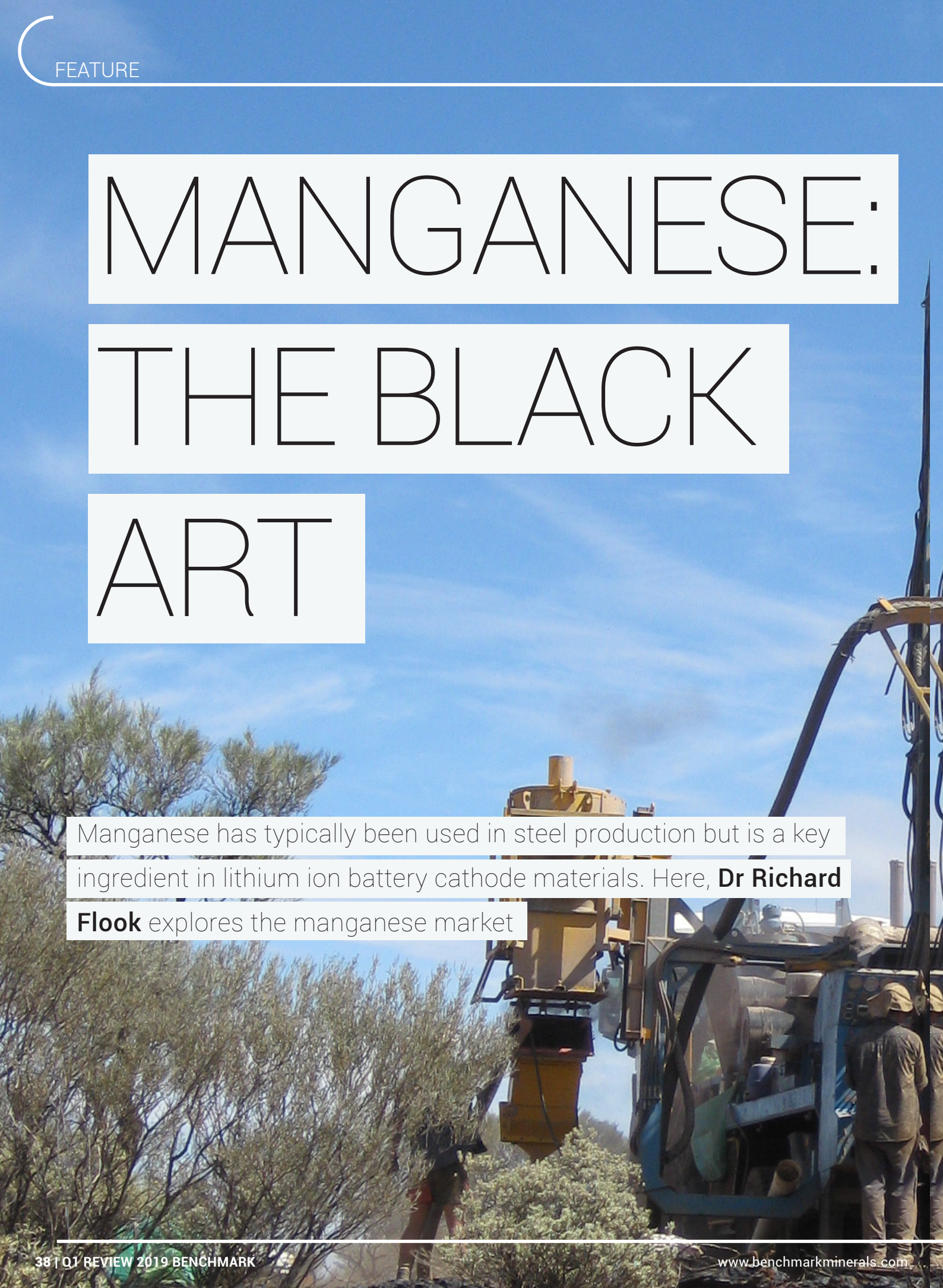
MANGANESE: THE BLACK ART



Manganese has typically been used in steel production but is a key ingredient in lithium ion battery cathode materials. Here, **Dr Richard Flook** explores the manganese market

Manganese received its name from the Latin word "magnes" meaning "magnet", or "magnesia nigri" meaning "black magnesia" which referred to pyrolusite (MnO_2). With common oxidation states ranging from +7 to +2, manganese is a versatile element with fascinating chemistry.

