Western Australia: a battery metal powerhouse

by

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Driving the battery-world economy

The generally improving individual wealth and living standards of the world's population are creating ever greater demands for energy, mobility and consumer goods, but there is also an increased awareness of anthropogenic pollution in the natural environment, and a desire to significantly mitigate this. Society is consequently moving towards greater use of renewable energy sources to power residential, retail and industrial centres, the global transportation network that connects these, and the burgeoning constellation of portable electronica.

Renewable energy sources are commonly periodic or transient in nature, which necessarily requires the use of rechargeable batteries to store and regulate the distribution of this energy. A battery comprises two electrodes (anode and cathode) made of different materials (single elements or multi-element compounds), connected by a cation-conducting fluid or gel electrolyte, but insulated against direct electron flow between electrodes, all contained in a casing (Fig. 1a). Battery component materials and architecture optimize application-specific characteristics such as terminal voltage, mass, energy density (amount of stored energy per unit mass or volume), durability, cost and safety, within constraints imposed by cost of raw materials and manufacturing, stability of component mixes, reversibility of electrochemical reactions (rechargeablility), and operating temperature ranges. The variety of possible battery chemistries is enormous, and continually expanding, collectively using a significant proportion of the periodic table (notably aluminium, antimony, arsenic, barium, cadmium, carbon, calcium, cobalt, iron, lanthanum, lead, lithium, manganese, nickel, phosphorus, selenium, sodium, sulfur, tin, titanium, vanadium and zinc).

There has been widespread use of so-called lithium-ion batteries because there is no practical constraint on their size, they are comparatively light, have voltages, energy densities and recharge rates generally exceeding those of other battery types, and their cost of manufacture is falling. Lithium is used as the charge-transport cation because it is efficiently released from and absorbed into the structure of the electrodes during discharge and recharge. However, the bulk of any Li-ion battery comprises many other materials. Those batteries with the highest energy density — suitable for large-scale grid power storage, and powering hybrid petrol–electric and fully electric vehicles — use significant amounts of nickel, cobalt, manganese, aluminium and graphite (Table 1; Fig. 1b).

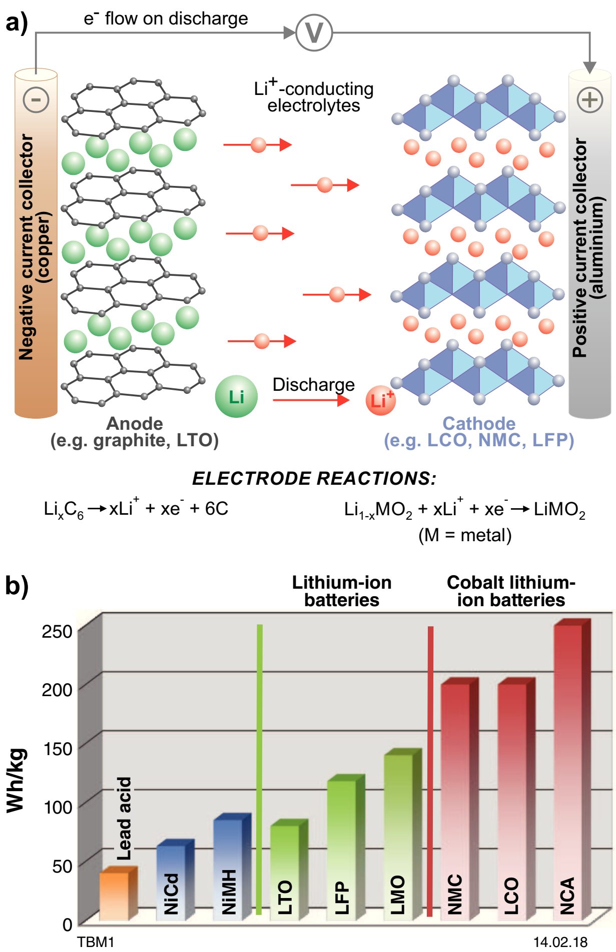


Figure 1. A synopsis of selected characteristics of (Li-ion) batteries: a) schematic architecture and electrode reactions (modified after Wiaux and Chanson, 2013); b) typical specific energies for common battery types. Abbreviations: NiCd, nickel–cadmium; NiMH, nickel–metal hydride; other abbreviations as per Table 1; modified after Battery University (2017, fig. 15)

