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Critical Metals in Alberta: Preliminary Evaluation of Vanadium and Nickel Potential in Alberta Bitumen and Bedrock

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Critical Metals in Alberta: Preliminary Evaluation of Vanadium and Nickel Potential in Alberta Bitumen and Bedrock

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Abstract

The advancement in the production of green and low carbon energy, combined with the intermittency of solar and wind energy production, puts additional pressure on the commercial availability of energy from such resources. Large-scale batteries for energy storage are already a part of the answer to such challenges. Alberta is a large-scale hydrocarbon producer exporting over ~477 700 m^3 per day (>3 million bbl/day) of mostly heavy oil in 2018–2020, but it is less known that value-added opportunities exist for battery-grade metals. While most attention is currently dedicated to lithium due to high demand for electric cars, laptops, cellular phones, and other types of mobile energy storage, it is less known that Alberta is enriched with significant amounts of vanadium (V) directly related to bitumen production. This monograph (review) will try to shed light on the distribution of V, its life cycle through, mostly, bitumen production and processing, and quantitative future opportunities. Some information on Alberta's nickel (Ni) potential is also presented.

Initial calculations show that Alberta has the potential to be a world player in V production. The main potential source of V is bitumen, which contains 210–240 ppm of V and 70–80 ppm of Ni. During 2017, oil sands mines extracted more than 17 000 t of V embedded in bitumen, with almost two-thirds precipitated into coke during upgrading. Most of the unprecipitated V is sequestered in the Shell Canada Limited Scotford refinery and upgrader, with the North West Redwater Partnership Sturgeon refinery becoming a potentially significant additional V source in the near future. These two facilities handle enough elemental V (~3735 t) to potentially produce about ~1100 MWh/yr of electricity storage in the form of vanadium redox batteries (VRBs). Partial upgrading of bitumen can potentially recover at least half of the V and Ni entrained in oil sands bitumen, which could place Alberta among the world leaders in V production. The total V in Alberta bitumen is about 34 000–39 000 t/yr, based on 2017 bitumen production.

The largest available resource of V and Ni is in existing petcoke stockpiles, which contain about 135 000 t of V and 42 000 t of Ni. However, due to differing storage practices, not all of these metals are available even if the petcoke would be accessible for some kind of recovery process (i.e., leaching). Annual petcoke production exceeded 10.1 Mt during 2017 containing about 10 900 t of V. With a slight increase due to higher production at the Canadian Natural Resources Limited Horizon mine starting in 2018, and only 50% extraction efficiency, petcoke has the potential to provide >5500 t of V or about 1800 MWh/yr of storage capacity in the form of VRBs. Vanadium from petcoke, froth treatment tailings (FTT), and partial upgrading is at least 90% recoverable if appropriate processes are applied such as roasting or gasification of FTT. Such a high recovery factor significantly enhances economic potential.

So far, a large portion of the V and Ni embedded in bitumen products is exported out of Alberta, mostly to the United States either as spent catalyst mixed with metallic sludge, or embedded within unrefined bitumen. Most of the exported bitumen is diluted (dilbit). Exports contain embedded V in the amount of >17 000 t/yr and more than 5700 t/yr of Ni. The total annual content of Ni within both mined and in situ bitumen is estimated at 11 000–13 000 t of Ni for 2017.

Potential for V also exists in near-surface ironstone deposits in northwestern Alberta, whereas potential for V, Ni, and other metals exists in shallow, highly metalliferous black shale in northeastern Alberta. There is no indication of when, if at all, either of these two types of deposits will be mined. However, the potential in these areas is worth noting.

Vanadium from two upgraders/refineries near Edmonton and two documented mineral exploration projects represent a value-added opportunity for an energy storage/battery industry in Alberta with an estimated value in the hundreds of millions of dollars per year, if V is manufactured into value-added forms such as VRBs.

1 Introduction

The introduction of higher energy- and cost-efficient solar panels and wind turbines requires storage systems that enable the extended use of green energy beyond the sunshine cycle or when the wind blows. Distributed production and utilization of electrical energy may favour batteries over other types of mass storage such as pumped storage. So far, the majority of electrical grid storage batteries are produced using lithium-ion (Li-ion) batteries, with vanadium redox batteries (VRBs) in second place. Even though new scientific advancement in the field of Li-sulphur (Li-S) batteries may continue to favour the use of lithium (Drexel University, 2018), it is less known that China regulated VRBs as the preferred means for storing green energy (Sparton Resources Inc., 2017) with a mandated capacity of at least 10% of the nominal installed power.

The choice of storage battery type depends on many factors, such as the speed of charging and discharging, stability of chemical components, corrosion resistance, fire-proofing, and available voltages among others. Whereas mobile batteries, such as the ones used in cars and laptops, have additional criteria like total weight and charge density per kilogram of weight, storage batteries are not necessarily limited to weight factors, but rather to price per kilowatt hour (kWh) of stored energy and long-term energy price. Such factors may actually work in favour of VRBs. Some earlier problems with energy density of VRBs and temperature sensitivity were recently addressed (Li et al., 2011). However, the purpose of this study is not the detailed discussion of the battery potential but to shed light on Alberta's potential to play a significant role as a supplier of raw materials for battery parts and other products.

There is a misconception that the demand for VRBs is driving the world price of V, which seems to be very volatile. The actual driver of a higher V price in 2018 was Chinese demand for higher quality steel, where V is used in the production of high-quality construction rebar (Vanitec Limited, 2018) to meet new regulations. This demand is mostly satisfied by iron and steel industry slag, termed a secondary supply, since certain iron ores contain an increased V content. The main producer of such ores and slags is China followed by Russia, South Africa, and Brazil (U.S. Geological Survey, 2021a). However, such high pricing may influence competitiveness of VRBs since electrolyte (mostly V) costs represent about one-third of the price of a VRB (Doetsch, 2018).

Annual world production of V from mines increased from 53 500 t in 2009 to 82 700 t in 2014, levelled off at ~70 000 t in 2017 and 2018, but jumped to 86 000 t in 2020 (U.S. Geological Survey, 2021a). In addition, a lot of V is produced from ashes and refinery residues (U.S. Geological Survey, 2021a). Alberta is a large-scale hydrocarbon producer exporting over ~477 700 m^3 per day (d; >3 million bbl/d) of crude oil (2018–2021 statistics; Canada Energy Regulator, 2022, Figure 3). However, no V is recovered from its residues despite the presence of V and other metals in them. These residues will receive special attention in this monograph since they are important in understanding Alberta's V potential.

The goal of this paper is to review the source and quantity of V and Ni resources in Alberta (Figure 1); hence, informing Albertans of a significant resource of critical elements required for green energy technology. This stage of identification and quantification of the resource is a precursor to economic evaluation, in that resource quantification precedes reserve and economic determination. Given sufficient resources, as a starting point of discussion, an energy storage/battery manufacturing industry in Alberta may be viable.

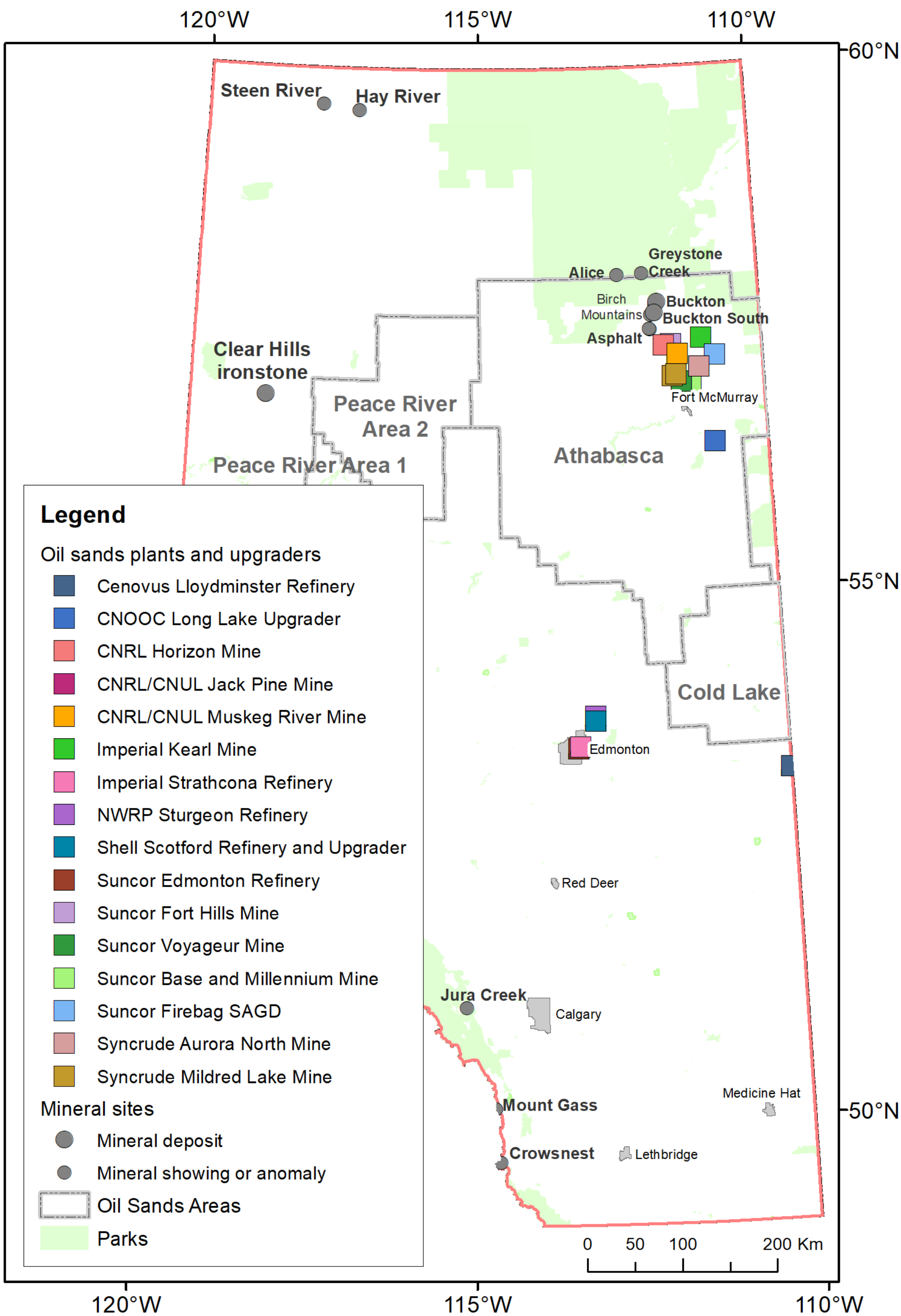

Figure 1. Location of oil sands plants, refineries, upgrading facilities, steam-assisted gravity drainage (SAGD) project, and mineral sites. Abbreviations: Cenovus, Cenovus Energy Inc.; CNOOC, CNOOC Petroleum North America ULC; CNRL, Canadian Natural Resources Limited; CNUL, Canadian Natural Upgrading Limited; Imperial, Imperial Oil Limited; NWRP, North West Redwater Partnership; Shell, Shell Canada Limited; Suncor, Suncor Energy Inc.; Syncrude, Syncrude Canada Ltd.