Although mostly used and essential in steel production, manganese has become an important element in both alkaline and more recently in lithium ion batteries (LIBs). The majority of processed manganese products needed for LIBs are currently produced in China.

Reduced manganese ore production in China is changing the overall supply and demand balance and is now creating opportunities for production of LIB grade manganese products outside China.

Credit: Element 25

Outcrop of manganese in Western Australia

Global resources

Manganese is the 12th most abundant element in the Earth's crust and it is considered to be a relatively abundant metal. Global manganese resources (expressed as manganese) are estimated to be over 17 billion tonnes not including large but largely unquantified seabed resources.

World economically recoverable reserves of manganese are estimated by the USGS to be about 680 million tonnes, and annual global production is about 16 million tonnes. However, despite the very large resources and reserves, the industry is very concentrated with four countries (South Africa, China Brazil and Australia) accounting for about 70% of both production and reserves (Table 1). In addition, South Africa accounts for 78% and Ukraine accounts for about 10% of manganese resources.

The International Manganese Institute (IMnI) estimated manganese production in 2017 to be significantly higher at about 18.6 million tonnes (Table 2, Figures 1 & 2). This was an increase of 23% from 2016 (or 3.4 million tonnes), driven by lower output in China combined with rising demand especially from China. China's manganese ore imports were 21.3 million wet tonnes in 2017, an increase of 25%. This trend is expected to continue due to declining ore grades and increased environmental regulations which are increasing extraction costs in China.

Manganese ores can contain up to 50% manganese but most commercially viable deposits contain about 35% manganese and sometimes as low as 15% manganese.

TABLE 1: WORLD MANGANESE PRODUCTION AND RESERVES (2017, USGS)

Manganese content	Production 2017		Reserves	
	Million tonnes	% of total	Million tonnes	% of total
South Africa	5.3	33%	200	29%
China	2.5	16%	48	7%
Australia	2.2	14%	94	14%
Gabon	1.6	10%	20	3%
Brazil	1.2	8%	120	18%
India	0.79	5%	34	5%
Ghana	0.55	3%	13	2%
Other	1.86	12%	151	22%
Total	**16.0**		**680**	

Source: USGS

Gabon, Australia and Brazil generally mine the highest grade ore (>43% manganese) and China and Ghana generally mine the lowest grades (15-20% manganese). The IMnI have estimated that global production is approximately equally split between high-grade ore (>44% manganese), mid-grade ore (30 – 44% manganese) and low-grade ore (<30% manganese).

The most common manganese ore minerals are oxides such as pyrolusite and carbonates such as rhodochrosite. Manganese silicates such as braunite are the major ore in the Kalahari district in South Africa; in Groote Eylandt, Australia; and in several districts in India (USGS).

The world's largest producer of manganese ore - with mines in both Australia and South Africa - and operator of the world's largest manganese mine at Groote Eylandt in Australia, is South32, formerly part of BHP Billiton. The company reported increased sales and prices and an EBITDA margin of 58% in 2018. Anglo American has 40% equity in the manganese operations.

The world's second largest manganese producer, Eramet operates the Moanda mine in Gabon. Eramet are also aspiring to develop a lithium deposit in Argentina and become a supplier of a range of battery raw materials including lithium carbonate, nickel salts, cobalt and manganese as well as evaluating opportunities in battery recycling. Eramet had previously sold Erachem, its manganese chemicals business, to the parent company of Prince International Corporation in December 2016.

Citic Dameng has manganese mining and ore processing operations in China and Gabon and downstream processing operations in China comprising hydrometallurgical processing and pyrometallurgical processing to produce electrolytic manganese metal (EMM), manganese briquette, electrolytic manganese dioxide (EMD), manganese sulphate monohydrate (MSM), silicomanganese alloys and lithium manganese oxide (LMO).

TABLE 2: WORLD MANGANESE PRODUCTION (2017, IMNI)

Manganese content	Production 2017	
	Million tonnes	% of total
South Africa	6.7	36%
Australia	2.8	15%
Gabon	2.2	12%
China	1.7	9%
Brazil	1.1	6%
India	0.75	4%
Ghana	0.75	4%
Other	2.61	14%
Total	**18.6**	

Source: IMnI

> Reduced manganese ore production in China is changing the overall supply and demand balance and is now creating opportunities for production of lithium ion battery grade manganese products outside China

Other major manganese ore producers are Assmang (South Africa), African Rainbow Minerals (South Africa), Consmin (Australia and Ghana), Jupiter Mines (South Africa), MOIL (India) and Vale (Brazil).

