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Investment in new tungsten mining projects

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ABSTRACT

This paper studies investments in new tungsten mining projects, analyzing in-depth five ready-to-go projects around the world that were presented to the financial markets by listed companies to obtain funds so that they could start operations in the near future: the Barruecopardo open-cut project in Spain (Ormonde Mining); Kilba open-cut project in Australia (Tungsten Mining); Hemerdon open-cut project in the United Kingdom (Wolf Minerals); Sangdong underground project in South Korea (Woulfe Mining); and King Island Scheelite, a mixed open-cut and underground project in Tasmania (King Island Scheelite). These investment projects were selected on the basis of having completed a Definitive Feasibility Study on October 2014 (Barruecopardo, Hemerdon, Sangdong and King Island Scheelite) according to Bloomberg. In addition, an Australian project was added within the study (Kilba) due to the high number of Australian mining companies that are developing tungsten mining projects around the world.

The conclusions of this research clearly define the future direction in which mining reporting standards should develop in relation to feasibility analysis and provide a strong tool to address the initial steps for analyzing future investments in tungsten mining projects by estimating the initial investment and processing plant costs and operating costs based on the planned mining and processing parameters.

1. Introduction

The Raw Materials Initiative was developed to manage and evaluate responses to the raw materials policy at the European level (European Commission, 2013). Within this initiative, twenty one critical raw materials were assessed as being fundamental to the European economy based on concerns regarding over supply security to Western processors in addition to other considerations, such as price increases and price volatility. Among these, tungsten is the raw material with the highest economic importance and with a medium supply risk; moreover, the British Geological Survey (2012) also ranked tungsten at the top of their metal "Risk List", immediately after the rare earth elements.

In accordance with this suggestion, the "Study on Critical Raw Materials at EU Level" (Chapman et al., 2013) proposed several actions. We would like to highlight two: "to establish links with the future coordination and support action under Horizon 2020 in which the concept of deposits of public importance will be explored" and "to identify more clearly and assess the exploitation of resources and reserves of critical and other raw materials in the EU and linked countries".

According to the Group (2011), the European Union (18.0%), United States (15.2%) and Japan (7.8%) are the major consumers behind China (52.8%). With the significant growth of domestic tungsten consumption in China, less Chinese tungsten is available for the world market. This will support high tungsten prices in the near future.

The primary supply of tungsten within the EU is currently less than 3%. China is the largest producer in the world, attaining 85% of total production, which represents approximately 90% of the supply of the European Union supply. Therefore, by attempting to secure reliable and undistorted access to critical raw materials at the EU level, future mining should occur in Europe. Most of this mining should be conducted in mines and ore bodies that have been exploited or, at least, previously studied. Although the ore grades of commercially mined deposits have declined over time, technical progress combined with increasing prices usually expands their potential, and there is no need to repeat previous expensive exploration efforts.

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Tungsten is essential for a wide range of modern technologies. Through its unique combination of characteristics (high density, highest melting point of all metals, and low reactivity/toxicity), it is irreplaceable in a wide range of applications: in cemented carbide, a ceramic providing a suitable combination of both hardness and toughness that is widely used for producing various machine tools; super alloys and high speed steels, increasing their durability, hardness and corrosion resistance in cutting and drilling tools; mill products; and several applications in the chemical industry.

The total yearly production of mined tungsten is very small compared with that of base metals; more recent estimates are that there is 90,000 t of primary tungsten production, equivalent to 114,000 t of tungsten trioxide.

The apportionment of a primary tungsten estimation is approximately as follows:

- 76,500 tpa (tons per annum) from Chinese mines (circa 85% of world production).
- 9000 tpa from Western (or Western-oriented) economies (circa 10%).
- 4500 tpa from other communist countries and members of the Commonwealth of Independent States (circa 5%).

According to Roskill Information Services, on September 2013, the forecasted average demand growth to 2020 for tungsten is expected to be moderate, 3–4.5%, with a balanced market.

This paper studies the investment in new tungsten mining projects, analyzing in-depth five ready-to-go projects around the world that were presented to the financial markets by listed companies to obtain funds so that they could begin operations in the next future: the Barruecopardo open-cut project in Spain (Ormonde Mining); Kilba open-cut project in Australia (Tungsten Mining); Hemerdon open-cut project in the United Kingdom (Wolf Minerals); Sangdong underground project in South Korea (Woulfe Mining); and King Island Scheelite, a mixed open-cut and underground project in Tasmania (King Island Scheelite). These projects were selected on the basis of having completed a Definitive Feasibility Study on October 2014 (Barruecopardo, Hemerdon, Sangdong and King Island Scheelite) according to Bloomberg. In addition, an Australian project was added to the study (Kilba) due to the high quantity of Australian mining companies that are developing tungsten mining projects around the world.

2. Forecast of tungsten prices

Prices for tungsten concentrates are mainly quoted in metric ton units (mtu), which consist of 10 kg of WO_3, as contained in the particular material (concentrates or APT). There are also quotes for a master alloy called ferro-tungsten as well as tungsten carbide, tungsten bar W-4 and tungsten oxide WO_3 99.95% minimum. The last three are solely quoted in China; therefore, we will focus our price forecasts on those with European quotations:

- Tungsten trioxide (WO_3), containing 79.3% of tungsten metal. Tungsten trioxide ore with 65% WO_3 minimum is quoted in China (RMB/mt) and in Russia (USD/mtu), whereas in Africa, the quote is for 50% WO_3 minimum (USD/mtu); tungsten trioxide with 99.95% WO_3 minimum is quoted solely in China, both in RMB/mt and FOB USD/mtu.
- Ammonium Paratungstate (APT) is the main secondary product made from concentrates. APT with a minimum of 88.5% WO_3 is quoted in China (RMB/mt and FOB USD/mtu) and in Europe (USD/mtu).
- Ferro-tungsten is a master alloy that is used in the production of tungsten-containing steels. This alloy is quoted in Europe with a minimum of 75% USD/kg W, in China (RMB/mt and FOB USD/kg W) and in Vietnam (USD/kg W).

That a product quotation implies a strict parameterization of the lot size, form, location, payments, chemical composition or accepted brands must be considered. Price specifications differ according to the product and the market, and the typical parameters must be considered in addition to the following: basis (FOB, in-warehouse, free-delivered duty-paid, domestic, etc.), origin, currency/unit, inco term, price type, frequency, publication, minimum lot size, minimum and maximum gauge, gauge unit, and sometimes, packaging (Metal Bulletin, 2014). It should be noted that the FOB (free on board) price includes the cost of the goods (including all transportation and insurance costs) from the manufacturer to the port of departure and the cost of loading the vessel in the quoted price, whereas the buyer must bear all costs and risks of loss or damage to the goods from that point.

2.1. SETAR model

To select a suitable model for developing tungsten price forecasting, we first attempted to develop an Auto-Regressive Integrated Moving Average (ARIMA) model (Kriechbaumer et al., 2014); however, from the twelve forecasted months, this model returned the average of the time series. Therefore, this model was not useful for our purposes.

Second, a feedforward artificial neural network model was used (Sánchez Lasheras et al., 2010). The results did not outperform the results obtained with the ARIMA model, even after using a multilayer perceptron with a backpropagation algorithm that is standard for any supervised-learning pattern recognition process. The results were not suitable because the algorithm memorized instead of learned.

Finally, SETAR models, first introduced in 1977 by Tong and fully developed in the pioneering paper by Tong and Lim (1980), were more suitable for long-term forecasting.

Self-Exciting Threshold AutoRegressive (SETAR) models are usually applied in statistics to time series data and are considered to be an extension of the autoregressive models; these allow a higher flexibility degree for modeling parameters through regime switching behavior.

Given "X_t", a time data series, the SETAR model allows for understanding and predicting future values for this series, assuming that when the series enters different regimes, its behavior changes. Switching from one regime to another depends on the past values of the series (this is why it is called Self-exciting).

Consisting of "k" autoregressive parts and belonging to different regimes, the model is known as the SETAR (k,p) model, with "k" being the number of regimes and "p" being the autoregressive part order.

