



Analysis of development prospects of deep-sea polymetallic nodules

Central South University, China

Revised in 2020



Report Outline

- 1. Land-based proven metals reserves**
- 2. Supply, demand and price in metal market**
- 3. Technical and economic evaluation of deep sea polymetallic nodules development**
- 4. Possible impact of deep sea polymetallic nodules development on the metal market**

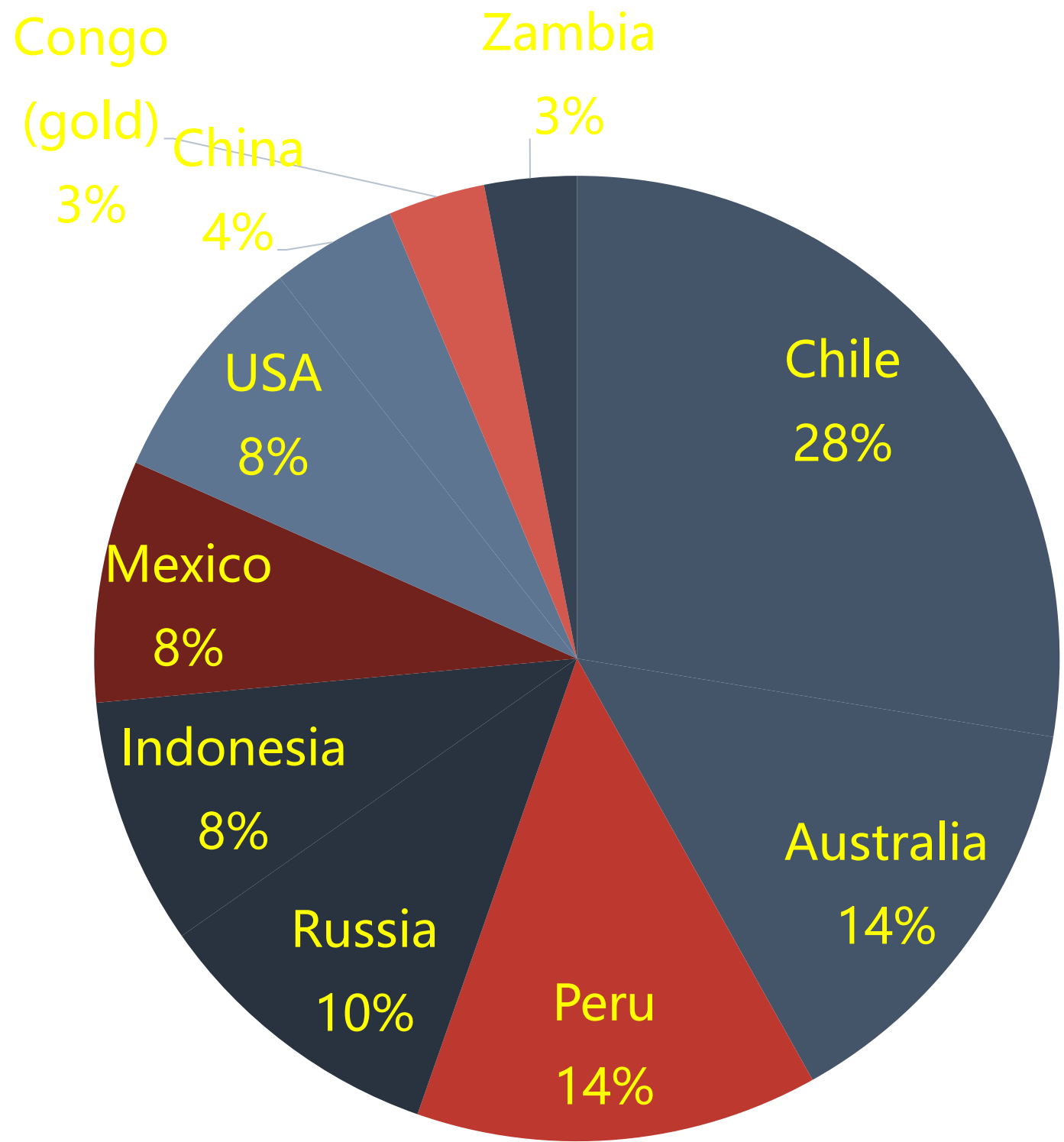
1. Land-based proven metals reserves — Copper

Metal	Global reserves (10,000 tons-metal amount)
Copper	83000
Nickel	8900
Cobalt	690
Manganese	76000

◆ According to the statistics of United States Geological Survey (USGS), the global proven copper reserves in 2018 are 830 million tons.