IMnI estimate that new projects and mine expansions would add about another 6.7 million wet tonnes pa capacity of manganese ore by 2020.

Manganese markets

About 88% of manganese ore is used to produce alloys (ferromanganese and silicomanganese) for integrated or mini-mill steel production (79%) or in foundry and welding (9%). About 9% of ore is used to produce EMM. The remaining 3% of manganese ore (about 0.5 million tonnes manganese) is mainly used to produce EMD

TABLE 3: ESTIMATED GLOBAL EMD PRODUCTION AND APPLICATIONS 2017

EMD production 2017 (tonnes)	China	Rest of world	Total	% change 2016
LMO grade	40,076	2,000	42,076	+47%
Alkaline & other battery grade	143,073	125,000	268,073	+3%
Carbon-zinc grade	85,810	2,000	87,810	-7%
Total production	268,959	129,000	397,959	+4%
Total Capacity	**328,700**	**149,000**	**477,700**	
Capacity utilisation ratio (%)	**82%**	**87%**	**83%**	

Source: IMnI

and chemicals, particularly manganese sulphate monohydrate (MSM) which in turn is commonly used as a fertiliser and as a precursor for manganese in lithium ion batteries. The distinction is that fertiliser grades of MSM have specifications based on limiting toxicity whereas battery grades of MSM have specifications based on limiting battery active impurities.

IMnI estimated that about 1.75 million tonnes of EMM was produced in 2017, predominantly (97%) in China. The world's largest producer is Ningxia Tianyuan Manganese Industry with capacity to produce 0.8 million tonnes of EMM.

IMnI also estimated that about 0.4 million tonnes of EMD was produced in 2017 of which about 40,000 tonnes was LMO battery grade and 268,000 tonnes was alkaline and other battery grade EMD (Table 3). China was again the major producer with 68% of global EMD production.

Tosoh produces EMD in Hyuga, Japan (Tosoh Hyuga Corporation) and Thessaloniki, Greece (Tosoh Hellas A.I.C.). Tosoh LMO grades of EMD specify 60.5% manganese which is equivalent to 95.7% MnO2 and three fine particle sizes (Table 4). Tosoh's EMD for alkaline dry batteries has lower purity (min 91% MnO2) and coarser particle sizing (80% less than 74 microns or 80% below 44 microns).