Considering an AR(p) model for a y_t time series:

$$y_t = \gamma_0 + \gamma_1 y_{t-1} + \gamma_2 y_{t-2} + \dots + \gamma_p y_{t-p} + \varepsilon_t$$

where:

γ_i for i= 1, 2,…, p are autoregressive coefficients that are assumed to be constant over time;

$\varepsilon_t \sim^{iid} WN(0; \sigma^2)$ is the white-noise error (with constant variance).

In vector form:

$$y_t = \mathbf{X_t}\boldsymbol{\gamma} + \sigma\varepsilon_t$$

where:

$\mathbf{X_t} = (1, y_{t-1}, y_{t-2}, \dots, y_{t-p})$ is the variables column vector;

$\boldsymbol{\gamma}$ is the parameters vector; and

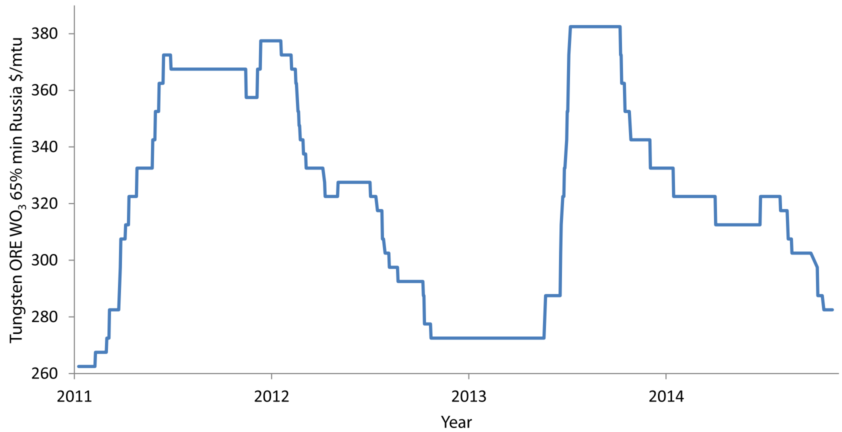

Fig. 1. Baseline situation of tungsten ore WO_3 65% minimum Russia USD/mtu.
Source: Asian Metal Inc.

$\varepsilon_t \sim^{iid} WN(0;\ 1)$ is the white-noise error (with constant variance).

SETAR models can be considered by means of auto-regressive model extension, allowing for changes in the modeling parameters according to weakly exogenous threshold variables that are assumed to be "y" past values, for example, "y_{t-d}", with "d" being the delay parameter.

Thus, the SETAR model may be represented as:

$$y_t = \mathbf{X_t}\boldsymbol{\gamma}^{(j)} + \sigma^{(j)}\varepsilon_t \quad if \quad r_{j-1} < z_t < r_j$$

where:

$\mathbf{X_t} = (1, y_{t-1}, y_{t-2}, \ldots, y_{t-p})$ is the variables column vector; and

$-\infty = r_0 < r_1 < \ldots < r_k = +\infty$ are non-trivial "$k+1$" thresholds that divide the "z_t" domain into k regimes.

Hansen (2011) provides a comprehensive review of the different model developments.

2.2. Tungsten ORE WO_3 65% minimum Russia USD/mtu

Fig. 1 presents the price evolution of the Tungsten ore from 2011 to November 2014 (Asian Metal Inc., 2014a). Applying the SETAR model, the forecast for the next five years is shown in Fig. 2.

According to this forecast, tungsten ore prices will tend to increase during the next five years; however, they will remain at approximately 320 USD/mtu from the end of 2016 onwards. This result is far from the maximum of 380 USD/mtu achieved in 2013.

2.3. Tungsten APT 88.5% minimum Europe USD/mtu

Fig. 3 shows the price evolution of the tungsten APT from 2006 to November 2014 (Asian Metal Inc., 2014b).

Applying the SETAR model, the forecast for the next five years is shown in Fig. 4.

The evolution is similar to that of tungsten ore, although the growth is more linear and less pronounced.

From 2018, the price is expected to maintain a value of approximately 360 USD/mtu; this is also far from the maximum of 450 USD/mtu achieved in 2011 or from 400 USD/mtu achieved in 2013.

2.4. Ferro-tungsten 75% minimum Europe USD/KG W

Fig. 5 presents the price evolution of ferro-tungsten from 2006 to November 2014 (Asian Metal Inc., 2014c).

Applying the SETAR model, the forecast for the next five years is shown in Fig. 6.

For the ferro-tungsten prices, the SETAR model forecasts a continued price reduction until 2017 and then a quick recovery, achieving a steady level in 2018 and then a price oscillation between 39 and 40 USD/kg W.

Therefore, tungsten prices will tend to increase during the ensuing five years in a steady manner, but remain far from the maximum prices achieved at the beginning of 2012 and the end of 2013.

The prices will also remain far from the minimum prices achieved at the end of 2009 and the beginning of 2010.

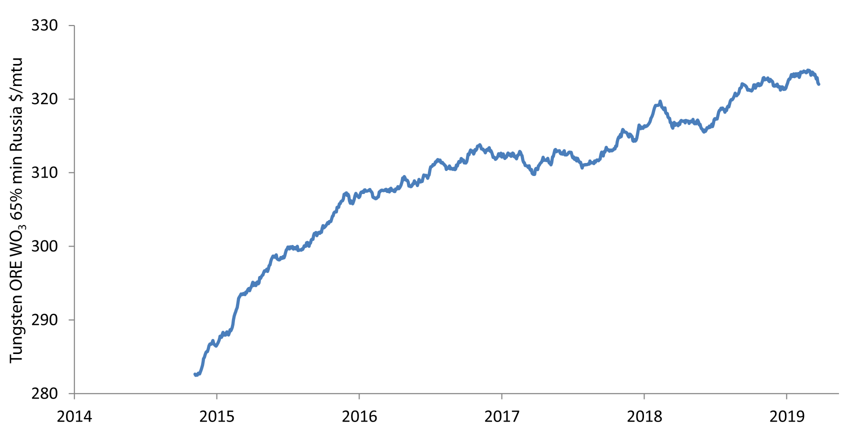

Fig. 2. Five years forecast of tungsten ore WO_3 65% minimum Russia USD/mtu.

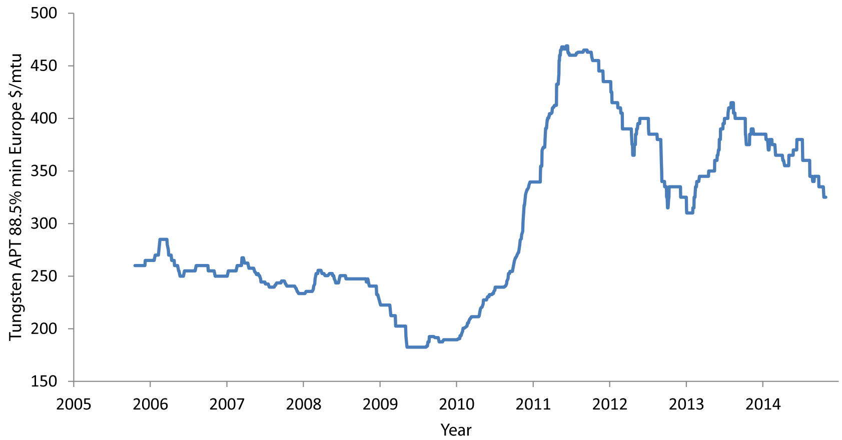

Fig. 3. Baseline situation of tungsten APT 88.5% minimum Europe USD/mtu.
Source: Asian Metal Inc.