2 Information Sources and Conversion Factors

Vanadium resource references were assembled from public literature, U.S. Geological Survey (USGS) publications, and reports submitted to the Alberta Energy Regulator (AER), which are available from the Electronic Record Keeping System (ERKS) at Alberta Environment and Parks (AEP). Some older reports may have been submitted to previous regulators of mining activity, such as Alberta's former Ministry of Environment and Sustainable Resource Development (now part of AEP). The available estimates of V resources are in most cases inferred resources (in-place or recoverable), and as such have very high uncertainty and are unsuitable for investment decisions or mine planning without significant further investigation. Other data sources are from limited sampling programs and have no associated resource estimate. All units are metric unless specified otherwise. For comparison purposes, final quantities of V are expressed as elemental values, unless designated as vanadium pentoxide (V_2O_5).

Recent and long-term average compositions and density of the Western Canadian Select (WCS) petroleum mix plus V and Ni contents of different petroleum oil streams, including varieties of diluted bitumen (dilbit), can be found at the CrudeMonitor website (https://www.crudemonitor.ca/). For the purpose of this paper and ease of calculations, it was assumed that the density of bitumen is 1 t/m^3.

PRISM Diversified Ltd. (PRISM; PRISM Diversified Ltd., 2018) presented that VRBs use about 1.65 t of V_2O_5/MWh of installed capacity. However, a more conservative estimate of 5.5 t of V/MWh of installed capacity was presented by Bushveld Energy Limited (2018) based on Ekroad (2007). Blanc (2009) provided 6.0 kg/kWh V_2O_5 necessary for a 30 kWh battery, the value close to Blanc and Rufer (2010), who used 83 L of a 2 molar solution for a 6 kWh VRB, which gives a value of 5.04 kg V_2O_5/kWh of storage capacity. Zhang et al. (2016) used 5.22 kg/kWh of V_2O_5 for the modelling of batteries. It was obvious that Bushveld Energy Limited (2018) meant V_2O_5 as "vanadium" but had not specified it in their presentation. Such a use of V_2O_5 at ~5.5 t/MWh capacity would correspond to roughly 3 t of pure V/MWh of installed VRB capacity. The authors used 5.5 t V_2O_5/MWh of energy storage capacity to calculate potential use of Alberta's bitumen in VRBs, whereas correction to elemental V was based on molecular weight.

3 Alberta's Role and Opportunities

Alberta has an abundance of V and Ni from at least three known sources:

1) V and Ni in oil sands
2) V in oolitic ironstone
3) V and Ni in metalliferous organic-rich shale (i.e., metalliferous black shales)

There are at least four different potential sources within the oil sands and heavy oil sections:

- partial upgrading
- petcoke
- petcoke fly ash
- froth treatment tailings

The following sections will review the V and Ni potential in each source within the oil sands.

3.1 Vanadium and Nickel in Oil Sands

Heavy oils are often rich in some metals with V and Ni being the primary metals (Hosterman et al., 1989; Moskalyk and Alfantazi, 2003). In addition to V and Ni, present at about 242 ppm and 83.3 ppm, respectively, Alberta bitumen is high in molybdenum (Mo) with a concentration of ~10.4 ppm (Bicalho et al., 2018). Kelley et al. (2017) discussed oil sands as a potential source of these metals, but did not quantify the resource; however, they mentioned that V can be concentrated within the refining streams or deposited on the catalyst. This V is mostly present as porphyrinic V (Bicalho et al., 2018) that is tightly bound within bitumen heavy hydrocarbon molecules. Thus, V is transported with bitumen and exported, mostly to the United States.

Heavy molecules in bitumen are mostly asphaltene that, in addition to V and Ni, contain relatively large quantities of sulphur (S = 3–5%) and nitrogen (N = 0.5–1%). In order to produce high quality fuels, all these impurities must be removed from the hydrocarbons. In addition, bitumen hydrocarbons are heavy complex molecules with a low content of hydrogen, which is often increased during the hydrocracking and refining processes. Often, upgrading and refining of heavy fuels, including bitumen, result in the creation of petroleum coke (petcoke), which is practically a carbon concentrate enriched in impurities such as metals and sulphur. Petcoke may also contain some minerals including rare-earth elements (REEs) that partition with bitumen during the production of froth from aqueous separation of bitumen from sand.

Four large bitumen mines, Canadian Natural Resources Limited (CNRL) Horizon mine, Suncor Energy Inc. (Suncor) Base and Millennium mine, and Syncrude Canada Ltd.'s (Syncrude) Mildred Lake (ML) and Aurora North (AN) mines, have upgraders and produce upgraded synthetic crude and petcoke. Bitumen production from all Albertan mines in 2017 is depicted in Table 1 with AER's Statistical Report (ST) 39 as a source (Alberta Energy Regulator, 2020a).

Suncor upgraded almost half of the bitumen produced from their Firebag steam-assisted gravity drainage (SAGD) project (northeast of Fort McMurray) at the Millennium upgrader, resulting in a higher accumulation of petcoke than mined bitumen. In 2017, the Millennium site received 12.4 Mt of bitumen from the Firebag SAGD project, processed 23.7 Mt and further delivered 6.5 Mt of bitumen (Table 1). From 23.7 Mt of processed bitumen, Suncor produced 18.83 Mt of synthetic bottomless crude containing practically no metals (CrudeMonitor, 2019). The rest of the bitumen was diluted with synthetic crude and shipped as so-called Borealis Heavy Blend (BHB). According to the CrudeMonitor (2019), the V and Ni content averaged 162.5 and 61.1 ppm, respectively, in the BHB blend over the previous five years. Assuming an ~30% volume/volume (v/v) mix with synthetic crude, that would represent about 232 ppm V and 87 ppm Ni in bitumen, or quite close to Bicalho et al. (2018) values.

From 23.7 Mt of processed bitumen, Suncor also produced 5.26 Mt of petcoke with approximately 22.2% yield weight/weight (w/w). It is assumed that almost all metals are sequestered in the petcoke, although a part of V and/or Ni may be deposited on a catalyst used during upgrading. In addition, one of Suncor's products is low residue heavy synthetic oil (OSH code; CrudeMonitor, 2019) with ~3.15% of S, but only about 10 ppm and 4 ppm of V and Ni, respectively, over the previous five years (CrudeMonitor, 2019). For the metal mass balance on the Base and Millennium mine site, this portion will be neglected, but the destiny of this OSH stream will be discussed since it may result in a very high metal percentage sludge at a refinery. For the calculation of V in petcoke, this 10 ppm level of V in the OSH stream was neglected.

In this study, it is assumed that practically all V and Ni is precipitated with petcoke within the upgraders, with the assumed metal content presented in Table 2 and V and Ni distribution in petcoke presented in Tables 3 and 4. The petcoke is mostly stored on mine sites with some small historical sales. A few million tonnes were used as a cap for the remediation of Suncor's Pond 5, floating on densified fluid tailings. So far, Suncor and Syncrude have used about 0.5 Mt/yr each to heat their boilers, with fly ash as a result. This fly ash is enriched in V but it has not been stored in the way that would preserve it as a V resource, although it contains about 3–4.5% V and about 1–1.5% of Ni (Scott and Fedorak, 2004; Nesbitt et al., 2017). This V outlet will be described in more detail within Section 3.1.3.

Vanadium concentration in raw bitumen products is regularly reported by CrudeMonitor (2019), which presents recent, six-month, one-year, and five-year average compositions of crude oils including metals (V, Ni) content as well as some physical properties such as density and API number. For example, Imperial Oil Limited (Imperial) Kearl crude, which is bitumen diluted by a paraffinic froth treatment (PFT), had a V content of about 140 ppm, whereas Ni content was 51.8 ppm (CrudeMonitor, 2019). Assuming 23% diluent content in PFT dilbit, it turns out that V content after PFT of de-asphalted bitumen from this location is about 182 ppm.

Table 1. Production of bitumen and petcoke in oil sands in Alberta in 2017 (data from Alberta Energy Regulator, 2020a, c).

Producer and Mine	Bitumen (tonnes)	Bitumen (tonnes/day)	Petcoke[1] (million tonnes)	∑ Petcoke On-Site (million tonnes)	Burnt Petcoke (million tonnes)	Sold Petcoke (million tonnes)
CNRL Horizon	11 417 853	31 328	2.3 (20.15%)	11.4		
CNRL/CNUL MRM[2]	8 431 054	43 556				
CNRL/CNUL JP[2]	7 443 518	20 428				
Suncor Fort Hills	122 070	1 971				
Imperial Kearl	11 382 738	31 232				
Suncor Base and Millennium and Firebag	17 713 656 23 703 328[3]	48 603	5.3 (22.20%)	41.8	0.54	0.874
Syncrude Mildred Lake and Aurora North	17 515 306	48 058	2.6 (14.70%)	60.2	0.54	0
Sum total + Firebag	74 026 195 80 015 867	202 811	10.1	113.4	1.07	0.87
In situ total[3,4] Unprocessed[3,4]	89 900 000 83 900 000	246 301				
Total oil sands	**163 900 000**	**449 041**				

[1] Percentages refer to yield of petcoke from bitumen upgraded into synthetic crude oil.
[2] Froth from Jack Pine mine (JP) processed at Muskeg River mine (MRM) and diluted bitumen sent to Shell Canada Limited's Scotford refinery and upgrader.
[3] About 6 Mt from Firebag steam-assisted gravity drainage (SAGD) project was processed at Suncor Millennium upgrader from 12.4 Mt that was delivered to the mine and upgrader facility.
[4] In-situ production rounded for the ease of calculation and discussion.
Abbreviations: CNRL, Canadian Natural Resources Limited; CNUL, Canadian Natural Upgrading Limited; Imperial, Imperial Oil Limited; Suncor, Suncor Energy Inc.; Syncrude, Syncrude Canada Ltd.

