detailed primary data from industry on individual unit processes, energy, and material inputs.

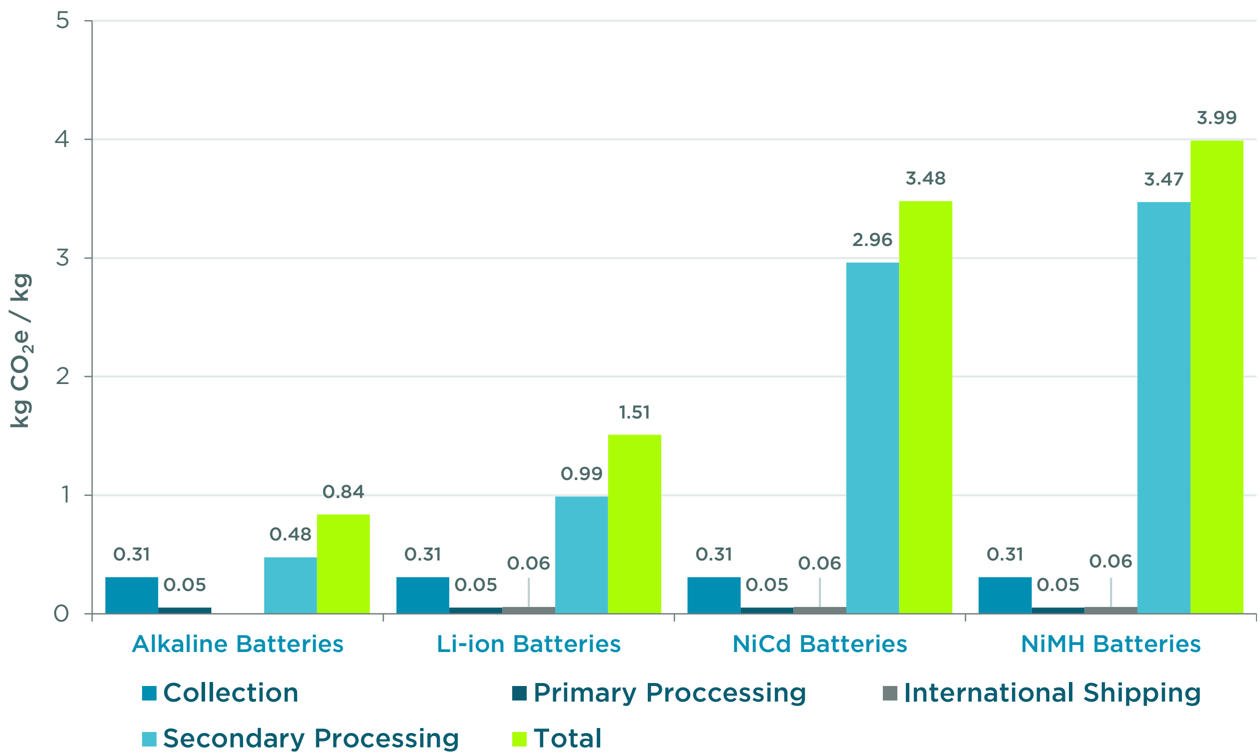
Figure 1. Impact assessment producing 1kg of high purity refined materials from each battery type through recycling (2021)



The GWP impacts of battery recycling is highlighted further in Figure 2 below. Impacts have been divided into five stages of recycling: collection (transport from collection points to recyclers), primary processing (shredding), shipping (to domestic and international secondary processors), and secondary processing (hydrometallurgy and/or pyrometallurgy that may be domestic or internationally located).

The largest impact to GWP across all battery types is in the secondary processing phase, due to the high energy and material inputs required to refine shredded material to a high purity material output. Alkaline batteries feature a lower secondary processing impact because of their more simplified anode and cathode material makeup. Notably, transportation of batteries from collection points to recyclers in Australia results in a larger impact than primary processing for most battery types, this is due to the large transport kilometres required to collect batteries across the country.

Figure 2. GWP for each stage of the battery recycling process per kilogram of recycled battery (2021)



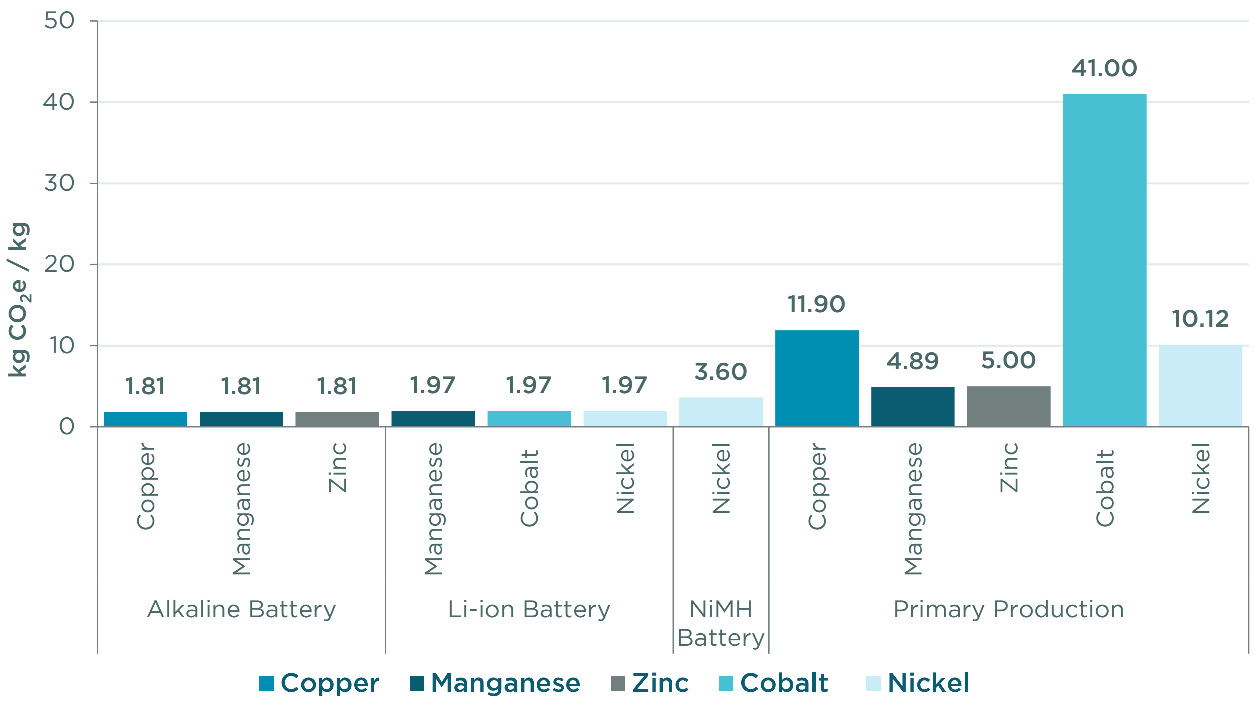
Producing highly refined materials from recycled batteries compared to primary production pathways.

This section compares the CO_2e emissions impacts of producing highly refined materials from recycled batteries and compares these impacts with the equivalent basket of goods from primary sources in Figure 3 on following page. According to our results:

Producing highly refined materials from recycled batteries (Alkaline, Li-ion, and NiMH batteries on the left) results in roughly half the CO_2e emissions of producing the equivalent basket of goods from primary production (primary production impacts on the right).

In some cases, the differences are more pronounced, for example cobalt from recycled lithium batteries is just under 2kg of CO_2e per kilogram of refined material, compared to cobalt from primary production, which is just over 40kg of CO_2e, a 95% greater impact.

Figure 3. GWP of producing highly refined materials through Alkaline, Li-ion, and NiMH battery recycling and primary production (2021)[3]



Exploring CO_2e savings by producing batteries with recycled content.

This section explores the potential for CO_2e savings if highly refined recycled battery material was placed onto the global materials market to offset the need for primary production in battery manufacturing. However, Australia only participates in collection, primary processing and secondary processing for Alkaline batteries and the actual recycling outcomes for other chemistries are not within the control of the Australian jurisdiction. Therefore, when reading through the results of this section the reader should keep in mind that global recycling practices for batteries may not be achieving the level of purity required to replace materials feeding into battery production and achieve the results presented.

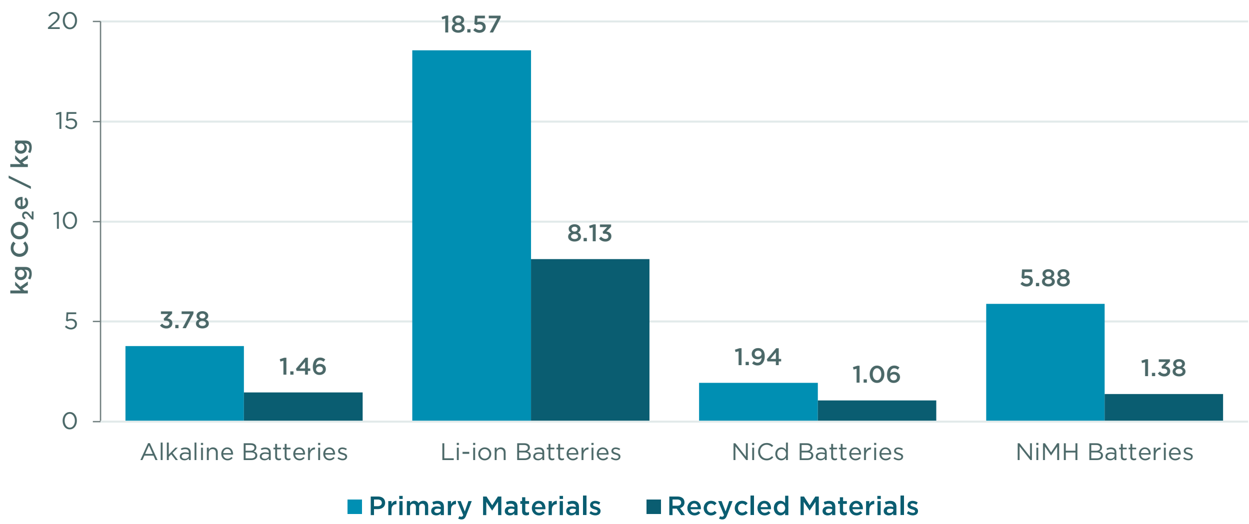
[3] Lithium does not feature as a material of focus for this analysis because, according to our research, lithium is not currently recycled.

These results on the assumption that both recycled and primary materials can be feedstock for new batteries. Figure 4 shows a comparison of battery materials sourced from these two production pathways, by battery type. These results are presented as CO_2e totals for each battery type in Figure 4 and the impacts are compared with an equivalent basket of goods sourced from primary production.

The results presented in Figure 4 highlight the positive impact that could be achieved if highly purified recycled battery material displaces battery materials from primary sources[4]. Based on these results, it is found that producing highly purified refined material from Li-ion batteries features the highest impact both from recycled batteries and from primary sources, this is due to the high percentage of cobalt present in the reference battery for this study[5]. However, production of Li-ion batteries using materials from primary sources still equates to more than double the impact (18.6kg of CO_2e per kilogram) compared to materials from recycled batteries (8.1kg CO_2e per kilogram).

+ Sourcing materials for NiCd batteries from highly purified recycled battery materials rather than primary sources reduces the CO_2e impact by around 50%.
+ Sourcing materials for Alkaline batteries from highly purified recycled battery materials rather than primary sources reduces the CO_2e impact by around 60%.
+ Sourcing highly purified recycled battery materials from NiMH batteries reduces the CO_2e impact by around 75% compared to primary sources.

Figure 4. GWP of producing battery materials from primary sources vs recycled batteries by battery type (2021)



[4] It is noted that the results only highlight the potential for emissions savings and make no attempt to assess the cost or feasibility of producing batteries with recycled content.

[5] For this study the NMC-111 battery type has been used to represent Li-ion battery chemistries.