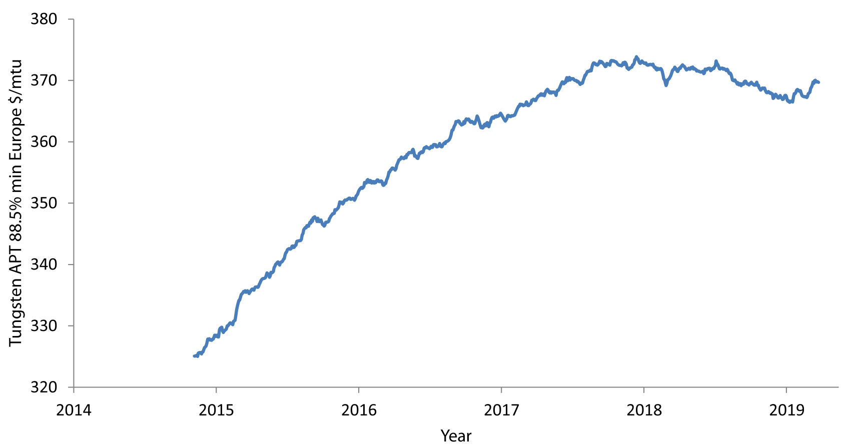

Fig. 4. Five year forecast of tungsten APT 88.5% minimum Europe USD/mtu.

Fig. 5. Baseline situation of ferro-tungsten 75% minimum Europe USD/kg W.
Source: Asian Metal Inc.

3. Barruecopardo project (Spain)

Barruecopardo Project, which is 100% owned by Ormonde Mining PLC and located in Western Spain (Salamanca), is a mine that was previously operated during the past century and produced a high grade tungsten concentrate; it has already obtained a Mining Concession and expects to begin operation in 2015.

Conceived as a nine year open-cut project with a strike length of over 1.6 km, the tungsten mineralization is predominantly coarse grained scheelite occurring in quartz veins, with minor traces of wolframite.

The project capital cost is 70 M€, including taxes, working capital and debt servicing, with cash operating costs of 99 €/mtu; it is expected to produce an average of 227,000 mtu WO_3 per year for nine years. The investment costs are shown in Table 1.

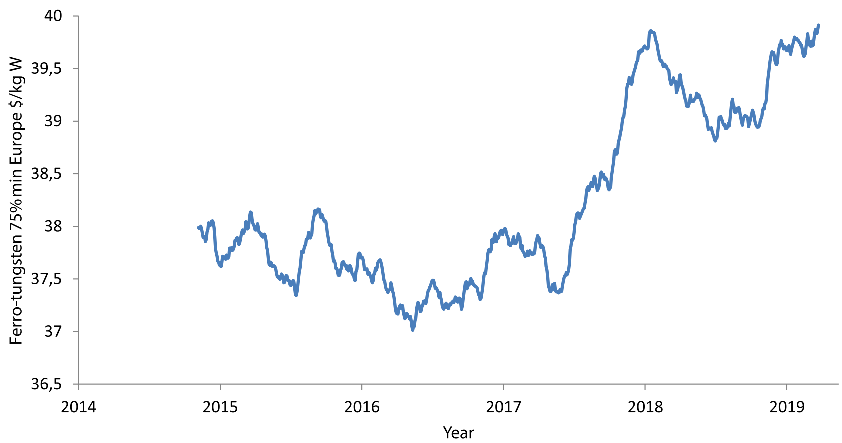

Fig. 6. Five year forecast of ferro-tungsten 75% minimum Europe USD/kg W.

Table 1
Barruecopardo capital costs. Source: Ormonde Mining Plc. (2013).

ITEM	COST (M€)
Mining	5.62
Process Plant, associated Infrastructure and EPCM	38.59
Water Management System	11.81
Owners Costs	7.49
Contingency	6.34
TOTAL	**70.0**

Table 2
Barruecopardo key financial outcomes. Source: Ormonde Mining Plc. (2013).

Euro/USD	1.30
APT Price	350 USD
Pre-tax ungeared NPV (8% discount rate)	120 M€
Pre-tax IRR	52%
Average annual pre-tax net operating cash flow	29 M€
Pre-tax net operating cash flows over life of mine	261 M€
Capital Payback Period (Years)	2.0

Table 3
Barruecopardo ore reserves. Source: Ormonde Mining Plc. (2013).

Classification	Mt	Grade (WO_3%)	mtu (WO_3) (M)
Proven	4.96	0.33	1.64
Probable	3.73	0.26	0.98
TOTAL	**8.69**	**0.30**	**2.61**

Table 2 shows the key financial outcomes of the feasibility study.

The ore reserves of Barruecopardo are shown in Table 3. The average strip ratio (waste to ore) is 6.3:1, providing a total of 63.1 Mt of material to be extracted.

This project combines traditional drill and blast open pit mining and uses local contractors; further processing of tungsten ore will use gravity-based concentration.

The processing plant will have a 78% recovery and is designed to produce a 74.6% WO_3 concentrate (the industry standard is 65%). The plant is based on three stages: a crushing circuit to obtain a 5-mm crush size, followed by screening at 1 mm; a gravity pre-concentration phase; and a final clean-up tabling circuit to remove sulfides.

Table 4
Barruecopardo mining and processing figures. Source: Ormonde Mining Plc. (2013).

Phase (9 years)	kt per year	kt total	Grade (WO_3%)
Mining	6930	62,370	–
Processing plant	1100	9900	0.3
Final product	2.27	20.43	74.6

Table 5
Barruecopardo operating costs. Source: Ormonde Mining Plc. (2013).

ITEM	€/t ore	€/mtu
Mining (ore)	4.07	17.3
Mining (waste)	14.47	61.6
Processing	3.50	14.9
General and Administration	1.27	5.4
TOTAL COST	**23.31**	**99.2**

Table 4 presents the quantities of material processed per year by the project.

The life of mine cash operating costs are 23.31 €/t ore and 99.2 €/mtu, delineated as shown in Table 5.

Figures expressed in €/t ore refer to the tons entering the processing plant and, to translate these to €/mtu, the grade of the mineral entering the plant (0.3% of WO_3), and the plant recovery (78%) must be considered:

$$23.31\text{ €/t ore}/(0.3 \times 0.78) \approx 99.2\text{ €/mtu}$$

4. Kilba project (Australia)

Tungsten Mining NL is an Australian resources company listed on the Australian Stock Exchange (ASX:TGN) whose main focus is a fully permitted project named Kilba, located in Western Australia. It was previously explored in the 1980s by Union Carbide and was targeting initial production for late 2014; however, this point has not yet been confirmed.

Conceived as a seven year open-cut project with a single elongated pit that is 1.2 km in length in the main zone, the tungsten bearing ore is scheelite within skarn-style

Table 6
Kilba capital costs. Source: Tungsten Mining NL (2013).

ITEM	COST (M€)
Process Plant	33.9
Infrastructure	6.9
Stores	2.3
TOTAL (including 15% contingency)	**43.1**

Table 7
Kilba key financial outcomes. Source: Tungsten Mining NL (2013).

Euro/USD	1.30
APT Price	440 USD
Pre-tax ungeared NPV (7% discount rate)	27.7 M€
Pre-tax IRR	34%
Capital Payback Period (Years)	1

Table 8
Kilba identified mineral resources. Source: Tungsten Mining NL (2013).

Classification	Mt	Grade (WO_3%)	mtu (WO_3) (M)
Indicated	1.3	0.30	4.0
Inferred	3.7	0.26	9.8
TOTAL	**5.0**	**0.27**	**1.4**

mineralization, which his easy to liberate and process.

The project capital cost is 43.1 M€ with cash operating costs of 163.1 €/mtu; in addition, the project expects to produce an average 154,000 mtu WO_3 per year for seven years. The capital costs are shown in Table 6 (the exchange rates used were: 1 €=1.30 USD and 1 €=1.45 AUD). The key financial outcomes of the feasibility study are shown in Table 7.

The different mineralization zones contain a total resource of 5 Mt with 0.27% WO_3 (based on a 0.10% WO_3 cut-off). Table 8 shows the Kilba identified mineral resources.

