



The impact of junior miners on the global supply of high-purity manganese sulfate monohydrate for the electric vehicle battery market

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Abstract

The minerals sector continues to draw attention from policy makers who would want to see both old and new mineral projects add value to the minerals in the host country. The current technological development in the leaching of manganese oxide ores to produce a high-purity manganese sulphate monohydrate, a compound that is used in the manufacture of batteries for electric vehicles or long-life storage cells for the renewable energy market, has led to junior mining companies spearheading this technology in new projects across the globe. In this paper, we researched the high-purity manganese sulphate monohydrate project pipeline and used projected production volumes and C1 cash costs to construct the industry supply curve for six projects, including the K.Hill project owned by Giyani Metals Corporation near Kanye, in the southern part of Botswana. The aim was to determine the ideal conditions that would provide a comparative advantage for further local value addition to high-purity manganese sulphate monohydrate and to the end user product. The results showed that while the estimated C1 cash costs would place the K.Hill project as the second highest cost producer from among five projects, it would nonetheless have healthy profit margins due to the high projected price of high-purity manganese sulphate monohydrate. The study recommended policy options, which, if implemented, could further encourage the exploitation and value addition of battery metals in Botswana.

Keywords

high-purity manganese sulfate monohydrate, battery metals, industry supply curve, electric vehicle

Introduction

The global supply of manganese, as estimated by the US Geological Survey for 2021, was 20 million metric tonnes (Schnebele, 2022). A brief analysis of the US Geological Survey's mineral commodity summary for manganese demonstrates the following: approximately 80% of manganese production during 2021 was from four countries, being South Africa (37%), Gabon (18%), Australia (16.7%), and China (6.5%). In terms of the distribution of known reserves, approximately 61% of these reserves occur in Africa, with South Africa accounting for the largest share, estimated at 42.7%, followed by Gabon and Ghana at 4.1% and 0.9%, respectively. Other countries with estimated significant shares of global manganese reserves are Australia and China at 18% and 4%, respectively. The characterisation and classification of manganese ores is based mainly on the manganese content, iron, and other impurities. Metallurgical ore contains more than 35% Mn, ferruginous ores and manganese ores contain 15% – 25% Mn and 5% – 10% Mn, respectively. Another common classification for manganese ore is high (>44% Mn), medium (30% – 44% Mn), and low (<30% Mn) (Ratshomo, 2013; Indian Bureau of Mines, 2014a). It is estimated that 90% of the global supply of manganese ore is used in ferrous and non-ferrous metallurgical applications for production of steel and ferroalloys (Indian Bureau of Mines, 2014b). In the ferrous metallurgical applications, approximately 30% of manganese ores are used in the steel-making process itself as reactants in the de-oxidation and desulfurisation stages, with the remainder being used as ferroalloys in the steel product (Indian Bureau of Mines, 2014a). In steel making, the ferroalloys impart the requisite properties of strength and workability to the steel, a property for which no substitutes for manganese currently exist (Steenkamp et al., 2020). The non-ferrous metallurgical application is based on the production of high-purity electrolytic manganese metal (EMM) and electrolytic manganese dioxide. The former is used in the production of some alloys of non-ferrous metal like aluminium, copper, magnesium, and nickel (Van Zyl et al., 2016; Indian Bureau of Mines,

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2014b). The main grades of alloys are high-carbon ferromanganese (HCFeMn: 65% – 80% Mn), medium-carbon ferromanganese (MCFeMn) and silicomanganese (SiMn: 50% – 74% Mn). The HCFeMn and SiMn require high-grade ores with over 44% Mn and low-grade ores at 33% – 35% Mn, respectively (Indian Bureau of Mines, 2014b). The remaining 10% of the global supply of manganese ore is used in non-metallurgical applications such as dry cell batteries, the glass industry, and a wide range of applications in the chemical and health industries (Van Zyl et al., 2016, Indian Bureau of Mines, 2014b).

In Botswana, the historical mining of manganese at Kgwakgwe Hill, which is currently referred to as K.Hill by the project owners, Giyani Metals Corporation, started in the pre-independence period and lasted fifteen years (from 1957 to 1972). The mining was focused on both the metallurgical and high-grade manganese oxide ores. Over the fifteen years of operation, the K.Hill area exported about 195 743 t of manganese ores (SRK Consulting UK Limited, 2020). In a Press Release dated April 6, 2023, Giyani Metals Corporation indicated that it had submitted an Environmental Impact Assessment (EIA) statement to the Department of Environmental Affairs of Botswana. The press release further states that the EIA statement, if approved, would lead to the company being granted a mining license for up to 25 years (Giyani Metals Corporation, 2023). The prospect of developing the K.Hill deposit into a manganese mine has generated interest from policy makers, as the government of Botswana issued an expression of interest in 2022, inviting possible joint venture partners for its electric mobility (e-mobility) programme under which the country intends to set up a factory for the manufacturing of electric vehicles (EV) (Kuhudzai, 2022). The K.Hill project would produce a precursor product, a high-purity manganese sulphate monohydrate (HPMSM), for the manufacturing of batteries for the EV market. The project will further provide some assurance about security of supply of the HPMSM to future local manufacturers of batteries for EVs. The other metals required in the lithium-ion batteries are nickel and cobalt. The Botswana Institute for Technology Research and Innovation (BITRI) and Process Research ORTECH (PRO) in Canada would carry out a study, which, if successful, would result in the setting up of a 30 000 t/a plant that would produce high-grade nickel and cobalt salts. This plant would be used to produce raw materials required to facilitate the production of EV and large energy storage batteries in Botswana (BITRI, 2022).

