Recycling

Supporting Information

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1. Methodology

CSIRO and ANL are national laboratories in Australia and the U.S. respectively that have diverse activities in R&D and commercialisation of technologies. Australia and the U.S. have long been collaborating in a variety of science and engineering fields. Both labs engage with a variety of stakeholders in lithium-ion battery recycling and the developing battery value chain. Whilst both countries are progressing in developing LIB recycling and industries in the supply chain, it has become clear that while each country's goals are very similar, varying factors are accelerating and, in some cases, slowing the development of the battery value chain. The purpose of this initial case study is to glean information from various stakeholders on what they see as some of the challenges, opportunities, areas for improvement and areas where collaboration will be critical. The approach presented here could be used by other countries to also consider and compare what has been undertaken within and between the two countries here to better enable them to understand what areas of the battery value chain to focus on and whether it may or may not be viable to establish a LIB recycling facility onshore. Holistically it allows for a broader discussion around global value chains that are rapidly developing, where integration may be a better option than duplication. It will be of interest to revisit this topic in 5- and 10-years' time to see the change that has occurred in both Australia and U.S., and globally as regulations and new requirements (i.e. Battery Passport, ESG etc) come into effect and countries progress developing viable and sustainable battery value chains and LIB recycling.

2. Background – Population Size and Distribution, and Land Area

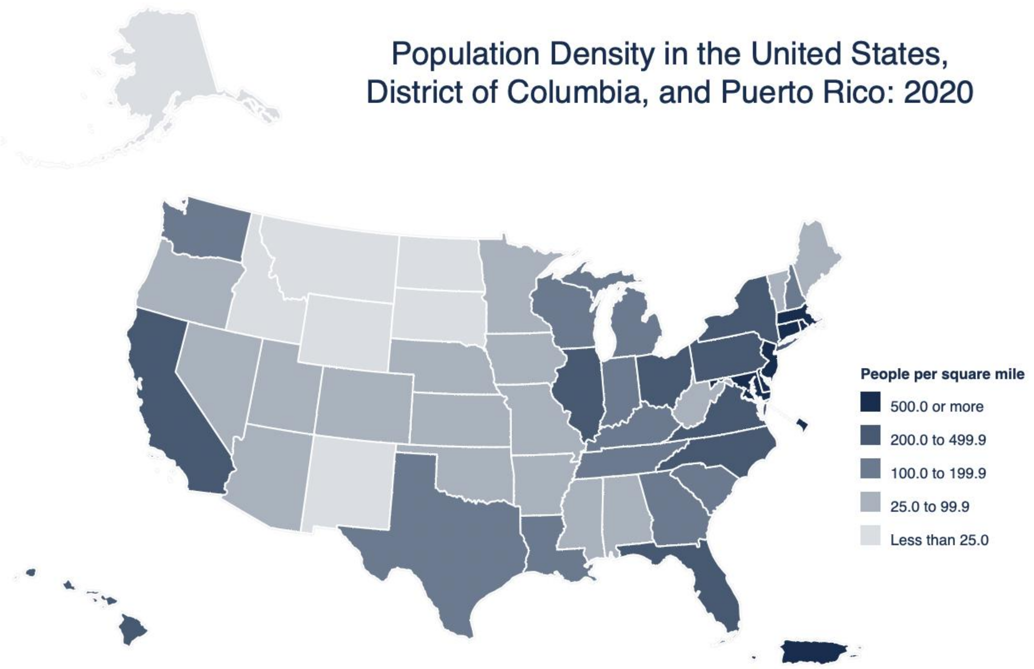

Figure S1. Population Density by State in the U.S. (Reproduced from U.S. Census Bureau[1]).

3. Battery Use – Battery Electric Vehicles (BEVs) and Battery Energy Storage Systems (BESSs)

In recent years, Australia has seen LIBs become a common topic of discussion around BEVs, but especially in BESS for large scale systems for grid storage to residential storage coupled with rooftop photovoltaics. Unlike the U.S. and other countries, Australia's uptake of BEVs has been slow and is in part constrained by the vast distances and low population densities across the country, with a corresponding sparse road network connecting major cities and regional centers.