◆ Based on 23 Mt global copper production in 2018, the global proven copper reserves have a static guarantee period of 36 years.

Note: Static Guarantee Period of Mineral Reserves means the number of years a mineral can be developed without new discoveries.

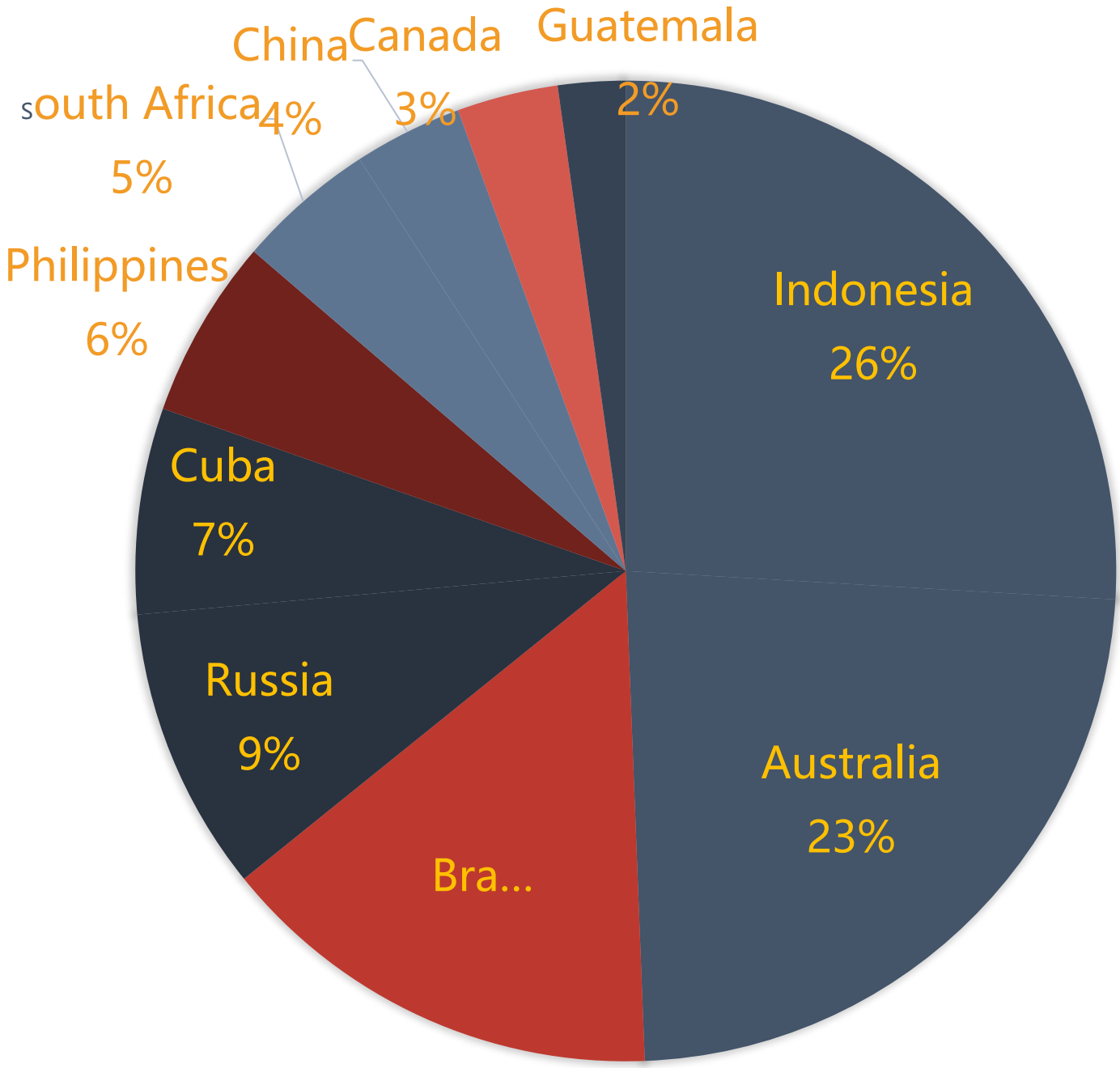
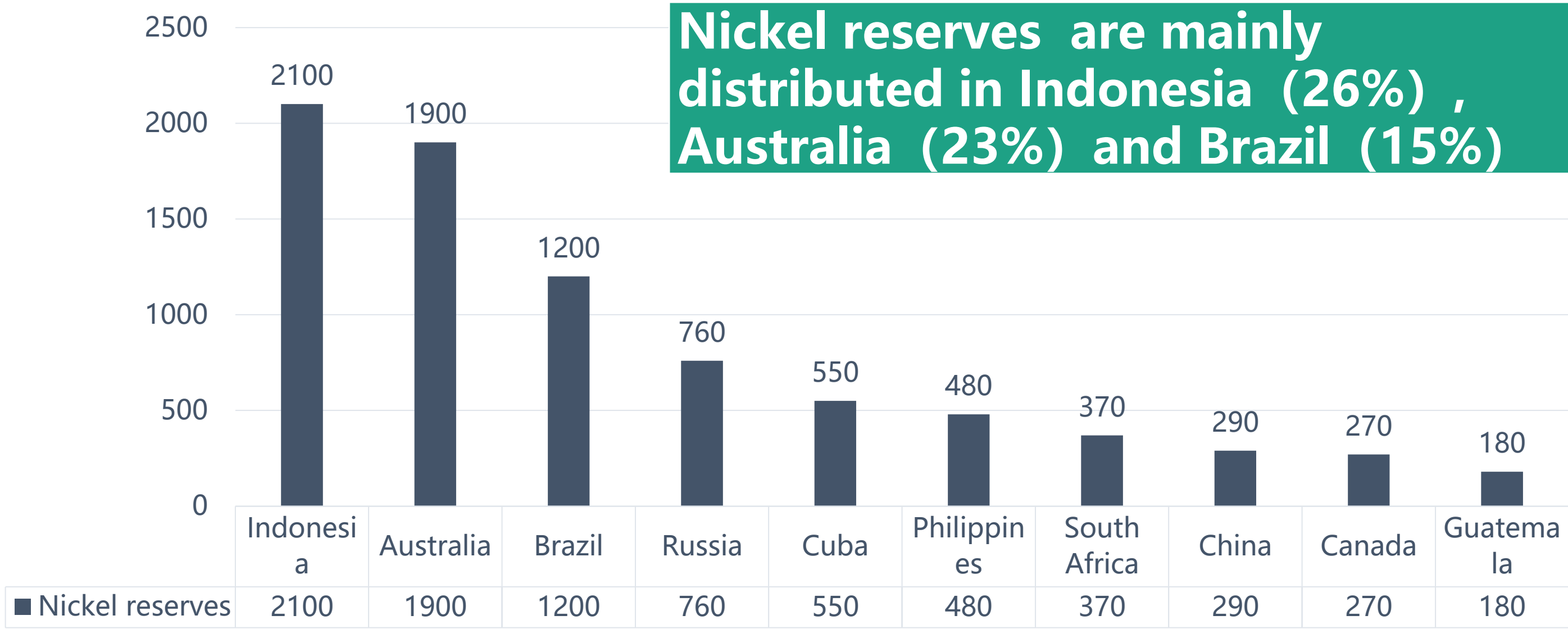


Top ten countries' reserves of copper (unit: 10,000 tons)

1. Land-based proven metals reserves — Nickel

Metal Name	Global reserves (10,000 tons-metal amount)
Copper	83000
Nickel	8900
Cobalt	690
Manganese	76000

- ◆ According to the statistics of USGS, the global proven nickel reserves in 2018 are 89 million tons.
- ◆ Based on 1.9 Mt global nickel production in 2018, the global proven nickel reserves have a static guarantee period of 46 years.