In this paper, we review the literature on publicly available information regarding the capacity and estimated unit costs to produce HPMSM by new or planned projects. This information is then used to construct the HPMSM industry supply curve to determine the likely competitiveness of the proposed K.Hill project. A further search of the literature is carried out to determine the ideal conditions that would provide a comparative advantage for further local value addition of the HPMSM beyond the precursor compound, manganese sulfate, and to the end user product, the battery or long-life storage cell for the EVs, and renewable energy markets. We conclude by providing policy options, which, if adopted, would further encourage the exploitation of battery metals in Botswana.

Geology, deposit size and mine production capacity

In this section, the major manganese mines in the world's top three producer countries, i.e., South Africa, Australia, and Gabon, are compared to establish any similarities in ore types, size of resources, and manganese beneficiation processes as well as the end product at

the mine gate. Selected new manganese projects are also reviewed to determine if any influence exists on the extraction technology resulting from the expected growth in the future demand for manganese in the EV battery market.

In South Africa, manganese ore is mined from the Kalahari Manganese Field that is located in the Northern Cape. This field is a banded iron formation with inter-bedded units of manganese ore, and it contains over 90% of South Africa's manganese resources. Globally, this field represents approximately 80% of land-based global resources of manganese ore. The field is estimated to host 4.2 Bt of manganese ore resources (Beukes et al., 2016). The overburden cover is shallow on the eastern side of the field and therefore amenable to exploitation by open-pit methods, such as at the Mamatwan mine, while it is deep seated on the western side, up to 1400 m. The depths of underground workings are estimated at approximately 400 m at the Wessels and Nchwaning mines (Beukes et al., 2016). The Kalahari Manganese Field covers an area that is approximately 15 km by 35 km in the EW and NS directions, respectively. There are two major ore types present. The first is a low-grade primary sedimentary-type ore rich in carbonates, primarily calcites, and dolomite with braunite ($2\text{Mn}_2\text{O}_3\text{MnSiO}_3$; 64.3% Mn) as the main manganese-bearing mineral. The second ore type is a high grade, structurally-controlled hydrothermal ore comprised mostly of oxides, mainly braunite and braunite II ($\text{Ca}(\text{MnFe})_{14}\text{SO}_{24}$), some hausmannite (Mn_3O_4 ; 72% Mn), bixbyite ($(\text{Mn},\text{Fe})_2\text{O}_3$), and hematite (Fe_2O_3) which is found in the northern part of the deposit (Tsikos et al., 2003; Ratshomo, 2013).

Manganese ore production in Australia is mainly concentrated in the Groote Eylandt deposits, Gulf of Carpentaria in the Northern Territory, and in the Woodie Woodie mine, eastern Pilbara Craton in Western Australia (NSW Department of Primary Industries, nd). The geology of Groote Eylandt is described as Early to Middle Cretaceous Mullaman beds (sandstone, claystone, pebble gravel, and manganese marl), unconformably overlain by lateritic Tertiary conglomerate. At the Groote Eylandt mine, the mineralised zones average 3 m in thickness, approximately 150 km² in areal extent, and the overburden cover ranges from 3 m – 12 m. The Groote Eylandt deposit is thought to have formed as a shallow water marine sedimentary deposit on a Proterozoic basement with post-enrichment processes. Conversely, the Woodie Woodie mine ores are thought to have formed from both supergene enrichment of manganese-bearing sedimentary rocks and filling of cavities and fissures in dolomite and fault zones. The ores consist mainly of pyrolusite (MnO_2 ; 60% – 63% Mn), cryptomelane ($\text{KMn}_8\text{O}_{16}$; 59.8% Mn), and minor manganite ($\text{Mn}_2\text{O}_3\text{H}_2\text{O}$; 62.5% Mn), and trace amounts of other manganese minerals (NSW Department of Primary Industries, nd).

The production of manganese ores is also widespread in West Africa, with Gabon hosting the most significant resources outside South Africa. The manganese deposits in Gabon are supergene manganocretaceous that developed on relatively unmetamorphosed and undeformed manganese-bearing black carbonaceous shale of the Francevillan Supergroup that overlies the Archaean basement in the northwestern part of the Congo Craton. The deposits are large and shallow and therefore exploited by open pit mining. The manganese resource is estimated to be 325 Mt at 49% Mn in the washed product, with a regional potential in the order of 100 Mt – 200 Mt. The ore minerals in the Franceville area consists of cryptomelane and pyrolusite with some nsutite and lithiophorite set in a goethitic, clay, and quartz matrix (Beukes et al., 2016).