The next section considers the total CO_2e impacts of recycling batteries considered within the scope of the B-cycle Scheme in Australia for the year 2021 (that is, historic data on batteries that were collected in 2021 by entities currently in the B-cycle Scheme has been used). Table 1 shows the total weight of batteries collected for recycling in Australia in 2021 by Australian battery collectors and recyclers.

A total of 2,240 tonnes of batteries were collected by Australian battery collectors and recyclers in 2021, the below table represents the battery quantities that have been used for our impact assessment. This impact assessment excludes lead acid batteries (approximately 3.5% of the quantity of batteries collected).

Table 1. Batteries collected in Australia for recycling (2021)

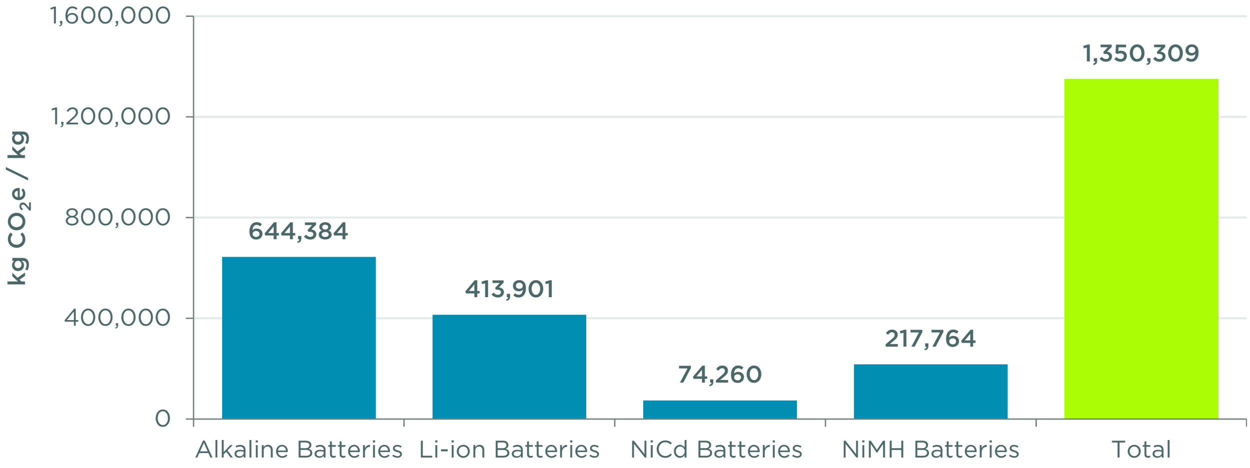
Chemistries	Amount (PA)	Unit	Data source	Data quality
Alkaline	1,295,001	kg	Survey	Good estimate
NiCd	38,187.7	kg	Survey	Good estimate
NiMH	122,918	kg	Survey	Good estimate
Li-ion	282,992	kg	Survey	Good estimate
Mixed	421,052	kg	Survey	Good estimate
Total	**2,160,150**	**kg**	**Survey**	**Good estimate**

Source: B-cycle benchmark, 2021.

Figure 5 shows the total CO_2e impact of batteries that were collected and recycled in Australia in 2021. The total CO_2e emissions impact of battery recycling is 1,350 tonnes of CO_2e emissions, or roughly the equivalent average annual emissions of 300 cars.

Alkaline batteries are responsible for the highest impact at 644 tonnes of CO_2e emissions in 2021, this is due largely because this battery type features the largest share of battery collections by weight in 2021. Li-ion batteries follow at 413 tonnes of CO_2e emissions. A smaller share of NiCd batteries and NiMH batteries by weight were collected for recycling in 2021, reflected in their smaller share of CO_2e emissions at 74 and 218 tonnes respectively.

Figure 5. GWP impacts of recycling batteries collected and processed in Australia (2021)[6]



1.4. Conclusions and further research

The results presented in this LCA are an excellent indicator of the environmental benefits of battery recycling in most cases. The benefits highlight the need to incentivise investment in improved capacity for the battery recycling sector in Australia, particularly if incentives facilitate recycling practices (such as hydrometallurgy) that produce high purity material. Despite the assumptions and data limitations of the study, a clear benefit can be observed if materials from recycled batteries are refined to a high purity and in turn reduce the demand on primary material production.

The results of the study highlight that placing highly purified recycled materials from batteries onto the materials market has the potential to offset the CO_2e emissions of material supply by around 50%.

Future research using detailed primary data from Australian industry participants in each process will help to strengthen LCA results and create a robust base for claimed benefits of the B-cycle Scheme. It is important to map all the processes with high accuracy to avoid excessive crediting or overestimation. Care should be used to understand the uncertainties and limitations inherent in these results, before relying on information provided in this LCA.

[6] Data on total batteries collected and processed in Australia sourced from: Langdon, R, Dominish, E., and Lara, H. (2023). B-cycle Benchmarking Program: Market Analysis and Fate Mapping.

2. Life Cycle Analysis (LCA) of Australian battery recycling

2.1. Introduction

A Life Cycle Assessment (LCA) was performed to understand the consequential life cycle impacts or benefits associated with the Battery Stewardship Council (BSC) B-cycle Scheme. The analysis followed a four-stage process that is common to most LCA studies.

1. Goal and scope setting – to understand the purpose and boundaries of the assessment.
2. Life Cycle Inventory (LCI) development – to estimate the flows and exchanges of Materials, Energy, Resources and Emissions between the product system and the environment.
3. Life Cycle Impact Assessment (LCIA) – to translate inventory items into quantified measures of environmental impact.
4. Results analysis and interpretation – to make judgements on the meaningfulness of results, their usefulness for communication or decision making, and to understand their limitations given the study design, available data sources and modelling approaches employed.

2.2. Goal, scope, and impact characterisation

2.2.1. Goal

The primary goal of this study is to analyse and quantify the consequential environmental benefits and impacts of recycling Alkaline, Lithium-ion (Li-ion), Nickel Metal Hydride (NiMH) and Nickel Cadmium (NiCd) batteries, within Australia. As part of this, the LCA seeks to understand the potential benefits of the BSC B-cycle Scheme by measuring the consequential impacts associated with recovering materials from spent batteries and the potential displacement of material production (which includes a mixture of primary and recycled materials) elsewhere in global material markets. This LCA provides an initial basis for BSC to understand the limitations of current datasets and design an approach to monitor the environmental performance of the B-cycle Stewardship Scheme. This will enable BSC to better understand the impacts and benefits of their actions and policies.

2.2.2. Functional unit

LCA results are expressed in relation to a 'functional unit'. Expressing results in relation to a functional unit normalises data for processes and product systems by expressing them on a functionally equivalent basis, and in doing so enables fair, like-for-like comparisons to be made between these systems. The functional unit for this analysis is defined as:

"the collection and waste management of 1kg of batteries in Australia via B-cycle".

This functional unit includes management of all battery materials, excluding casing and attachments.

The LCA focuses on Alkaline, Li-ion, NiMH and NiCd chemistries as these make up the bulk of batteries imported, collected, and recycled in Australia (within the scope of B-cycle at the time of this analysis).

2.2.3. Timeframe

The focus of this analysis is a benchmark of current recycling performance for those batteries currently included in B-cycle, the benchmark year is calendar year 2021.

2.2.4. Geography

Australia is the primary focus of this study. In 2021, collection of Alkaline, Li-ion, NiMH and NiCd batteries occurred at approximately 1,000 Drop off point locations around the country. Drop off point locations are predominantly focused at large retailers, for example, Aldi, Bunnings Warehouse, Officeworks, and Woolworths stores. Batteries are received from the public via container receptacles of differing materials, and once a container is full, collected and transported by van or truck to aggregation facilities in each state or territory.

Batteries are then transported to processing facilities to be sorted and processed in Melbourne, Victoria. At the processing facility, batteries are sorted by chemistry, battery casings are disassembled, in some cases cells are discharged, and cells and casing by-products then move through processing pathways that are company specific.

In summary

- Plastic and metal by-products are transported domestically for recycling.
- Lithium battery cells are processed (shredded) within Australia, and the resulting black mass is shipped to the global material market, typically to South Korea or Singapore, as mixed metal dust for further processing.
- Alkaline battery cells are processed (shredded) within Australia, and the resulting black mass is transported for further processing and use in domestic by-products.

2.2.5. System boundaries

The system boundary for this LCA includes relevant collection, sorting, and recycling processes. Figure 6 shows the system boundary for Li-ion batteries, Figure 7 for Alkaline, and Figure 8 focuses on NiCd and NiMH batteries. The boundary for each chemistry excludes the upstream manufacturing and use phases. The process represented is based on the processed used by Australian battery recyclers who currently process batteries within Australia and export Mixed Metal Dust to both domestic and global material markets.

The green box indicates all processes presently performed in Australia, while some but not all downstream processes (such as pyrometallurgy and hydrometallurgy) primarily fall outside the Australian jurisdiction.

It should be noted that some of these downstream processes are included when quantifying and comparing the impacts of producing refined materials from recycled batteries and refined materials from primary sources. The material being sent to landfill also sits outside the LCA system boundary for this study as limited data was available to model the impacts of batteries ending up in landfill. This is proposed as an area of future research given the potential impact of these materials on surrounding environments.

The goal of the LCA is to understand the consequential benefits of material recovery and recycling from collected batteries in Australia. Therefore, the overall system boundaries include the production of an equivalent basket of goods or materials (e.g. cobalt, manganese, nickel) sourced from the global materials market (predominantly primary material) and the assumption is that highly purified recycled battery material avoids or displaces the demand for primary material on the materials market, essentially offsetting the impacts of primary production.

Figure 6. System boundary for Li-ion batteries (2021)

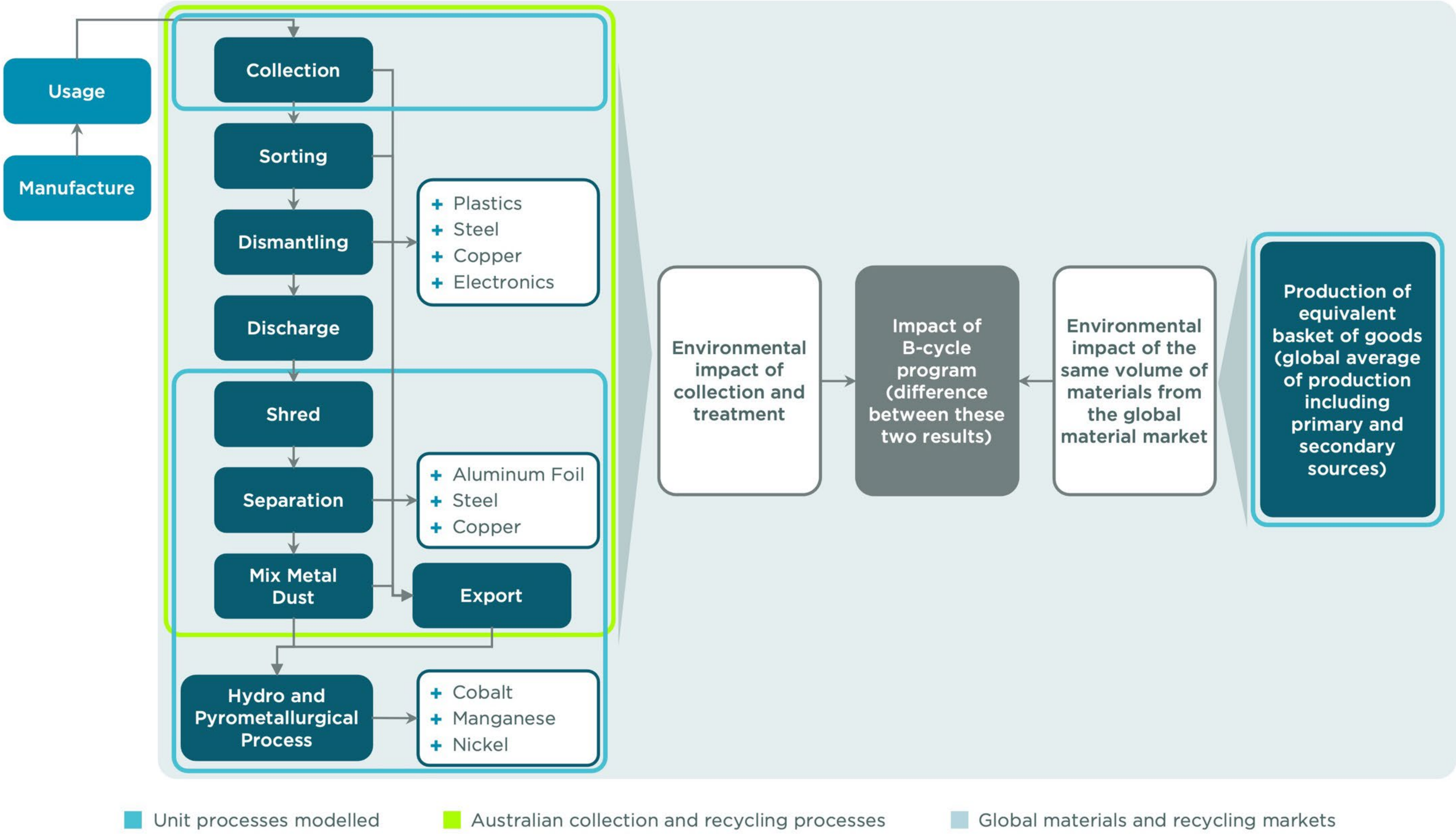


Figure 7. System boundary for Alkaline batteries (2021)