The compliant resource statements of the different projects usually refer to the Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (JORC Code, 2012); the Canadian standards for public disclosure that an issuer provides containing scientific and technical information concerning the mineral properties/projects (National Instrument 43-101, 2011); or the European standard (PERC Reporting Standard, 2013). In all of these codes, a mineral reserve is "the economically mineable part of a measured and/or indicated mineral resource"; therefore, the Kilba project has, according to the information provided in Table 8, a quantity of mineral reserves of 1.3 Mt @ 0.3%.

Kilba proposed a conventional drill-and-blast mining operation to feed a processing plant with a capacity of 750,000 t per year, but initially only treating the ore mined portion above a cut-off limit of 0.3% to compress mining solely within the first 3 years of operation at a rate of 1.7 Mt ore per year.

The processing plant, which has an 80% recovery, was designed to produce 68% WO_3 concentrate (the industry standard is 65%), with a plan to process higher grade ore during the initial years to obtain a capital payback period of 1 year.

The processing plant is based on three stages: a two-stage crushing circuit, followed by rod-mill grinding, and a gravity separation phase. Table 9 presents the quantities processed per year by the project.

The life of mine cash operating costs are 23.31 €/t ore and 163.1 €/mtu, delineated as shown in Table 10.

Table 9
Kilba mining and processing figures. Source: Tungsten Mining NL (2013).

Phase (7 years)	kt per year	kt total	Grade (WO_3%)
Mining (3 years)	1842	5526	–
Processing plant	750	5250	0.25
Product	1.54	10.78	> 68

Table 10
Kilba operating costs. Source: Tungsten Mining NL (2013).

ITEM	€/t ore	€/mtu (average)
Mining	1.69	11.0
Processing	16.9	111.5
Administration	6.15	40.7
TOTAL COST	**24.7**	**163.1**

Table 11
Hemerdon capital costs. Source: Wolf Minerals Ltd. (2011, 2014).

ITEM	COST (M€)
Process Plant	93.7
Infrastructure	17.1
Land and Property Purchases	17.5
Owner costs	20.1
Contingency	8.8
TOTAL	**157.2**

Table 12
Hemerdon key financial outcomes of the feasibility study. Source: Wolf Minerals Ltd. (2011, 2014).

Euro/USD	1.30
APT Price	360 USD
NPV (8% discount rate)	81.4 M€
IRR	21%
Capital Payback Period (Years)	3.25

5. Hemerdon project (United Kingdom)

The Hemerdon Project (Devon, United Kingdom) is a 7-year open-cut project from Wolf Minerals Ltd, another Australian resources company that is also listed on the Australian Stock Exchange (ASX:WLF). This project is located in an area that was previously studied by AMAX (1976–1980). The project will extract wolframite and cassiterite (tin) from large granite deposits and plans to begin production in 2015.

The project capital cost is 157.2 M€, with cash operating costs of 99.2 €/mtu, and it expects to produce an average 345,000 mtu WO_3 per year plus 460 tpa of tin. The capital costs are shown in Table 11 (exchange rates used were: 1 €=1.30 USD and 1 €=1.45 AUD).

The key financial outcomes of the feasibility study are shown in Table 12.

Wolf Minerals Ltd has scheduled reserves over a 10-year life period (although the project is initially planned to last for 7 years), with a strip ratio of 1.5:1 and a waste-to-ore strip ratio of 0.7:1, providing a maximum material movement of 7–10 Mtpa to be extracted from the pit. The proposed pit design is 800 m by 450 m

Table 13
Hemerdon identified ore reserves. Source: Wolf Minerals Ltd. (2011, 2014).

Classification	Mt	Grade (WO_3%)	Sn%	mtu (WO_3) (M)
Proven	23.5	0.19	0.03	4.47
Probable	3.2	0.19	0.03	0.61
TOTAL	26.7	0.19	0.03	5.08

Table 14
Hemerdon mining and processing figures. Source: Wolf Minerals Ltd. (2011, 2014).

Phase (7 years)	kt per year	kt total	Grade (WO_3%)
Mining	8500	59,500	–
Processing plant	3000	21,000	0.25
Product	3.45	24.15	65

Table 15
Hemerdon operating costs. Source: Wolf Minerals Ltd. (2011, 2014).

ITEM	€/t ore	€/mtu
Mining	6.17	49.2
Processing	4.89	40.8
Administration	1.42	9.2
SUBTOTAL COST	**12.48**	**99.2**
Tin credits	–	(15.4)
TOTAL COST	**12.48**	**83.8**

and is 200 m deep.

Table 13 shows the Hemerdon identified ore reserves.

The processing plant will separate gangue from Wolframite and Cassiterite using the following operations: crushing, screening and scrubbing; dense media separation; de-slime and gravity separation; concentrate processing; and finally, tailings thickening and disposal.

The processing plant of the Hemerdon project, designed for 3 Mtpa, will produce tungsten concentrate (65% WO_3) and tin concentrate (40% Sn), with a tungsten recovery between 58% for soft granite and 66% for hard granite. Table 14 presents the quantities processed per year in the project.

Finally, a breakdown of the estimates of the life of mine operating costs for the Hemerdon Project is shown in Table 15.

6. Sangdong project (Republic of Korea)

The Sangdong Project, which is completely developed by Woulfe Mining Corporation, is located in the Republic of Korea (South Korea) and is situated approximately 170 km from Seoul. The deposit was mined from 1940 to 1992 using underground methods. The ore is a tungsten skarn deposit, with scheelite as the primary tungsten mineral, containing molybdenite, pyrrhotite, bismuthinite, sphalerite and chalcopyrite.

This project was planned through an underground transverse drift- and -fill mining method, which is suited to high-productivity, for a mine life of 11.5 years. Based on the mining method, the project will extract 1.2 Mt per year, with an extraction ratio of 81% of the indicated resource.

The project capital cost is 116.4 M€, with cash operating costs of 131.63 €/mtu, and it expects to produce an average 435,000 mtu of APT per year at a grade of 88.63% WO_3. Molybdenum was not included in the project because additional processing engineering would be required to obtain a saleable product, and the project did not want to increase the amount of investment needed.

Table 16
Sangdong capital costs. Source: Woulfe Mining Corporation (2012).

ITEM	COST (M€)
Process Plant	51.0
APT Process Plant	14.8
Infrastructure	13.0
Mining	28.9
Owner costs	2.2
Contingency	6.0
TOTAL	**115.9**

Table 17
Sangdong key financial outcomes of the feasibility study. Source: Woulfe Mining Corporation (2012).

Euro/USD	1.3
APT Price	398 USD
NPV (8% discount rate)	307.9 M€
IRR	46%
Capital Payback Period (Years)	2.2

Table 18
Sangdong ore reserves. Source: Woulfe Mining Corporation (2012).

Classification	Mt	Grade (WO_3%)	MoS_2%	mtu (WO_3) (M)
Probable	13.3	0.425	0.039	5.65
TOTAL	**13.3**	**0.425**	**0.039**	**5.65**

Table 19
Sangdong mining and processing figures. Source: Woulfe Mining Corporation (2012).

Phase (11.5 years)	kt per year	kt total	Grade (WO_3%)
Mining	1200	13,300	0.425
Processing plant	1200	13,300	0.425
Product (APT)	4.35	50.02	88.63

Table 20
Sangdong operating costs. Source: Woulfe Mining Corporation (2012).

ITEM	€/t ore	€/mtu
Mining and backfill	29.4	81.38
Processing	15.85	43.88
Administration	2.3	6.37
TOTAL COST	**47.55**	**131.63**

The capital costs are shown in Table 16 (exchange rates used were: 1 € = 1.30 USD and 1 € = 1.45 AUD). The key financial outcomes are shown in Table 17.

The indicated resource of the project has been converted to probable mineable reserves assaying 13.3 Mt @ 0.425% WO_3. Table 18 shows Sangdong's probable reserves.

A processing plant was designed incorporating two-stage grinding plus two-stage cycloning. This process will be followed by an all-flotation concentration process for scheelite, enabling the recovery of molybdenite and bismuth.

This intermediate concentrate will then be processed to produce a final scheelite concentrate that will be treated in an APT plant to produce APT as the final product. Table 19 presents the quantities processed per year by the project.