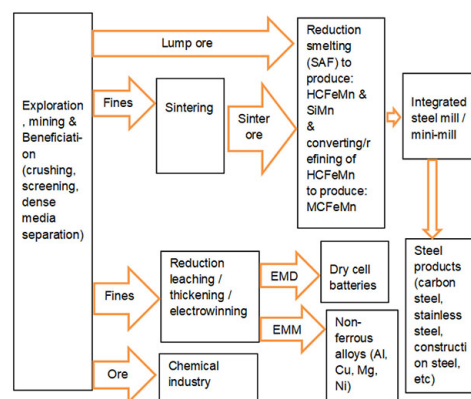
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The preceding three descriptions are examples of large-scale manganese deposits that are exploited by companies based in the world top three manganese ore-producing countries. Jupiter Mines, which is a 49.9% shareholder in the Tshipi é Ntle Manganese Mining Proprietary Limited (Tshipi) located in the Kalahari Manganese Field in the Northern Cape, RSA, is already a major manganese ore producer with target production of 3.6 Mt of manganese ore of which 600 kt is low grade (30% Mn). The low-grade ore would be supplied to a proposed HPMSM facility to be located in either Canada, USA, or Europe (Jupiter Mines Ltd, 2024). It joins a list of five other HPMSM projects at different project study stages, such as the Giyani Metals Corporation's K.Hill project in Botswana (Giyani Metals Corporation, 2022; Keating, 2023), Canadian Manganese's Woodstock manganese project in New Brunswick, Canada (Sprout Capital Partners Equity Research, 2022), Manganese X Energy Corporation's Battery Hill project near Woodstock, New Brunswick (Manganese X Energy Corp., 2022), Euro Manganese's Chvaletice Manganese project, Chvaletice, Czech Republic (Tetra Tech Canada Inc., 2022), and the Butcherbird project by Element 25 in Western Australia, of which the project will produce manganese concentrates to be sold under an off-take agreement to the company's HPMSM facility in Louisiana (Element 25 Limited, 2022). The common business objective of these projects is to produce HPMSM for the expected high demand in the EV battery market.

Manganese extraction technologies

One of the key factors influencing the choice of extraction

technology for manganese between pyrometallurgical approaches employing reduction smelting in either blast furnace or submerged arc electric smelting furnaces (SAF), or hydrometallurgy involving leaching followed by solvent extraction and electrowinning, is the size of the deposit. Table 1 indicates that, for the major manganese ore producers, there is very limited production of ferroalloys in their home countries apart from China, which is the world's leading producer of steel and manganese ferroalloys such as SiMn and HCFeMn. It is therefore apparent that the manganese value chain for large or world class deposits follows the pyrometallurgical route as depicted in Figure 1.



Source: Compiled by the authors based on (Steenkamp et al., 2018; Van Zyl, et al., 2016)

Figure 1—A simplified value chain for manganese for world class deposits

Table 1

Recent ore reserves or resources and production from selected major manganese ore producing countries

Mine, company and country	Resources / reserves	Ore processing method and capacity	Saleable product
Mamatwan, Hotazel Manganese Mines, Northern Cape, South 32 Limited, RSA. ¹	As of June 2022: Proven and probable-45Mt @ 36.2% Mn; Total resources-72 Mt @ 35% Mn; LoM as at Jan 2022-14 years.	Ore production in 2022 was 2.069 Mt. ¹	Washed lump ore, and Sinter for SAF smelting locally and for export.
Tshipi é Ntle Manganese Mining Pty Ltd (Tshipi), Jupiter Mines Ltd, Northern Cape, RSA. ²	As of February 2022: Measured – 129.21 Mt @33.85% Mn; Indicated – 70.15 Mt @ 33.28% manganese and inferred – 225.80 Mt @ 32.77% Mn. Total mineral resources – 425 Mt @ 33.18% Mn.	Ore production capacity is 3.6 Mtpa. In 2023, it was 3.34 Mt down from 3.68 Mt in 2022.	Washed lump ore and future HPMSM product for EV batteries.
Groote Eylandt Mining Company, South 32 Limited Northern Territory, Australia. ¹	As of June 2022: Proven and probable- 35 Mt @ 43% Mn and 4.8 Mt Sands @ 40% Mn; Total resources- 138 Mt @ 43% Mn and 9.0 Mt sands @ 19.5% Mn; LoM as at Jan 2022-3.9 years.	Ore production in 2022 was 3.363 Mt. ¹	Washed lump ore and fines all exported.
Moanda mine, ERAMET (Comilog), Gabon. ³	Company webpage attributes 25% of global reserves and grades at 30% Mn. ²	Estimated ore production is 4.0 Mt but it is projected to increase to 7.0 Mtpa. ²	Lump ore, sinter and ferroalloys (silico manganese) for the export market.