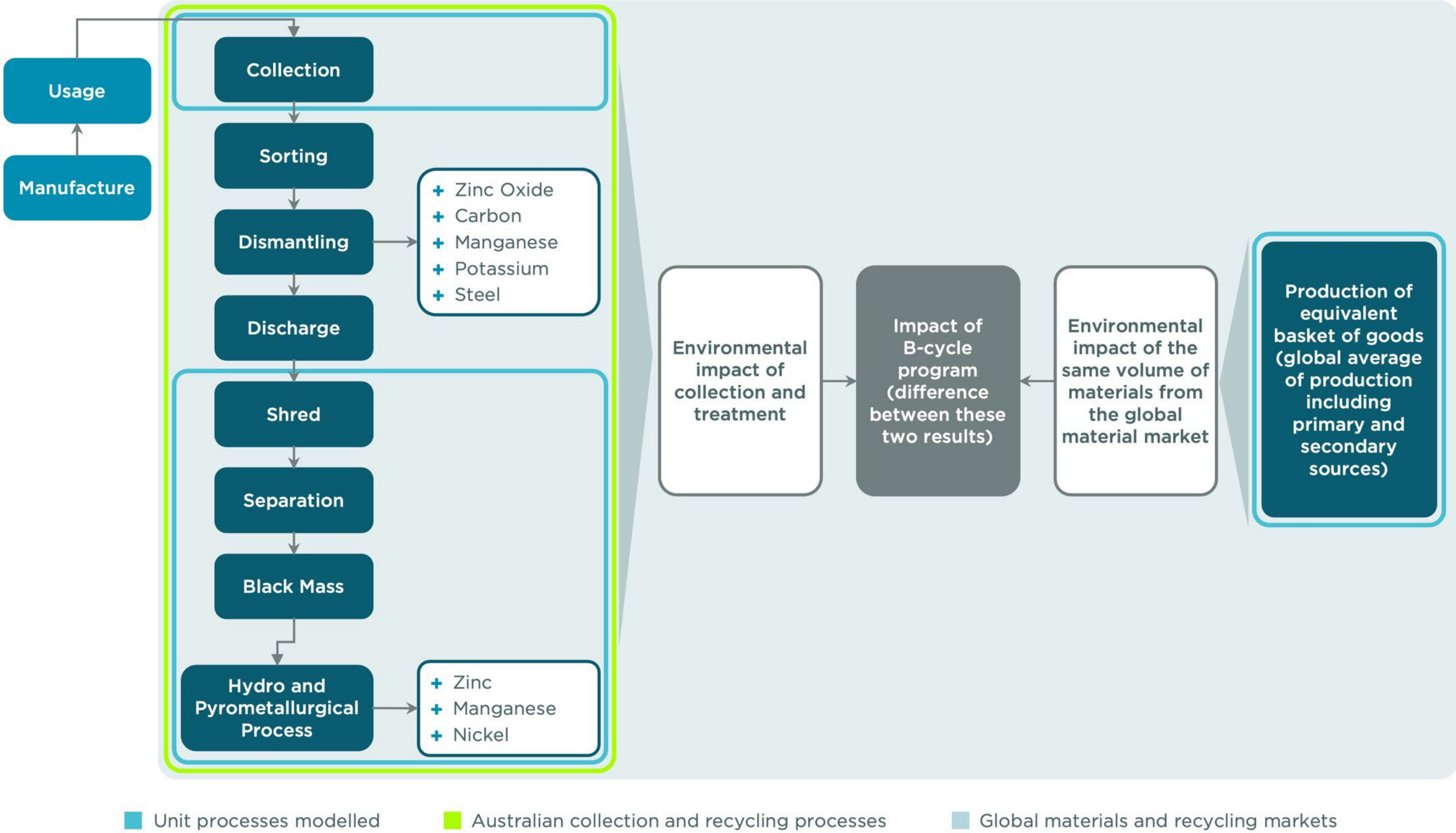
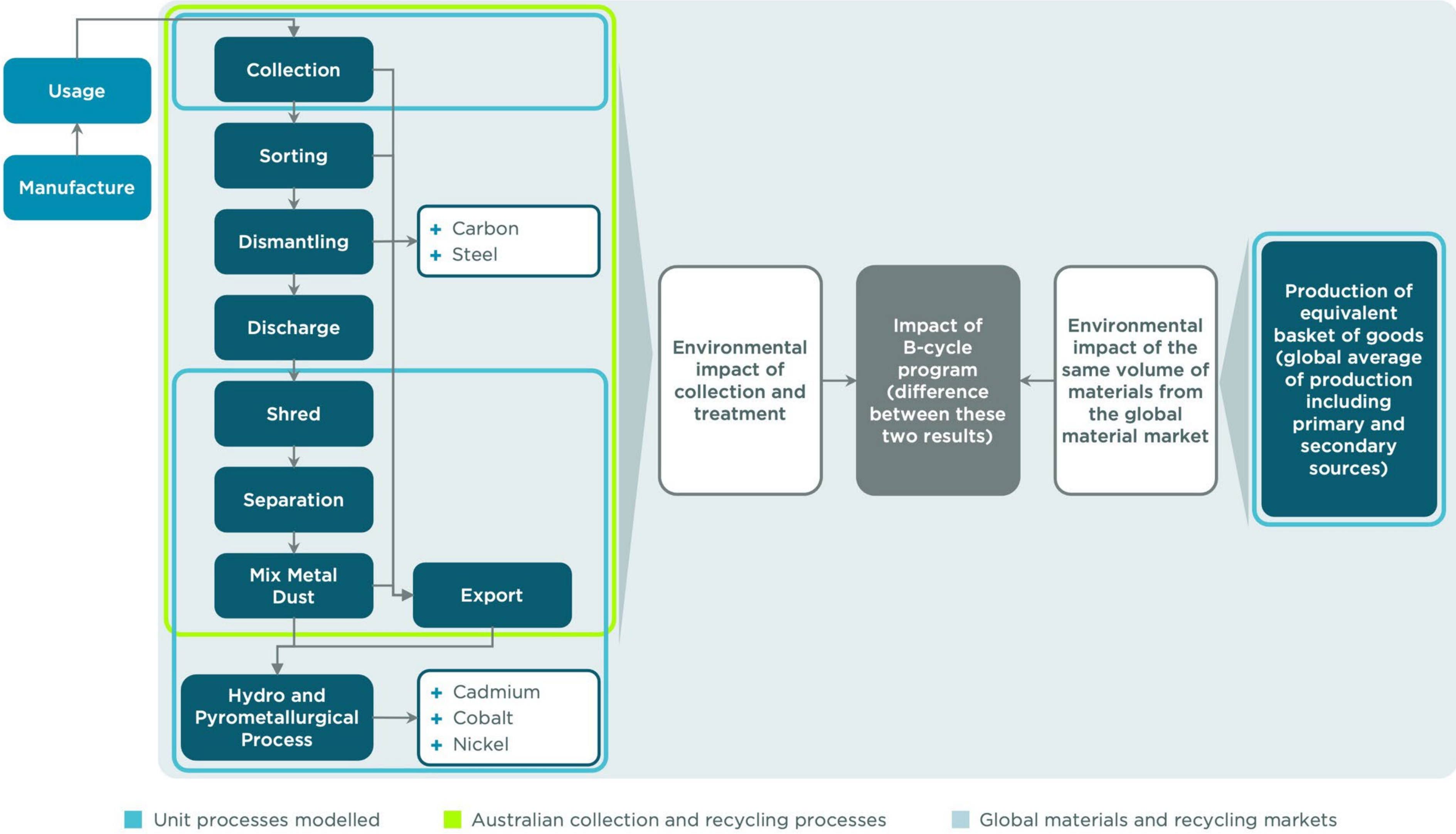


Figure 8. System boundary for NiCd and NiMH batteries (2021)



2.2.6. Life Cycle Impact Assessment (LCIA) categories

LCIA converts the outputs of a LCI into quantifiable and comparable environmental impact estimates using defined impact characterisation procedures. Many competing impact assessment models and indicators can be used to understand the environmental impacts of product systems. The Australian Life Cycle Assessment Society has provided recommendations for impact indicators and method selection in the Australian context (Renouf et al., 2018). The currently recommended indicators for use in Australia are shown in Table 2.

Table 2. ALCAS recommended mid-point impact characterisation methods for use in the Australian context (2018)

Impact Category	Indicator	Unit	Description
Acidification	Acidification Potential (AP)	kg SO_2- eq.	Acidification potential based on the change in critical load exceedance. This impact quantifies the acidifying impacts when acid precursor compounds are released into the air and subsequently deposited on land or water. The most accounted substances are nitrogen oxides, sulphur oxides, sulphuric acids and ammonia.
Climate Change	Global Warming Potential (GWP100)	kg CO_2- eq.	Change to cumulative radiative forcing over a 100-year time period. This impact quantifies the global warming impacts of human activities on the climate.
Eutrophication	Eutrophication potential	kg PO_4- eq.	Eutrophying impacts when macro-nutrients are released to air, water, and soil. The most common nutrients accounted for are nitrogen, phosphorous and organic compounds.
Freshwater Ecotoxicity	Comparative Toxic Units	CTU-e	Comparative toxic units for ecosystems (CTU-e), representing potentially affected fraction of freshwater species integrated over time and volume.
Human Toxicity	Comparative Toxic Units	CTU-h	Potential increase in human disease morbidity with equal weighting for cancer and non-cancerous effects.
Ionising Radiation (Human Health)		kBq ^{235}U- eq.	Human exposure efficiency relative to ^{235}U.
Photochemical Ozone Formation (Oxidation)	Photochemical Ozone Creation Potential (POCP)	C_2H_4- eq.	Photochemical ozone creation potential (POCP) quantifies the impacts of increases in ozone concentrations in the troposphere, which is formed as a secondary contaminant from the oxidation of the primary contaminants in the presence of nitrogen oxides (NO_x) and under the influence of light.

Impact Category	Indicator	Unit	Description
Particulate Matter Formation (Respiratory Effects)	Intake Fraction	kg PM2.5- eq.	Mass of PM2.5 emitted to air that is inhaled.
Ozone Layer Depletion	Ozone Depletion Potential (ODP)	kg CFC-11- eq.	Ozone Depletion Potential (ODP) characterises the reduction in concentrations of ozone in the stratosphere (ozone layer) when ozone-depleting substances (ODS) are released into the air.
Resource Depletion (Minerals)	Abiotic Resource Depletion (Reserves)	kg SB- eq.	Contribution to the depletion of mineral reserves.
Resource Depletion (Fossil Fuels)	Abiotic Resource Depletion (ADP, fossil)	MJ NCV	Net calorific value of fuels consumed based upon lower heating value (LHV).
Water Scarcity	Water Stress	m^3 H_2O- eq.	Combined consumptive and degradative water use impacts equivalent to the global average for 1m^3 of freshwater withdrawal.