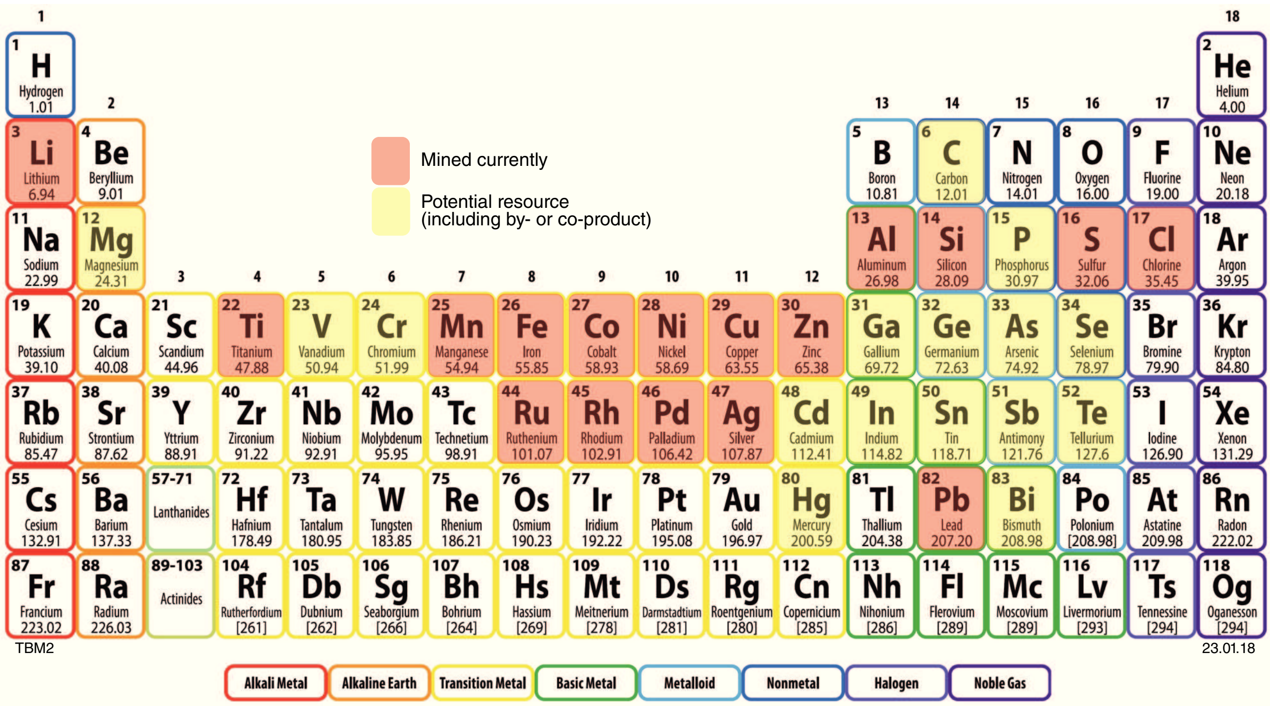
Table 1. Common Li-ion battery types, listing cathode composition and typical applications (compiled from Battery University, 2017). High-capacity types currently favoured for mobile devices, electric vehicles and grid power storage in bold