Source:

¹Compiled by the authors from (South32 Limited, 2022)

²Compiled by the authors from (Jupiter Mines Ltd, 2024; Jupiter Mines Ltd, 2023)

³Compiled by the authors from (Comilog, n.d.)

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The manganese project pipeline is presented in Table 2. It is apparent that these projects are at different stages of study, ranging from scoping studies or preliminary economic assessment to feasibility studies. The K.Hill project in Botswana is at the feasibility study stage but due to a recent fourfold increase in its Indicated Mineral Resources from 2.0 Mt to 8.6 Mt, the company is planning to conduct a preliminary economic assessment to consider this improvement in resources and possibly increasing the life of mine to beyond 25 years (Keating, 2023). The Butcherbird project, has completed a feasibility study to produce HPMSM from manganese

concentrates. For the five other projects, which consist of two projects in Canada, one each in the Czech Republic and Botswana, it will produce HPMSM. Lastly, the HPMSM project by Jupiter Mines Ltd is at the scoping study stage and its HPMSM facility may be located in either Canada, the US, or Europe.

The processing methods of the ore would depend on the ore type with direct leaching of ores or concentrates using dilute sulfuric acid applied in manganese carbonate ores while reduction leaching is applied in oxide ores (Manganese X Energy Corp, 2021; Tetra Tech Canada Inc, 2019). If the ores are manganese oxides,

Project, company and country	Manganese ore minerals	Resources / reserves	Ore processing method and capacity	% Recovery and saleable product
Battery Hill, Manganese X Energy Corp., Canada ¹	Manganese carbonate and manganese carbonate-silicate-oxide.	Measured – 11.26 Mt @6.75% Mn; Indicated – 23.60 Mt @ 6.26% Mn and Inferred – 25.91 Mt @6.66% Mn.	Direct leaching of RoM ore at 365kt per annum to produce 68 kt/a HPMSM in year 3 from project start date.	Recovery – 78%; HPMSM.
Butcherbird HPMSM project, Element 25, Australia ²	Manganiferous shale (Pyrolusite).	Measured – 16.0 Mt @11.6% Mn; Indicated – 41Mt @10% Mn, and Inferred – 206 Mt @ 9.8%.	1.3 Mtpa RoM beneficiated to produce lump ore fines concentrates; HPMSM future project based on concentration feed.	Lump ore, and In future HPMSM and HPEMM.
Chevaltice, Euro Manganese, Czech Republic ³	Tailings from old pyrite mines; 81% of ore is manganese carbonate and the rest manganese carbonate-silicates.	Indicated – 464 kt @7.85% Mn; Measured – 26.496 Mt @7.32% Mn.	Direct leaching of RoM ore at 1,1 Mtpa starting in year 4 from project start date to produce 120 -150 kt / year a HPMSM.	Recovery – 59.2% (Overall) HPEMM HPMSM.
K.Hill, Giyani Metals Corp., Botswana ⁴	Manganiferous shale, that occurs in layers 3–4 m thick and are high grade manganese oxides, Pyrolusite (MnO ₂)	Indicated Resource of 8.6 Mt ore at 15.2 MnO at a cut-off grade of 7.3% MnO. Inferred Resource of 6.1 Mt at 14.1% MnO.	Direct leaching of RoM ore at 200 kt per year starting in 2025 to produce 120 kt/ year of HPMSM.	Recovery – 88.5%; HPMSM.
Tshipi é Ntle Manganese Mining Pty Ltd (Tshipi), Jupiter Mines Ltd, Northern Cape, RSA ⁵	Low grade - primary sedimentary-type ore rich in carbonates High grade – oxides, mainly braunite and braunite II	As at February 2022: Measured – 129.21 Mt @33.85% Mn; Indicated – 70.15 Mt @ 33.28% Manganese and Inferred – 225.80 Mt @ 32.77% Mn. Total mineral resources – 425 Mt @ 33.18% Mn.	Low grade ore production of 600 kta. HPMSM plant located in either Canada, USA or Europe. Estimated HPMSM capacity is 80 – 120 kt/year in 2028.	HPMSM product for EV batteries.
Woodstock project, Canadian Manganese Company Inc., New Brunswick, Canada ⁶	Manganese carbonates, mainly Rhodochrosite.	Inferred – 44.8 Mt @9.9% Mn.	Initially 700tpd RoM and direct leaching of concentrate to produce 60kt/a of HPMSM. Potential for 150kt/a by 2040.	Recovery – 77.1%; HPMSM.