The total operating costs are shown in Table 20.

7. King Island Scheelite project (Tasmania)

The project by King Island Scheelite, another Australian resources company listed on the Australian Stock Exchange (ASX: KIS), scopes an open-cut operation for the first 4–5 years (planning to start in mid-2016), followed by a 9-year underground

Table 21
King Island Scheelite capital costs. Source: King Island Scheelite (2014).

ITEM	COST (M€)
Process Plant	28.4
Tailings	1.1
Mining	29.6
Administration	1.2
Bonds	2.3
Contingency	6.0
TOTAL	**68.6**

Table 22
King Island Scheelite key financial outcomes of the feasibility study. Source: King Island Scheelite (2014).

Euro/USD	1.3
APT Price	375 USD
NPV (8% discount rate)	85.4 M€
IRR	35%
Capital Payback Period (Years)	–

Table 23
King Island Scheelite identified mineral resources and ore reserves. Source: King Island Scheelite (2014).

Classification	Mt	Grade (WO_3%)	mtu (WO_3) (M)
Indicated	9.92	0.95	9.39
Probable	3.30	0.99	0.33
TOTAL	**13.22**	**0.96**	**9.72**

extraction. The mine was previously operated until the early 1990s, when it was closed due to the tungsten price evolution.

The mineralization is skarn type and has been metamorphosed by contact. The minerals include scheelite, with minor powellite, whereas no wolframite was detected. There are trace amounts of sulfides and some molybdenum, which can attract a penalty on the sales prices.

The initial project capital cost is 68.6 M€, including the investment for the underground mine due for the final year of the open-cut operation (23.1 M€), with cash operating costs of 99.3 €/mtu, and it expects to produce an average 280,000 mtu WO_3 per year over a 13 year mine life. The capital costs are shown in Table 21 (exchange rates used were: 1 € = 1.30 USD and 1 € = 1.45 AUD).

The key financial outcomes are shown in Table 22.

Table 23 shows King Island Scheelite identified mineral resources and ore reserves.

The plan is to produce 4720 t of concentrate with a grade of 55% WO_3 per year. The processing will include three stage crushing, followed by grinding, flotation, attrition and a cleaner flotation to obtain the final concentrate.

Table 24
King Island scheelite mining and processing figures. Source: King Island Scheelite (2014).

Phase (13 years)	kt per year	kt total	Grade (WO_3%)
Mining	481	6253	0.75
Processing plant	400	5200	0.83
Product	4.72	61.30	55.00

Table 25
King Island scheelite operating costs. Source: King Island Scheelite (2014).

ITEM	€/mtu open-cut	€/mtu underground
Mining	22.3	69.2
Processing	60.0	37.7
TOTAL COST	**82.3**	**106.9**

The company plans to produce a 55% WO_3 concentrate, instead of the normal 65%, to reduce the amount of molybdenum in the concentrate. The King Island Scheelite project envisages a discount of a 22% for the concentrate grade over the APT price plus a penalty due to the molybdenum content of 8%, resulting in a 30% discount over the APT price.

Table 24 presents the amounts processed per year by the project.

The total operating costs are shown by area in Table 25.

8. Discussion

Although five projects are studied, there are common aspects that may be of interest to develop an analysis of future tungsten mining projects.

First, we must highlight that the Kilba project has certain figures that do not match what can be considered "normal" in a feasibility analysis; to obtain the Net Present Value (NPV), it uses an APT price of 440 USD/mtu, 22% greater than the prices used by Barruecopardo (350 USD/mtu) and Hemerdon (360 USD/mtu). In addition, 440 USD/mtu was the highest recorded price of APT. Moreover, the project uses the lowest discount rate, 7%, against a more reasonable 8% used by Barruecopardo and Hemerdon. Despite these figures, the Kilba project obtains an NPV of 27 M€; therefore, in our opinion, this project may be considered weak in many points, sullying its entire economic plan.

8.1. Initial investment

First, we will attempt to obtain an estimation of the current initial investment for a generic tungsten mining project.

Auger and Guzmán (2010), regarding investment decisions made in copper mines, obtained a direct relation between investment and mine capacity; therefore, we will attempt to achieve similar results according to the specific characteristics of tungsten mining (and processing) projects.

A strong relation was found within the five projects between the following parameters:

- Initial investment in M€.
- Processing kt per annum entering the processing plant.
- Grade of the mineral entering the processing plant.

Fig. 7 shows a scatterplot and regression model of the values obtained for the different projects while comparing these parameters.

The average value of this relation for the five projects is 0.217, considering King Island Scheelite's underground investment.

An important conclusion can be drawn from this relation: underground (Sangdong) or mixed open-cut and underground projects (King Island Scheelite) compensate for their larger investment in mining infrastructure with a higher mineral grade entering the processing plant.

Another interesting conclusion is that the final product grade is not critical regarding the initial investment.

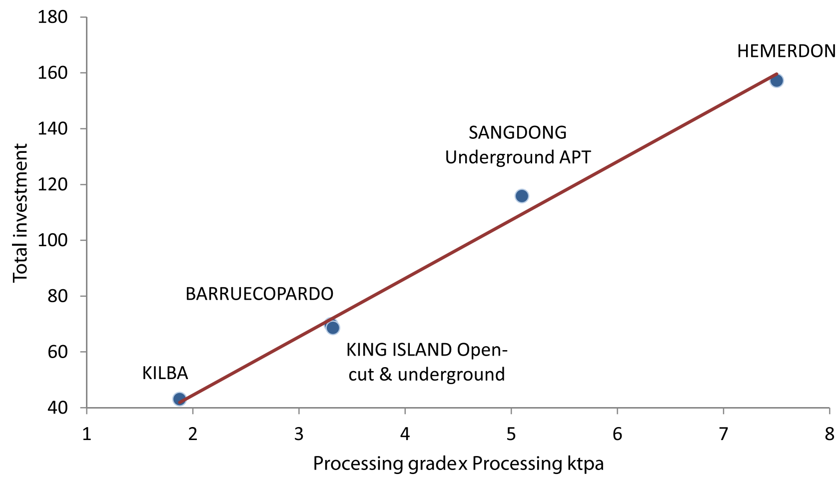

Fig. 7. Investment (M€)/(Processing grade × Processing ktpa).

Therefore, given a tungsten project design, it is possible to estimate the project's initial investment through the planned kt per annum to be treated in the processing plant and the grade of the mineral.

8.2. Mineral grades entering the processing plant

Fig. 8 shows the mineral grades entering the processing plant for the different projects.

According to this figure, the typical mineral grades entering the processing plant that can be currently considered to typical tungsten mining projects are the following:

- Open-cut projects: **0.25–0.30 WO_3%**.
- Underground projects: **0.40–0.75 WO_3%**.

8.3. Processing plant cost

There is also an interesting relation between the initial investments and the cost of the processing plants.

Fig. 9 shows the relations between these two figures for the projects being analyzed.

The average figure for the projects that gives the relation between the processing plant cost and the initial investment is 56.3%. If we consider the Barruecopardo, Sangdong and Hemerdon projects, we obtain a relation of 57.2%, a similar figure to, but without the special characteristics of, the King Island Scheelite investment (23.1 M€ of mining investment will occur during the 5th year of operation) and the poorly developed Kilba project.

8.4. Operating costs

Fig. 10 presents the operating costs in €/mtu of the different projects.

Surprisingly, the Barruecopardo, King Island Scheelite and Hemerdon projects have nearly the same total operating costs: 99.2 €/mtu, whereas Kilba has 163.2 €/mtu and Sangdong, the full underground project, has 131.63 €/mtu.

In an attempt to obtain a common relation for the processing costs, we considered the following variables: mining ktpa, mineral grade entering the processing plant, processing ktpa and product grade.