2.2.7. Life Cycle Inventory (LCI)

A LCI provides a quantitative description of the flows of Resources, Energy, Materials, Products, Waste and Emissions between a process or product system and the broader environment and technosphere or economy. Figure 9 shows an example of inventory flows for a simplified process. A LCI was developed for each unit process described in the system boundary descriptions.

Figure 9. Overview of LCI flows (2021)

The following sub-sections describe the data collection strategy, data sources, limitations and uncertainties of the data used to derive the LCIs for the battery recycling processes.

2.2.7.1. Data collection and sources

Detailed data on battery material flows was collected under the broader scope of this project. Data on rates of battery collection was obtained from current B-cycle partners. The data collected from industry provided a detailed breakdown of the total amount of batteries collected by type, the fate of batteries, and processed material outputs. Interviews with industry partners enabled the overall collection and recycling process to be understood and mapped into generic system process diagrams.

Energy and material data was unavailable from industry partners for this study, to fill this gap data representative energy and material consumption data was taken from similar battery recycling processes, compiled from academic and technical literature, industry publications, and LCI databases (in particular, Ecoinvent). Third-party data was used as a proxy to represent Australian recycling processes in the absence of primary data for most inventory items of importance for these product systems. The use of secondary data in place of primary data introduces considerable uncertainty into the LCA and uncertainty of results presented hereafter should be considered carefully before relying on information presented.

Wherever possible, the assumptions and equivalency of third-party data to Australian processes were informed based upon interviews and discussions conducted throughout the project. Inventory items for each unit process were then mapped to equivalent flows in the Ecoinvent version 3.8 consequential database using Simapro to provide coverage of the full life cycle of each inventory item (e.g. Global Material Production, Recycling Processes, Waste, etc.). The sections below provide a detailed description of the data collected and assumptions made for each stage of the battery end-of-life process.

2.2.7.2. Collection and transportation

Table 3 shows the total weight of batteries collected for recycling in Australia in 2021 by those entities currently in the B-cycle Scheme (the Scheme commenced in 2022). A total of 2,240 tonnes of batteries were collected by B-cycle Scheme participants in 2021, the below table represents the battery quantities that have been used for our impact assessment. This impact assessment excludes Lead Acid batteries (approximately 3.5% of the quantity of batteries collected). The battery collection data also provided the fate of the batteries after primary processing and some information was provided on domestic transport vehicles.

Table 3. Breakdown of battery collected (2021)

Chemistries	Amount (PA)	Unit	Data Source	Data Quality
Alkaline	1,295,001	kg	Survey	Good estimate
NiCd	38,187.7	kg	Survey	Good estimate
NiMH	122,918	kg	Survey	Good estimate
Li-Ion	282,992	kg	Survey	Good estimate
Mixed	421,052	kg	Survey	Good estimate
Total	**2,160,150**	**kg**	**Survey**	**Good estimate**

A combination of 1 tonne trucks and 8 tonne trucks were used for collection of batteries in most cases. The total distance travelled in 2021 for domestic transportation was then averaged by assuming an 80% load capacity on every kilometre travelled. The LCI inventory for the collection process was then constructed on the basis of derived tonne. Kilometres and Ecoinvent processes for freight transport using vehicles with Euro 3 emission standards. The transport type used for modelling the collection process was "transport, lorry 3.5t–7.5t Euro3" in the Ecoinvent database.

2.2.7.3. Primary processing

Industry partners indicated that most collected batteries are sorted and mechanically processed before any secondary refining process. The sorting is performed manually and then batteries are put through a shredding process, where the batteries are reduced to small particle sizes. Outputs from the shredding process include pelleted metallic foils (including aluminium, steel, and copper), pelletised plastics, and anode or cathode black mass. These materials are separated into their respective streams and go through secondary processing stages such as hydrometallurgy and pyrometallurgy. The purity level of these materials is unknown and so materials that leave recyclers in Melbourne are assumed to go through a further downstream refining process to achieve an output material of high purity. Table 4 shows the material outputs of battery recycling and their fates in Australia in 2021.

Table 4. Breakdown of material after primary production (2021)

Outputs	Amount	Unit	Data Source	Data Quality	Fate	Fate Location
Metals Total	702,166.0	kg	BSC and interviews	Good estimate	**Metal recycler**	Domestic
Copper		kg	BSC and interviews	Good estimate	**Metal recycler**	Domestic
Steel		kg	BSC and interviews	Good estimate	**Metal recycler**	Domestic
Nickel		kg	BSC and interviews	Good estimate	**Metal recycler**	Domestic
Aluminium		kg	BSC and interviews	Good estimate	**Metal recycler**	Domestic
Plastics	280,508.4	kg	BSC and interviews	Good estimate	**Recycler**	Domestic
Black Sand (Li-ion)	218,461.7	kg	BSC and interviews	Good estimate	**Recycler**	International
Black Sand (Alkaline)	543,628.8	kg	BSC and interviews	Good estimate	**Steel manufacturing**	Domestic
Mixed Black Mass	182,455.8	kg	BSC and interviews	Good estimate	**Steel manufacturing**	Domestic

Outputs	Amount	Unit	Data Source	Data Quality	Fate	Fate Location
NiCd and NiMH Batteries Shredded	3,100.0	kg	BSC and interviews	Good estimate	**Metal recycler**	Domestic
Lead Acid Battery (LAB)	81,182.1	kg	BSC and interviews	Good estimate	**Recycler**	Domestic
NiCd and NIiMH Batteries Exported	35,087.1	kg	BSC and interviews	Good estimate	**Secondary processing**	International

Black sand from Li-ion, as well as NiMH and NiCd batteries are predominantly exported, whereas black sand from Alkaline batteries is sent for domestic secondary processing. Energy consumption is a particularly important inventory item for these processes and was based on data that was derived for the EverBatt model (Dai et al. 2019) based on their pathway of pre-treatment and hydrometallurgy. Plastics separated at this stage were assumed to be recycled and so are assumed to have a consequential benefit of avoiding plastic production elsewhere in the economy. Separated electrolytes are assumed to be treated and sent to landfill.

2.2.7.4. Secondary processing

Following the primary shredding and separation processes, secondary processing is then undertaken to further refine recovered materials. The secondary processing has been divided into two-unit processes. The first unit process is the domestic processing of Alkaline batteries after primary processing. There are significant information and data gaps regarding the exact process and inventory requirements of secondary processes – particularly as metal refining plants have highly integrated processes and so there are conceptual difficulties when attempting to disaggregate process configurations and data across different metal product streams and categories.

It is assumed based on information provided by industry that secondary processing for Alkaline battery material outputs happens at an average zinc refinery in Australia. Data for processing consumables at a similar site have previously been published (Ramshaw, 2013) and were used as an initial basis for constructing an inventory, with basic mass allocation performed based on assumed inputs and outputs of battery material and other products from the site.

Data for emissions to air, land and water for the process were collected from the National Pollutant Inventory. The derived LCI dataset was used to represent the processing pathway for Alkaline batteries, but it should be noted that there is considerable uncertainty inherent in derived inventory items. The LCI data for secondary processing is shown in Table 5.

Table 5. LCI of secondary process in Australia (2021)

Input From Technosphere

Material	Total	Unit
Sodium Hydroxide	1.215	g
Sulfamic Acid	2.468	g
Hydrogen Peroxide	0.368	g
Quicklime	16.443	g
Strontium Carbonate	1.107	g
Ammonium Chloride	0.26	g
Sodium Hydroxide	1.9	g
Lime (Hydrated)	10.072	g
Electricity	0.232	kWh

Emissions of Feedstock Processed

Substance	Air Total	Land Total	Water Total	Unit
Antimony and Compounds	0.000000779	0.0	0.0000055	kg
Arsenic and Compounds	0.0000049	0.0	0.00000379	kg
Beryllium and Compounds	0.000000004	0.0	0.000000386	kg
Cadmium and Compounds	0.00000348	0.0	0.00000286	kg
Carbon Monoxide	0.079403	0.0	0.0	kg
Chromium iii. Compounds	0.000000143	0.0	0.000000289	kg
Chromium vi. Compounds	0.000000018	0.0	0.0	kg
Cobalt and Compounds	0.00000001	0.0	0.000000343	kg
Copper and Compounds	0.00000353	0.0	0.0000112	kg
Fluoride Compounds	0.0000112	0.0	0.000125	kg
Hydrochloric Acid	0.000141	0.0	0.0	kg
Lead and Compounds	0.000198	0.0	0.0000616	kg
Magnesium Oxide Fume	0.00000461	0.0	0.0	kg
Manganese and Compounds	0.00000171	0.0	0.00000739	kg
Mercury and Compounds	0.00000028	0.0	0.000000013	kg
Nickel and Compounds	0.00000026	0.0	0.000000461	kg
Oxides of Nitrogen	0.002048	0.0	0.0	kg

Substance	Air Total	Land Total	Water Total	Unit
Particulate Matter (10.0um)	0.000586	0.0	0.0	kg
Particulate Matter (2.5um)	0.0000859	0.0	0.0	kg
Polychlorinated Dioxins and Furans (TEQ)	0.0	0.0	0.0	kg
Polycyclic Aromatic Hydrocarbons (B[a]P_{eq})	0.000000285	0.0	0.0	kg
Selenium and Compounds	0.00000972	0.0	0.00000424	kg
Sulphur Dioxide	0.017932	0.0	0.0	kg
Sulfuric Acid	0.0000124	0.00000107	0.0	kg
Total Nitrogen	0.0	0.0	0.0000124	kg
Total Phosphorus	0.0	0.0	0.00000261	kg
Total Volatile Organic Compounds	0.0000468	0.0	0.0	kg
Zinc and Compounds	0.000151	0.0	0.0000869	kg

Output

Substance	Total	Unit
Marketable Metal	1	kg

The second unit process, shown in Table 6, considers the international processing of black sand, which has been exported. Transportation of the black sand was modelled as a container ship travelling from Australia to East Asia. The black sand is then assumed to be processed via hydrometallurgy. This assumption was based on publicly available information regarding a battery recycling partnership with a company in Korea. Korean recycling companies utilise hydrometallurgy as a part of their recycling process (Sojka et al., 2020). Due to data limitations, Ecoinvent waste treatment processes utilising hydrometallurgy to recover metal products were assumed to be a suitable proxy for international recycling processes. These were used to derive LCI for the international processing of Australian exported black sand.

The refined metal products from this process were then assumed to offset or displace the production of an equivalent basket of goods on the global materials market. This process exists within the Ecoinvent database as part of the waste treatment stream which was converted to a processing stream in the LCA model. The process is a global average of a hydrometallurgical unit process. The process of primary processing via shredding, separation, and secondary processing via domestic material refining and international export and refining of black sand was selected as the processing pathway for Li-ion, NiMH and NiCd batteries. Due to data limitations, these processes were unable to be disaggregated for the treatment of specific battery types and so a general mass allocation was applied to represent the differentiations in battery type.