Source: Compiled by the authors from:

¹(Manganese X Energy Corp., 2022)

²(Element 25 Limited, 2022)

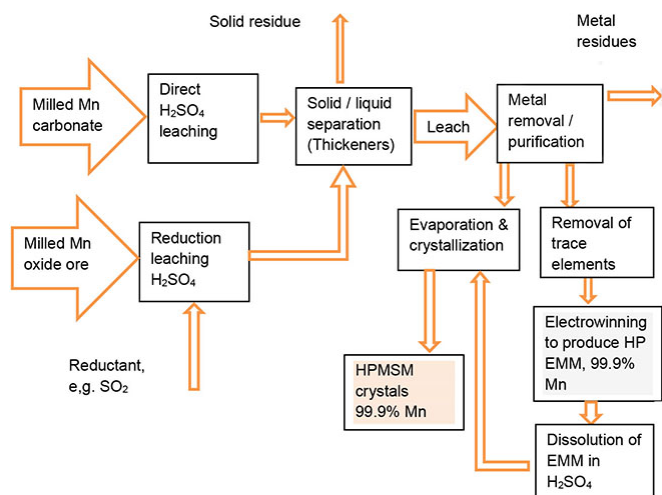
³(Tetra Tech Canada Inc., 2019)

⁴(Keating, 2023; Giyani Metals Corporation, 2022; SRK Consulting UK Limited, 2020)

⁵(Jupiter Mines Ltd, 2024; Jupiter Mines Ltd, 2023)

⁶(Sprott Capital Partners Equity Research, 2022)

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Source: Compiled by the authors based on (Giyani Metals Corporation, 2022; Manganese X Energy Corp, 2021; Sprott Capital Partners Equity Research, 2022)

Figure 2—A simplified block diagram for the production of HPMSM for EV batteries

studies have demonstrated that reduction leaching is possible using a variety of reductants such as sulfur dioxide, sucrose, ferrous sulphates, and many others (Giyani Metals Corporation, 2022; Kumar, Purcell, 2019). Another pathway that manganese producers are likely to adopt is to extend the EMM pathway by leaching this product, which is about 99.7% Mn, followed by evaporation and crystallisation to produce HPMSM at 99.9%Mn (Winjobi, Kelly, 2021). The Chevaltice process flow diagramme demonstrates this (Tetra Tech Canada Inc., 2022). Figure 2 depicts a block diagramme for the production of HPMSM from the direct leaching of manganese carbonate ores and reductive leaching of manganese oxide ores.

Structure of the EV market

At the global level, the EV market can be divided geographically into four major regions of Europe, China, US, and the rest of the world as depicted in Table 3, and in general, robust growth in the production of EVs is projected in all the four world regions. This may be attributed to a number of factors, which include meeting the consumer concerns on issues such as: driving distance, availability of charging points, price premium over the ICE vehicles,

Table 3
The EV markets and the top five selling brands

Region / auto maker ¹	EV market share of new car sales in 2021 (6.6 M EVs) ²	Projected growth in EV share of new car sales by specified date
Europe 1. BMW 2. VW 3. Renault 4. Tesla 5. Mercedes	2.3 million EVs 17% of new car sales	40% by 2030 ³
China 1. BYD 2. BJEV 3. Roewe 4. Tesla 5. Chery	3.3 million EVs 16% of new car sales	20% by 2025 ² 50% by 2025 ⁴
US 1. Tesla 2. Chevrolet 3. Nissan 4. Toyota 5. Ford	0.63 million EVs 4.5% of new car sales	14% by 2030 US states of California, New York and Massachusetts - 100% by 2035 ⁴
Rest of World 1. Nissan 2. Tesla 3. Mitsubishi 4. Toyota 5. Hyundai	4.5% of new car sales	100% by 2050 ⁴

Sources: Compiled by the authors from the following sources:

¹(Li, et al.,2021)

²(International Energy Agency, 2022)

³(Chege, 2021)

⁴(MacIntosh, et al., 2022)

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introduction of laws that penalise the continued use of ICE vehicles through emission taxes and prohibition of access to cities, and providing incentives for switching to EVs (Deloitte, n.d.). Fiscal incentives such as price subsidies and, to a lesser extent, recurrent fees paid by vehicle owners such as emissions taxes, coupled with a well-developed, accessible, and harmonised payment system and a high-quality charging network, are the main drivers that influence the uptake of EVs (MacIntosh et al., 2022; Vanpée et al., 2022). Disregarding the policy interventions, there is a general agreement among analysts that the cost of the battery pack for the EVs must reduce from USD121/kWh in 2021 to below USD100/kWh (MacIntosh et al., 2022).

The top five global auto maker's as indicated in Table 3 accounted for some 41% of global car sales in 2020 compared to the top five global battery makers who accounted for 83% of the sales in the same year. This reflects an oligopolistic market structure in EV trade, which may lead to higher battery prices. This situation may lead to the top five auto makers entering into joint ventures with battery makers to achieve a lower price for the EV batteries (Goldman Sachs Equity Research, 2022).