Table 2. Data and assumptions used for calculations of metal (vanadium, nickel, and molybdenum) content.

Compound	Density (tonnes/m^3)	V (ppm)	Ni (ppm)	Mo (ppm)
Bitumen	1.00	210–240	70–80	8–10.4
Petcoke[1]	-	945–1600	330–400	40–50
WCS	0.93	137	57	-
Paraffinic dilbit	0.985	160–180	52–60	8.3
Paraffinic asphaltene in FTT	1.20	800–950	250–280	30
Ironstone (V_2O_5)	-	2000	-	-

[1] Reported in metric tonnes in Statistical Report 39 (Alberta Energy Regulator, 2020a); V and Ni may be partially deposited on a catalyst in the upgrader.
Abbreviations: dilbit, diluted bitumen; FTT, froth treatment tailings; V_2O_5, vanadium pentoxide; WCS, Western Canadian Select

Table 3. Processing estimates of vanadium (V) in mined bitumen, petcoke, diluted bitumen (dilbit), and asphaltene in 2017 in Alberta (data from Alberta Energy Regulator, 2020a, c). Assumed V concentration in bitumen at two levels: 210 and 240 ppm.

		V = 210 ppm				V = 240 ppm			
Producer and Mine	**Processed Bitumen (tonnes)**	**V in Bitumen (tonnes)**	**V in Petcoke (ppm)**	**Loss of V to: (tonnes)**	**Shipped V (tonnes)**	**V in Bitumen (tonnes)**	**V in Petcoke (ppm)**	**Loss of V to: (tonnes)**	**Shipped V (tonnes)**
NFT				**Petcoke**				**Petcoke**	
CNRL Horizon	11 417 853	2 398	1 040	2 392	0	2 740	1 180	2 715	
Suncor Base+Millenium[1]	23 703 328	4 978	945	4 973	826[2]	5 689	1 070	5 630	935[2]
Syncrude ML+AN	17 515 306	3 678	1 400	3 604	0	4 204	1 600	4 119	
Total	52 636 487	11 054		10 970		12 633		12 641	
PFT			**V in Asphaltene**	**Paraffinic FTT**	**Dilbit (160 ppm)**		**V in Asphaltene**	**Paraffinic FTT**	**Dilbit (180 ppm)**
CNRL/CNUL MRM+JP	15 874 572	3 334	800	933	2 349	3 810	950	1 108	2 642
Suncor Fort Hills	122 070	26		0[3]		29			
Imperial Kearl	11 382 738	2 390	800	769	1 668	2 732	950	914	1 876
Total	27 379 381	5 750		1 702	4 016	6 571		2 021	4 518
Total mines	**80 015 867**	**16 803**		**12 672**	**4 842**	**19 204**		**14 485**	**5 453**
Total in situ[4]	**83 900 000**	**17 619**			**17 619**	**20 136**			**20 136**
Total oil sands	**163 900 000**	**34 419**			**22 461**	**39 336**			**25 589**

[1] Includes ~6 Mt from Firebag in situ facility
[2] Exported in petcoke, V in heavy oil taken as minimal
[3] Froth sent to Suncor Millennium upgrader for processing in 2017
[4] Excludes ~6 Mt from Firebag processed at Suncor Millennium upgrader
Abbreviations: AN, Aurora North; CNRL, Canadian Natural Resources Limited; CNUL, Canadian Natural Upgrading Limited; FTT, froth treatment tailings; Imperial, Imperial Oil Limited; JP, Jack Pine; ML, Mildred Lake; MRM, Muskeg River mine; NFT, naphtha-based froth treatment; PFT, paraffinic froth treatment; Suncor, Suncor Energy Inc.; Syncrude, Syncrude Canada Ltd.

Table 4. Processing estimates of nickel (Ni) in mined bitumen, petcoke, diluted bitumen (dilbit), and asphaltene in 2017 in Alberta (data from Alberta Energy Regulator, 2020a, c). Assumed Ni concentration in bitumen at two levels: 70 and 80 ppm.

		Ni = 70 ppm				Ni = 80 ppm			
Producer and Mine	**Processed Bitumen (tonnes)**	**Ni in Bitumen (tonnes)**	**Ni in Petcoke (ppm)**	**Loss of Ni to: (tonnes)**	**Shipped Ni (tonnes)**	**Ni in Bitumen (tonnes)**	**Ni in Petcoke (ppm)**	**Loss of Ni to: (tonnes)**	**Shipped Ni (tonnes)**
NFT				**Petcoke**				**Petcoke**	
CNRL Horizon	11 417 853	799	360	828	0	913	390	897	0
Suncor Base+Millenium[1]	23 703 328	1 659	330	1 737	288[2]	1 896	355	1 868	310[2]
Syncrude ML+AN	17 515 306	1 226	400	1 056	0	1 401	530	1 365	0
Total	52 636 487	3 685		3 620		4 211		4 130	
PFT			**Ni in Asphaltene**	**Paraffinic FTT**	**Dilbit (52 ppm)**		**Ni in Asphaltene**	**Paraffinic FTT**	**Dilbit (60 ppm)**
CNRL/CNUL MRM+JP	15 874 572	1 111	250	291	763	1 270	280	326	881
Suncor Fort Hills	122 070	9		0[3]	0	10			0
Imperial Kearl	11 382 738	797	250	240	542	911	280	269	625
Total	27 379 380	1 917		532	1 305	2 190		596	1 506
Total mines	**80 015 867**	**5 601**		**4 152**	**1 593**	**6 401**		**4 724**	**1 816**
Total in situ[4]	**83 900 000**	**5 873**			**5 873**	**6 712**			**6 712**
Total oil sands	**163 900 000**	**11 473**			**7 466**	**13 112**			**8 528**

[1] Includes ~6 Mt from Firebag in situ facility
[2] Exported in petcoke, Ni in heavy oil taken as minimal
[3] Froth sent to Suncor Millennium upgrader for processing in 2017
[4] Excludes ~6 Mt from Firebag processed at Suncor Millennium upgrader
Abbreviations: AN, Aurora North; CNRL, Canadian Natural Resources Limited; CNUL, Canadian Natural Upgrading Limited; FTT, froth treatment tailings; Imperial, Imperial Oil Limited; JP, Jack Pine; ML, Mildred Lake; MRM, Muskeg River mine; NFT, naphtha-based froth treatment; PFT, paraffinic froth treatment; Suncor, Suncor Energy Inc.; Syncrude, Syncrude Canada Ltd.

Paraffinic bitumen extraction from bitumen froth is very similar to aqueous-based gravity separation extraction of bitumen from sand, but it is followed by the treatment of bitumen froth with a light pentane/hexane diluent mix, which further separates impurities and also precipitates part of the heavy asphaltene fraction; the latter of which is disposed at the mine in the form of froth treatment tailings (FTT). Although somewhat depleted in metals, this type of dilbit still contains most of the porphyrinic V and Ni. Some of that V is precipitated at Shell Canada Limited's (Shell) Scotford refinery and upgrader near Edmonton, whereas most V is exported with other types of dilbit from in situ bitumen producers. Basically, V and Ni in exported bitumen, >17 000 t and >5 700 t, respectively, is lost for Alberta and Canada, although a part of it might be recovered somewhere in the US.

Tables 1, 3, and 4 show bitumen and petcoke production in Alberta in 2017, with data sourced from the AER (Alberta Energy Regulator, 2020a, c). During 2017, bitumen production in oil sands mines was ~74 Mt (Alberta Energy Regulator, 2020a), while the total production including in situ was ~163.9 Mt (Table 1), which means that in situ production exceeded mining by about 15.9 Mt/yr. The 6 Mt of bitumen from the Firebag SAGD in situ project were processed at the Millennium upgrader, leaving unprocessed in situ dilbit production at about 83.9 Mt in 2017 (Table 1). Assumptions for the calculations of V and Ni value-added potential from bitumen and potential metallic mines are presented in Table 2.

3.1.1 Effect of Partial Upgrading on Vanadium and Nickel Production

Partial upgrading increases pumpability of bitumen through a chemical change of heavy molecules. The resulting product is a lighter petroleum oil with lower viscosity and a higher API number (Jacobs Consultancy Inc., 2018). Most of the processes also crack asphaltene and a very viscous gumlike product. As a result, a portion of the S and metals (including V) may be precipitated (Auterra, Inc., 2012, 2017; Jacobs Consultancy Inc., 2018; Litz, 2018). Such an upgrading process is not only cost effective but also presents an opportunity for further metal recovery. Regardless of chosen technology, an installation with only ~158 987 m^3/d (1 million bbl/d) of partial bitumen upgrading capacity would result in the processing of roughly 58 Mt/yr of bitumen. Assuming only 160 ppm of V and 60 ppm of Ni, combined with 50% recovery in the process with partial oxidation (akin to Auterra, Inc., 2017), partial upgrading could recover about 4640 t/yr of elemental V, or roughly 8283 t/yr of V_2O_5, plus ~1740 t/yr of elemental Ni.

3.1.2 Vanadium and Nickel in Petcoke

Currently, there are three operating upgraders in oil sands mines and they use two basic processes for coking—so-called fluid coke (Syncrude) and delayed coke (Suncor, CNRL). Annual production and cumulative amounts of petcoke at the mines are shown in Table 1. The CNRL Horizon upgrader scaled up production capacity in 2018 to 40 000 m^3/d (~250,000 bbl/d; Alberta Energy Regulator, 2020a).

Concentration of V and Ni in petcoke partially depends on the type of upgrading process and assumed initial concentrations. Thus, a conservative estimate of ~210–240 ppm of V in bitumen, with ~5–6.5 times concentration during coking, was used. Indeed, Nesbitt et al. (2017) estimated an average V concentration in Syncrude coke as 1280 ppm plus 230 ppm of Ni. Har (1981) showed that some V concentrations in petcoke were as high as 1500–1900 ppm.