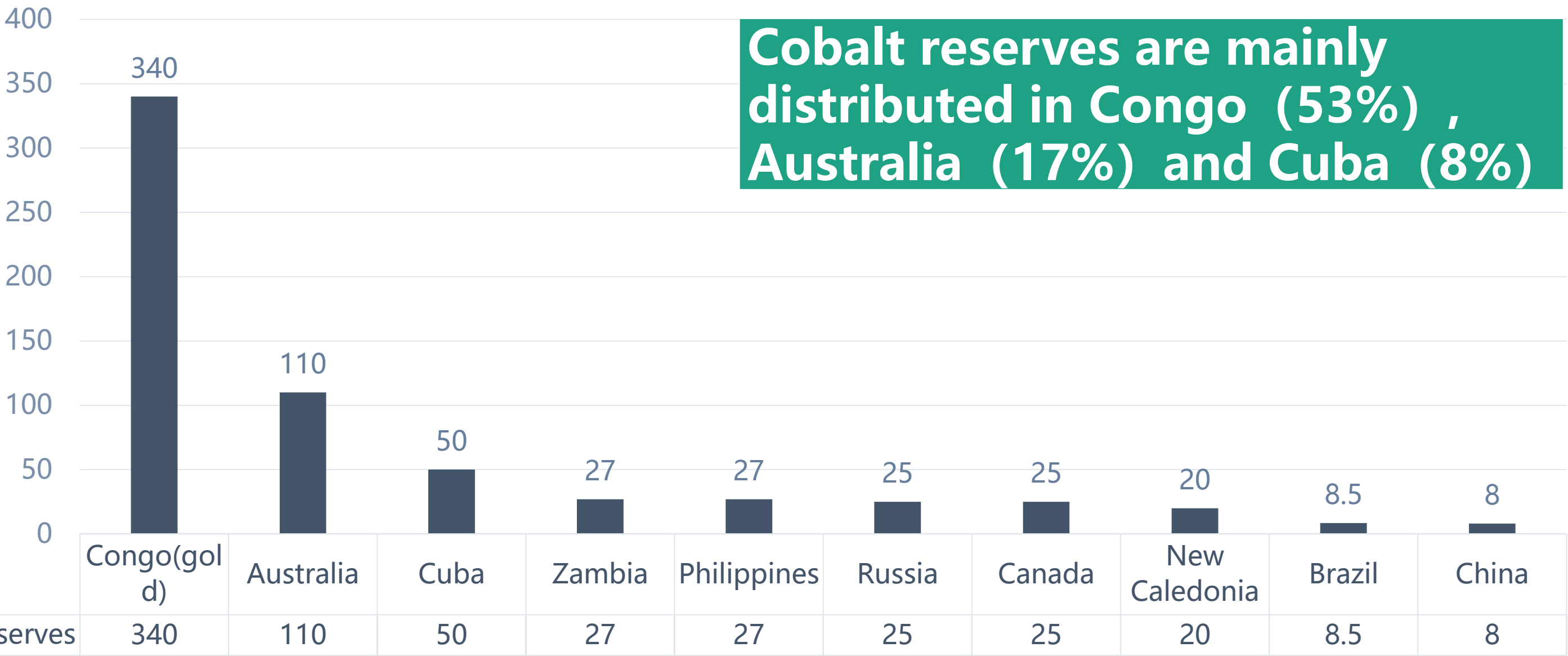


Top ten countries' reserves of nickel (unit: 10,000 tons)