Supply outlook of HPMSM for the EV battery market

Global production of HPMSM is dominated by China, which in 2017 produced some 80 kt, representing 87% of global production, with the balance of about 12 kt or 13% attributed to a US company with production plants in both Mexico and Belgium (Tetra Tech Canada Inc., 2019). It was estimated that China was planning to increase its HPMSM capacity to 940 kt/a by 2022. An HPMSM plant with a capacity of some 30 kt/a came into production in Indonesia (Tetra Tech Canada Inc., 2019). The planned HPMSM projects are looking at the regional demand for HPMSM in their regions, for instance both the Woodstock and Battery Hill projects by Canadian Manganese Company Inc. and Manganese X Inc. are targeting mainly the North American EV battery market (Manganese X Energy Corp., 2022) while the Chevaltice project by Euro Manganese is targeting the European EV battery market (Tetra Tech Canada Inc., 2019). If all the six HPMSM projects in Table 2 are successfully developed and brought into production over the near term, then they would add approximately 530 kt HPMSM to the global market for HPMSM.

Demand outlook for HPMSM for the EV battery market

As approximately 90% of global manganese production is used in the steel industry, and given that there is no substitute for manganese in steel making, it justifies the assumption that the growth in global manganese consumption will follow that for steel. Global steel production is forecast to grow from some 1.8 Bt in 2022 to 2.3 Bt in 2030, which represents a compound annual growth rate of 3% over the period (Globenews Wire, 2023). The demand for EVs, and therefore EV batteries, is driven by commitments that member countries made at the UN Conference of the Parties, COP26, that was held in Glasgow in October 2021. The member countries agreed to timelines for adopting zero-emission vehicles (ZEV) with countries setting target dates over the period 2025 to 2050 but with the majority of signatories, which excluded developed countries with leading automobile makers such as the U.S., Germany, Japan, South Korea, and China, setting targets for the period 2025 to 2040 (MacIntosh et al., 2022). As part of this policy, there has been tremendous growth in EVs and this is forecast to continue at a compound annual growth rate of 30%, from a base of 21 million vehicles in 2022, excluding two and three wheelers, to 200 million vehicles by the year 2030 (International Energy

Agency, 2022). The exponential growth in EV demand is forecast to create a demand for lithium-ion batteries that will, in turn, lead to an exponential growth in demand for HPMSM. Some forecasts indicate that HPMSM demand will grow from 225 kt in 2022 to over 600 kt by 2030 (Sprott Capital Partners Equity Research, 2022).

Materials and methods

Production theory defines the industry supply or cost curve as a horizontal summation of the individual firm's supply curves. Direct cash production costs (C1) are defined to include royalties, costs of mining, processing, and site general and administration costs less any byproduct credits. The C1 cash costs for the six HPMSM projects are presented in Table 4. Half of these projects are at the scoping study stage, represented as Class 5, under the American Association of Cost Engineers (AACE) while the other half is at the feasibility study stage, represented as Class 3. The level of accuracy reported is for the particular study and not necessarily the generic class.

The six HPMSM projects are arranged in ascending order by their C1 cash costs expressed in USD/t of HPMSM produced, as shown in the last column of Table 5. A Microsoft Excel based algorithm, which enables the computation to transform the data into a form for plotting the cost curve for the six projects was then used (Tholana et al., 2013). The data for plotting the HPMSM supply curve are presented in Table 6.

Results and discussion

The HPMSM supply curve for the six projects is depicted in Figure 3, which can be used to analyse the competitiveness of these projects relative to one another. The supply curve ranks the Chevaltice Manganese Project as the highest cost producer with direct cash costs at USD2,319/t, followed by K.Hill at USD1,846/t and Butcherbird at USD1,188/t HPMSM produced. These three projects are at the Class 3 or feasibility study stage with an accuracy level in the range -15% to +20% as shown in Table 4. The other three projects were at the scoping study stage or Class 5 with their level of accuracy also shown in Table 4 being in the range of -30% to +50%. The lowest cost project would be Battery Hill at USD654/t followed by Woodstock at USD675/t and Jupiter Mines at USD1,020/t of HPMSM produced. When the different levels of accuracy of the cost estimates in Table 4 are taken into account, the ranking of these projects on the computed supply curve remains unchanged. All projects were modelled on different HPMSM price assumptions and they demonstrated positive margins and real net present values (NPV). For instance, the Battery Hill project's preliminary economic assessment assumed a long term price of USD2,900/t HPMSM while the K.Hill project used a long term price of USD2,993/t HPMSM in 2026 rising to USD3,918 in 2030 and remaining at that level to end of mine life in 2035 even though their sales are to the same markets in the US and Western Europe as would the Battery Hill project.