Table 6. LCI of global average process of refining battery materials through hydrometallurgy (2021)

Input From Technosphere

Material	Amount	Unit
Water	0.00072	m^3
Chemical Inorganic	0.025	Kg
Electricity	0.14	kWh
Lime, Hydrated	0.116	Kg
Sulfuric Acid	0.23058	Km
Transport	0.5	tkm

Emissions

Emission to Air	Amount	Unit
Heat Waste	0.504	MJ
Non-Methane Volatile Organic Compounds	0.0000025	kg
Sulphur Dioxide	0.0000045	kg

Emission to Water	Amount	Unit
Cobalt	0.000000017	kg
Cod	0.00003	kg
Copper	–	kg
Fluoride	0.00000003	kg
Hydrocarbons	0.00000001	kg
Nickel	–	kg
Suspended Solids (Inorganic)	0.000012	kg

Output – Waste and Emission to Treatment

Material	Amount	Unit
Gypsum	0.339	kg
Inert Waste	0.202	kg
Paper	0.065	kg
Plastics	0.065	kg

2.2.7.5. Refined battery material production processes

The scope of the design focuses on battery materials that have been refined to a high purity. Battery materials that are placed on the global materials market are predominantly made up of materials from primary sources (mined), however a percentage of these materials are likely secondary or recycled materials (the percentage is currently unknown but assumed to be low). Production processes for various materials from the global materials market (sourced from the Ecoinvent database) are compared with processes used to produce refined recycled material from battery recycling.

Component manufacturing has been excluded from the LCA scope as high purity battery materials feed into this process, irrespective of whether they come from primary or recycled sources. Furthermore, based on literature review, component manufacturing is considered to represent a small part of the resource usage and emissions of the battery manufacturing process (Amarakoon et al., 2013; Hamade et al., 2020). Table 7 to Table 10 show the weight composition of refined battery grade materials that make up each battery type.

Table 7. Weight composition of a generic Alkaline battery (2020)

Material	Weight Composition (% of total mass of battery)
Zinc	11–16
Manganese Dioxide	32–38
Carbon	3–5
Nickel Plated Steel	19–23
Brass	2
Plastics	1
Potassium Hydroxide	5–9
Water, Paper, Other	Balance

Source: (Almeida et al., 2006; Hamade et al., 2020).

Table 8. Material composition active materials of Li-ion batteries (2014)

Material	Weight Composition (% of total mass of battery)
Active Cathode Material	34.0
Graphite	19.4
Carbon Black	2.3
Binder: PVDF	3.0
Copper	15.7
Aluminium	8.2

Material	Weight Composition (% of total mass of battery)
Electrolyte: LiPF6	2.0–2.2
Electrolyte: EC	6.0–6.2
Electrolyte: DMC	6.2
Plastic: PP	1.5
Plastic: PE	0.3
Plastic: PET	0.3
Cell Mass (kg)	0.8

Active Cathode Material Weight Distribution

Material	Weight Composition (% of total mass of cathode)
Cobalt	30–35
Nickel	30–35
Manganese	30–35
Lithium	1–5

Source: (Dai et al., 2019; Zeng et al., 2014).

Table 9. Material composition active material of NiCd batteries (2014)

Material	Weight Composition (% of total mass of battery)
External Case	27
Negative Active Powder	20
Positive Active Powder	23
Separator and Plastics	5
Negative Support Plate	13
Positive Support Plate	12

Material in Active Powder	Weight Composition (% of total mass of battery)
Carbon	0.52
Cadmium	17.76
Cobalt	0.67
Nickel	13.20

Source: (Hazotte et al. 2014)

Table 10. Material composition active material of NiMH batteries (2022)

Material	Weight Composition (% of total mass of battery)
Hydrogen Absorbing Alloy	20–40
Nickel-Cobalt-Zinc Oxide	15–25
Nickel	5–15
Iron	20–40
Carbon	0–1
Potassium Hydroxide	0–15
Sodium Hydroxide	0–15
Lithium Hydroxide	0–15

Material Composition in Active Material	Weight Composition (% of total mass of battery)
Lanthanum	7.7
Cerium	12
Cobalt	6.5
Neodymium	4.0
Nickel	29
Copper	6.5

Source: (Jha et al. 2022)

The production was calculated using the Ecoinvent data of market-based material production in each case using mass allocation. The production of balance of cell materials such as casing, electrolytes and electronics are constant in each case, therefore the comparison of impacts for active materials will provide the tangible differences in impact. Materials such as lithium, electronics and rare earth elements do not have a recycled stream within the recycling process and so are not assessed as part of this study.

2.2.7.6. Limitation and uncertainty

Primary data sources from industry partners only provided details regarding the mass and chemistries of batteries collected and processed. A detailed process map and specific quantities of material and energy consumption were not directly provided and instead had to be based on third-party data sources and a series of educated assumptions. Therefore, the results of this LCA should be considered highly uncertain.

The primary processing was modelled as a straightforward shredding process with subsequent material separation. There can be considerable variability in the inventory requirements of these types of processes depending upon important processing variables, such as final product particle sizes, as well as the specific separation processes used (e.g., magnetic separation, gravity separation, etc.) and their separation efficiencies. This creates potential variability and uncertainty regarding the energy and material consumption of these processes. Data for battery shredding was not readily disaggregated from overall recycling processes within the LCA literature or industry publications, most studies incorporate processing stages together in aggregated form as broader unit processes such as pyrometallurgical or hydrometallurgical processing. Within Australia, shredding and physical separation processes occur in different locations to downstream metal refining, with some material being exported before final refining occurs, and so addressing these boundary issues required assumptions that introduce high degrees of uncertainty.

There was also uncertainty regarding the specific fate of battery materials from the various recycling processes. Overall process descriptions were provided by participants; however, assumptions were made regarding the finer details of processing stages such as material destination, intermediate processing steps used, and the material input and emissions generated by processes. There may be a considerable difference between the actual process and the assumed process, as there are several different ways that battery material can be refined.

Another uncertainty is inherent in the dataset used for the assumptions of total outputs using mass allocation. For example, the emissions data used to represent the refining stage of secondary processing was derived from total emissions for 2021 from a zinc refinery and then extrapolated using assumed production data based on mass allocation per unit mass. Uncertainty can result from overestimating or underestimating the effect of the different end products, as each product will be produced from different process streams and circuits within the refining operation. This can also create inconsistencies with some allocation procedures used in the consequential Ecoinvent database used for the background inventory data.

Another uncertainty is the unavailability of some inventories such as energy intensity, specific company level inventories were unobtainable and so derived from secondary sources. Electricity inventory flows were generated using secondary process data and then linked to national average datasets[7]. Averages have also been used to represent the transport scenario for both regional and city collection patterns.

[7] National averages for energy emissions intensity have been used rather than state specific datasets due to the dispersed nature of sorting, primary processing, and secondary processing stages. Different processing stages are located across states and territories and inventories were unable to be linked to individual processes due to the aggregated nature of each unit process represented.

Limitations and uncertainties are normal in LCA as there are always constraints on the data collected, particularly when primary data measurements and reporting are not available. However, it is emphasised that the accuracy of this LCA study can be improved dramatically through the provision of more detailed industry data from Australian battery recycling market participants.

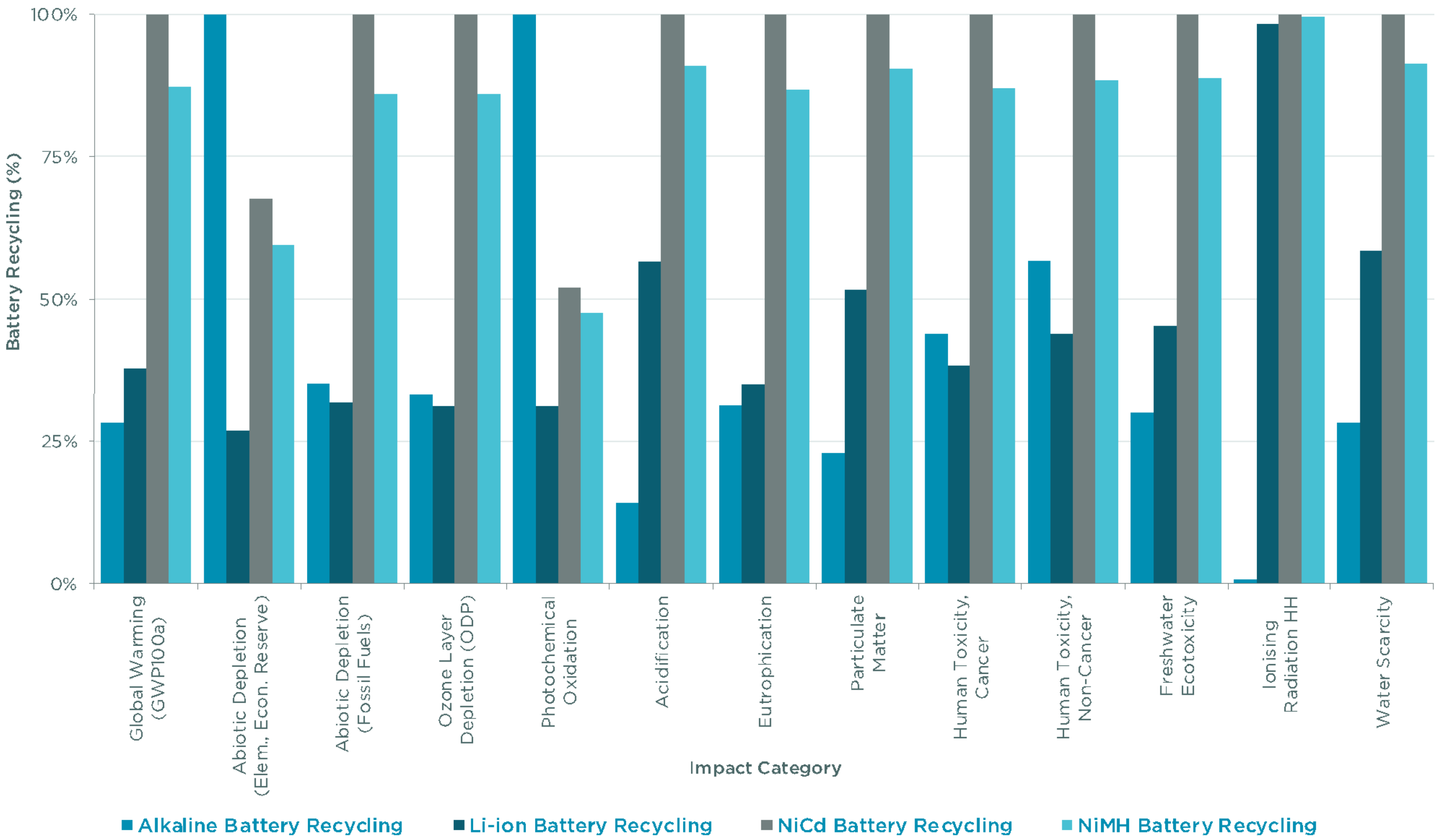
2.3. Results of Life Cycle Impact Assessment (LCIA)

2.3.1. Recycling impact of different battery chemistries

Variations in battery composition translate into altered recycling processes and differences in the environmental impacts associated with battery recycling. This section analyses the impact of recycling different battery types. The impact is modelled on producing 1kg of refined battery materials from the recycling process. Figure 10 shows a summary of the impact assessment for all four battery types undergoing recycling.

Recycling of NiCd and NiMH batteries show similarly high impacts across all impact categories. The absolute impact values are significantly lower for Alkaline batteries due, in part, to the higher efficiency of the recycling processes. However, abiotic depletion and photochemical oxidation are high for Alkaline batteries. Recycling of NiCd and NiMH creates a similar order of magnitude of impact as they fall under the same family of battery chemistry. Recycling Li-ion chemistries results in higher impacts in Acidification, Ionising Radiation, and Water Scarcity.