Tables 3 and 4 show the approximate mass distribution of V and Ni in mined bitumen, petcoke, dilbit, and precipitated asphaltene. Obviously, from the majority of 80 Mt of processed bitumen containing roughly 16 800–19 200 t of embedded V, about 65% of the V was left in petcoke or about 10 970 t. The authors' assumption that the asphaltene fraction disposed within the paraffinic FTT has about 800 ppm of V is confirmed by Kotlyar et al. (1999). Kotlyar et al. also noticed that the ultrafine solids fraction, associated with asphaltene, is responsible for water-in-oil emulsions and could be separated together with residual water using high G-force in centrifuges. This asphaltene-loving fraction contains minerals high in iron, calcium, and titanium, which corresponds to enrichment in siderite/pyrite, calcite/dolomite, and titanium-bearing minerals, such as rutile and ilmenite. The V and Ni were largely unaffected by centrifugation, evidenced by their presence in a non-mineral structure.

It appears that the total V and Ni in petcoke could be at least 135 000 t of V and 42 000 t of Ni in 2017, based on 113 Mt of petcoke (Table 1) and concentrations of 945–1600 ppm V and 330–530 ppm Ni (Table 2). With a recent increase in bitumen production at the CNRL Horizon mine and assumed extraction efficiency of only 50%, annual V in petcoke exceeds 5500 t with the potential to produce VRBs with ~1800 MWh of storage capacity.

It must be acknowledged that some Ni may be left on the surface of the catalyst used for bitumen cracking, resulting in a lower Ni concentration in petcoke. From the processing view, Ni 'stays' at the upgrader although it may be 'exported' with the used catalyst, the destiny of which is unknown at this point in time.

Vanadium in asphaltenes was assumed to be approximately 800–950 ppm for the asphaltene produced during PFT (Table 3); however, the range of concentrations is probably much larger than that. It was reported as low as 715 ppm (B. Komishke, pers. comm., 2018) to as high as >1600 ppm as reported in an asphaltene fraction from the CNOOC Petroleum North America ULC (CNOOC) Long Lake upgrader (Mahapatra, 2014; Mahapatra et al., 2015; Kurian et al., 2015; Kurian and Gupta, 2016).

3.1.2.1 Petcoke Reactivity and Potential Vanadium/Nickel Loss

Until recently, it was assumed that petcoke in oil sands was largely an inert material that could also be used in reclamation, such as at Suncor's Pond 5. However, recent findings (Meina, 2020) show that weathering of petcoke even in tailings ponds does occur. Nesbitt and Lindsay (2017) and Nesbitt et al. (2017) showed that surface water at Syncrude's Mildred Lake Settling Basin (MLSB) petcoke beach had a slightly lower pH and a somewhat increased metal concentration than deeper pore water at the same petcoke beach. Similar findings of metals leached from petcoke were demonstrated from both Syncrude and Suncor petcoke (Squires, 2005). Syncrude's use of fresh petcoke to remove organics from oil sands process water showed increased V and Mo concentrations both in the process water after treatment and in petcoke leachate afterwards (Syncrude Canada Limited, 2015). Squires (2005) also described that coke pore water contains an elevated metals concentration, however, water with a lower pH (only 5) showed the highest potential to leach metals from petcoke.

The type and quantity of metal loss needs to be determined in order to establish the certainty of V and Ni mass balance and availability from coke stockpiles. Although V and Ni in petcoke are mostly porphyrinic in nature and more resistant to leaching, a smaller loss in the range of 5–20% might be possible over longer periods of time. In addition, the presence and role of potential low pH triggers, such as the FTT beach deposit that is in the vicinity of petcoke within the MLSB, needs to be clarified.

3.1.3 Vanadium and Nickel in Petcoke Fly Ash

Suncor and Syncrude have been using petcoke as a source of energy at the oil sands mines for the heating of process water and electricity cogeneration. As mentioned previously, Scott and Fedorak (2004) specified that V in the fly ash can be above 4% whereas Ni is in the 1–1.5% range. Jang and Etsell (2005) produced ash from petcoke and found that Suncor coke had a higher percentage of V despite the initial material being similar to Scott and Fedorak's (i.e., bitumen). Jang and Etsell gradually increased the temperature from low temperature ashing (LTA) up to 1200^{o}C. In this case, Suncor coke had V in the 5–6.5% range whereas Syncrude coke had a lower V content of about 3.6–4.4%. The yield of Suncor's ash ranged from 2.7 to 3.1% V whereas Syncrude ash yield ranged from 8.5 to 8.9%. Details of petcoke origin were not described.

Due to higher processing temperature of Syncrude's fluid coke, it may be that V was partially volatilized in the plant and coprecipitated with some distillate streams, but the analysis of fresh petcoke usually shows V concentration higher than 1000 ppm. Thus, there may be some other mechanism that resulted in the V loss reported in Jang and Etsell (2005). For example, if Syncrude's petcoke was obtained from the FTT beach deposit, a portion of the metals could have already been leached out.

A rough estimate of about 1 Mt of burned petcoke and an ~4% average ash yield would estimate this resource as containing about 1500 t of V and 500 t of Ni per year. Due to uncontrolled disposal of this resource, which seems to be richer in V and Ni than most world ores, this stream should be considered lost. Presently, >30 000 t of V and >10 000 t of Ni have been lost in this waste material based on the reported coke consumption in AER ST39 (Alberta Energy Regulator, 2020a) and the discontinued Energy Resources Conservation Board ST43 report (Energy Resources Conservation Board, 2009; last published in 2009), and petcoke composition assumed in Table 2. Part of this fly ash had been stored in the northeastern area of Suncor's Pond 1 (now Wapisiw Lookout, formerly Tar Island Dyke Pond), but most seems to have been disposed with the tailings. Quantity and quality of Suncor's fly ash at Pond 1 needs to be established. Uncertainty exists about the recoverability of metals from this fly ash deposit.

3.1.4 Vanadium and Nickel in Froth Treatment Tailings

As shown in Tables 3 and 4, V in paraffinic FTT was about 1700–2000 t in 2017. If this stream is ever to be processed, it would also produce Ni in the amount of ~530–600 t/yr. This amount can be increased by about one-third in 2019 due to increasing capacity at Imperial Kearl (from 11.38 Mt in 2017 to 12.80 Mt in 2019) and Suncor Fort Hills mines (from 0.12 Mt in 2017 to 9.50 Mt in 2019), or an additional 10.8 Mt of bitumen, which would result in approximately an additional 175–220 t/yr of Ni and 570–670 t/yr of V. That would mean that the VRB potential in 2019 from V embedded in paraffinic FTT exceeds 700 MWh and maybe 800 MWh of installed VRB energy storage capacity based on ~3 t of pure V per MWh of VRB capacity.

Naphtha-based FTT contain bitumen similar in composition to recovered bitumen. It is accounted for as general bitumen loss and is not reported separately in AER ST39 statistics (Alberta Energy Regulator, 2020a). It is assumed that hydrocarbons in this stream represent about 2% of the total bitumen reported in Tables 1 and 3 (Greenhouse gasses and froth treatment tailings, Clifton Engineering Group Inc., work in progress, 2022). If only 52.6 Mt of naphtha-based bitumen produced in 2017 (Table 3) is considered, naphtha-based FTT should contain about 220–250 t of V and 73–83 t of Ni. On its own it is not much, but those metals could be significant contributors to the economics of FTT processing, together with other hydrocarbons and minerals.

4 Western Canada Refineries and Upgraders

4.1 Vanadium and Nickel at the Scotford Refinery and Upgrader

Shell's Scotford refinery and upgrader (Scotford) receives most of its bitumen from CNRL/Canadian Natural Upgrading Limited's (CNUL) Muskeg River mine (MRM) and Jack Pine mine (JP). This bitumen is PFT-type bitumen that has already lost some asphaltene. Thus, the concentration of V in the PFT bitumen was taken as ~160 ppm (B. Komishke, pers. comm., 2018), although there are indications that it could be as high as 187 ppm.

From roughly 17.6 Mt of bitumen receipts, it is calculated that in 2017 Scotford received about 2800 t of elemental V, 1000 t of Ni, and about 144 t of Mo. From the total receipts (Alberta Energy Regulator, 2020a), a further ~1.74 Mt was delivered, while 15.85 Mt was processed. The majority of Scotford products are fuels or high-quality synthetic oil (Premium Albian Synthetic [PAS] or Shell Synthetic Light [SSX]) that apparently have no V (CrudeMonitor, 2019). There is also a type of heavy synthetic oil (Albian Heavy Synthetic [AHS]) that is similar to a partially upgraded dilbit with a reduced content of S and metals. It was assumed that AHS contains ~100 ppm V and ~52 ppm Ni (CrudeMonitor, 2019). The ST39 report for Scotford (Alberta Energy Regulator, 2020a) contains details on intermediate hydrocarbon production, but it is impossible to deduce which hydrocarbon stream is being described. Even if an assumption is made that all of it is the AHS fraction, exported to pipelines and not to the refinery on site, exported AHS stream would deduct only 100 t of V, leaving about 2435 t of V on site in 2017 plus about

950 t of Ni. Almost all of this V may be recovered even if part of it is commingled with the catalyst (Baritto et al., 2022).

The authors estimate that Scotford processing facilities processed about 120 t of Mo embedded in bitumen and most probably it precipitated together with V and Ni. Since CrudeMonitor (2019) does not report on Mo in process streams, it is impossible to estimate how much Mo was exported from Scotford within heavy synthetic crude. However, such amounts should perhaps be only a few tonnes. Thus, Scotford could handle in excess of 100 t of Mo annually. One should keep in mind that a significant amount of Mo may be present within the catalyst, which is often based on MoS_x.

The V:Ni ratio in the original bitumen is 3:1 yet it is roughly a 2:1 ratio in the AHS stream, which shows that V seems to be a more labile metal during upgrading; thus, sludge and precipitates obtained earlier in upgrading and refining or from bottoms should potentially contain a higher proportion of V, that is, 4:1. Besides being deposited on the catalyst, the metallic concentrate (sludge) is mixed with spent catalyst and apparently sold to a company in the United States. The concentration of V in this export may be comparable to that in V ore concentrate.