Chemical name (abbreviation)	*Cathode material*	*Anode material*	*Nominal voltage per cell (V)*	*Specific energy (Wh/kg)*	*Applications*
Lithium cobalt oxide (LCO)	**$LiCoO_2$**	**graphite**	**3.60**	**150–200**	**Mobile phones,tablets, laptops, cameras**
Lithium manganese oxide (LMO)	$LiMn_2O_4$	graphite	3.70, 3.80	100–150	Power tools, electric vehicles, medical devices, hobbyist
Lithium iron phosphate (LFP)	$LiFePO_4$	graphite	3.20, 3.30	90–120	Power tools, electric vehicles, medical devices, hobbyist
Lithium nickel manganese cobalt oxide (NMC)	**$LiNiMnCoO_2$**	**graphite**	**3.60, 3.70**	**150–220**	**Power tools, electric vehicles, medical devices, hobbyist**
Lithium nickel cobalt aluminium oxide (NCA)	**$LiNiCoAlO_2$**	**graphite**	**3.60**	**200–260**	**Electric vehicles, grid storage, medical devices**
Lithium titanate (LTO)	LMO or NMC cathode	$Li_4Ti_5O_{12}$	2.40	50–80	Electric vehicles, grid storage, solar street lighting

Battery metal contributions from Western Australia

Western Australia can now, or could in the future, supply many if not most commodities required by the battery manufacturing industry (Figs 2, 3). In light of recent commercial emphasis on the development of Li-ion battery technology, Western Australia's actual or potential contribution is herein illustrated for six currently prominent metals used in such batteries — lithium, graphite (though not technically a metal), nickel, cobalt, manganese and vanadium (Table 2).

Lithium is primarily sourced from pegmatites and evaporitic lake brines (Dill, 2010). Western Australia has no known brine deposits, but is well endowed with lithian pegmatites (Fig. 3), including the world's largest single deposit (at Greenbushes). The State has four operating lithium mines at Greenbushes (Talison Lithium Pty Ltd), Mt Marion (Reed Industrial Minerals Pty Ltd), Mt Cattlin (Galaxy Resources Ltd), and Wodgina (Mineral Resources Ltd), and has been the world's largest lithium producer since 2013 (ahead of Chile, Argentina and China), contributing 41% (14.3 kt) of global supply in 2016 (Jaskula, 2017). Rising demand and projected consumption for lithium have driven prices upwards and impelled a surge in lithium exploration and development that, in Western Australia, has yielded significantly increased resources (11.6 Mt at the end of 2017; Fig. 4a; Table 2), ranking fourth globally in 2016 (behind Argentina, Chile, and China; Jaskula, 2017).



[modified from original obtained from https://sciencenotes.org/printable-periodic table/]

Figure 2. Periodic table of the elements (sans lanthanides and actinides), highlighting those commonly used in batteries, and that now are, or may in the future be, mined in Western Australia