Figure 10. Impact assessment of producing 1kg refined material from each battery type through recycling (2021)



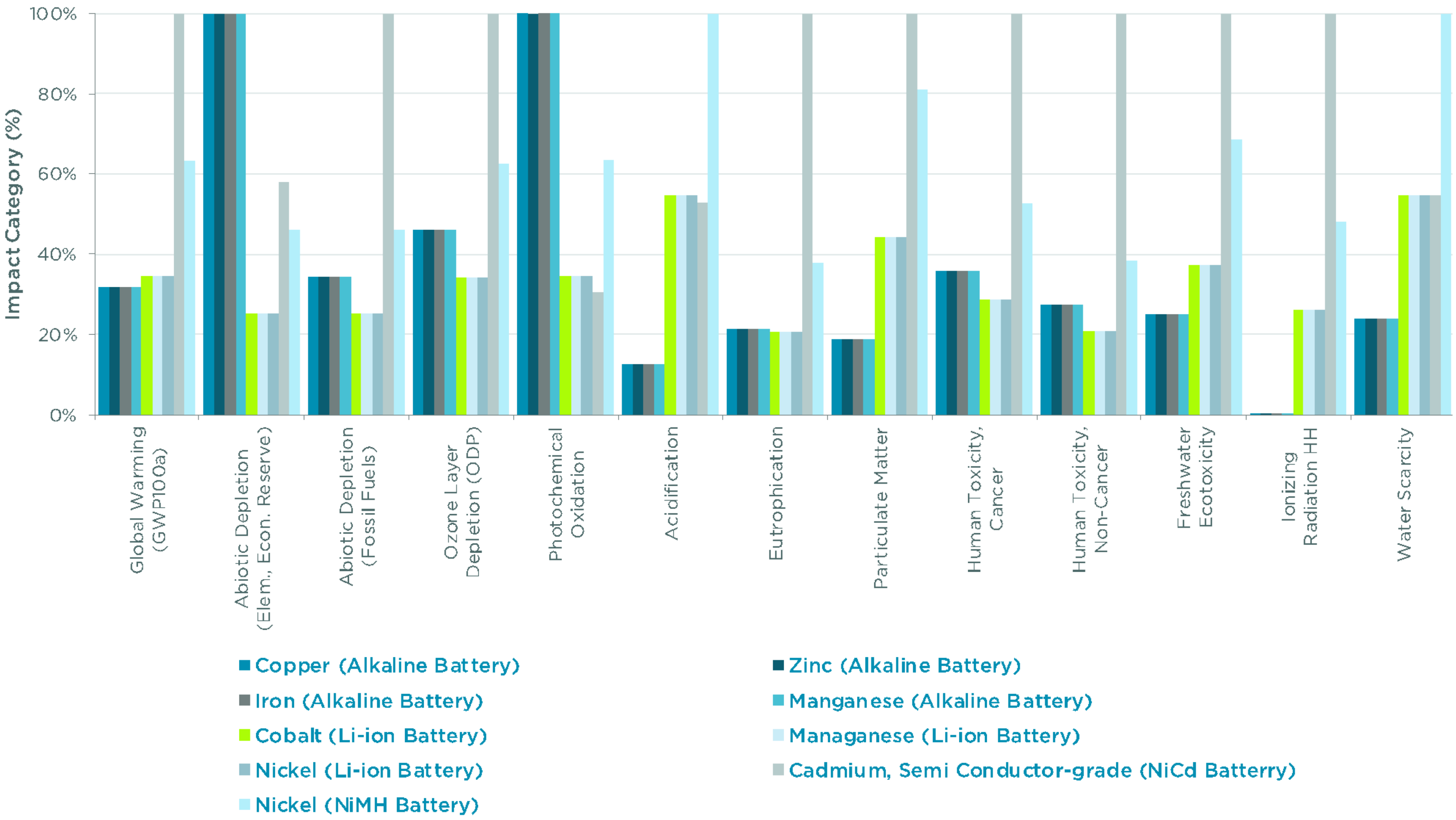
2.3.2. Impacts of producing refined materials from recycled batteries

This section compares the impacts of recycling batteries in more detail. The results show the impacts of producing a range of highly purified materials from recycled batteries ready for the materials market. The impact assessment shows the results of impacts incurred through the battery recycling and material refining stages to produce 1kg of high purity material. Figure 11 shows the impact assessment for individual materials with the relevant battery chemistries referred to in brackets.

The graph provides a general overview of the material outputs of battery recycling from different battery types and the environmental impacts of these material outputs. Based on the results presented below, the following observations are made:

+ Recycling and refining of cadmium from NiCd batteries results in high GWP impacts, 35% higher than that of nickel recycling and refining from NiMH batteries.
+ Recycling and refining of cobalt, manganese, and nickel from Li-ion batteries results in a slightly higher impact than recycling and refining copper, zinc, iron, and manganese from Alkaline batteries.
+ Nickel can be produced by recycling both Li-ion batteries and NiMH batteries. The processes for refining nickel from recycled Li-ion batteries results in less impact across all categories compared to nickel refined from recycled NiMH batteries. This occurs because Li-ion batteries feature a mixture of cathode materials (including cobalt) which can be refined and purified under the same process as nickel, resulting in the sharing of impacts between commodity production.
+ Cadmium is extracted from recycled NiCd batteries as a semi-conductor grade metal with the highest overall impact.
+ The recycling of NiCd batteries results in high impacts across all categories, except photochemical oxidation. Recycling NiCd batteries is significantly worse for human toxicity in both cancerous and non-cancerous forms, compared to other batteries.

Figure 11. Impact assessment producing 1kg of refined metals from recycling (2021)



2.3.3. Comparison of high purity materials from primary production vs recycled batteries

This section compares the impacts of producing refined recycled materials with the same level of purity as equivalent materials available on the global materials market (which includes a significant share of materials from primary sources but may also contain a percentage of recycled materials). Figure 12 demonstrates the impacts of materials sourced from both streams.

Results indicate that recycled materials, even after refining to a highly purified grade, results in less impacts across all categories. All recycled materials have a lower impact compared with primary sourced materials. This is especially significant for cobalt which is more than 20 times more impactful in terms of CO_2e emissions. Copper production from primary sources also features a high impact at around 65% more CO_2e emissions than producing copper from Alkaline batteries. The results indicate a clear environmental advantage inherent in recycled batteries.

Figure 12. Impact assessment of producing metals through recycling vs global materials market average (2021)

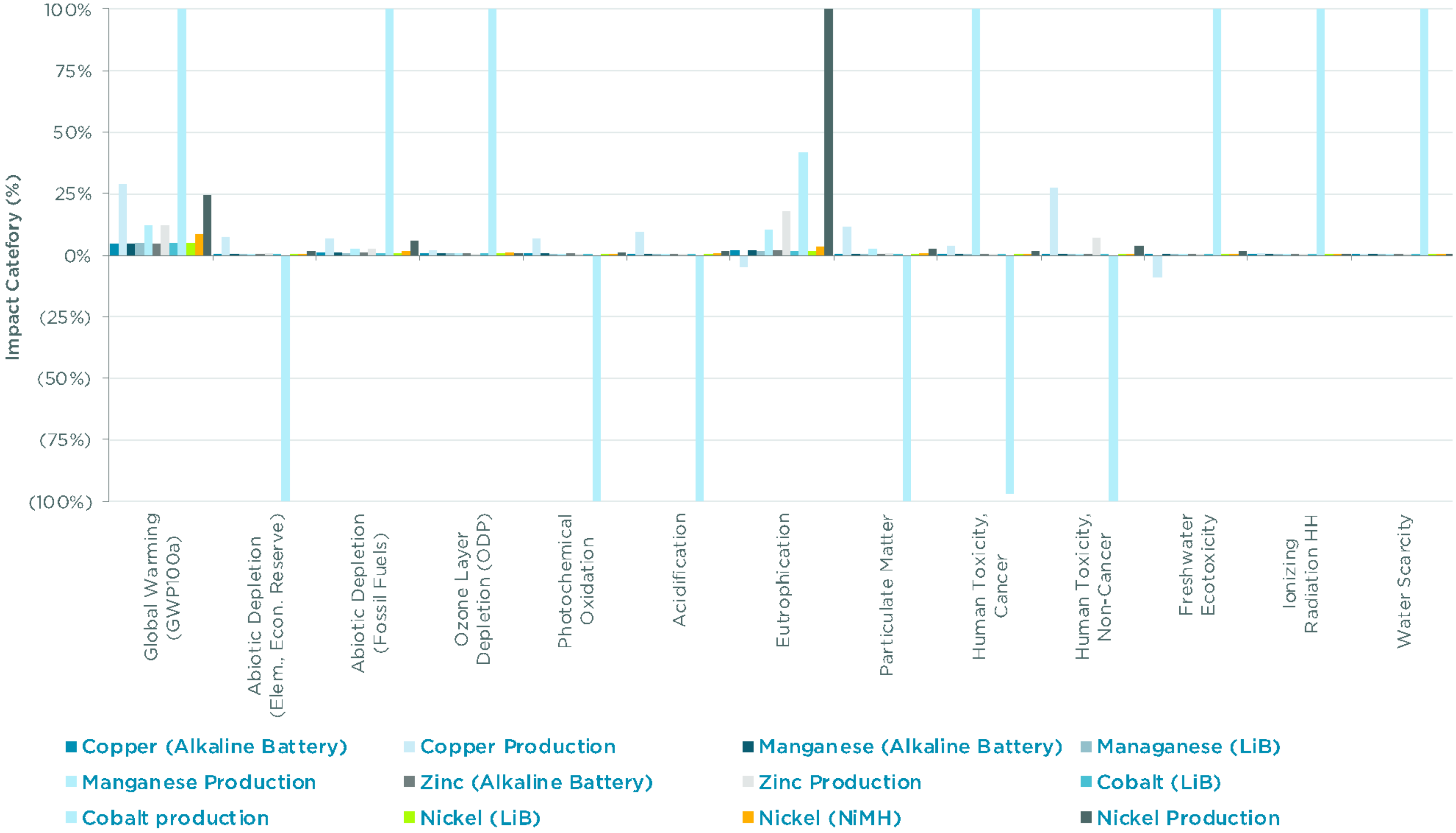
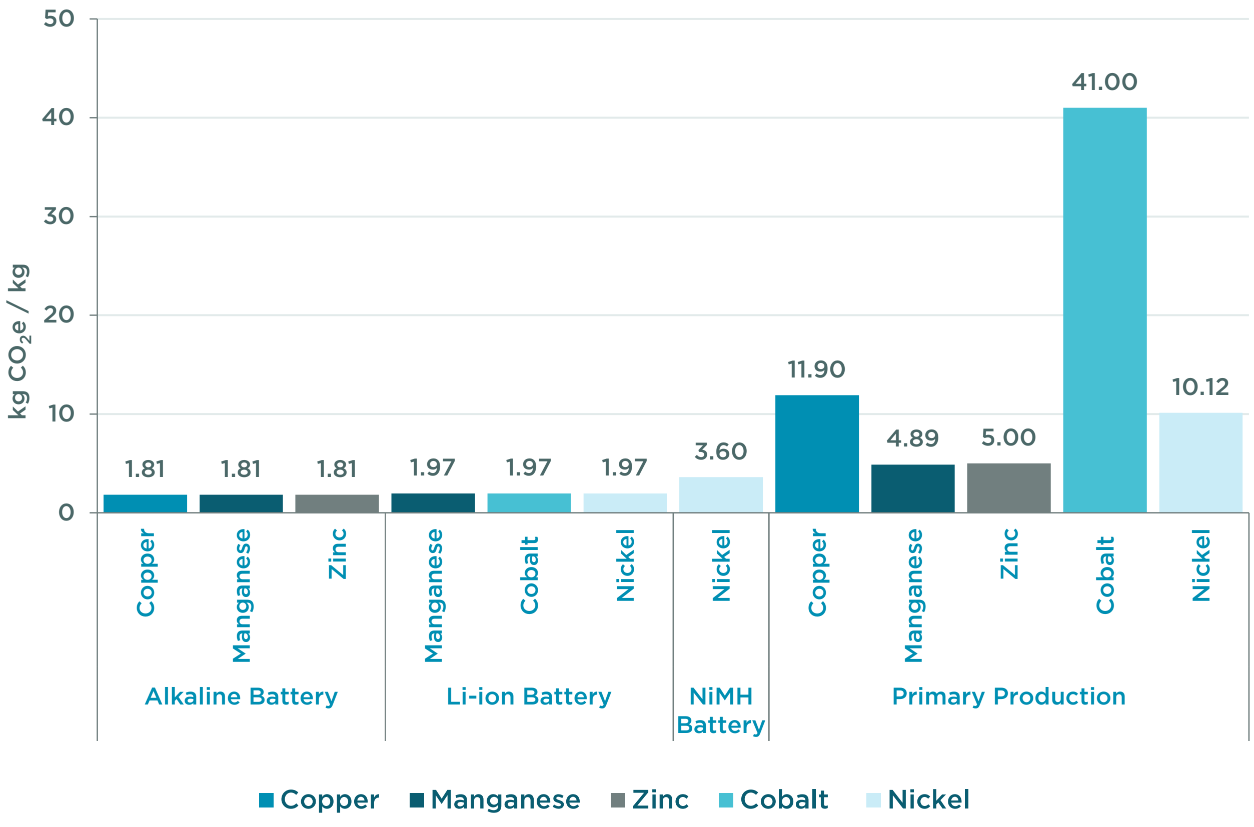


Figure 13 compares the CO_2e emissions impacts of producing a range pure battery grade materials – processed and refined from both recycled batteries ('Alkaline Battery', 'Li-ion Battery', and 'NiMH Battery' to the left) and from primary sources ('production' to the right). Impacts have been quantified for copper, manganese, and zinc from Alkaline batteries, manganese, cobalt and nickel from Li-ion batteries, and nickel from NiMH batteries. These impacts are compared to copper, manganese, zinc, cobalt, and nickel produced from primary materials extraction and refining.