4.2 Vanadium and Nickel at the Sturgeon Refinery

North West Redwater Partnership (NWRP) plans to process ~7962 m^3 of bitumen in each of three phases at the Sturgeon refinery (formerly the North West Upgrader; North West Redwater Partnership, 2012). At the time of writing, bitumen processing was still not at maximum capacity. However, it seems that dilbit is being processed (intermediate hydrocarbon). Until July 2018, the refinery produced mostly diesel from synthetic crude. The project will not produce coke due to gasification of the asphaltene fraction, meaning that all the embedded metals will be precipitated, probably as metallic sludge or a mix with spent catalyst.

The NWRP amendment application (North West Redwater Partnership, 2012) specified that the S in the feed would increase to about 3.7%, meaning the refinery feed would be heavier bitumen with about 18% more S than originally planned. The same application specified bulk feed composition as having 140 ppm of V and 46 ppm of Ni. In the authors' opinion, this feed carrying diluent is a part of the 12 261 m^3/d of total capacity as described by North West Redwater Partnership (2012). Source bitumen was roughly equal amounts of dilbit from the Cold Lake and Athabasca regions, totalling 11 147 m^3/d, mixed with 960–1520 m^3/d of sour synthetic (North West Redwater Partnership, 2012). Cold Lake dilbit (CL code), according to CrudeMonitor (2019), had a five-year average of 159.3 and 62.4 ppm of V and Ni, respectively, meaning that the V concentration in mined bitumen is ~225 ppm. Dilbits from the Athabasca region have a similar composition of roughly 160 ppm V and 60 ppm Ni.

Conservatively assuming that used Athabasca dilbit from PFT producers has 160 ppm V and 60 ppm Ni, annual 'production' of metals in the ash or a metallic sludge can be calculated as around 445 t of V, 167 t of Ni, and ~22 t of Mo based on 350 working days or 2 786 624 m^3 annual production. Expansion of the capacity to 23 885 m^3/d would triple the proposed amounts yielding about 1335 t/yr of V or ~2383 t/yr of V_2O_5. Using similar factors as outlined in Section 2, this V would be sufficient for ~433 MWh of VRB capacity per year.

Since feed bitumen is probably heavier and with a higher metal content, one should keep in mind that these calculated values could easily be 20–35% higher.

4.3 Other Large Refineries in Alberta

4.3.1 Imperial Oil Strathcona Refinery

Although refinery production is described as 27 800 m^3/d (Alberta Energy Regulator, 2020b), Imperial says that its capacity at the Strathcona refinery is about 31 847 m^3/d (Table 5; Imperial Oil Limited, 2017). Besides fuels, the refinery also produces asphalt that may contain increased levels of metals. The refinery receives Imperial's entire share in the Syncrude 25% portfolio, which is mostly synthetic crude oil (SCO) that has practically no significant amounts of V and Ni. The other feed is Cold Lake dilbit that is accepted in the refinery; naphtha is boiled off and sent back to Cold Lake for reuse, and the bitumen is processed. Part of the process includes the recovery of catalyst after coke deposition by burning it in the recovery unit, which is prone to liberate, and maybe concentrate, some V and Ni. Bitumen supply was assumed to be Cold Lake (CL) heavy whereas heavy oil for this refinery was calculated based on Western Canadian Blend (WCB) metal content. Light oil supply was assumed to be Mixed Sweet Blend (MSW) with 9 and 4 ppm of V and Ni, respectively, and 0.82 g/cm^3 density. Any other sourer light oil would contain more metals.

4.3.2 Suncor Edmonton Refinery

The Suncor Edmonton refinery (Table 5) has a capacity of 22 611 m^3/d and had been optimized to accept oil sands crude feedstock (Canadian Energy Research Institute, 2018; Suncor Energy Inc., 2020). Besides fuels, it also produces petcoke and sulphur. Feedstock is sweet and sour SCO and bitumen. Canadian Energy Research Institute (2018) stated that the Suncor refinery processed 6529 m^3/d of bitumen and 7006 m^3/d of sour SCO with the remaining 9076 m^3/d (57,000 bbl/d) being sweet SCO without a significant content of metals.

For this study, it has been assumed that sweet SCO has no metals and the bitumen is regular Suncor undiluted bitumen with code BHB (CrudeMonitor, 2019). Assuming that 30% SCO was added into BHB bitumen, V and Ni content were 230 ppm of V and 85 ppm of Ni in undiluted BHB bitumen.

Sour naphtha (OSH code) was taken as Suncor's heavy synthetic crude and is a minor source of V and Ni.

4.4 Smaller Refineries in Western Canada

Table 6 provides a short list of petroleum processors where V and Ni collection is probably not economical due to small amounts of input metals. Asphalt-producing refineries concentrate metals in the refinery bottoms together with asphaltene. Due to the very high viscosity of such products, separation of metals would probably require development of a separate extraction process, which could compromise the established production of different paving products.

The Cenovus Energy Inc. upgrader on the Saskatchewan side of Lloydminster processes heavier oils and bitumen from in situ projects in eastern Alberta, which are high in metals. The input of metals is probably higher than or comparable to the first phase at the Sturgeon refinery, which would mean that the total V input exceeds 420 t/yr. Depending on the upgrading process, potential VRB capacity probably exceeds 100 MWh.

Table 5. Vanadium (V) and nickel (Ni) potential in other large refineries in Alberta (data from Natural Resources Canada, 2005; Imperial Oil Limited, 2017; Canadian Energy Research Institute, 2018).

Refinery	Type	Capacity	Oil Feedstock		Code[1]	Density	V	Ni	V	Ni
		(m^3/day)	(type)	(m^3/day)		(tonnes/m^3)	(ppm)	(ppm)	(tonnes)	(tonnes)
Imperial Strathcona	Cracking	~31 847	Light	6 242	MSW	0.82	9	4	16.8	7.5
			Heavy	1 768	WCB	0.93	95	44	56.9	26.4
			Bitumen	2 611	CL	1	226	88	215.1	83.8
Suncor Edmonton	Coking	22 611	Bitumen	6 529	BHB	1	230	85	547.3	202.3
			Sour SCO	7 006	OSH	0.936	11	5	26.3	12.0
Total									**862.4**	**332.0**

[1] Fuel type codes as reported by CrudeMonitor (2019)

Abbreviations: BHB, Borealis Heavy Blend; CL, Cold Lake; Imperial, Imperial Oil Limited; MSW, Mixed Sweet Blend; OSH, Suncor Synthetic H; SCO, synthetic crude oil; Suncor, Suncor Energy Inc.; WCB, Western Canadian Blend

Table 6. Smaller refineries in western Canada, considered as having low potential as a source of metals at present (data from Natural Resources Canada, 2005).

Refinery	Type	Capacity (m^3/day)	Main Product	Comment
Gibson Energy Moose Jaw, SK	Topping	2 707	Asphalt	Produces drilling mud oils and roofing material
Tidewater Prince George, BC	Cracking	1 910	Fuels and propane/butane	
Cenovus Lloydminster, AB	Topping	3 981	Asphalt, fuels, condensate	30 types of asphalt, condensate for dilbit
Cenovus Lloydminster, SK	Upgrader	13 057	Diesel, SCO, coke	Coke sold for cement and aluminum industry
CNOOC Long Lake Anzac, AB	Upgrader	11 465	SCO, sulphur	Idled

Abbreviations: Cenovus, Cenovus Energy Inc.; CNOOC, CNOOC Petroleum North America ULC; dilbit, diluted bitumen; Gibson Energy, Gibson Energy Inc.; SCO, synthetic crude oil; Tidewater, Tidewater Midstream and Infrastructure Ltd.

The CNOOC Long Lake upgrader was designed to completely process asphaltene from bitumen upgrading, and would produce metal-rich bottoms with high concentrations of V and Ni. This stream would be similar to Scotford's, representing easily accessible V concentrate with a potential of up to 600 t/yr and 200 MWh of VRB capacity.

5 Other Sources of Vanadium and Nickel

This section reviews the mineralization of V and Ni in bedrock at a few sites in Alberta. The authors believe these sites provide significant resources and also suggest the potential for similar mineralization in other areas of Alberta. The definitions and determination of resources, reserves, and economic evaluations are strictly controlled by the provincial and territorial securities commissions as a safeguard for the public and investors. Definitions for many of the terms used herein are provided in Appendix 1.

5.1 Vanadium in Oolitic Ironstone

The Clear Hills iron-vanadium deposit (Figure 1) is situated on the eastern slopes of the Clear Hills in northwestern Alberta, about 80 km northwest of the town of Peace River. The deposit is a near-surface, up to 15 m thick, flat-lying, oolitic ironstone bed hosted by the Bad Heart Formation (Arseneau and Johnson, 2012). The deposit is under a glacial overburden of 1 to 72 m, with the thickness increasing to the west. The deposit was discovered in 1924, then evaluated and tested intermittently between the late 1950s and mid-1970s for the recovery of iron. It was intensively drilled in 2008, 2011, and 2012, and bulk sampling was performed for process development and pilot plant tests. The exploration property comprises four main areas: Rambling Creek, North Whitemud River, South Whitemud River, and Worsley.

Mineral resources were estimated in 2012 (Arseneau and Johnson, 2012) based on data from 230 diamond-drill cores. The indicated resource totalled 557 738 000 t at 33.3% Fe and 0.2% V_2O_5, which translates to 182 000 000 t of Fe and 1 116 000 t of V_2O_5 (Table 7; Arseneau and Johnson, 2012). That resource estimate assumed a cutoff grade of 25% Fe, metallurgical recovery of 82%, as well as mining costs and values of products extracted. The extent of the indicated resource is 64 km^2 (16 by 4 km), with an average thickness of 10 m. The deposit owner's (PRISM) design involves proprietary technology that uses an Fe carbonylation process to directly refine the Fe and V resource into high purity metallurgical powders with broad commercial applications (PRISM Diversified Ltd., 2023). A scenario proposed by PRISM (PRISM Diversified Limited, 2018) focused on supporting the demand for steel production from its iron ore, which could produce about 500 000 t of high-grade steel and about 8.5 million pounds of V_2O_5 annually, or 3859 t/yr, at full scale after approximately five years of production. An additional 94 664 000 t of rock material were estimated as an inferred resource surrounding the indicated resource (Arseneau and Johnson, 2012). This material has a recoverable grade estimate of 34.11% Fe, however, no grade was estimated for V. Multiple ironstone occurrences mapped by the Alberta Geological Survey (AGS; Olson et al., 2006; Kafle, 2008) exist outside of the inferred resource suggesting that the Rambling Creek–North Whitemud River deposit is open, and extends to the east, west, and south.