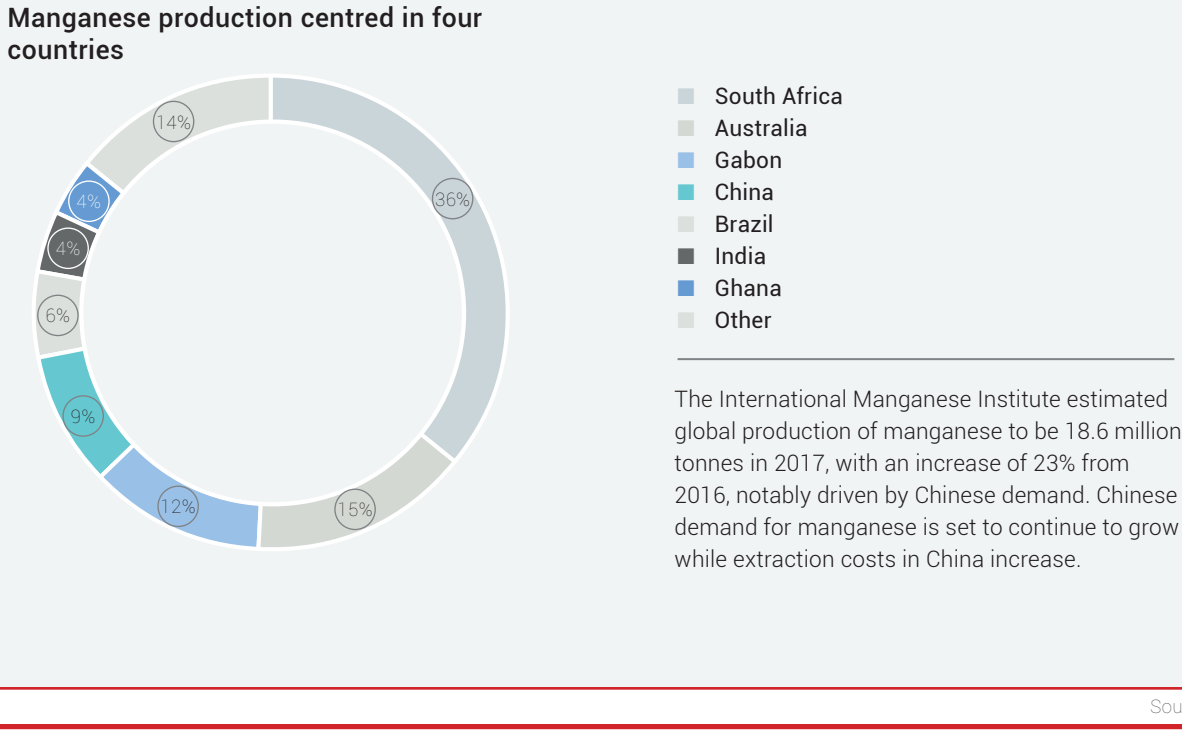
As well as operating the largest manganese mine in China, Citic Dameng is a globally significant producer of downstream products. In 2017, the company sold 141 kt pa of EMM, 27ktpa of EMD and 27kt pa of MSM as well as 92kt pa of other manganese based products. Citic Dameng recently issued a profit forecast upgrade partly due to the increasing significance of battery materials. In the first half of 2018, the proportion of downstream processing revenue from battery materials had increased from 10% to 17% and the proportion of gross profit from battery materials had increased from 10% of total

TABLE 4: TOSOH EMD LMO BATTERY GRADES

Grade	LM05	LM10	LM25
Particle	5µ	10µ	25µ
D10 (µm)	2.1	3.1	9.0
D50 (µm)	5.1	9.7	24.0
D90 (µm)	8.4	21.2	42.4
Mn (%)	60.5	60.5	60.5
S (ppm)	3,600	3,400	3,500
Na (ppm)	170	160	200
Fe (ppm)	34	35	37
Cu (ppm)	<1	<1	<1
Zn (ppm)	<1	<1	<1
Pb (ppm)	<1	<1	<1