Cobalt shows the highest CO_2e emissions impact from primary production and is almost 95% higher than cobalt production from recycled li-ion batteries. Copper production from primary sources is roughly three times higher than copper production from recycled batteries. Manganese production from primary sources is twice the impact of production from recycled Alkaline and Li-ion batteries. The CO_2e impact of nickel production from primary sources is three times that of nickel from Li-ion batteries and just over double the impact of nickel from NiMH batteries.

The results presented in Figure 13 clearly articulate that materials sourced from recycled batteries have a lower impact than producing the same materials from primary material sources.

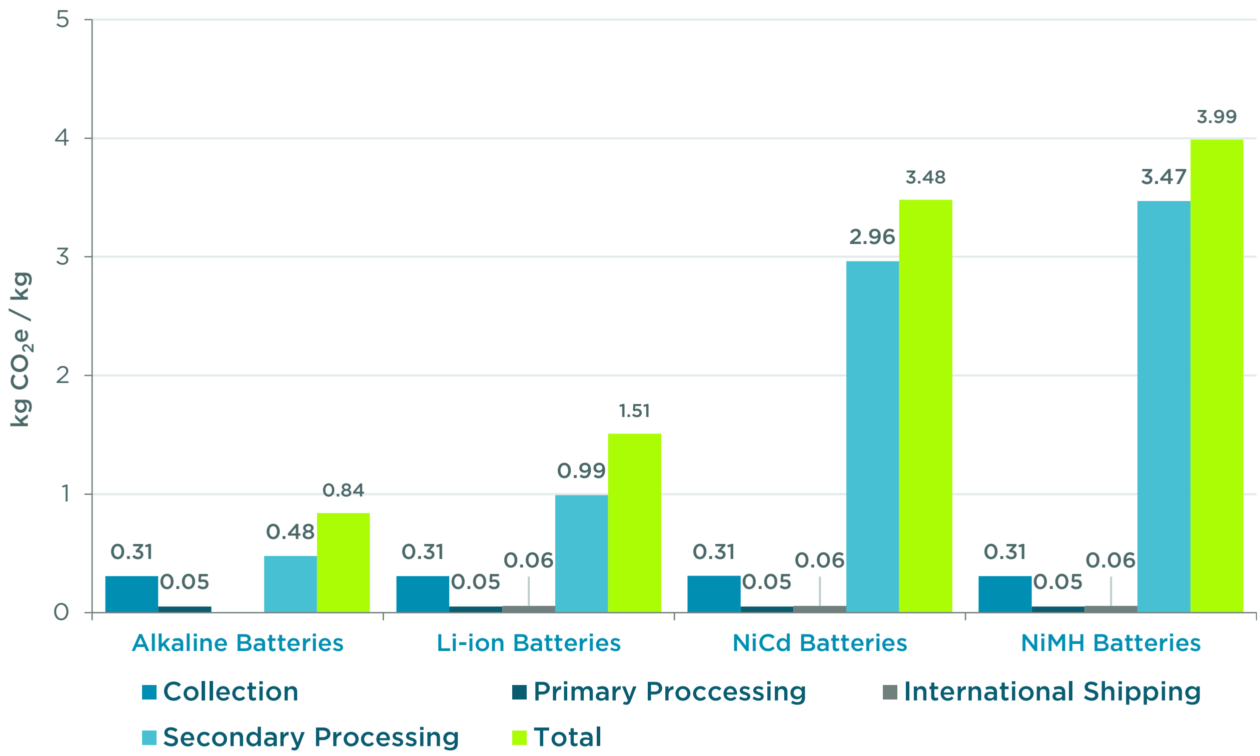
Figure 13. GWP of producing battery grade materials through Alkaline, Li-ion and NiMH battery recycling and primary (production) sources (2021)



2.3.4. GWP impact comparison across phases of battery recycling by battery type

This section provides a summary of GWP for individual stages of battery recycling. The data represents recycling 1kg of battery material through each stage. Figure 14 represents the GWP in kilograms of CO_2 equivalent (CO_2e) per kilogram of battery material recycled. The totals for each stage are represented in yellow.

Figure 14. GWP for each stage of the battery recycling process per kilogram of recycled battery (2021)



Alkaline batteries are processed locally; therefore, no impact is characterised for international shipping. Secondary processing features the highest impact due to the reliance on a significant number of resources and energy compared to other stages.

For example, material refining, which is required to produce high purity material, is one of the most energy intensive parts of the battery recycling process. Comparatively, shredding batteries which occurs during primary processing, features a lower impact due to less energy and material intensity of the process. Transport of batteries from collection points results in CO_2e emissions that are almost as high as primary processing for Li-ion, NiCd and NiMH batteries. Both primary processing and international shipping present significantly lower CO_2e impacts than the initial collection and secondary processing.

2.3.5. Total GWP impact of batteries recycled in Australia

The next section considers the total CO_2e impacts of recycling B-cycle scope batteries in Australia for the year 2021 (that is, batteries that were collected in 2021 by entities currently in the B-cycle Scheme). Table 11 shows the total weight of batteries collected for recycling in Australia in 2021 by those entities currently in the B-cycle Scheme (the Scheme commenced in 2022). A total of 2,240 tonnes of batteries were collected by B-cycle Scheme participants in 2021 and of these the below table represents the battery quantities that have been used for our impact assessment. This impact assessment excludes lead acid batteries (approximately 3.5% of the quantity of batteries collected).

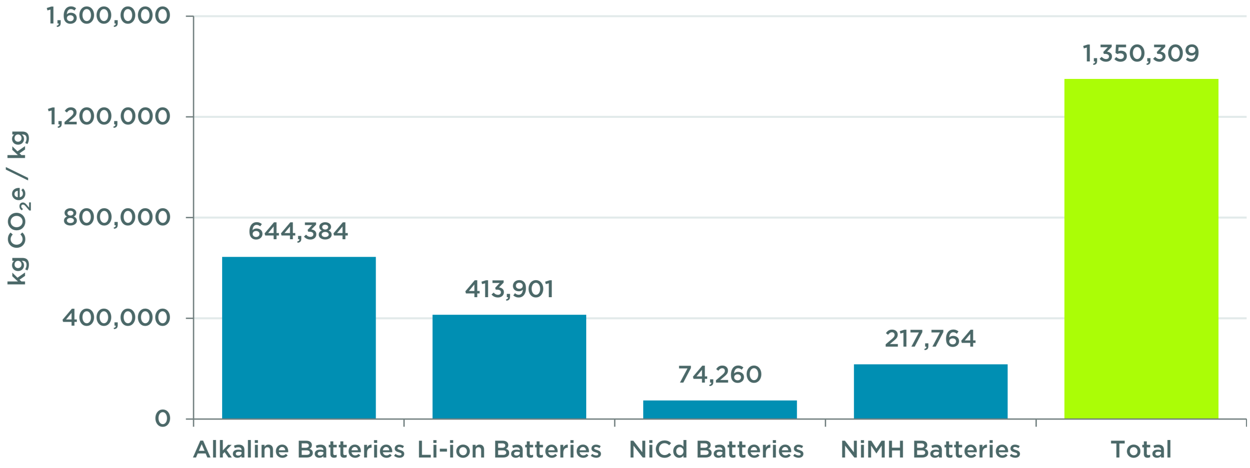
Table 11. Batteries collected in Australia by B-cycle participants (2021)

Chemistries	Amount (PA)	Unit	Data Source	Data Quality
Alkaline	1,295,001	kg	Survey	Good estimate
NiCd	38,187.7	kg	Survey	Good estimate
NiMH	122,918	kg	Survey	Good estimate
Li-ion	282,992	kg	Survey	Good estimate
Mixed	421,052	kg	Survey	Good estimate
Total	**2,160,150**	**kg**	**Survey**	**Good estimate**

Figure 14 shows the total CO_2e impacts of batteries that were collected and recycled in Australia in 2021 by current B-cycle participants. The total CO_2e emissions impact of battery recycling is 1,350 tonnes of CO_2e emissions, or roughly the equivalent of 300 cars driving for a year.

Alkaline batteries are responsible for the highest impact at 644 tonnes of CO_2e emissions in 2021, this is due largely because this battery type features the largest share of battery collections by weight in 2021. Li-ion batteries follow at 413 tonnes of CO_2e emissions. A smaller share of NiCd batteries and NiMH batteries by weight were collected for recycling in 2021, reflected in their smaller share of CO_2e emissions at 74 and 218 tonnes respectively.

Figure 15. GWP impacts of recycling batteries collected and processed in Australia (2021)



2.3.6. Comparison of battery materials sourced from battery recycling vs primary sources

Both recycled and primary materials can be feedstock for new batteries. Figure 16 shows a comparison of battery materials sourced from these two production pathways, by battery type. These results are presented as CO_2e totals for each battery type and the impacts are compared with an equivalent basket of goods sourced from primary production.

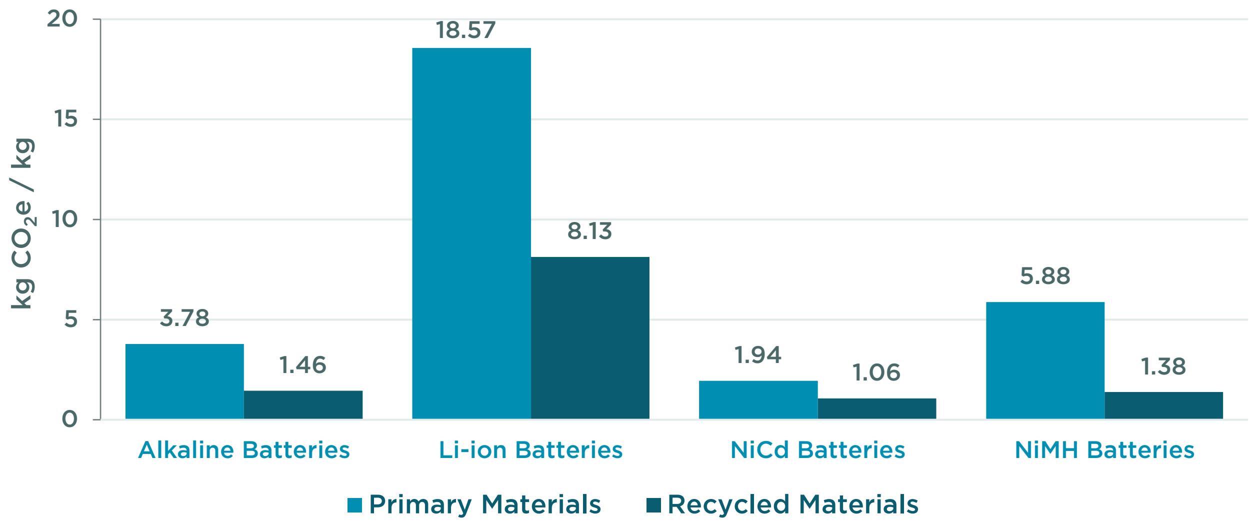
The results presented in Figure 16 highlight the positive impact that could be achieved if highly purity recycled battery material displaces battery materials from primary sources[8]. Based on these results, it is found that:

- Producing highly purified refined material from Li-ion batteries features the highest impact both from recycled batteries and from primary sources, this is due to the high percentage of cobalt present in the reference battery for this study[9]. However, production of Li-ion batteries using materials from primary sources still equates to more than double the impact (18.6kg of CO_2e per kilogram) compared to materials from recycled batteries (8.1kg CO_2e per kilogram).
- Sourcing materials for NiCd batteries from recycled batteries rather than primary sources reduces the CO_2e impact by around 50%.
- Sourcing materials for Alkaline batteries from recycled batteries rather than primary sources reduces the CO_2e impact by around 60%.
- Sourcing recycled materials for NiMH batteries reduces the CO_2e impact by around 75%.