Apart from the K.Hill project, which would be mining and processing a manganese oxide ore, the other five projects presented in Table 4 are based on manganese carbonate ores. The oxide ore would require reduction leaching using dilute sulfuric acid with sulfur dioxide as a reductant, while the other five projects would apply direct leaching of the manganese carbonate ores using dilute sulfuric acid only. The high cost for the Chevaltice Manganese Project, at USD2,106/t HPMSM, sits at the high end of this curve. The high production costs for Chevaltice can be explained by the processing route in which the project first produces high-purity electrolytic manganese metal (HPEMM) followed by the production

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Table 4

C1 Cash costs and their level of accuracy

Project	C1 Cash costs (US\$/t HPMSM)	Class of estimate and Accuracy level	Range of C1 cash costs (US\$/t HPMSM)
Battery Hill ¹	654.45	Class 5: -30% – +40%	458.12–916.23
Butcherbird ²	1,188.00	Class 3: -10% – +15%	1,069.2–1,366.2
Woodstock ³	674.75	Class 5: -30% – +50%	472.33–1,021.13
Chevaltice ⁴	2,105.94	Class 3: -10% – +20%	1,895.35–2,527.13
Jupiter Mines ⁵	1,020	Class 5: -30% – +30%	714.00–1326.00
K.Hill ⁶	1,846.03	Class 3: -10% – +15%	1,661.43–2,122.93

Source: Cost data are compiled by the authors from the following sources:

¹Table 21-3 Total Operating costs over LOM, Technical Report on the Preliminary Economic Assessment of the Battery Hill Manganese Project Woodstock, New Brunswick, Canada (Manganese X Energy Corp., 2022)

²Feasibility study - battery grade high purity manganese processing facility (Element 25 Limited, 2023)

³(Sprott Capital Partners Equity Research, 2022)

⁴Table 21-3 LOM Average operating cost summary, Technical Report and Feasibility Study for the Chvaltice Manganese Project, Czech Republic (Tetra Tech Canada Inc., 2022)

⁵Operating costs, pp 7 (Jupiter Mines Ltd. 2024)

⁶Table 4 Summary of Project operating expenditure per tonne processed (Giyani Metals Corporation, 2022)

Table 5

Input data for computing C1 cash costs in USD/t milled

Project	HPMSM production (kt)	Roy (USD/t milled)	Mining (USD/t milled)	Processing (USD/t milled)	Tailings facility (USD/t milled)	G&A ^b (USD/t milled)	Total C1 Cash Costs (USD/t milled)	Total C1 Cash Costs (USD/t HPMSM)
Battery Hill ¹	68	0	23.03	116.81	5.35	7.68	152.87	654.45
Woodstock ²	60	na	na	na	na	na	159.51	674.75
Jupiter Mines ³	100							1,020.00
Butcherbird ⁴	130							1,188.00
K.Hill ⁵	73	2.00	20.00	636.40	2.00	13.40	673.80	1,846.03
Chevaltice ⁶	98.6 ^a	0.00	2.44	143.18	0.66	13.78	194.79	2,105.94

Notes:

^aOn average the Chevaltice project will produce 47.5 kt of HPEMM /year and 67% of this would be converted to HPMSM yielding 98.6 kt/a (Tetra Tech Canada Inc., 2022)

^bG&A – General and administrative costs

Source: Cost data are compiled by the authors from the following sources:

¹Table 21-3 Total Operating costs over LOM, Technical Report on the Preliminary Economic Assessment of the Battery Hill Manganese Project Woodstock, New Brunswick, Canada (Manganese X Energy Corp., 2022)

²Feasibility study - battery grade high purity manganese processing facility (Element 25 Limited, 2023)

³Operating costs, pp7 (Jupiter Mines Ltd. 2024);

⁴(Sprott Capital Partners Equity Research, 2022);

⁵Table 4 Summary of Project operating expenditure per tonne processed (Giyani Metals Corporation, 2022)

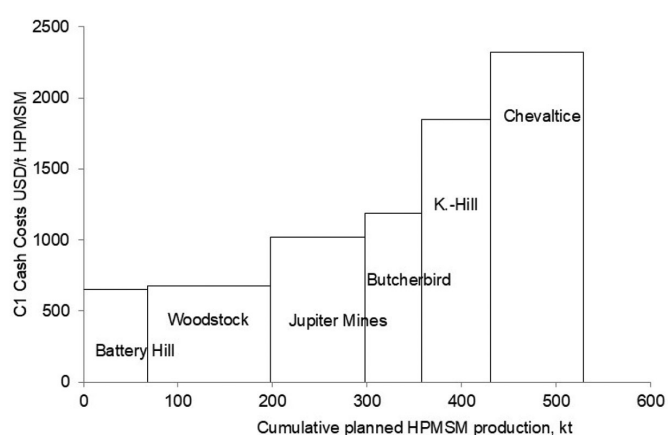
⁶Table 21-3 LOM Average operating cost summary, Technical Report and Feasibility Study for the Chvaltice Manganese Project, Czech Republic (Tetra Tech Canada Inc., 2022)

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Table 6
Data for plotting the HPMSM cost curve

	HPMSM Production (kt)	Cum. HPMSM production (kt)	Unit Cost (US\$/t HPMSM)	X-error (-)	Y-error (-)	Y-error (+)
Battery Hill	68	68	654.45	68.00	654.45	20.30
Woodstock	130	198	674.75	130.00	674.75	345.25
Jupiter Mines	100	298	1,020.00	100.00	1,020.00	168.00
Butcherbird	60	358	1,188.00	60.00	1,188.00	658.03
K.Hill	73	431	1,846.03	73.00	1,846.03	473.01
Chevaltice	98.6	529.6	2,319.04	98.60	2,319.04	-2,319.04