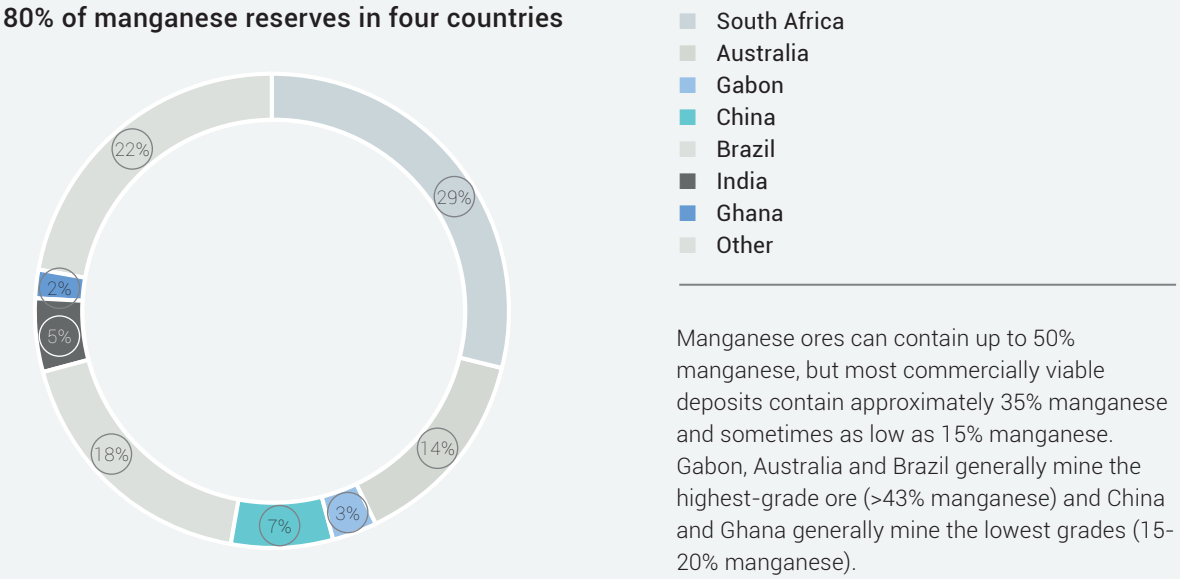
Source: Tosoh EMD LMO Battery Grades

FIGURE 1: WORLD MANGANESE PRODUCTION 18.6M TONNES 2017



Source: IMnI

FIGURE 2: WORLD MANGANESE RESERVES 680M TONNES 2017



Manganese ores can contain up to 50% manganese, but most commercially viable deposits contain approximately 35% manganese and sometimes as low as 15% manganese. Gabon, Australia and Brazil generally mine the highest-grade ore (>43% manganese) and China and Ghana generally mine the lowest grades (15-20% manganese).

Source: USGS

1

2

3

Manganese metal flakes and ore

Credit: Element 25

downstream processing gross profit in 2017 to 24% in 2018. Citic Dameng's MSM grade properties are given in Table 5 together with battery grade MSM from ISKY.

Business developments

In the past decade there have been a number of attempts to enter the downstream manganese processing market. In 2010 for example, Galaxy Ventures conducted a pre-feasibility study into establishing a plant with capacity of producing 40,000 tonnes pa of battery grade EMD using up to 70,000 tonnes pa of manganese ore from Consmin. The capital cost was estimated to be A$97M and despite an impressive IRR of 58% the project did not proceed.

Also in the past decade there have been significant changes in existing manganese processing facilities.

In 2014, Delta EMD, a specialist EMD producer, with plants in South Africa closed and sold its assets due to overcapacity and low prices in the EMD market, particularly for product from China. The company had closed its Australian EMD plant in 2007.

In 2016, Eramet sold Erachem the world's leading manganese chemicals business which had sales of US187M in 2015 and bases in USA, Mexico, China and Belgium for approximately US193 million. This sale was part of a business rationalisation following low manganese prices and Eramet have indicated that they may re-enter the market possibly through battery recycling.

In 2018, Tronox sold its Electrolytic Division which produces EMD, LMO and boron chemicals in Nevada, USA to EMD Acquisition LLC for $6 million in and recorded a pre-tax loss on the sale of $31 million. Again, this sale was part of a business rationalisation following merger initiation with its titanium

dioxide competitor Cristal.

However, more recently there has been renewed interest in downstream manganese processing based on the anticipated growth of manganese in lithium ion batteries.

Element 25 is proceeding to a pre-feasibility Study (PFS), due for completion in 2019, evaluating production of high purity manganese sulphate (HPMS) for lithium ion batteries and high purity electrolytic manganese metal (HPEMM).

The company claims that their hydrometallurgical leach processing and purification process which was developed with the CSIRO is the key factor in utilising manganese ore from their Butcherbird manganese ore deposit in Western Australia. Recent laboratory tests have produced 99.95% EMM (Table 6).

Justin Brown, Executive Director of Element 25, outlined the following project comparisons:

"We have a very large resource, currently over 180Mt and with the current base case of 100kt pa EMM we would have a mine life in excess of 100 years. The geology is simple and unique. The orebody outcrops, with a life of mine strip ratio of 0.2:1 meaning our manganese units are very low cost.

"We have excellent infrastructure, with a bitumen highway and gas pipeline going straight through the project. The availability of gas coupled with cheap renewable energy will provide a very competitive cost of power.

"We use a wet scrubbing process to upgrade the ore from around 12% to around 28% manganese which is the feed for the leach circuit. Our process extracts 95% of the manganese in around 30 minutes at ambient temperature and at atmospheric pressure.

"The reaction happens efficiently from 75micron right up to around 4-6mm particle size. Most of our competitors have to fine grind and either roast the ore or use a sulphuric acid leach with leach times of between 6 and 24 hours.

"The compound effect of these competitive advantages means that we expect to have a very long life project with a sustainable production cost at the lower end of the bottom quartile and likely the lowest globally."