Australia's involvement with electrified transport began in the mid-1990s. The Holden ECOmmodore,(2) coupling a General Motors 95kW, 2.0-litre, four-cylinder ICE with a CSIRO developed 50kW electric motor (charged by lead acid batteries backed up by supercapacitors), allowed a full family size car to be produced with the goal of reducing hydrocarbon and greenhouse emissions (**Figure S2**).

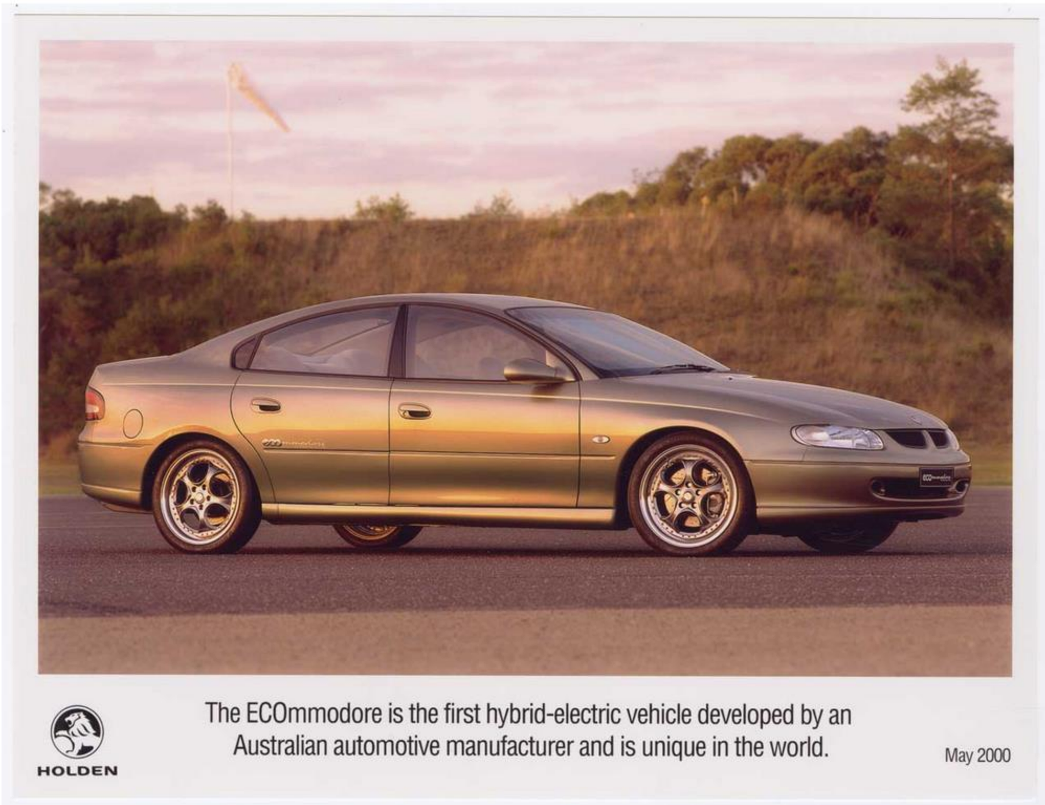

Figure S2. Part of ECOmmodore national media launch kit (Reproduced from [2]).

To put this in context, as of 2022 in Australia the progress of uptake of BEV can be summarized by the following points;[3, 4]

- From 2011 to 2022, just over 83000 PHEV and BEVs have been sold in Australia, with signs of strong growth over the last few years (**Figure S3**)
- Currently, as of 2022, there are now 25 different EV models for sale
- All BEVs vehicles are imported (none manufactured or assembled in Australia)
- Of the 15 top-selling BEV models (2022 data), 13 were BEVs, while only 2 were PEVs. The trend towards BEVs is due to the types of vehicles offered in this class, being primarily small compact cars and SUV types, typically favoured in our densely populated cities
- Towards the end of 2022, reports started to show the introduction of new large SUVs and larger 4WD vehicles, which are commonly used in long distance transportation across Australia. However, new models of diesel and petrol vehicles still dominate the market whilst more PEVs, rather than full BEVs, are expected to arrive in 2023.[3] This would suggest that concerns remain around fast charging times, infrastructure availability and range anxiety and as to whether BEVs can accommodate the vast, remote, harsh environmental conditions.
- This is substantiated by the small number of public charging locations (2,147) across Australia, with a total of 3,669 individual BEV chargers.