5.2 Vanadium and Other Metals in Highly Metalliferous Organic-Rich Shale

The AGS and the minerals exploration industry have identified a number of occurrences of V, coexisting with other metals, in marine organic-rich shale and mudstone (or black shales) of the Western Canada Sedimentary Basin (WCSB) in Alberta (Table 8; Sabag, 1998; Dufresne et al., 2001; Prior et al., 2008; Rukhlov and Pawlowicz, 2011; Puritch et al., 2013; Rokosh et al., 2016; Lopez et al., 2020). These metalliferous black shales are particularly attractive for exploration in northern Alberta where Cretaceous metal-enriched beds occur at or near-surface making them feasible for near-surface extraction, as opposed to the central and southern parts of Alberta where metal-rich black shales are deeper.

In northern Alberta, multiple highly metalliferous zones (Zn+V+Ni+Mo+Se >1500 ppm; Johnson et al., 2017) in organic-rich black shales were discovered by industry within the Upper Cretaceous Second White Specks Formation over vast areas of the Birch Mountains region (Figure 1; Sabag, 2008, 2010, 2012). Elsewhere in northwestern Alberta, a number of highly metalliferous geochemical showings and anomalies have been identified by the AGS, particularly in the Hay and Steen River areas (Figure 1). These occur in the Loon River and Shaftesbury formations (Dufresne et al., 2001; Prior et al., 2008; Rokosh et al., 2016; Lopez et al., 2020), of which the initial data from the Loon River Formation compares in grade to the grade from the Second White Specks Formation.

Table 7. Cumulative vanadium (V) and vanadium pentoxide (V_2O_5) and nickel (Ni) potential of major sources in Alberta.

V Source	Recoverable V_2O_5 (tonnes)	Annual V (tonnes)	Annual V_2O_5 (tonnes)	VRBs (MWh/yr)	Annual Ni (tonnes)
Clear Hills ironstone deposit[1]	1 116 000	2 130	3 859	691	
Metalliferous organic-rich shale deposits[2]	276 500				
Shell Scotford refinery and upgrader		2 400	4 282	779	884
NWRP Sturgeon refinery (all three phases)		1 335	2 383	433	500
Total potential		**5 865**	**10 524**	**~1 900**	**1 384**

[1] Data from a presentation by the developer (Arseneau and Johnson, 2012)
[2] Puritch et al. (2013); Eccles et al. (2013c, d)
Abbreviations: NWRP, North West Redwater Partnership; Shell, Shell Canada Ltd.; VRB, vanadium redox batteries

Most mineral exploration activities have focused on the highly metalliferous black shales in the Birch Mountains (Figure 1). These highly metalliferous occurrences were identified by regional reconnaissance and sampling followed by infill sampling and anomaly identification carried out by industry in the mid- to late 1990s (Sabag, 1996a–c, 1998, 1999). That exploration work identified multiple zones with elevated concentrations of metals, including V, in the Upper Cretaceous Second White Specks Formation (Dufresne et al., 2001). In particular, the Buckton, Buckton South, and Asphalt zones, represent three of six metalliferous occurrences identified in the area that are under relatively thin surface cover and easily accessible to transportation. Mineralization in the three zones was confirmed by industry drilling conducted in 1997 and the early 2010s. A National Instrument 43-101 maiden inferred resource estimate was completed for the Buckton zone in 2011 followed by updated and expanded estimates in 2012–2013 to include the overlying strata and REEs as an additional recoverable resource (e.g., Dufresne et al., 2011; Eccles et al., 2012a, 2013a, b). Lastly, a preliminary economic assessment for the Buckton zone was released in 2013 (Puritch et al., 2013), which included pit-mining scenarios and results of bioleaching tests. Earlier that same year, a National Instrument 43-101 compliant maiden inferred resource estimate for the Buckton South zone was also completed (Eccles et al., 2013c, d). Notwithstanding that these resource estimates define the Buckton and Buckton South zones as mineral deposits, these resources are not classified as mineral reserves as they are not yet conclusively demonstrated as being economically viable (Puritch et al., 2013; Eccles et al., 2013a–d).

The Buckton zone (Figure 1, Table 8), located approximately 130 km north of Fort McMurray, is under an overburden of less than 75 m. The zone contains two extensive, low-grade metal-enriched horizons interbedded within a major shale package over an area of 14 km^2 (Eccles et al., 2013a–c). The Buckton zone inferred resource comprises recoverable Mo, Ni, U, V, Zn, Co, Cu, Li, Y, Th, Sc, and REEs from the near-surface Labiche and Second White Specks formations (Eccles et al., 2012b, 2013a, b). The inferred resource estimate totals 4.4 billion t of shale package from the two formations with a raw average grade of 606.4 ppm V_2O_5 and 43.1 ppm Ni. Recovery values for V and Ni, based on preliminary lab testing using low-cost bioheap leaching, was demonstrated to be 7% and 64%, respectively. Thus, the recoverable inferred resource for V was estimated to be 188 000 t of V_2O_5 (Table 8), 191 000 t of Ni, 3058 t of MoO_3, and 391 683 t of Zn (Puritch et al., 2013). The area of the inferred resources in the Buckton zone is now partially within the Kitaskino Nuwenëné Wildland Provincial Park and extends outside the park to the south and west.

The Buckton South zone, which is located 7 km south of the Buckton zone (Figure 1), has a maiden inferred resource that comprises recoverable Mo, Ni, U, V, Zn, Co, Cu, Li, Y, Th, Sc, and REEs from the near-surface Labiche and Second White Specks formations. Mineralization extends for 3.3 km^2 under an overburden of less than 75 m (Eccles et al., 2013c, d). The maiden inferred resource totalled 496.7 Mt of shale package for both formations with average recoverable grades of 720.6 ppm V_2O_5 and 60.5 ppm Ni. Thus, the recoverable resource for V and Ni is estimated at 88 489 t of V_2O_5 (Table 8) and 30 000 t of Ni (Eccles et al., 2013c, d). No systematic infill sampling and drilling have been done between the Buckton and Buckton South zones to test if mineralization is continuous between the two zones. The extensive nature of metalliferous black shale deposits worldwide and the presence of some occurrences at surface between the two zones suggest that mineralization may be continuous, however, further exploration by drilling is needed to confirm that hypothesis.

Table 8. Summary of vanadium occurrences in metalliferous organic-rich shale in Alberta.

Name	Location	Stratigraphic Units (formation)	Description	V_2O_5 Inferred Resource (tonnes)
Buckton zone	Birch Mountains	Second White Specks, Labiche	Classified as a mineral deposit (now partially within wildland provincial park)	188 000[1]
Buckton South zone	Birch Mountains	Second White Specks, Labiche	Classified as a mineral deposit	88 500[2]
Asphalt zone	Birch Mountains	Second White Specks, Labiche	Two boreholes intersected ~11 m thick horizon with average grades of 674 ppm V and 131 ppm Ni[3]	Geochemical anomalies; no estimate
Alice	Birch Mountains	Second White Specks	Outcrop samples yielded up to 863 ppm V, 653 ppm Zn, 295 ppm Ni (within national and provincial parks)[4]	Geochemical anomalies; no estimate
Greystone Creek	Birch Mountains	Shaftesbury	Two outcrop samples yielded up to 939 ppm V, 761 ppm Zn, 228 ppm Ni (within national and provincial parks)[5]	Geochemical anomalies; no estimate
Hay River	Northwestern Alberta	Loon River	Six samples from four oil and gas well cores, over area of 30 by 50 km^2, depths <90 m, yielded between 515 and 1071 ppm V[6]	Geochemical anomalies; no estimate
Steen River	Northwestern Alberta	Loon River	Two core samples from drillhole ST-001 with 1184 and 581 ppm V at 215.5 and 218.5 m depth, respectively[7]	Geochemical anomalies; no estimate
Jura Creek	Mountains/Foothills	Exshaw	Ten rock grab samples yielded V >900 ppm over 4 m section, one sample up to 1545 ppm V; unknown areal extent[8]	Geochemical anomalies; no estimate
Mount Gass	Mountains/Foothills	Exshaw	Anomalies detected by handheld X-ray fluorescence analyzer[9]	Geochemical anomalies; no estimate
Crowsnest Pass	Mountains/Foothills	Exshaw	Three rock grab samples with V >900 ppm, one up to 3939 ppm, unknown vertical and areal extent[8]	Geochemical anomalies; no estimate

[1] Puritch et al. (2013)
[2] Eccles et al. (2013c, d)
[3] Sabag (1996b)
[4] Sabag (1996c)
[5] Dufresne et al. (2001)
[6] Lopez et al. (2020)
[7] Molak et al. (2002)
[8] Rukhlov and Pawlowicz (2011)
[9] Rokosh et al. (2016)
Abbreviations: Mountains/Foothills, Rocky Mountains and Alberta Rocky Mountain Foothills; V_2O_5, vanadium pentoxide

The Asphalt zone, which is located 30 km south of the Buckton zone (Figure 1), does not have a resource estimate due to insufficient drilling, however, it is a mineralized zone that warrants further exploration. Drilling results (two boreholes) identified an 11 m thick interval enriched in metals with weighted average grades of 674 ppm V_2O_5 and 131 ppm Ni (Table 8; Sabag, 1996b), which are similar to the grades found in the Buckton and Buckton South zones.

Other highly metalliferous black shale occurrences containing V and Ni exist in other parts of Alberta as well, however, they are underexplored and no resource estimates have been made (Figure 1, Table 8). For example, interesting geochemical anomalies exist in the Loon River Formation in northwestern Alberta. Metal concentrations from oil and gas well drillcore samples collected by the AGS yielded up to 1071 ppm V with anomalies occurring intermittently within a 25 m thick package extending for over 30 km in the Hay River area (Figure 1, Table 8; Lopez et al., 2020). Anomalies also occur in the Steen River area (Figure 1, Table 8) where two core samples from borehole ST-001 yielded 1184 and 581 ppm V at 215.5 and 218.5 m depth, respectively (Molak et al., 2002).