Euro Manganese's Chvaletice project in the Czech Republic aims to recycle 27 million tonnes of tailings material over 25 years to

TABLE 5: CITIC DAMENG AND ISKY MSM GRADES

Grade	Citic Dameng MSM	ISKY Battery Grade MSM
MnSO4.H20	>98%	>98%
Mn (%)	>31.8	>31.8%
Fe (ppm)	<4	<10
Cl (ppm)	<4	
As(ppm)	<0.5	<10
Cd(ppm)	<0.5	<10
Pb (ppm)	<0.5	<10
Hg(ppm)	<0.05	
Insolubles (%)	<0.05	
pH	5.0-8.0	
Ca, Mg, Na (ppm)		<50
Zn, Cu (ppm)		<10

Source: Citic Dameng & ISKY

TABLE 6: ELEMENT 25 EMM LABORATORY GRADE

Grade	Element 25 EMM Average
Mn (%)	99.95
Si (ppm)	275
Se (ppm)	51
S (ppm)	46
Cr (ppm)	28
K (ppm)	24
Mg (ppm)	19
All other (ppm)	43

Source: Element 25 Announcement 12 February 2019

Credit: Element 25

Manganese taken from Element 25's Butcherbird project

TABLE 7: HIGH VALUE MANGANESE MARKETS 2018-27 (ELEMENT 25, 2018)

Million tonnes	Market estimate 2018		Market forecast 2027 %		CAGR 2018-27	
	Product	Manganese	Product	Manganese	Product & Manganese	
EMM	1.7	1.7	2.1	2.1	2.4%	
EMD	0.4	0.25	0.6	0.38	4.6%	
MSM	0.4	0.13	0.7	0.23	6.4%	
Total	**2.5**	**2.08**	**3.4**	**2.70**	**3.5%**	**3.0%**

Source: Adapted from Element 25 Scoping Study May 2018

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produce 1.19 million tonnes of HPEMM, which is anticipated to be sold as 404,100 tonnes of HPEMM and 2.35 million tonnes of high purity manganese sulphate (HPMSM).

Project economics are based on projected average HPEMM (>99.9% Mn) price of $4,617/tonne and HPMSM (>32% Mn) price of $2,666/tonne over the 25 year project life. Capital requirements were estimated to be $404M initial capital, $25M annual sustaining capital and $31M working capital.

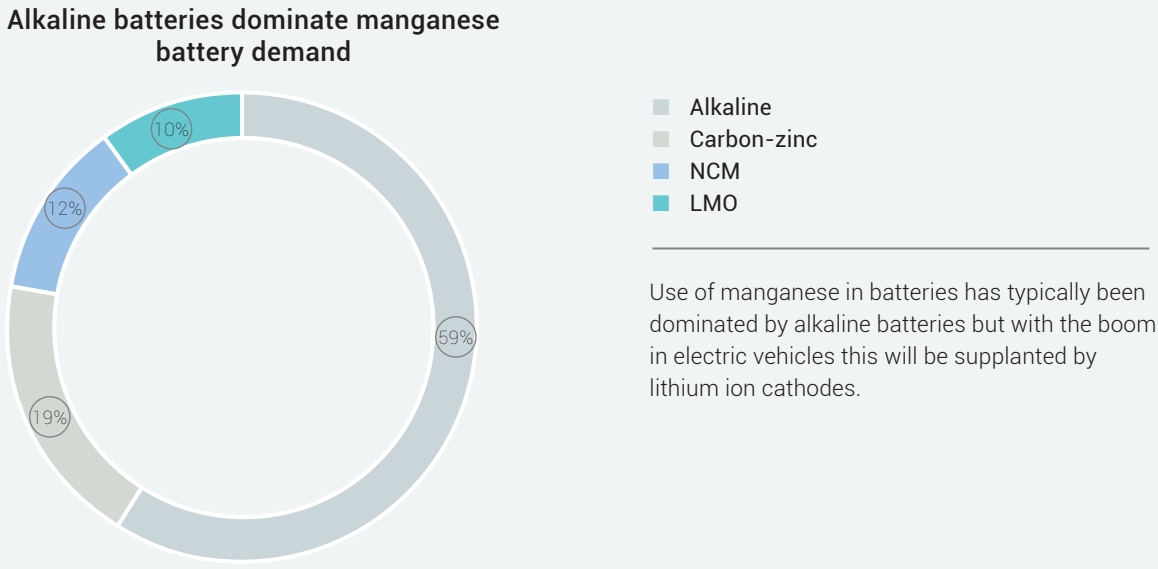
The company's next step is to build a demonstration plant in 2019 and produce products for commercial evaluation.