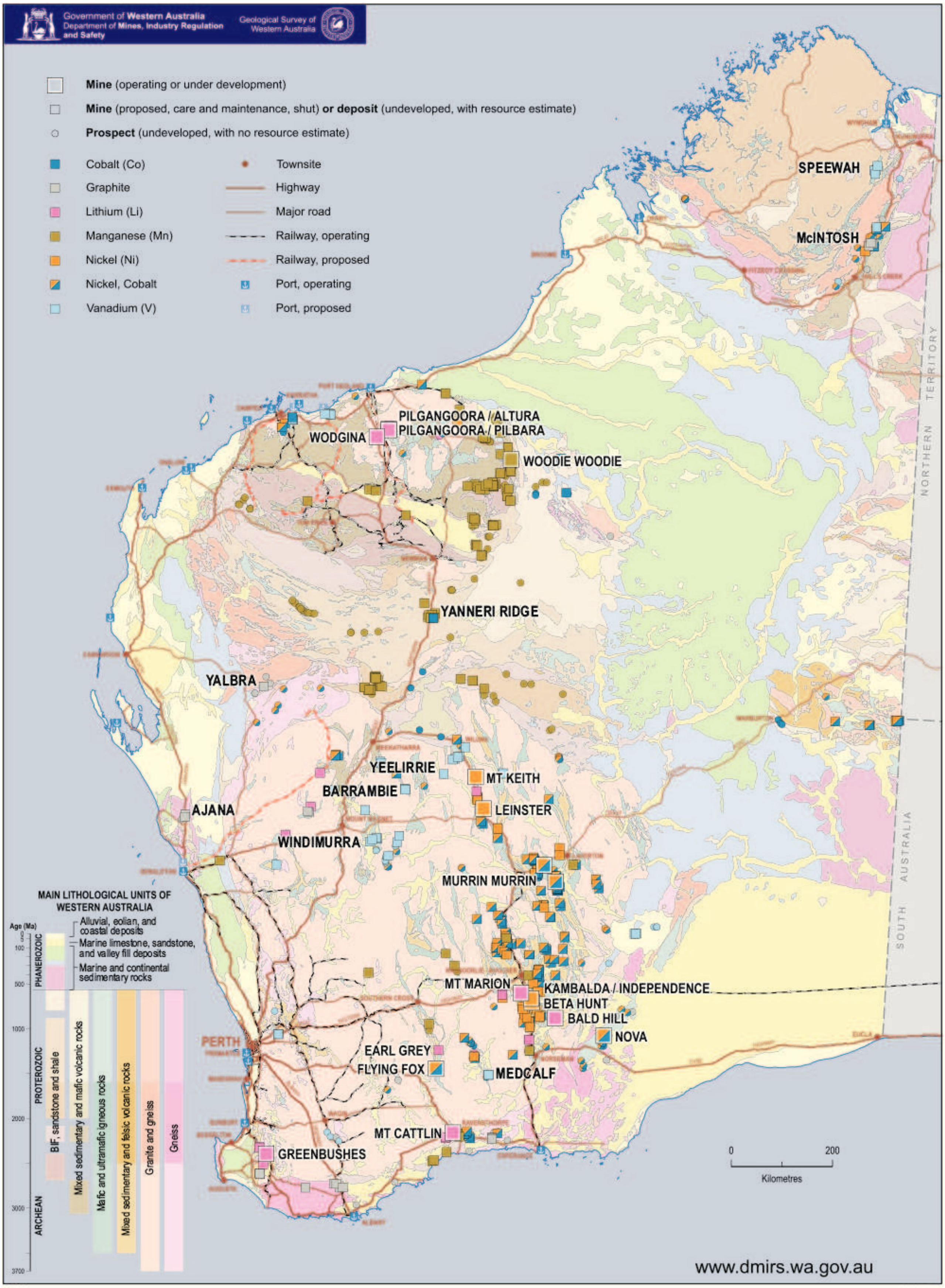


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Figure 3. **Significant Western Australian deposits and other occurrences of the six prominent 'battery metals': cobalt, graphite, lithium, manganese, nickel and vanadium**

Table 2. Western Australia's resource and production estimates and global ranking for six important 'battery metals'

Commodity	*Resources (kt)[(a)]*	*% of global resources[(b)]*	*Global resource ranking[(b)]*	*Production 2016 (kt)[(b)]*	*% of global production[(b)]*	*Global production ranking[(b)]*
Lithium (Li_2O)	11 572.1	11.4	4	14.3[(c)]	41	1
Graphite (TGC)[(d)]	1 931.0	negligible	–	0	0	–
Nickel (Ni)	34 945.8	26.9	1	206[(e)]	9.1	4
Cobalt (Co)	1 319.5	14.3	2	5.1	4.2	5
Manganese (Mn)	88 687.1	6.4[(f)]	4	0[(g)]	0	–
Vanadium (V_2O_5)	23 867.8	9.5[(h)]	4	0	0	–