Highly metalliferous black shales also occur along the Rocky Mountains and Alberta Rocky Mountain Foothills, where long-lived deformation and uplift brought some of the older and deeper shale units of the WCSB to the surface. These occurrences include metal anomalies in black shale of the Exshaw Formation at Jura Creek, Mount Gass, and Crowsnest Pass (Figure 1, Table 8) and are associated with bentonite, barite, and phosphate (Rukhlov and Pawlowicz, 2011). At Jura Creek (Figure 1, Table 8), the basal bed of the Exshaw Formation consists of a conglomeratic sandstone with bone fragments and fish scales and exhibits high Zn content, whereas the black shale above contains phosphate nodules, calcareous to cherty concretions, and disseminated sulphide and shows high V values (Rukhlov and Pawlowicz, 2011; Rokosh et al., 2016). At Mount Gass, the Exshaw Formation black shale showed elevated Zn and Ni anomalies at the base, and high V in the middle and upper portions, measured using a portable X-ray fluorescence (XRF) analyzer (Figure 1, Table 8; Rukhlov and Pawlowicz, 2011). The Exshaw Formation shale at Crowsnest Pass is highly enriched in V with concentrations up to 3939 ppm (Figure 1, Table 8; Rukhlov and Pawlowicz, 2011). This is the highest V concentration found in near-surface shale in Alberta and merits further sampling and investigation.

5.3 Vanadium in Coal Fly Ash

Until recently, the majority of electricity in Alberta has been supplied from thermal coal-powered stations with significant capacity. Goodarzi (2006) described the composition of coal and different ashes from Capital Power Corporation's Genesee power plant west of Edmonton, which burns sub-bituminous coal. The content of V in the coal varies from 18 to 34 ppm, whereas in bottom and fly ash it was more concentrated, reaching 161 ppm in fly ash samples. It is interesting that the V:Ni ratio in coal fly ash was very similar to the ratio in bitumen, being approximately 3:1. The concentration is comparable to that in some heavy oils or dilbit.

6 Summary Discussion: Cumulative Potential of Major Sources in Alberta

Vanadium from petcoke, FTT, and partial upgrading may be up to 90% recoverable if appropriate processes are applied such as roasting or gasification of FTT. Such a potentially high recovery factor significantly enhances economic potential. Gupta et al. (2019) achieved ~98% recovery of hydrocarbons from FTT in laboratory settings. Thus, it is safe to assume that the potential recovery of V and Ni could be in a similar range of ~90%. During ashing or upgrading, V tends to be volatile and it may be expected to be found in columns where condensation and separation of hydrocarbon fractions occur (R. Gupta, pers. comm., 2019).

The authors regard the V and Ni development potential from refineries and fly ash as immediate, whereas the Clear Hills ironstone and Birch Mountains metalliferous organic-rich shale deposits have future potential, as development of these is not presently occurring. Combining the four major potential sources of V—Clear Hills ironstone, Birch Mountains metalliferous deposits, Scotford refinery and upgrader, and the Sturgeon refinery— results in a potential cumulative annual V_2O_5 production of ~10 500 t (Table 7). When compared with a world mining production of roughly 86 000 t in 2020 (U.S. Geological Survey, 2021a), this suggests that Alberta has the potential to become a significant player, not only in the production of V, but also VRBs. Realistically, if only the two refineries/upgraders are considered, Scotford and Sturgeon, the estimated 3735 t of V, is equivalent to a potential of ~6000 t of recoverable V_2O_5 assuming 90% recoverability (Table 7), or approximately 1100 MWh/yr of VRB capacity. In addition, there is no reason to think that at least part of V and Ni is recoverable from Imperial's and Suncor's refineries in the vicinity of Edmonton (Table 5).

Nickel in Alberta bitumen is present at a level that is about three times lower than V, but it is a valuable by-product that will contribute to the cost effectiveness of V production. In addition, a major Ni producer and refiner, Sherritt International Corporation, is located near Edmonton in the vicinity of the Scotford refinery and upgrader. Thus, further processing into value-added products such as battery electrodes and high-grade alloys aside from the high-grade metal may be more viable for Ni (Umicore, 2022). Following an announcement of Ontario and federal subsidies for Ford Motor Company of Canada's electrical vehicles and battery plants (The Canadian Press, 2020), it may be attractive for Alberta to become a part of such a value chain. Metallic wastes from two adjacent refineries, Scotford and Sturgeon, may produce about 1300 t of Ni annually (Table 7) with a potential to recover an additional ~300 t of Ni from Imperial's and Suncor's refineries in the vicinity of Edmonton (Table 5).

Alberta 'mined' about 11 000–13 000 t of Ni based on 2017 bitumen production (Table 4). In the meantime, production of mined bitumen increased from 74 Mt in 2017 (Table 1) to 90 Mt in 2019 or 21.6% (Alberta Energy Regulator, 2020a). Most of that increase was from PFT mines such as Suncor's Fort Hills, which ramped up production to 9.5 Mt, Imperial Kearl's 2nd oil sands processing train, and CNRL's 3rd processing train at the Horizon mine, which reached production levels higher than expected resulting in increased coke production of ~2.8 Mt in 2019 (Alberta Energy Regulator, 2020a). Such Ni tonnage may be able to contribute to a future Ontario supply chain of electrical vehicles (Unifor, 2020).

As described in Appendix 2, Tables 9 and 10, other refineries in Canada receive significant input of V and Ni embedded in heavy oils and bitumen. Although Alberta's accessing of these resources could require interprovincial and federal coordination, amounts of V and Ni are significant enough to improve the economics of their recovery if pooled together with Alberta resources.

Every additional 100,000 bbl/d of bitumen production capacity means that 1200–1390 t of V are pulled out from the ground every year in addition to 400–460 t of Ni. Although an increase in bitumen production beyond 2021 is uncertain, this study clearly demonstrates the potential of Alberta bitumen and its waste streams for the production of critical metals.

Molybdenum quantity in bitumen is much smaller than V and Ni concentrations, with Mo concentrations of only 8–10.4 ppm. Considering the total world production of about 300 000 t in 2020 (U.S. Geological Survey, 2021b) and with no country having production in excess of 50% of world capacity, the recovery of Mo from Alberta sources may not be as attractive as V and Ni. However, if Mo from such resources is recovered at minimal extra cost, then it may be a valuable contributor to the economics of V and Ni exploitation and production in Alberta. Based on Table 7, and assuming recoverable Mo as ~1/20 of V (Table 2), Mo potential from bitumen processing is in the range of 180–200 t of Mo metal just from the two upgraders/refineries—Scotford and Sturgeon. It is expected that Mo concentration is also increased in other streams such as FTT.

7 Conclusions

Vanadium has major potential to be extracted in Alberta since it is derived from heavy oils and bitumen that are premined, often preconcentrated in different forms, and are near- or at the surface. Such sources may not need the specific environmental and regulatory approvals that are expected from dedicated mines, making them accessible in a shorter period of time and more feasible for further exploitation and development. Vanadium concentrates, such as fly ash or metallic sludges, are often richer than average vanadium ores and practically ready for further processing.

Obtaining vanadium and nickel from froth treatment tailings (FTT) may be even more attractive than obtaining it from petcoke due to the economics of recovering them along with the hydrocarbons and other minerals. Considering other environmental benefits of processing FTT—such as reduction of pollution, odors, and major fugitive greenhouse gases—this stream may deserve more economic attention than normally given to other types of tailings. In addition, vanadium from two upgraders/refineries near Edmonton and two documented mineral exploration projects represent a value-added opportunity for an energy storage/battery industry in Alberta.

Nickel in Alberta bitumen is present at a level that is about three times lower than vanadium, but it is a valuable by-product that will contribute to the cost effectiveness of vanadium production. Further processing into value-added products—such as battery parts and high-grade alloys—may be more viable for nickel based on the proximity of processing plants and their development plans.

The economics of mining vanadium or nickel from bedrock in Alberta are at present uncertain, in part due to very little historical mining for metals in Alberta. The available estimates of metal resources are in most cases inferred (in-place or recoverable), and as such have very high uncertainty and are unsuitable for investment decisions or mine planning without significant further investigation. This is not meant to understate the high potential that the authors believe exists in Alberta.

Current provincial, national, and international efforts to advance electricity production from renewable sources requires an increased ability to store electricity for use during the time when renewable sources are less available and, potentially, for the stabilization of the electrical grid. In addition, distributed energy production may also require additional storage. Regardless of the motive, vanadium redox batteries are considered a stable long-term alternative. Alberta has been enriched with significant vanadium potential that could satisfy Canadian demand, and potentially beyond, for metals and batteries for the lower carbon economy.

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Appendix 1 – Acronyms and Definitions

Acronyms

AHS	Albian Heavy Synthetic [partially upgraded diluted bitumen (dilbit) produced from Shell Canada Limited Scotford refinery and upgrader]
AN	Aurora North [mine]
API	American Petroleum Institute
BHB	Borealis Heavy Blend [Suncor Energy Inc.'s diluted bitumen (dilbit)]
BCL	BC Light [light sour conventional crude produced from a number of oil battery sites in northeastern British Columbia]
BDY	Boundary Lake [light sour conventional crude oil produced in British Columbia]
CL	Cold Lake [bitumen produced from Cold Lake oil sands]
CHV	Conventional Heavy [oil]
FTT	froth treatment tailings
JP	Jack Pine mine
kbbl	thousand barrels
ML	Mildred Lake [mine]
MLSB	Mildred Lake Settling Basin
MRM	Muskeg River mine
MSW	Mixed Sweet Blend [benchmark conventionally produced light sweet crude oil for western Canada]
Mt	million tonnes [mega tonnes]
NFT	naphtha-based froth treatment
OSH	Suncor Synthetic H [Suncor Energy Inc.'s upgraded bottomless sour synthetic blend]
PAS	Premium Albian Synthetic [light sweet synthetic crude oil produced from Shell Canada Limited Scotford refinery and upgrader]
PFT	paraffinic froth treatment
ppm	parts per million
SCO	synthetic crude oil
SAGD	steam-assisted gravity drainage
SSX	Shell Synthetic Light [light sweet synthetic crude oil produced from Shell Canada Limited Scotford refinery and upgrader]
VRB	vanadium redox batteries
WCB	Western Canadian Blend [aggregate of heavy sour crude oil production]
WCS	Western Canadian Select [heavy sour blend of crude oil]

Definitions

Definitions for these terms come from a mixture of sources including Alberta Energy, Alberta Energy Regulator, Canadian Institute for Mining, Metallurgy and Petroleum, Society of Economic Geologists, and Natural Resources Canada.