Using these variables, the processing costs in €/mtu can be approximately calculated through the following expression:

Process costs = 0.20 × Processing ktpa/(Mining ktpa × Processing grade × Product grade)

Fig. 11 shows the differences between the real values and the calculated values for the processing costs. We must remark that the King Island Scheelite project does not include any

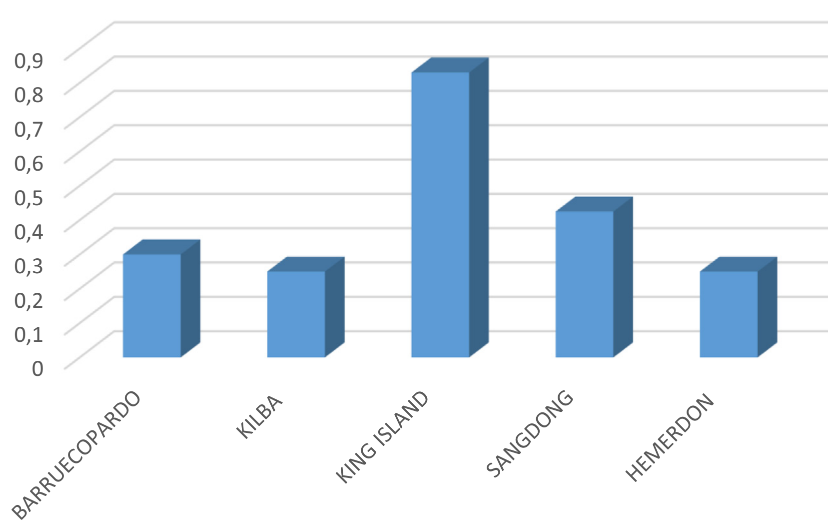

Fig. 8. Mineral grades entering the processing plant.

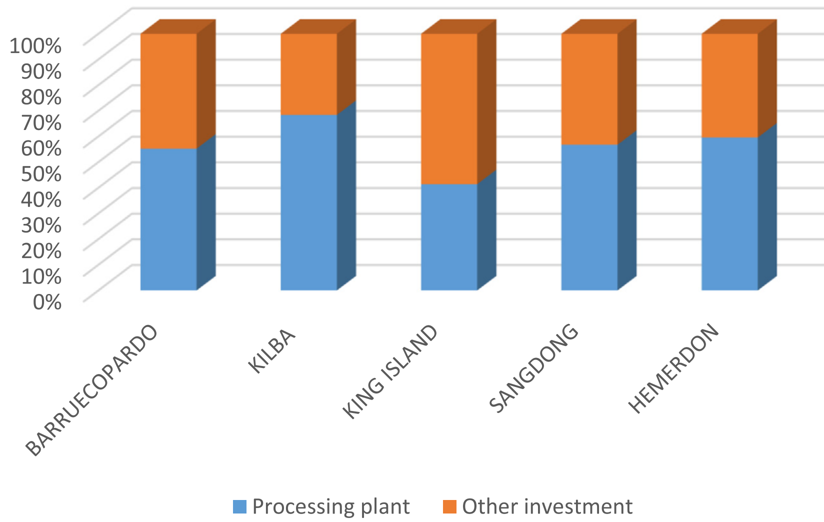

Fig. 9. Relation between processing plant costs and the remainder of the investments.

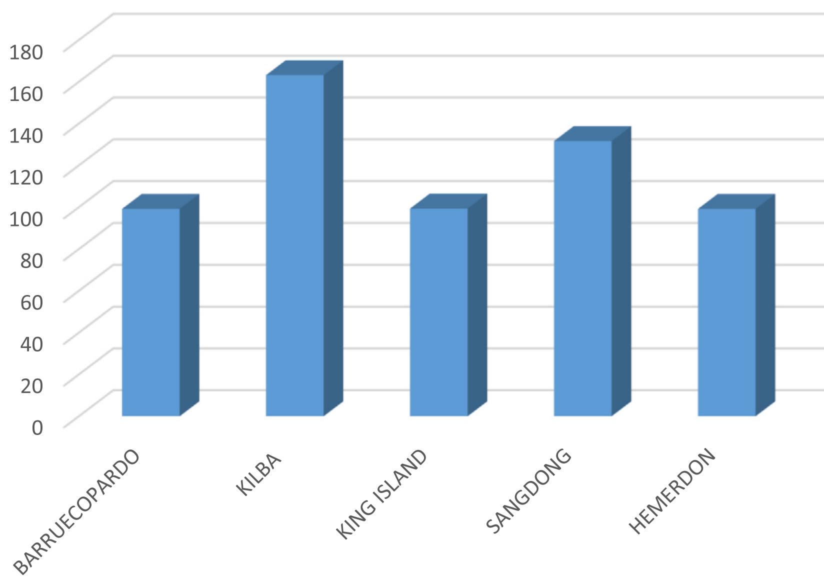

Fig. 10. Operating costs in €/mtu.

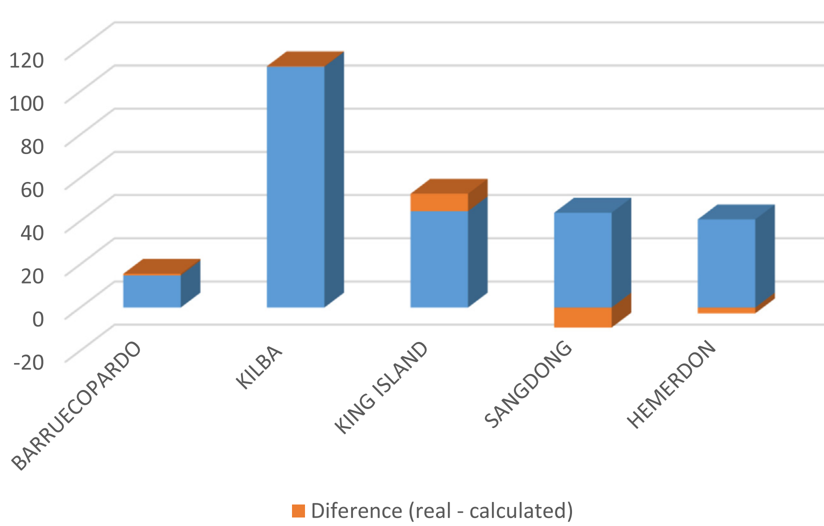

Fig. 11. Differences between real and calculated processing costs.

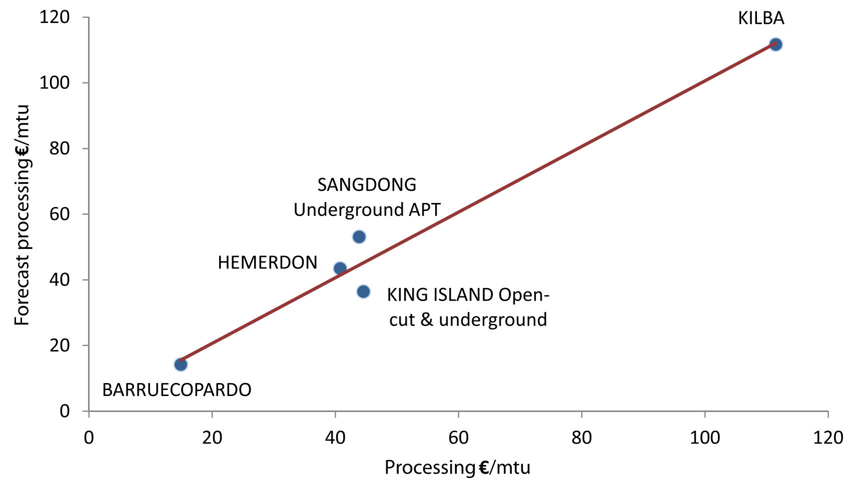

Fig. 12. Scatterplot and regression model of forecast vs. real processing costs.