Source: HPMSM production data from sources cited for Table 5 while plotting data were computed by the authors applying the cost curve algorithm (Tholana et al., 2013)



Source: Compiled by the authors based on (Giyani Metals Corporation, 2022; Manganese X Energy Corp, 2021; Sprott Capital Partners Equity Research, 2022)

Figure 3—The HPMSM cost curve for the five selected projects

of HPMSM from the HPEMM. The costs of these processing stages are estimated to constitute 33% and 13%, respectively, of the on mine direct production costs (Tetra Tech Canada Inc., 2022). It is estimated that approximately two thirds of the HPEMM produced from the electrowinning stage is further dissolved followed by purification and crystallisation to produce the HPMSM product (Tetra Tech Canada Inc., 2022).

The processing costs per tonne of ore milled are presented in Table 5 and they demonstrate that the K.Hill project, at USD636/t of ore milled would be approximately four times greater than those for the Battery Hill project at USD153/t of ore milled. The high processing costs for K.Hill are attributed to international import freight cost of reagents, which are estimated at 36% of the total reagent costs for the project. As expected, for the mining stage, costs would be lowest for Chevaltice as it would be treating tailings and therefore would not require drilling and blasting for excavating the manganese ore.

Possible policy options for attracting EV and EV battery manufacturers

The government of Botswana has made its intentions known regarding its e-mobility programme and by taking action through an expression of interest for a joint venture partnership with the private sector in developing EVs (Kuhudzai, 2022). Of the base

metals that would be used as inputs in electric cars, the country currently produces only copper, but plans by a local subsidiary of Premium Nickel Resources Limited (PNRL) to revive the BCL Ltd mines, which would produce nickel, copper, and cobalt, would lead to a re-start of the mining operations by 2026 (Mguni, 2023).

The e-mobility programme aims to encourage the setting up of production facilities for EVs and EV batteries. Depending on the structure that would be adopted by EV investors, they may well choose to integrate and produce their own EV batteries. The question then is what policy options are there for supporting an integrated EV and EV battery maker.

Many researchers have studied the types of policies and incentives in the world's leading markets for EVs. These are categorised based on their aim, which may be to encourage diffusion or dissemination of products through support to the supply and demand sides of the EV market; to encourage research and development (R&D) for the development of technologies to support the growth of e-mobility, and finally encourage the development of infrastructure such as charging infrastructure for the EV market (see Sousa, Costa, 2022 for a review). The policy approach to encourage diffusion of EVs in the leading EV market countries is fiscal incentives in the form of price subsidies and lower licensing costs. These subsidies are paid out of the fees paid by owners of the ICE vehicles (Kohn et al., 2022).

It is apparent that the major EV market countries have set targets by which they plan to have reached zero emissions of greenhouse gases (MacIntosh et al., 2022). The policies to achieve these targets rely on the adoption of zero emission vehicles in these countries. As the EV market is non-existent in Botswana and the Southern African region, this suggests that the policy options would have to include all of the three categories to first conduct R&D in the use of the available raw materials in the production of EVs and EV batteries, the provision of a robust charging network infrastructure, and lastly to determine the fiscal incentives to cushion the consumer in the purchase of EVs.

From a raw materials perspective, the availability of nickel, copper, cobalt, manganese, and HPMSM would provide comfort over the security of supply to an EV or EV battery manufacturer located in the country.

Conclusions

This study set out to review publicly available information on

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planned manganese projects globally that would produce HPMSM for use in EV batteries because of the policy-induced growth in the global demand for EVs. The approach adopted involved gathering both the C1 project cash costs and the estimated production capacities for each of HPMSM projects studied and plotting a cost curve for the estimated supply of HPMSM from the six projects in this study. This cost curve was then used to assess the cost competitiveness of the K.Hill project, which is currently at an advanced stage of exploration by Giyani Metals Corporation. We conclude that the K.Hill project would be the second highest cost producer of HPMSM and this is largely due to the processing costs for reduction leaching of the oxide ore with sulfuric acid and using sulfur dioxide as a reductant. While its costs, at USD1,846/t HPMSM are lower than those for the Chevaltice Manganese Project at USD2,319/t HPMSM, they would still cost about twice as much as each of the three projects on the lower end of the cost curve. The three projects at the lower end of the HPMSM supply curve are based on manganese carbonate ores that are amenable to direct leaching using only dilute sulfuric acid. It is worth noting, however, that projected long term prices for the HPMSM still present a substantial margin over the C1 cash costs for the K.Hill project.

Regarding the policy option to encourage the development of the EV and EV battery industry in the country, the study concludes that the local availability of raw materials would offer security of supply to any future investor.

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