NOTES:
(a) Total contained metal or oxide resources as at 31 December 2017. Source: DMIRS MINEDEX database <www.dmp.wa.gov.au/minedex>
(b) Estimates are based on resource and production figures from the USGS Mineral Commodity Summaries for 2016, unless otherwise indicated: Lithium – Jaskula (2017); Nickel – Schnebele (2017); Cobalt – Shedd (2017); Manganese – Corathers (2017); Vanadium – Polyak (2017)
(c) Western Australia accounted for all Australian lithium production in 2016 (Britt et al., 2016)
(d) TGC – Total graphitic carbon
(e) Nickel production and global percentage estimates are for Australia, but in 2016 Western Australia accounted for all of these
(f) Estimate is for 2015, determined using Western Australia resources from DMIRS MINEDEX database <www.dmp.wa.gov.au/minedex>, total Australia resources from Britt et al. (2016) and global estimates from Corathers (2016)
(g) Western Australia's only operating Mn mine at Woodie Woodie went into care and maintenance in January 2016, and recommenced mining in late 2017
(h) Australian V_2O_5 resources are predominantly in Western Australia, but the estimate by Polyak (2017) is likely to be significantly understated

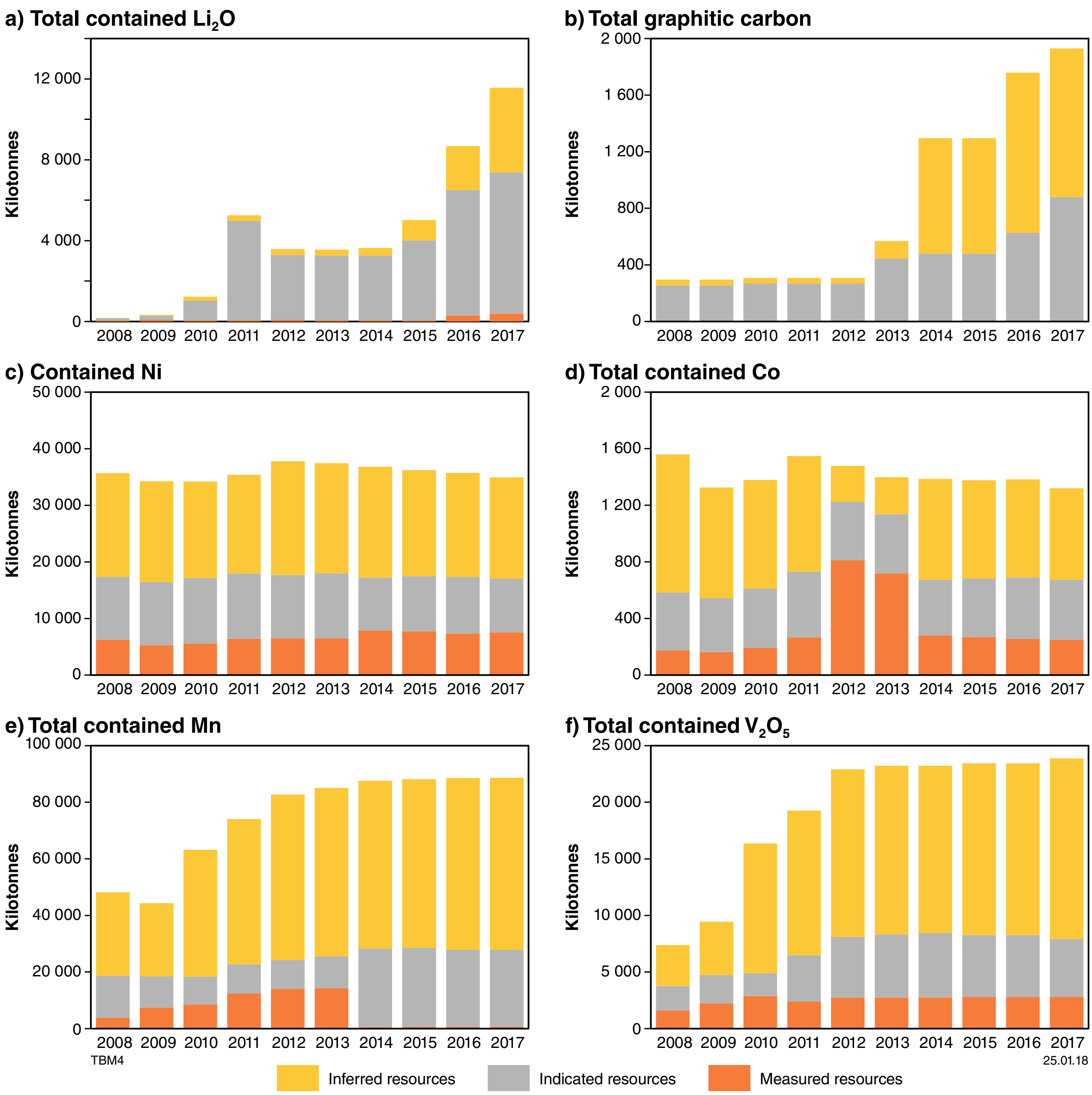

Figure 4. Cumulative total Western Australian resources by year for: a) lithium; b) total graphitic carbon; c) nickel; d) cobalt; e) manganese; f) vanadium (source: <www.dmp.wa.gov.au/minedex>)

Talison Lithium Pty Ltd will soon double spodumene production at Greenbushes (to ~800 ktpa), and several other projects are rapidly advancing towards mining at Pilgangoora (Pilbara Minerals; Altura Mining), Bald Hill (Tawana Resources NL/Alliance Mineral Assets Ltd), and Earl Grey (Kidman Resources Ltd/Sociedad Quimica y Minera de Chile SA).