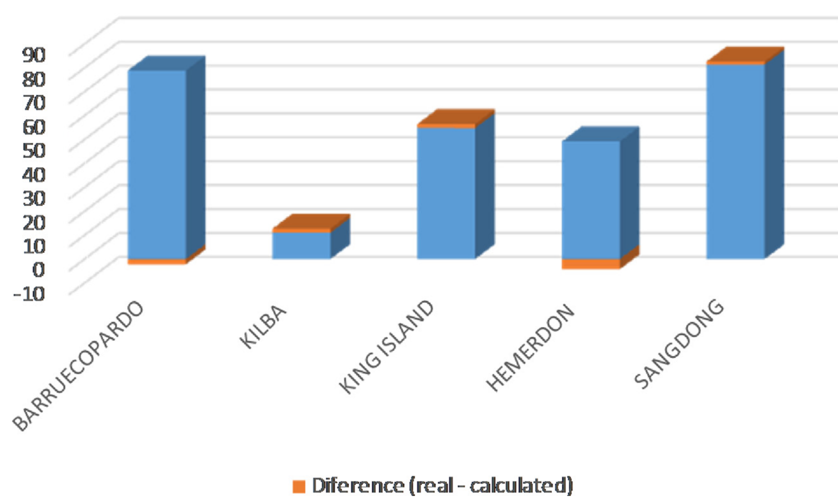

Fig. 13. Differences between the real and calculated mining costs.

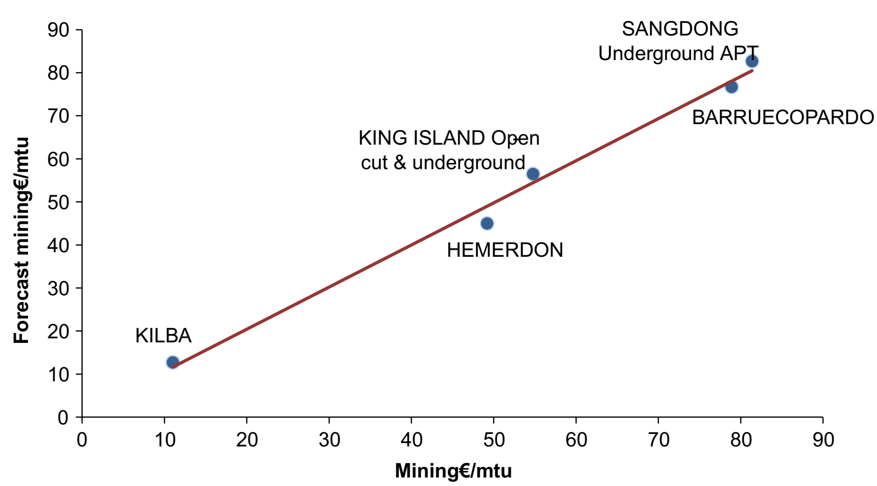

Fig. 14. Scatterplot and regression model of the forecasted vs. real mining costs.

administration costs; therefore, this may be one of the reasons explaining why the calculated value is lower than their claimed value of the processing costs.

The fact that the Sangdong final product will be APT instead of concentrate may also explain the difference between their real and calculated processing costs.

Fig. 12 presents a scatterplot and regression model for the comparison between forecasted and real processing costs. As shown, the bias of prediction remains in a controlled interval.

To obtain an expression for the mining costs, we will consider another set of variables: mining ktpa, mining grade, product ktpa and product grade.

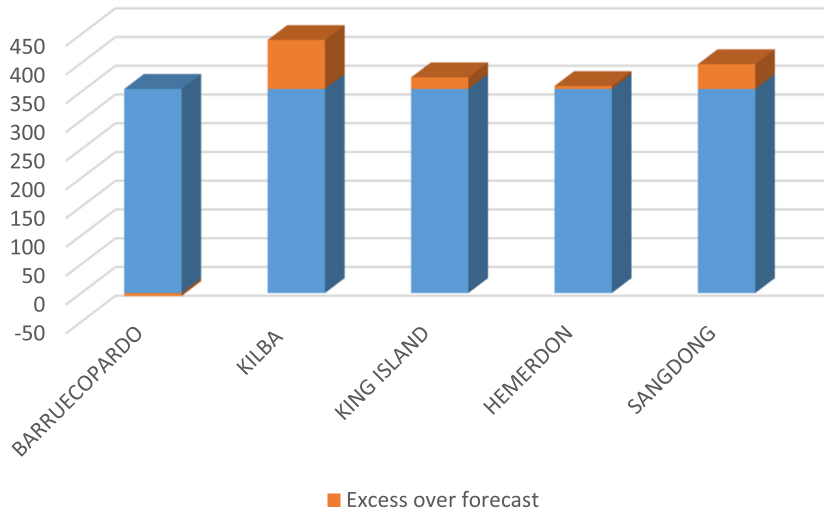

Fig. 15. APT prices used for obtaining the NPV with the excess over forecast.

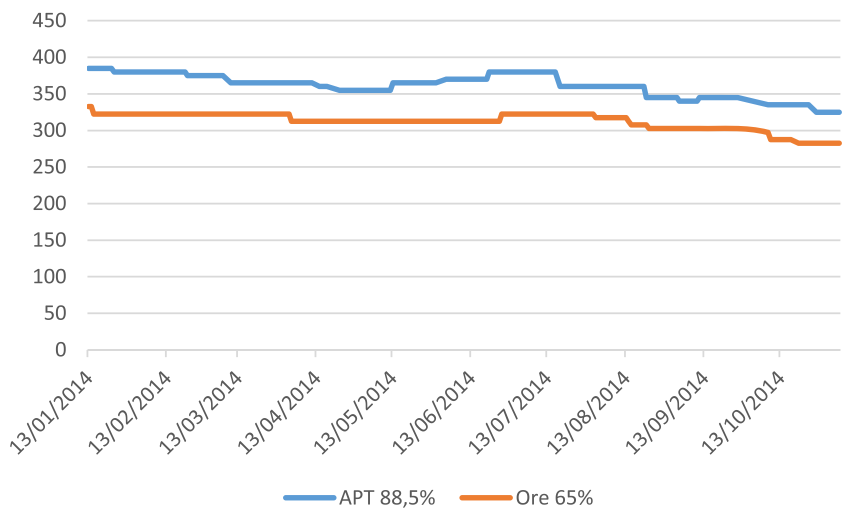

Fig. 16. APT prices (88.5% WO_3) against Ore prices (65% WO_3) during 2014. *Source:* Asian Metal.

Using these variables, open-cut mining costs in €/mtu can be approximately calculated through the following expression:

Mining costs (Open-cut) = 6.25 × (Mining ktpa × Mining grade)/(Product ktpa × Product grade)

The mining costs for the underground project will be 10 times the relation found for the open-cut projects (this finding does not mean that underground mining costs are 10 times larger than open-cut mining costs), whereas the mining costs for mixed projects (open-cut and underground) will be between those amounts. In the case of the King Island Scheelite project, multiplying the expression by 6.5 makes it possible to obtain nearly the exact same value.

Fig. 13 shows the difference between the real values and the calculated values for the mining costs.

Fig. 14 presents a scatterplot and regression model for the comparison between the forecasted and real mining costs. In this case, the bias of prediction remains in a more controlled interval.

Finally, the administration costs can be approximately calculated as 6% of the processing costs plus the mining costs.

8.5. APT prices

The APT prices used by the different projects to obtain the Net Present Value (NPV) are presented in Fig. 15. Our best estimation of the APT future price was 355 USD/mtu; therefore, the Barruecopardo Project alone adopts a more conservative value (350 USD/mtu).

Sangdong uses 398 USD/mtu, an excess of 43 USD/mtu over our forecasted price, and Kilba uses 440 USD/mtu, an excess of 85 €/mtu. This represents a 24% increase, which is difficult to maintain or to defend in any manner.

8.6. APT discount

Fig. 16 depicts European APT prices (88.5% WO_3) against Russian Ore prices (65% WO_3) in USD/mtu during 2014 (Asian Metal Inc., 2014b,c). The average difference between these two prices is 49.04 USD/mtu, which is equivalent to a 13.53% discount.

Most of the companies apply a 20% discount over the APT price for tungsten concentrate, which could be a truly conservative attitude if this is compared with the 13.53% market discount between these products.