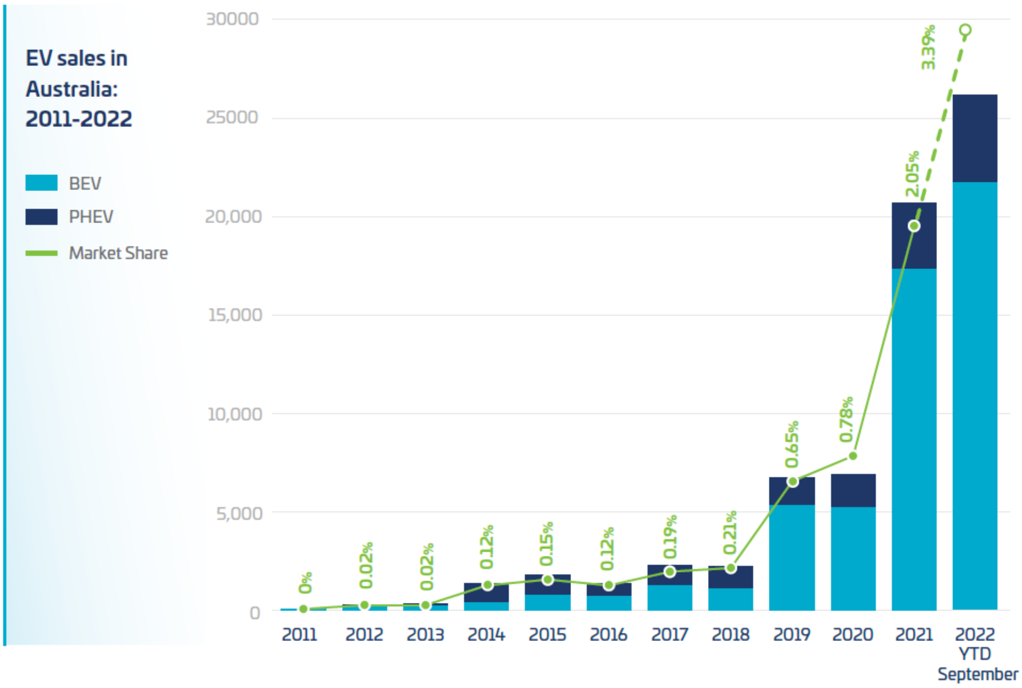

Figure S3. BEV and PEV sales in Australia since 2011 (Reproduced from [3]).

Figure S4. The Tesla Powerpacks in Hornsdale, Australia (Reproduced from [5]).

Figure S5. The 2021 The Victorian Big Battery in Geelong, Australia.(Reproduced from [6]).

Australia's solar, hydro and wind-based energy accounted for more than 18% of the country's total electricity generation in 2020, and has increased to 32% in 2022.[7, 8] These intermittent energy generation sources need to be coupled to energy storage systems; a critical stage in the transition to a sustainable energy system.[8] The Australia energy storage market expects a compound annual growth rate of greater than 10% during the forecast period of 2022 – 2027. For instance, the Clean Energy Council of Australia, recorded approximately 23,796 BESS installed units with a combined capacity of 238 MWh in 2020, an increase of 5.19%, compared to the previous year.

Table S1. Utility-Scale Battery Systems Under Construction at the End of 2021 (Reproduced from [7]).