Graphite is a significant component of many battery types (typically for the anode), but the raw material must be of high purity and appropriate grain size. Western Australia's more than 100 graphite occurrences are overwhelmingly in Archean to Mesoproterozoic graphitic schists or gneisses (metamorphosed carbonaceous sedimentary rocks), although sporadic hydrothermal vein- and pegmatite-hosted deposits are known (e.g. Ajana – Anson Resources Ltd; and near Katanning). Defined graphite resources of ~2 Mt (Fig. 4b; Table 2) are contained in four of Western Australia's 13 'active' graphite projects, all in graphitic schists and gneisses, but the state is not yet a graphite producer. The two most advanced projects are McIntosh, in the east Kimberley (Hexagon Resources Ltd), and Yalbra, in the Gascoyne (Buxton Resources Ltd/ Montezuma Mining Ltd). The state's graphite resources are negligible on the global scale, but can potentially yield high-purity, coarse (large and jumbo flake) graphite suitable for production of spherical graphite, and graphene, the new wonder material!

Nickel is found predominantly in sulfides in ultramafic (komatiitic) volcanic and mafic intrusive rocks, and in oxides in supergene-enriched laterites developed over originally sulfidic host rocks (Dill, 2010). Western Australia is well endowed with all these mineral deposit types, and has the world's largest nickel resources (~27% of the total, or ~35 Mt contained Ni in 87 deposits; Fig. 4c; Table 2). The state is currently Australia's only nickel producer, supplied from just eight mines while nickel prices are depressed (currently about US$13 000 per tonne, well down from about US$20 000/tonne in 2014; <www.kitcometals.com/charts/nickel_historical_large.html>, accessed 17 January 2018). Mining yielded ~206 kt of Ni in 2016, or 9.1% of the global total, ranking Western Australia fourth in the world (after Canada, the Philippines and Russia). Twenty-five other mines remain under care and maintenance, but many of these could reopen if nickel prices increase sufficiently.