Moreover, the Sangdong feasibility study includes an APT plant designed with a capacity to treat 6000 tpa of tungsten concentrate and subsequently produce 4000 tpa of high-grade APT (the APT plant was designed with additional capacity to treat potential third-party tungsten concentrates). The capital cost of the projected APT plant was 9.82 M€, and the installation costs were 5 M €. These figures result in a total cost (including plant amortization) of 4.49 USD/mtu; therefore, a good business may be to transform concentrate into APT, not to mine and process Tungsten.

This fact may explain why the Sangdong calculated processing costs are larger than their actual figures.

8.7. Cost of capital and capital payback period

All of the projects, except Kilba, used an 8% cost of capital to calculate the Net Present Value (NPV). This coincidence appears to be more similar to a sector standard than the real cost of capital of the different companies.

Therefore, in this case, the Internal Rate of Return (IRR) could be a more reliable figure to consider because it does not depend on the cost of capital of the different companies.

Finally, all of the projects, except Kilba, have a minimal capital payback period, which is between 2 and 3.25 years.

9. Conclusions

Although companies and stakeholders are worried about the accuracy of mineral and ore reserves due to the existence of the JORC Code (2012) in Australia, the PERC Reporting Standard (2013) in Europe or the National Instrument 43-101 (2011) in Canada, these or similar codes should begin confronting the need for a more structured and rigorous feasibility study.

In most of the cases analyzed, the initial investment lacks detailed information regarding taxes, working capital, debt servicing, and land and property purchases.

Conversely, the APT prices used to calculate the Net Present Value (NPV) also lack a minimum rigor in their selection, and no contrasted methodology is applied or noted within the different reports. Specifically, adapted mathematical tools (times series, neural networks or genetic algorithms) may fill this gap and will allow for a comparable means of establishing this crucial parameter.

Moreover, the cost of capital used within the NPV calculation, which is the same in four of the five companies analyzed (8%), appears to be more similar to a standard figure within the mining sector than a real value, which should be different for each company.

Continuing the feasibility analysis, after obtaining the first results of any model, a sensitivity analysis on key variables should be conducted, studying how the uncertainty in the output of the model can be apportioned to different sources of uncertainty in the model input. No information is provided within the different reports regarding key variables or how their sensitivity is managed to obtain robust and reliable values of the NPV and the Internal Rate of Return (IRR).

Tendencies noted by Slade (2001) regarding general practices for evaluating projects by the nonferrous-metal-mining companies (introducing a sensitive analysis such as Monte Carlo techniques, using a long-run commodity price, and adjusting risk by a hurdle rate) appear to be forgotten, regardless of the large advance in the reporting standards for mineral and ore reserves.

Nevertheless, the estimations for initial investments, processing plant costs and operating costs obtained during this research may represent a strong tool when addressing the first steps of future tungsten mining investment analysis.

Finally, we would like to highlight that all of the projects analyzed within this study were developed over previously operated or, at least, previously studied areas. This fact is congruent with the decision of the European Commission (2014) to finance, within their Horizon 2020 Programme and the specific topic “Coordinating and supporting raw materials research and innovation”, different issues. Examples of these topics are “Raw materials intelligence capacity” to develop methodologies for reviewing and selecting relevant tools and for methods attempting to provide quality expertize among the different stakeholders and “Mineral deposits of public importance” to define and protect relevant mineral deposits.

Acknowledgments

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References

Asian Metal Inc., 2014a. Prices of Ferro-tungsten 75% min Europe USD/kg W. ⟨http://www.asianmetal.com⟩.
Asian Metal Inc., 2014b. Prices of Tungsten APT 88.5% min Europe USD/mtu. ⟨http://www.asianmetal.com⟩.
Asian Metal Inc., 2014c. Prices of Tungsten ORE WO3 65% min Russia USD/mtu. ⟨http://www.asianmetal.com⟩.
Auger, F., Guzmán, J.I., 2010. How rational are investment decisions in the copper industry? Resour. Policy 35, 292–300.
British Geological Survey, 2012. Risk List 2012. ⟨http://www.bgs.ac.uk/mineralsuk/statistics/risklist.html⟩.
Chapman, A., et al., 2013. Study on Critical Raw Materials at EU Level. Report for DG Enterprise and Industry. Oakdene Hollins and Fraunhofer ISI ⟨http://ec.europa.eu/DocsRoom/documents/5605/attachments/1/translations/en/renditions/native⟩.
CMGroup, 2011. The Ten –Year Strategic Outlook for the Global Tungsten Market. Clark & Marron Pty Ltd., Adelaide, Australia.
European Commission, 2013. Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the implementation of the Raw Materials Initiative. COM(2013) 442 final. ⟨http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52013DC0442&from=EN⟩.
Hansen, B.E., 2011. Threshold autoregression in economics. Stat. Interface 4, 123–127.
JORC Code, 2012. Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves. The Joint Ore Reserves Committee of The Australasian Institute of Mining and Metallurgy, Australian Institute of Geoscientists and Minerals Council of Australia). ⟨http://www.jorc.org⟩.
King Island Sheelite, 2014. Breakaway Research: King Island Sheelite. Breakaway Investment Group. Sydney, Australia. ⟨http://www.kingislandscheelite.com.au/client-assets/files/News/201404%20Breakaway%20Research%20Report.pdf⟩.
Kriechbaumer, T., Angus, A., Parsons, D., Rivas Casado, M., 2014. An improved wavelet–ARIMA approach for forecasting metal prices. Resour. Policy 39, 32–41.
Metal Bulletin, 2014. Price Specifications March 2014. ⟨http://www.metalbulletin.com/Assets/pdf/MB%20PRICE%20SPECIFICATIONS/Price%20Specifications_Finished_Version.pdf⟩.
National Instrument 43-101, 2011. Standards of Disclosure for Mineral Projects. Canadian Securities Administrators. ⟨http://web.cim.org/standards/documents/Block484_Doc111.pdf⟩.
Ormonde Mining Plc., 2013. Annual Report and Accounts 2013. Dublin, Ireland. ⟨http://ormondemining.com/uf/Annual%20Reports/Ormonde%20Annual%20Report%202012%20Web%20Version.pdf⟩.
PERC Reporting Standard, 2013. Pan-European Standard for Reporting of Exploration Results, Mineral Resources and Reserves. The Pan-European Reserves and Resources Reporting Committee. Belgium. ⟨http://www.vmine.net/perc/documents/PERC_REPORTING_STANDARD_2013%20rev1.pdf⟩.
Sánchez Lasheras, F., Vilán Vilán, J.A., García Nieto, P.J., del Coz Díaz, J.J., 2010. The use of design of experiments to improve a neural network model in order to predict the thickness of the chromium layer in a hard chromium plating process. Math. Comput. Model. 52 (7–8), 1169–1176.
Slade, M.E., 2001. Valuing managerial flexibility: an application of real-option theory to mining investments. J. Environ. Econ. Manag. 41, 193–233.
Tong, H., Lim, K.S., 1980. Threshold autoregression, limit cycles and cyclical data (with discussion). J. R. Stat. Soc. Ser. B 42, 245–292.
Tungsten Mining NL, 2013. Kilba Project Scoping Study June 2013. ASX

Announcement. ⟨http://tungsteninvestingnews.com/files/2013/06/TGN__Study_Announce_Final.pdf⟩.
Wolf Minerals Ltd., 2011. Hemerdon Tungsten and Tin Project Definitive Feasibility Study Results. ASX Announcement. ⟨http://wolfminerals.com.au/useruploads/files/definitive-feasibility-study.pdf⟩.
Wolf Minerals Ltd., 2014. Investor Presentation September 2014. Western Australia. ⟨http://wlf2.live.hqi.com.au/IRM/Company/ShowPage.aspx/PDFs/1490-99939942/InvestorPresentationSeptember2014⟩.
Woulfe Mining Corp., 2012. Sangdong Project Feasibility Study. Report to Woulfe Mining Corp. Tetra Tech Wardrop. U.K. ⟨http://www.woulfemining.com/i/pdf/techreports/Sangdong_Feasibility_Study.pdf⟩.