[8] It is noted that our results only highlight the potential for emissions savings and make no attempt to assess the cost or feasibility of producing batteries with recycled content.

[9] For this study the NMC-111 battery type has been used to represent Li-ion battery chemistries.

Figure 16. GWP of producing battery materials from primary materials vs producing battery materials from recycled batteries by battery type (2021)



2.4. Conclusion and further research

The results presented in this LCA are an excellent indicator of the environmental benefits of battery recycling in most cases. The benefits highlight the need to incentivise investment in improved capacity for the battery recycling sector in Australia, particularly if incentives facilitate recycling practices (such as hydrometallurgy) that produce high purity material. Despite the assumptions and data limitations of the study, a clear benefit can be observed if materials from recycled batteries are refined to a high purity and in turn offset the need for primary material production.

The results of the study highlight that placing highly purified recycled materials from batteries onto the materials market has the potential to offset the CO_2e emissions of material supply by around 50%.

Future research using detailed primary data from Australian industry participants in each process will help to strengthen LCA results and create a robust base for claimed benefits of the B-cycle Scheme. It is important to map all the processes with high accuracy to avoid excessive crediting or overestimation. Care should be used to understand the uncertainties and limitations inherent in these results, before relying on information provided in this LCA.

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Appendix A: LCA data

Table 12. Impact assessment of recycling different types of batteries to produce 1kg of refined materials (2021)

Impact Category	Unit	Alkaline Battery	Li-ion Battery	NiCd Battery	NiMH Battery
Global Warming (GWP100a)	kg CO_2- eq.	28.26%	37.84%	100.00%	87.22%
Abiotic Depletion (Elem., Econ. Reserve)	kg SB- eq.	100.00%	26.95%	67.68%	59.45%
Abiotic Depletion (Fossil Fuels)	MJ NCV	35.15%	31.84%	100.00%	86.02%
Ozone Layer Depletion (ODP)	kg CFC-11- eq.	33.26%	31.18%	100.00%	85.91%
Photochemical Oxidation	kg C_2H_4- eq.	100.00%	31.21%	51.95%	47.62%
Acidification	kg SO_2- eq.	14.13%	56.53%	100.00%	90.88%
Eutrophication	kg PO_4- eq.	31.22%	35.07%	100.00%	86.65%
Particulate Matter	kg PM2.5	23.06%	51.53%	100.00%	90.39%
Human Toxicity (Cancer)	CTU-h	43.90%	38.33%	100.00%	87.11%
Human Toxicity (Non-Cancer)	CTU-h	56.65%	43.82%	100.00%	88.44%
Freshwater Ecotoxicity	CTU-e	30.00%	45.29%	100.00%	88.82%
Ionising Radiation (Human Health)	kBq ^{235}U- eq.	0.77%	98.34%	100.00%	99.52%
Water Scarcity	m^3 H_2O- eq.	28.26%	58.55%	100.00%	91.30%

Table 13. Impact assessment of producing 1kg refined materials (2021)

Impact Category	Unit	Copper(1)	Zinc(1)	Iron(1)	Manganese(1)	Cobalt(2)	Manganese(2)	Nickel(2)	Cadmium(3)(4)	Nickel(5)
Global Warming (GWP100a)	kg CO_2- eq.	31.89%	31.88%	31.89%	31.89%	34.56%	34.56%	34.56%	100.00%	63.28%
Abiotic Depletion (Elem., Econ. Reserve)	kg SB- eq.	100.00%	99.97%	100.01%	99.99%	25.19%	25.19%	25.19%	57.96%	46.12%
Abiotic Depletion (Fossil Fuels)	MJ NCV	34.40%	34.39%	34.40%	34.39%	25.06%	25.06%	25.06%	100.00%	45.88%
Ozone Layer Depletion (ODP)	kg CFC-11- eq.	45.98%	45.97%	45.99%	45.98%	34.09%	34.09%	34.09%	100.00%	62.43%
Photochemical Oxidation	kg C_2H_4- eq.	100.03%	100.00%	100.04%	100.02%	34.70%	34.70%	34.70%	30.59%	63.54%
Acidification	kg SO_2- eq.	12.52%	12.52%	12.52%	12.52%	54.61%	54.61%	54.61%	52.83%	100.00%
Eutrophication	kg PO_4- eq.	21.24%	21.23%	21.24%	21.23%	20.63%	20.63%	20.63%	100.00%	37.78%
Particulate Matter	kg PM2.5	18.79%	18.78%	18.79%	18.79%	44.33%	44.33%	44.33%	100.00%	81.18%
Human Toxicity (Cancer)	CTU-h	35.79%	35.78%	35.79%	35.78%	28.71%	28.71%	28.71%	100.00%	52.57%
Human Toxicity (Non-Cancer)	CTU-h	27.56%	27.56%	27.57%	27.56%	20.94%	20.94%	20.94%	100.00%	38.34%
Freshwater Ecotoxicity	CTU-e	24.95%	24.94%	24.95%	24.95%	37.48%	37.48%	37.48%	100.00%	68.64%
Ionising Radiation (Human Health)	kBq ^{235}U- eq.	0.16%	0.16%	0.16%	0.16%	26.17%	26.17%	26.17%	100.00%	47.92%
Water Scarcity	m^3 H_2O- eq.	23.92%	23.91%	23.92%	23.92%	54.61%	54.61%	54.61%	54.53%	100.00%

(1) Alkaline Battery; (2) Li-ion Battery; (3) Semi Conductor-grade; (4) NiCd Battery; (4) NiMH Battery.

Table 14. Impact assessment comparison of 1kg refined materials from recycled battery vs 1kg primary material production (2021)

Impact Category	Unit	Copper(1)	Copper Production	Manganese(1)	Manganese(2)	Manganese Production	Zinc(1)	Zinc Production	Cobalt(2)	Cobalt Production	Nickel(2)	Nickel(3)	Nickel Production
Global Warming (GWP100a)	kg CO_2- eq.	4.42%	29.01%	4.42%	4.79%	11.93%	4.42%	12.18%	4.79%	100.00%	4.79%	8.78%	24.68%
Abiotic Depletion (Elem., Econ. Reserve)	kg SB- eq.	0.04%	7.45%	0.04%	0.01%	0.11%	0.04%	0.77%	0.01%	(100.00%)	0.01%	0.02%	1.53%
Abiotic Depletion (Fossil Fuels)	MJ NCV	1.25%	6.63%	1.25%	0.91%	2.41%	1.25%	2.66%	0.91%	100.00%	0.91%	1.67%	5.74%
Ozone Layer Depletion (ODP)	kg CFC-11- eq.	0.93%	2.21%	0.93%	0.69%	0.71%	0.93%	0.27%	0.69%	100.00%	0.69%	1.26%	0.71%
Photochemical Oxidation	kg C2H4- eq.	0.78%	6.62%	0.78%	0.27%	0.27%	0.78%	0.33%	0.27%	(100.00%)	0.27%	0.49%	1.12%
Acidification	kg SO2- eq.	0.08%	9.41%	0.08%	0.37%	0.38%	0.08%	0.52%	0.37%	(100.00%)	0.37%	0.68%	1.58%
Eutrophication	kg PO4- eq.	1.93%	(4.91%)	1.93%	1.88%	10.26%	1.93%	17.70%	1.88%	42.02%	1.88%	3.44%	100.00%
Particulate Matter	kg PM2.5	0.23%	11.72%	0.23%	0.54%	2.61%	0.23%	0.93%	0.54%	(100.00%)	0.54%	0.98%	2.40%
Human Toxicity (Cancer)	CTU-h	0.09%	3.58%	0.09%	0.07%	100.00%	0.09%	0.37%	0.07%	(96.87%)	0.07%	0.13%	1.83%
Human Toxicity (Non-Cancer)	CTU-h	0.10%	27.25%	0.10%	0.08%	0.27%	0.10%	7.15%	0.08%	(100.00%)	0.08%	0.14%	3.60%
Freshwater Ecotoxicity	CTU-e	0.04%	(9.04%)	0.04%	0.06%	0.48%	0.04%	0.49%	0.06%	100.00%	0.06%	0.10%	1.78%
Ionising Radiation (Human Health)	kBq ^{235}U- eq.	0.00%	1.03%	0.00%	0.15%	0.52%	0.00%	0.00%	0.15%	100.00%	0.15%	0.27%	0.02%
Water Scarcity	m^3 H_2O- eq.	0.01%	0.45%	0.01%	0.02%	0.01%	0.01%	0.12%	0.02%	100.00%	0.02%	0.04%	0.16%

(1) Alkaline Battery; (2) Li-ion Battery; (3) NiMH Battery.

Table 15. GWP impacts of each recycling stages (2021)

Recycling Stage	Recycled Alkaline Batteries (CO_2e / kg)	Recycled Li-ion Batteries (CO_2e / kg)	Recycled NiCd Batteries (CO_2e / kg)	Recycled NiMh Batteries (CO_2e / kg)
Collection	0.309051994	0.309024086	0.309655254	0.309158521
Primary Processing	0.788870467	0.461809513	0.362094147	0.361597414
International Shipping	–	0.518869731	0.518869731	0.518869731
Secondary Processing	1.266019701	1.508534137	3.480700915	3.989775942

Table 16. GWP impacts of battery materials from primary and recycled battery sources (2021)

Battery Type	Primary Materials (CO_2e / kg)	Recycled Materials (CO_2e / kg)
Alkaline Batteries	3.784585454	1.456491255
Li-ion Batteries	18.565888689	8.127075856
NiCd Batteries	1.944604583	1.063760538
NiMH Batteries	5.880429888	1.380000000

Table 17. GWP impact for all batteries recycled in Australia (2021)

Battery Type	Total Impact (kg CO_2e)
Alkaline Batteries	644,384
Li-ion Batteries	413,901
NiCd Batteries	74,260
NiMH Batteries	217,764
Total	**1,350,309**

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Battery Stewardship Council

B-cycle
Battery
Recycling

Battery Life Cycle Analysis

The environmental impacts of battery recycling in Australia

This technical report represents the findings from a benchmarking project commissioned by the Battery Stewardship Council (BSC), undertaken by the Institute for Sustainable Futures (ISF) at the University of Technology Sydney (UTS).

The goal of the study was to understand the consequential benefits of material recovery from recycled batteries in Australia.

It confirms that the inclusion of highly purified recycled battery material in new batteries reduces emissions by around 50% over battery materials supply; prompting the need to incentivise investment in improved capacity for the battery recycling sector.

Australian Government Accredited Product Stewardship Scheme

This Scheme is authorised by the Australian Competition & Consumer Commission (ACCC), accredited by the Australian Government, and has received financial support from the Australian Government and industry.