State*	Project	Owner	Locality	Size
SA	Torrens Island Battery	AGL	Torrens Island	250 MW/250 MWh
VIC	Hazelwood Battery Energy Storage System	Engie	Hazelwood	150 MW/150 MWh
ACT	Capital Battery	Neoen	Jerrabomerra	100 MW/150 MWh
WA	Perth (Kwinana)	Synergy	Kwinana	100 MW/200 MWh
NSW	Wallgrove Grid Battery	Transgrid	Wallgrove	52 MW/78 MWh
NSW	New England Solar Farm	UPC/AC Renewables	Uralla	50 MW/50 MWh
WA	Koodaideri Mine Solar Farm	Rio Tinto	Newman	45 MW/12 MWh
WA	Pilbara Project Energy Connect Battery Energy Storage System	Fortescue Metals	Chichester	42 MW/13 MWh
NT	Darwin-Katherine Battery Energy Storage System	Territory Generation	Darwin	35 MW/20 MWh
VIC	Bulgana Green Power Hub	Neoen	Joel South	20 MW/34 MWh
WA	BHP Leinster Nickel Mine	TransAlta Southern Cross Energy	Mount Keith	10 MW/5 MWh
SA	Adelaide Desalination Plant Solar Farm Stage 1	SA Water	Adelaide	6 MW/12 MWh
NT	Katherine Solar Power Station	Eni Australia	Cossack	6 MW/3 MWh
VIC	West Gippsland Battery	E22	Longwary	5 MW/8 MWh
WA	Gold Fields Gruyere Mine Microgrid	APA Group	Cosmo Newbery	4 MW/4 MWh
NSW	Narellan Shopping Centre Solar Project	CEP Energy	Narellan	4 MW/10 MWh
VIC	Mortlake South Wind Farms	ACCIONA	Kolora	5 MW
QLD	Black River Substation	Energy Queensland	Townsville	4 MW/8 MWh
QLD	Tanby Substation	Energy Queensland	Yeppoon	4 MW/8 MWh
QLD	Bargara Substation	Energy Queensland	Bundaberg	4 MW/8 MWh
QLD	Torquay Substation	Energy Queensland	Hervey Bay	4 MW/8 MWh
QLD	Torrington	Energy Queensland	Toowoomba	4 MW/8 MWh
SA	Happy Valley Reservoir	SA Water	Happy Valley	4 MW/10 MWh
VIC	RayGen Power Plant	RayGen Resources	Carwarp	3 MW/50 MWh
NT	Jabiru Hybrid Renewable Project	EDL	Jabiru	3 MW/5 MWh
QLD	Dalby Solar Farm – Stage 1	Fotowatio Renewable Ventures	Dalby	3 MW/5 MWh
QLD	Kennedy Energy Park	Windlab	Hughenden	2 MW/4 MWh
WA	Garden Island Microgrid	Carnegie Clean Energy	Garden Island	2 MW/1 MWh
SA	Aldinga Wastewater Treatment Plant Reserve	SA Water	Aldinga	1 MW/1 MWh

* SA – South Australia, VIC – Victoria, ACT – Australian Capital Territory, NSW – New South Wales, WA – Western Australia, NT – Northern Territory and QLD - Queensland.

4. LIB Supply Chain – From Raw Materials to End-of-Life

Table S2. Australia's critical minerals list, resources, and production with global comparisons (Reproduced from [9]).