QMB New Energy Materials is a joint venture of battery recycling company GEM, Tsingshan Industries, Brunp Recycling (part of CATL) and Hanwa will invest $700 million to build a hydrometallurgical base in Indonesia. Capacity will be not less than 50,000 tonnes of nickel metal and 4,000 tonnes of cobalt metal, with an output of 50,000 tonnes of nickel hydroxide intermediate, 150,000 tonnes of battery-grade nickel sulphate, 20,000 tonnes of battery-grade cobalt sulphate and 30,000 tonnes of battery-grade manganese sulphate.

Credit: Element 25

Drilling at Element 25's Butcherbird Manganese project

FIGURE 3: MANGANESE DEMAND FROM BATTERIES 2017



Source: IMnI & R Flook estimates

Pilbara Metals Group are aiming to establish a processing plant in Perth in Western Australia to produce up to 20,000 tonnes pa of HPMSM from manganese ore sourced from third parties in Western Australia. An additional 20,000 tonnes pa of lower grade MSM is also planned for agricultural applications to replace current imports (about 30,000 tonne pa).

Bryah Resources is exploring for manganese in the highly prospective Bryah Basin in Western Australia where mining of high grade ore (>40%Mn) has previously occurred. Tenements cover 720 km2 over the western half of the basin.

American Manganese have adapted their hydrometallurgical technology originally developed to extract manganese from low quality (2-3% Mn) ores to recycle cathode materials in lithium ion batteries. The company initially intends to build a 1,100 tonnes pa capacity commercial plant.

Manganese in batteries

It is estimated that about 250,000 tonnes of manganese was used in all types of batteries in 2017 and about 22% was used in lithium ion batteries (Figure 3).

The amount of manganese in individual lithium ion batteries can vary significantly depending on the cathode chemistry (Figure 4).

LMO batteries which use γ-EMD and which currently contain the highest level of manganese are losing market share. NCM batteries which require HPMSM (or HPEMM to produce HPMSM) are gaining market share and are expected to increase their market share from about 50% in 2018 to about 75% in 2028. Unfortunately, the trend to lower cobalt levels in cathode formulations is favouring a move to NCM batteries also with lower manganese levels.

However the long term picture may be more promising for manganese. The uptake of NCM 811 may not be as rapid as initially thought. In addition, BASF are reported to be developing a cathode chemistry with 70%

TABLE 8: BATTERY CATHODE METALS FORECAST (ERAMET 2018)

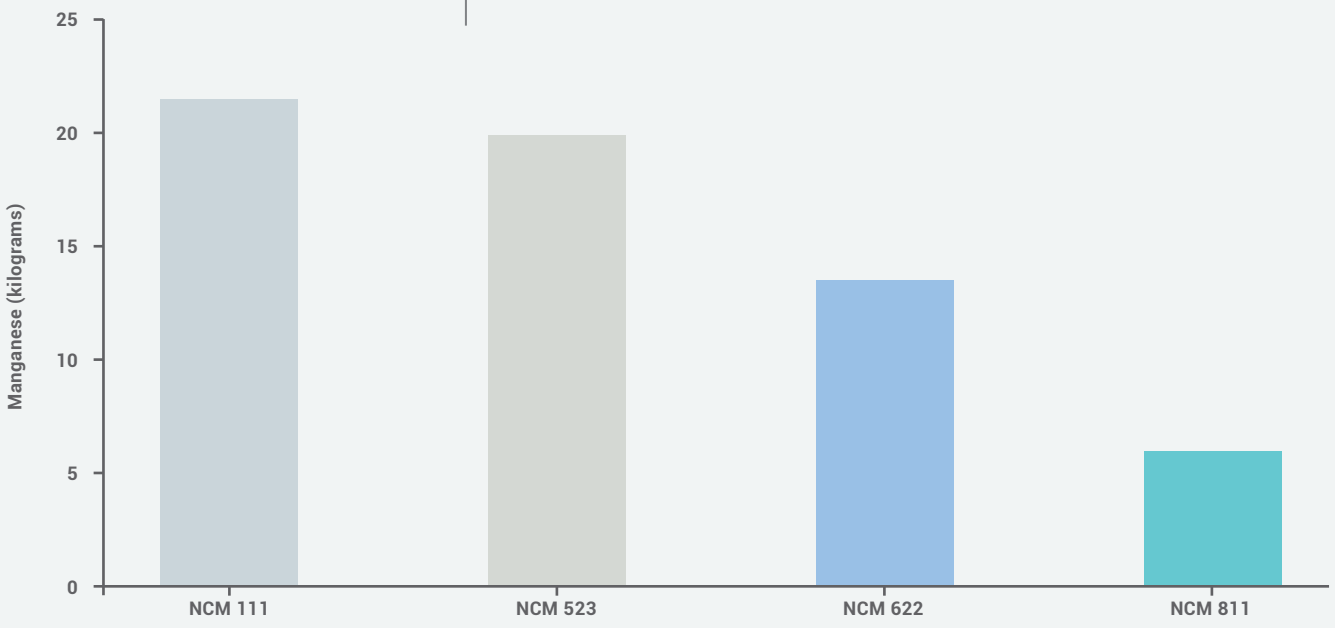
Annual consumption (kt) & Growth (%)	All markets	Battery market (EV & storage)		
	2018	2018	2025	CAGR (%)
Manganese	15,000	<10	100	>39%
Lithium	215	55	350	30%
Nickel in salts	120	50	310	30%
Cobalt	110	20	90	24%
Electric Vehicles (M)	100	3	>25	>35%