Cobalt is a critical component in many battery designs, and perceptions of susceptibility to supply restriction have driven prices upwards — 47% in 2016, and a further ~57% in 2017 (to about US$51 000/t in March 2017). Cobalt principally occurs as a trace element associated with copper in mafic or ultramafic magmatic Ni–Cu deposits and stratabound, sediment-hosted Cu deposits (Dill, 2010). Known Co resources in Western Australia rank second globally after the Democratic Republic of the Congo (DRC), totalling ~1.32 Mt in Ni–Cu sulfide and Ni laterite ores in 37 mafic and ultramafic magmatic deposits (Fig. 4d; Table 2). All cobalt production to date from Western Australian operations has been as a byproduct in Ni sulfide and laterite ores (5140 t in 2016; <www.dmp.wa.gov.au/minedex>), representing 4.1% of global production (fourth globally after China, Canada and the Democratic Republic of the Congo). Cobalt grades rarely approach economic in their own right unless subsequently enriched by supergene processes. Despite this, interest has recently turned to defining standalone resources in Western Australia, although prospective deposits are mostly at prefeasibility stage.

Manganese deposits may originally be magmatic hydrothermal (volcanic exhalative, epithermal, skarn), structurally controlled hydrothermal, or marine sedimentary exhalative or clastic (including black shale-hosted, carbonate-hosted, and deep-marine nodules). All of these might also show subsequent (commonly economically necessary) supergene enrichment (Dill, 2010). Western Australia's significant known Mn deposits are conventionally considered to be supergene-enriched exhalative or clastic sedimentary deposits in marine shales, carbonates, and iron formations, although Jones (2011) suggested that supergene-enriched carbonate-hosted deposits in the Woodie Woodie camp may instead have a structurally controlled hydrothermal primary origin. Western Australia's Mn inventory is largely in the Pilbara–Capricorn region, and exceeds 88 Mt (Fig. 4e), the bulk contained in just 14 of the 39 defined resources. This represents ~6.4% of the global inventory, and is the fourth largest after Brazil, South Africa and the Ukraine (Table 2). Western Australia has been producing Mn for more than 50 years, almost exclusively for metallurgical use in the steel industry (its principal application), although the only presently active mine is at Woodie Woodie (Consolidated Minerals Pty Ltd), which recently reopened as Mn economics have improved. Global demand for Mn has doubled over the past decade (to ~20 Mt in 2017), driven in part by increasing demand for high-purity electrolytic Mn-dioxide for use in several high-capacity lithium-ion battery types used in grid storage, electric vehicles and medical devices. Some Western Australia-based companies are therefore evaluating their projects specifically as sources of electrolytic Mn-dioxide (e.g. Yanneri Ridge, Montezuma Mining Ltd).

Vanadium resources in Western Australia are currently ~24 Mt V_2O_5, the fourth highest globally (after China, Russia and South Africa), at ~9.5% of the total (Fig. 4f; Table 2). They occur predominantly in vanadiferous titanomagnetite in orthomagmatic mafic–ultramafic intrusions (e.g. Windimurra, Speewah, Barrambie). The Speewah deposit (King River Copper Ltd) in the east Kimberley region is Australia's largest titanomagnetite deposit, containing more than half of Western Australia's known resources, but total V_2O_5 production in this state since 2000 is just 14 100 t, and the only developed vanadium deposit — at Windimurra (Atlantic Ltd) — remains under care and maintenance. Vanadium resources in Western Australia are also known in lateritic regolith over pyroxenite (Medcalf, Audalia Resources Ltd), and associated with sandstone- and calcrete-hosted uranium (Yeelirrie, Cameco Australia Pty Ltd). Other possible vanadium resources include heavy mineral placers and hydrothermal base metal vein deposits, though none is yet known or defined in Western Australia.