AER ST Reports: Serial publications termed 'Statistical Reports' issued on a regular basis (monthly, quarterly, annually) by the Alberta Energy Regulator. Each title is assigned a unique publication number prefixed by the two-letter code 'ST'. The reports and data are accessible online (https://www.aer.ca/providing-information/data-and-reports/statistical-reports.html).

asphaltenes: Molecular substances found in crude oil, along with resins, aromatic hydrocarbons, and saturates.

dilbit: Bitumen diluted with one or more lighter petroleum products, typically natural-gas condensates such as pentane, or naphtha from synthetic crude oil production. Diluting bitumen makes it much easier to transport, for example in pipelines.

preliminary economic assessment: A study, preliminary to a prefeasibility or feasibility study, that includes an economic analysis of the potential viability of the extraction of mineral resources.

geochemical anomaly: A concentration of one or more elements in rock, soil, sediment, vegetation, or water that is markedly higher or lower than background. The term may also be applied to hydrocarbon concentrations in soils. A threshold relative to the background is defined to determine higher and lower values.

green energy: Energy from natural resources such as sunlight, wind, rain, tides, plants, algae, and geothermal heat. These energy resources are renewable, meaning they are naturally replenished.

mineral deposit: Natural concentration of minerals in the Earth's crust that has been explored and delimited.

mineral occurrence: Natural concentration of a mineral, of no specified tonnage, which is anomalous by some measure.

mineral resources: "Concentration or occurrence of solid material of economic interest in or on the earth's crust in such form, grade or quality and quantity that there are reasonable prospects for eventual economic extraction." "Mineral resources are sub-divided, in order of increasing geological confidence, into inferred, indicated and measured categories."[1]

mineral reserves: "Those parts of Mineral Resources which, after the application of all mining factors, result in an estimated tonnage and grade which...is the basis of an economically viable project after taking account of all relevant Modifying Factors." "Modifying Factors...include, but are not restricted to, mining, processing, metallurgical, infrastructure, economic, marketing, legal, environmental, social and governmental factors." "Mineral reserves are sub-divided in order of increasing confidence into Probable Mineral Reserves and Proven Mineral Reserves."[1]

National Instrument 43-101: The *Standards of Disclosure for Mineral Projects* in Canada. It "governs a company's public disclosure of scientific and technical information about its mineral projects...based on information provided by a 'qualified person'."[2] This includes information about the exploration, appraisal, and development of mineral projects.

ore deposit: Mineral deposit that has been tested and can be mined at a profit.

pumped storage: Storing water in a reservoir and then generating energy by moving the water to a reservoir at a lower elevation.

showing: Mineral occurrence with no indicated economic feasibility; it may or may not warrant additional study.

[1] CIM Standing Committee on Reserve Definitions (2014): CIM Definition Standards for Mineral Resources & Mineral Reserves; Canadian Institute of Mining, Metallurgy and Petroleum, 9 p., URL <https://mrmr.cim.org/media/1128/cim-definition-standards_2014.pdf> [March 2022].

[2] Canadian Institute of Mining, Metallurgy and Petroleum (2022): Canadian Securities Regulatory Standards for Mineral Projects; Canadian Institute of Mining, Metallurgy and Petroleum, URL <https://mrmr.cim.org/en/standards/canadian-securities-regulatory-standards-for-mineral-projects/> [March 2022].

Appendix 2 – Other Refineries

Regina Co-op Refinery

The Regina refinery is owned by Federated Co-operatives Limited (FCL). Its raw oil supply (Table 9) was modelled based on a Fosterton Heavy (F) blend that has about 106 ppm of V and 46 ppm of Ni (CrudeMonitor, 2019). This refinery received about 8600 m^3/day (d; 54,000 bbl/d) of heavy crude with the rest being synthetic crude oil (SCO) in 2017 (Canadian Energy Research Institute, 2018). Based on the metal content in Fosterton Heavy, it turns out that the Regina refinery receives annually in excess of 300 t of V and about 130 t of Ni. Although the authors are not sure if any of this quantity is recoverable, the amount of V and Ni may be a complementary source of battery metals for a potential metal refinery and/or battery plant.

Chevron Burnaby Refinery

Although Canadian Energy Research Institute (2018) showed an 8758 m^3/d (55,000 bbl/d) capacity with some heavy oil and coking capacity at the Chevron Burnaby refinery, National Energy Board (2019) indicated that deliveries of heavy oil (bitumen) to Burnaby (Table 9) in 2017 were very low, while the great majority of heavy oil was exported through the Sumas terminal at about 3981 m^3/d (25 kbbl/d). These exports increased in 2018. Thus, V in the Chevron Burnaby refinery was assumed to come from northeastern British Columbia light oils with 11 ppm of V and 4 ppm of Ni in light oil (BC Light [BCL] and Boundary Lake [BDY] mix; see CrudeMonitor, 2019 for fuel codes), while heavy oil was assumed to contain 95 and 44 ppm of V and Ni, respectively, as is in the Western Canadian Blend (WCB; CrudeMonitor, 2019). This refinery has an input of about 21 t of Ni annually. Total metals seem to be low in this refinery although the concentrations of V and Ni in its metallic sludge are probably high.

Eastern Canada Refineries

The assessment of the potential of the refineries in eastern Canada for metals was based on the Canadian Energy Research Institute (2018) report that provided the type of feedstock, and real utilization versus total capacity (Table 10). Bitumen was assumed to be diluted bitumen (dilbit) with limited V and Ni concentrations of 160 ppm and 60 ppm, respectively. Light oil metal content was based on a Mixed Sweet Blend (MSW; Superior) with a low V and Ni content, whereas heavy oil was assumed to be similar to Conventional Heavy (CHV) at Superior blending point. For this purpose, it was assumed that SCO doesn't have any metals. The refinery in Come by Chance, Newfoundland, was not considered since it is entirely supplied by imported oil.

Table 9. Potential of vanadium (V) and nickel (Ni) in western Canada refineries (outside Alberta; data from Natural Resources Canada, 2005; Canadian Energy Research Institute, 2018).

Refinery	Type	Capacity (m^3/day)	Oil Feedstock (type)	Oil Feedstock (m^3/day)	Code[1]	Density (tonnes/m^3)	V (ppm)	Ni (ppm)	V (tonnes)	Ni (tonnes)
FCL Regina, SK	Hydro-cracking/ coking	23 089	Heavy	8 599	F	0.925	106	46	307.3	133.3
Chevron Burnaby, BC	Coking	8 758	Light	2 882	BCL BDY	0.83	11	4	9.6	3.5
			Heavy	366	WCB	0.93	95	44	11.8	5.5
Total									**319.7**	**142.3**

[1] Fuel type codes as reported by CrudeMonitor (2019)

Abbreviations: BCL, BC Light; BDY, Boundary Lake; Chevron, Chevron Corporation; F, Fosterton Heavy; FCL, Federated Co-operatives Limited; WCB, Western Canadian Blend

Although eastern refineries have a larger installed capacity than those in the Prairies, they processed only 7978 m^3/d (50.1 kbbl/d) of bitumen and 12 882 m^3/d (80.9 kbbl/d) of heavy oil resulting in a lower metal input to these plants. The SCO was used at 28 662 m^3/d (~180 kbbl/d), whereas the supply of light oil was about 120 860 m^3/d (759 kbbl/d; Canadian Energy Research Institute, 2018).

Rough calculations show that an approximate V input into those plants is about 1180 t (Table 10) or about 394 MWh of battery storage capacity.

The input of Ni into eastern refineries is in the ballpark of 510 t annually (Table 10), but not much is known about its potential.

Molybdenum input into eastern refineries, based on only 8 ppm in bitumen is about 23 t/yr, plus potentially smaller amounts in heavy oil. Recovering this Mo together with V and Ni would make sense only if they are combined with other sources of V and Ni from bitumen.

Table 10. Potential of vanadium (V) and nickel (Ni) in eastern Canada refineries (data from Natural Resources Canada, 2005; Canadian Energy Research Institute, 2018; CrudeMonitor, 2019).

Refinery	Type	Capacity (m^3/day)	Oil Feedstock (type)	Oil Feedstock (m^3/day)	Code[1]	Density (tonnes/m^3)	V (ppm)	Ni (ppm)	V (tonnes)	Ni (tonnes)
Imperial	Coking	19 268	Light	8 185	MSW	0.832	6.6	4	16.4	9.9
Sarnia,			Heavy	955	CHV	0.925	120	50	38.7	16.1
ON			Bitumen	4 013	Dilbit	0.985	160	60	230.5	86.4
Shell	Cracking	11 943	Light	5 971	MSW	0.832	6.6	4	12.0	7.2
Corunna,			Heavy	2 357	CHV	0.925	120	50	95.3	39.7
ON										
Suncor	Hydro-	13 535	Light	7 484	MSW	0.832	6.6	4	15.0	9.1
Sarnia,	cracking		Heavy	2 357	CHV	0.925	120	50	95.3	39.7
ON										
Imperial	Cracking	17 835	Light	9 825	MSW	0.832	6.6	4	19.7	11.9
Nanticoke,			Heavy	2 357	PCH	0.925	120	50	95.3	39.7
ON										
Suncor	Cracking	21 815	Light	17 357	MSW	0.832	6.6	4	34.7	21.1
Montreal,			Bitumen	2 611	Dilbit	0.985	160	60	150.0	56.2
QC										
Valero	Cracking	42 197	Light	21 003	MSW	0.832	6.6	4	42.0	25.5
Levis,			Heavy	1 290	CHV	0.925	120	50	52.2	21.7
QC			Bitumen	1 847	Dilbit	0.985	160	60	106.1	39.8
Irving	Cracking	50 637	Light	39 905	MSW	0.832	6.6	4	79.9	48.4
St. John,			Heavy	2 436	CHV	0.925	120	50	98.6	41.1
NB										
Total									**1 181.6**	**513.7**

[1] Fuel type codes as reported by CrudeMonitor (2019)
Abbreviations: CHV, Conventional Heavy; dilbit, diluted bitumen; Imperial, Imperial Oil Limited; Irving, Irving Oil Limited; MSW, Mixed Sweet Blend; PCH, Premium Conventional Heavy; Shell, Shell Canada Limited; Suncor, Suncor Energy Inc.; Valero, Valero Energy Corporation