Source: Eramet Investor Presentation September 2018

FIGURE 4: BATTERY GRADE MANGANESE IN AVERAGE LITHIUM ION BATTERY PACK IN KILOGRAMS

Estimated battery grade manganese in average battery pack

The volume of each raw material in a battery pack differs depending on the chemistry of the cathode. The current trend is to move to higher nickel cathodes, at the expense of cobalt and manganese. This chart illustrates how battery grade manganese volume in lithium ion batteries is dependent on the cathode used.



Source: Benchmark Mineral Intelligence

manganese, 20% nickel and less than 5% cobalt, possibly for production in 2021.

At the same time research on manganese in batteries is continuing. For example, studies of lithium–sulphur batteries with manganese dioxide nano-sheets in a 25wt% manganese/sulphur cathode have shown that the batteries should be capable of energy storage several times greater than conventional lithium-ion batteries and with a reduced cost.

In their 2018 scoping study, Element 25 considered three high value manganese products, HPEMM, HPEMD and HPMSM and forecast a combined global market growth from 2.1 million tonnes in 2018 to over 2.7 million tonnes (manganese equivalent) in 2027. Highest growth was expected to come from the HPMSM market with a forecast CAGR of 6.4% (Table 7).

Euro Manganese have indicated that the market for manganese in lithium ion batteries could reach 200,000 tonnes in 2025, 500,000 tonnes in 2030 and 1 million tonnes in 2040 (Euro Manganese Corporate Presentation January 30, 2019).

On the other hand, Eramet recently estimated that less than 10,000 tonnes of manganese was used in EV and storage battery markets in 2018 but that this market will grow at a CAGR of greater than 39% to about 100,000 tonnes by 2025 (Table 8).

While all these projections are for a rising market for manganese in batteries, without access to detailed background and assumptions it is difficult to compare the apparently disparate projections.

This may be simply an example of "it is difficult to predict, especially the future" (to quote Niels Bohr and others), but it is also a consequence of the dynamic state of the growing and evolving global battery industry.

ABOUT THE AUTHOR

Dr Richard Flook has worked for both suppliers and consumers of minerals with global companies including, Steetley plc, Anglo American, Commercial Minerals (now Sibelco), Normandy Mining Ltd, Omya AG and Shinagawa Refractories.

Richard has been CEO, Managing Director & Director of Asian and Australasian companies. He has specialised in new business opportunities including strategic planning, trading, market development and acquisitions in the industrial minerals industry and has been involved in managing and developing mineral operations and businesses in Asia and Australasia.

Richard is a Fellow of the Australasian Institute of Mining & Metallurgy (FAusIMM (CP)) and the Australian Institute of Company Directors (FAICD). Richard is a graduate of Sydney University (BSc First Class Honours, PhD) and the University of NSW (Master of Commerce). Since 2014, Richard has been the Managing Director of Mosman Resources, a private consulting business, specialising in the production and marketing of industrial minerals and chemicals.