Critical Mineral	US list[1]	EU list[2]	Japan list[3]	India list[4]	Australian Geological Potential[5]	Australian Economic Demonstrated Resources (2020)[6]	Australia Production (2020)[6]	World Mine Production (2020)[6]
High-purity alumina	Yes	Yes	No	No	Moderate	No data	No data	No data
Antimony	Yes	Yes	Yes	Yes	Moderate	125.2 kt	3.9 kt	155 kt
Beryllium	Yes	Yes	Yes	Yes	Moderate	No data	No data	240 t
Bismuth	Yes	Yes	Yes	Yes	Moderate	No data	No data	17 kt
Chromium	Yes	No	Yes	Yes	Moderate	0	0	40,000 kt
Cobalt	Yes	Yes	Yes	Yes	High	1,495 kt	5.6 kt	135 kt
Gallium	Yes	Yes	Yes	Yes	High	No data	No data	300 t
Germanium	Yes	Yes	Yes	Yes	High	No data	No data	130 t
Graphite	Yes	Yes	Yes	Yes	Moderate	7,970 kt	0	1,100 kt
Hafnium	Yes	Yes	Yes	No	High	14.5 kt	No data	No data
Helium	No	No	No	No	Moderate	No data	4 hm^3	140 hm^3
Indium	Yes	Yes	Yes	Yes	Moderate	No data	No data	900 t
Lithium	Yes	Yes	Yes	Yes	High	6,174 kt	40 kt	82 kt
Magnesium	Yes	Yes	Yes	No	High	Magnesite: 286,000 kt	Magnesite: 799 kt	Magnesite: 26,000 kt
Manganese	Yes	No	Yes	No	High	Manganese ore: 276,000 kt	Manganese ore: 4,800 kt	17,200 kt
Niobium	Yes	Yes	Yes	Yes	High	216 kt	No data	78 kt
Platinum-group elements	Yes	Yes	Yes	Yes	Moderate	107 t	0.522 t	380 t
Rare-earth elements	Yes	Yes	Yes	Yes	High	4,200 kt	20 kt	240 kt
Rhenium	No	No	Yes	Yes	Moderate	No data	No data	53 t
Scandium	Yes	Yes	No	No	High	30.34 kt	No data	No data
Silicon	No	Yes	Yes	Yes	High	No data	No data	8 kt
Tantalum	Yes	Yes	Yes	Yes	High	99.4 kt	0.1 kt	1.8 kt
Titanium	Yes	Yes	Yes	No	High	Ilmenite: 274,000 kt; Rutile: 35,000 kt	Ilmenite: 1,100 kt; Rutile: 200 kt	Ilmenite: 12,000 kt; Rutile: 1,000 kt
Tungsten	Yes	Yes	Yes	No	High	577 kt	<1 kt	84 kt
Vanadium	Yes	Yes	Yes	Yes	High	7,408 kt	0	86 kt
Zirconium	Yes	No	Yes	Yes	High	Zircon: 79,300 kt	Zircon: 400 kt	Zircon: 2,000 kt