Many other metals are also used in particular battery designs, such as aluminium, antimony, arsenic, barium, cadmium, calcium, copper, iron, lead, phosphorus, some rare earth elements, selenium, sodium, sulfur, tin, titanium and zinc. Western Australia has defined resources for many of these metals, and is already a significant supplier of several from particular deposit types (e.g. Al, Cu, Fe, Na, Pb, REE, S, Ti, Zn). Several of these also occur in deposits that cannot yet be developed economically (e.g. Ti in titanomagnetite in layered mafic intrusions; high-purity Al in kaolin clays), as do several of the less abundant battery metals (e.g. P in sedimentary phosphates; Sn in pegmatites), though some of these are already being exported as beneficial or deleterious byproducts in other ores (e.g. Se in Cu ores and coal; Cd in Zn ores).

Local processing of Western Australian battery metals?

All ‘battery metals’ presently exported from Western Australia are in raw mineral concentrates, for secondary processing and value-adding by third parties in foreign plants. However, many current and potential battery metal miners are working to develop in-house or co-invested processing of their product to maximize returns to shareholders.

Tianqi Lithium Australia PL (51% owner of Talison Lithium Pty Ltd and the Greenbushes mine) is constructing a lithium hydroxide processing plant (LHPP) at Kwinana, south of Perth, to process its share of spodumene concentrate from the Greenbushes mine (announced 5 November 2016). The LHPP will reputedly be the largest of its kind and produce the highest quality lithium hydroxide in the world. In November 2017, Greenbushes partner Albermarle Ltd proposed to build its own Li-hydroxide plant at Kemerton. BHP announced in August 2017 that it would build the world’s largest Ni-sulfate plant at Kwinana, to produce 100 000 tonnes of electrolytic nickel per year, and Northern Minerals will soon commission a pilot hydrometallurgical plant (at the mine site) to produce mixed rare earth carbonates from its Browns Range ores.

Lithium-focused companies such as Lepidico Ltd, Lithium Australia Ltd and NeoMetals Ltd are developing several novel, proprietary hydrometallurgical processes that promise to allow production of Li-carbonate, Li-hydroxide and Li-titanate from a wider variety of ‘hardrock’ Li-bearing silicate minerals. This will potentially make many other pegmatitic lithium deposits economically viable (the L-max, SiLeach and ‘LiOH acid-leach’ processes, respectively). Other companies are attempting to develop and commercialize alternative, more cost-effective hydrometallurgical and/or electrochemical processes to extract Co and Ni from lateritic deposits (e.g. atmospheric pressure HCl leaching – Ardea Resources Ltd), V, Ti and Fe from titanomagnetite ores (e.g. NEOMET process – NeoMetals Ltd), and high-purity alumina from kaolin (Altech Chemicals Ltd). Montezuma Mining has commissioned CSIRO to develop a process to produce electrolytic Mn-dioxide from the Butcherbird (Yanneri Ridge) Mn deposits. Given appropriate economics, some of these novel processing plants might be established in Western Australia, though it seems likely that many will be located interstate or offshore.

Western Australia — future battery powerhouse

Battery research and development are dynamic fields that have produced an enormous and continually expanding variety of chemistries and architectures that directly influence global demand for a considerable proportion of the periodic table. Such work also continually improves existing battery performances, potentially allowing previously less-competitive designs to challenge the pre-eminence of other battery types (e.g. Black, 2017, following Wei et al., 2017). Global environmental concerns and national interest priorities — such as the European Union’s METGROW+ initiative <http://metgrowplus.eu/> — are also influencing raw material resource economics by driving the development of technologies to profitably extract all potentially valuable or otherwise ‘critical’ elements from low-grade mineralization, metallurgical waste (slags, slimes, etc.), and discarded manufactured items (‘e-waste’).

Western Australia’s high-ranking status as a resource investment destination (Jackson and Green, 2017) and expansive resource inventory will probably ensure this State’s position as a supplier of raw materials to the battery manufacturing industry into the future, regardless of technological and economic developments. With appropriate market conditions, government policies and infrastructure development, the State could also reap significant extra economic benefits from further expansion of the domestic downstream battery material processing and manufacturing sector.

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