Table notes
1. https://www.usgs.gov/news/national-news-release/us-geological-survey-releases-2022-list-critical-minerals
2. https://rmis.jrc.ec.europa.eu/?page=crm-list-2020-e294f6
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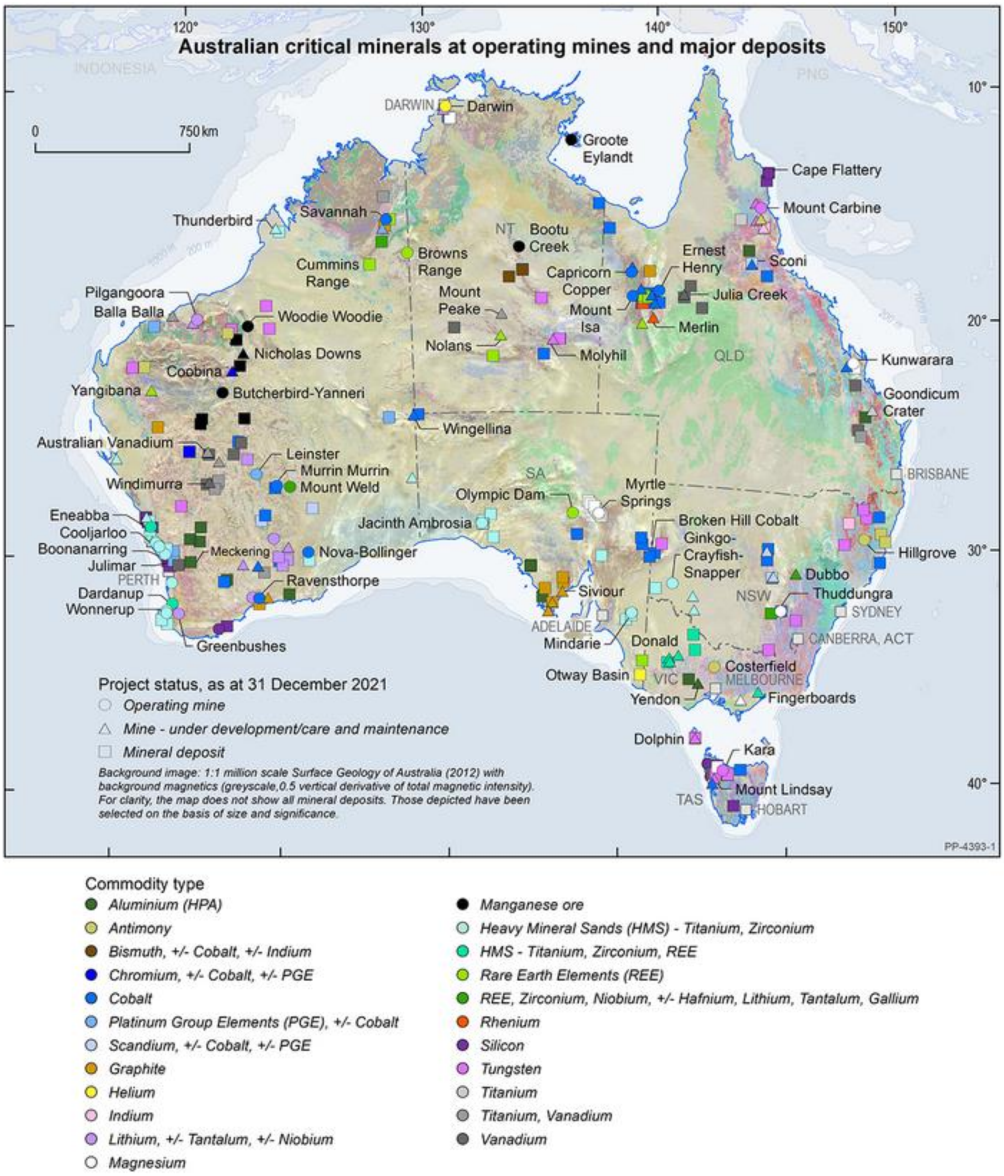

Figure S6. Australian Critical Minerals Map (Reproduced from [9]).

In addition to these critical minerals, Australia has natural resources of other base metals, such as copper, aluminium, and nickel, that are key components in LIBs as shown in **Figure S7**.

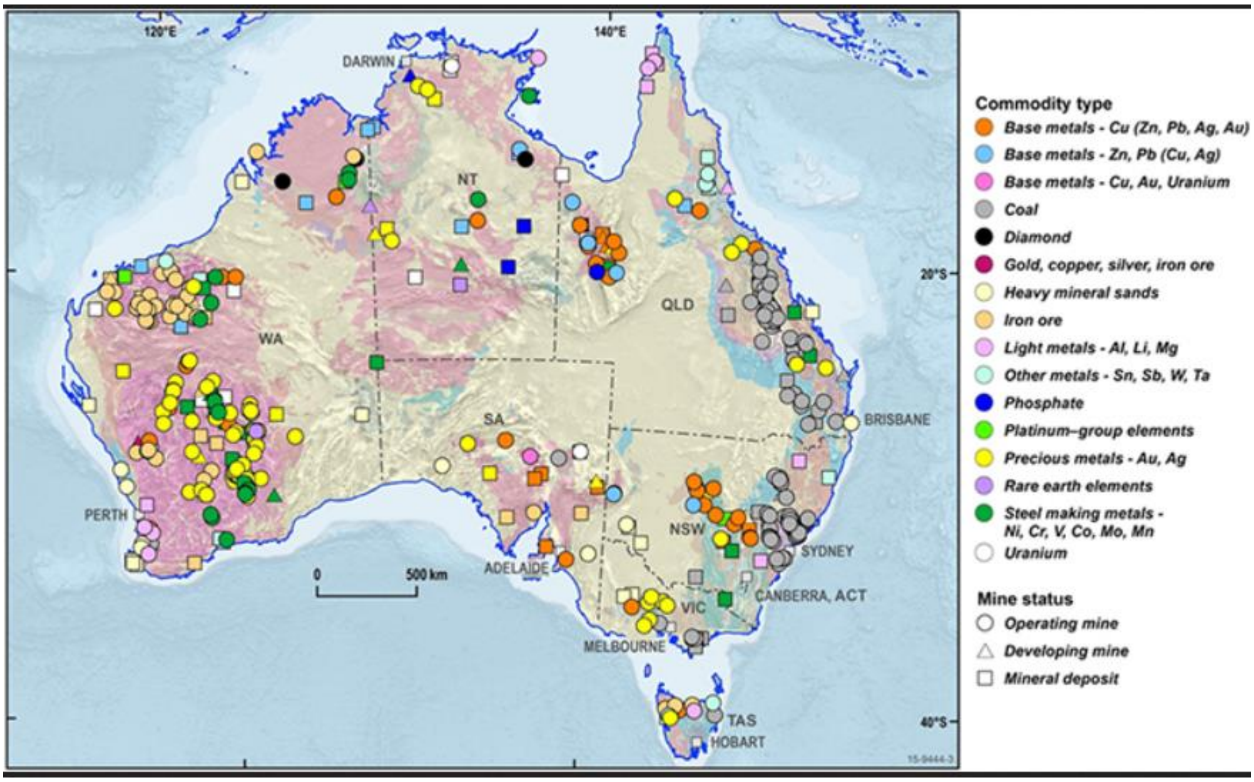

Figure S7. Major mining and mineral deposits in Australia (Reproduced from [10]).

5. LIB Supply Chain – Battery Recycling

Table S3. Notable Players in the U.S. battery Recycling Industry

Activity	Company	Facility Location	Capacity	Description (ref)
Remanufacturer /Repurposer	RePurpose Energy	Fairfield, California	N/A	Repurpose PEV battery for stationary energy storage; 275 kWh demonstration project based on Nissan Leaf battery completed in 2019 [11]
	Spiers New Technologies (Cox)	Oklahoma City, Oklahoma	N/A	Repair, refurbish, remanufacture EV batteries; repurpose EV batteries for non-vehicle applications [12]
Preprocessor	Ascend Elements	Covington, Georgia	30,000 t/yr	Fully operational in August 2022. Produce battery-grade Li, Co, and Ni salts from EOL batteries and scrap; Can produce black mass to supply its Kentucky facility [13]
	Li-Cycle	Rochester, New York; Gilbert, Arizona; Tuscaloosa, Alabama; Warren, Ohio	40,000 t/yr	Spokes. Produce black mass from batteries and scrap [14]
Recycler	American Battery Technology Company	Fernley, Nevada	20,000 t/yr	Under construction. Will produce battery-grade materials from EOL batteries via an automated deconstruction process plus hydro [15, 16]
	Ascend Elements	Hopkinsville, Kentucky	N/A	Construction to begin in Q4 2022; Operation to begin in late 2023. Will produce precursor (GA) and cathode active material (KY) from black mass based on the Hydro-to-Cathode technology. Can produce battery materials for 250,000 PEVs per year [17]
	Cirba Solutions	Lancaster, Ohio	N/A	Under expansion. Will produce battery-grade critical minerals from batteries. Received $75 million in funding from the Bipartisan Infrastructure Law. Can produce battery materials for 200,000 EVs per year [18]
	Li-Cycle	Rochester, New York	35,000 t/yr	Hub. Commission to begin in 2023. Will produce battery-grade materials, including Li_2CO_3 from black mass via hydro [14]
	Redwood Materials	Carson City, Nevada	N/A	Under construction. Will produce cathode and anode from batteries and scrap. Can produce materials for 1 million EVs in 2025, 5 million in 2030 [19]
Direct recycler	Li Industries	Blacksburg, Virginia (HQ)	N/A	Separate and regenerate cathode material from EOL batteries. Plan to build and open a commercial battery sorting and recycling facility in 2023 [20, 21]
	Princeton NuEnergy	Mckinney, Texas	500 t/yr	Reclaim and repair cathode material from batteries and scrap via a low-temperature plasma-assisted process [22]

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