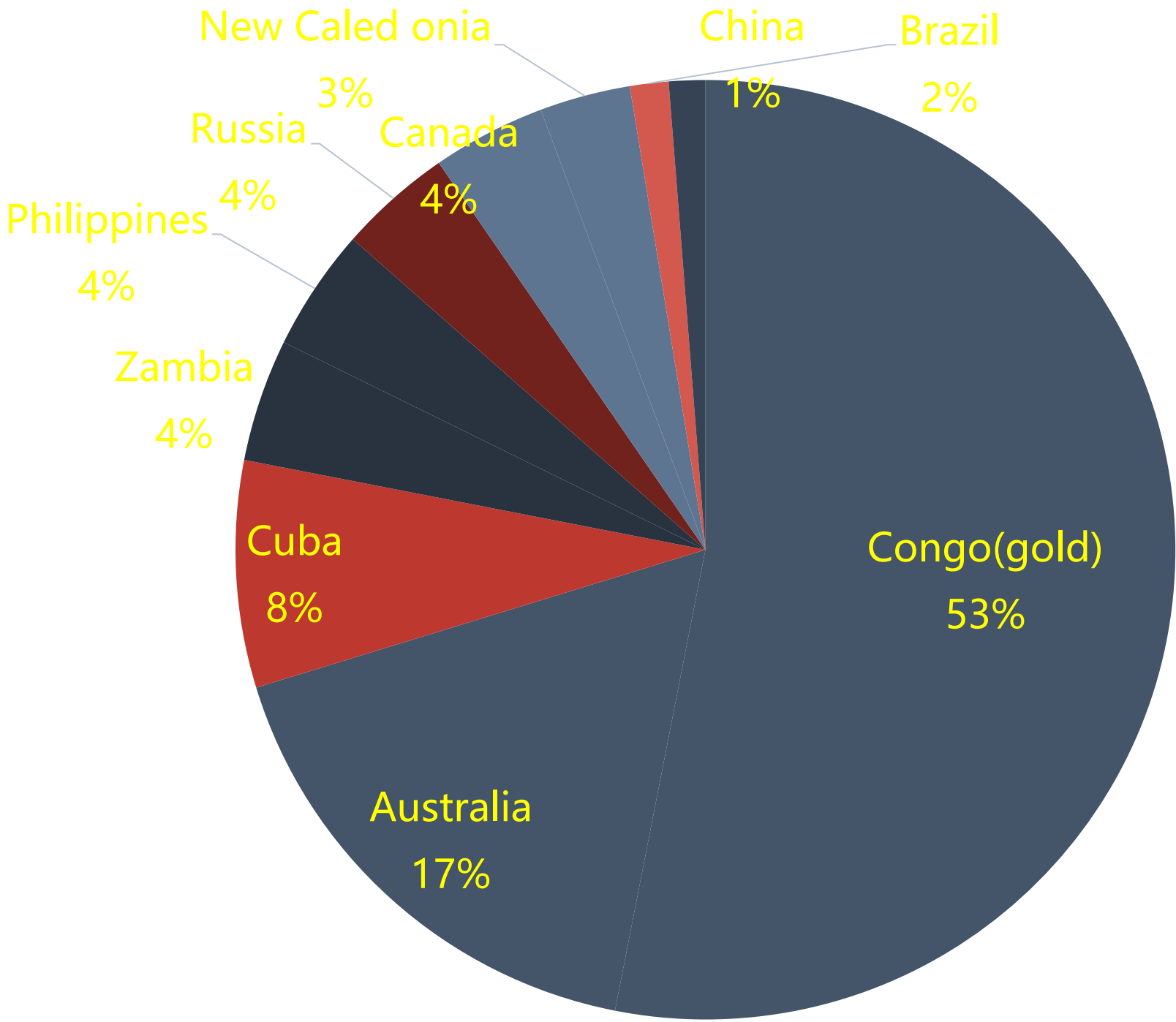
1. Land-based proven metals reserves — Cobalt

Metal Name	Global reserves (10,000 tons-metal amount)
Copper	83000
Nickel	8900
Cobalt	690
Manganese	76000

- ◆ According to the statistics of USGS, the global proven cobalt reserves in 2018 are 6.9 million tons.
- ◆ Based on 0.146 Mt global cobalt production in 2018, the global proven cobalt reserves have a static guarantee period of 47 years.



Cobalt reserves are mainly distributed in Congo (53%) , Australia (17%) and Cuba (8%)

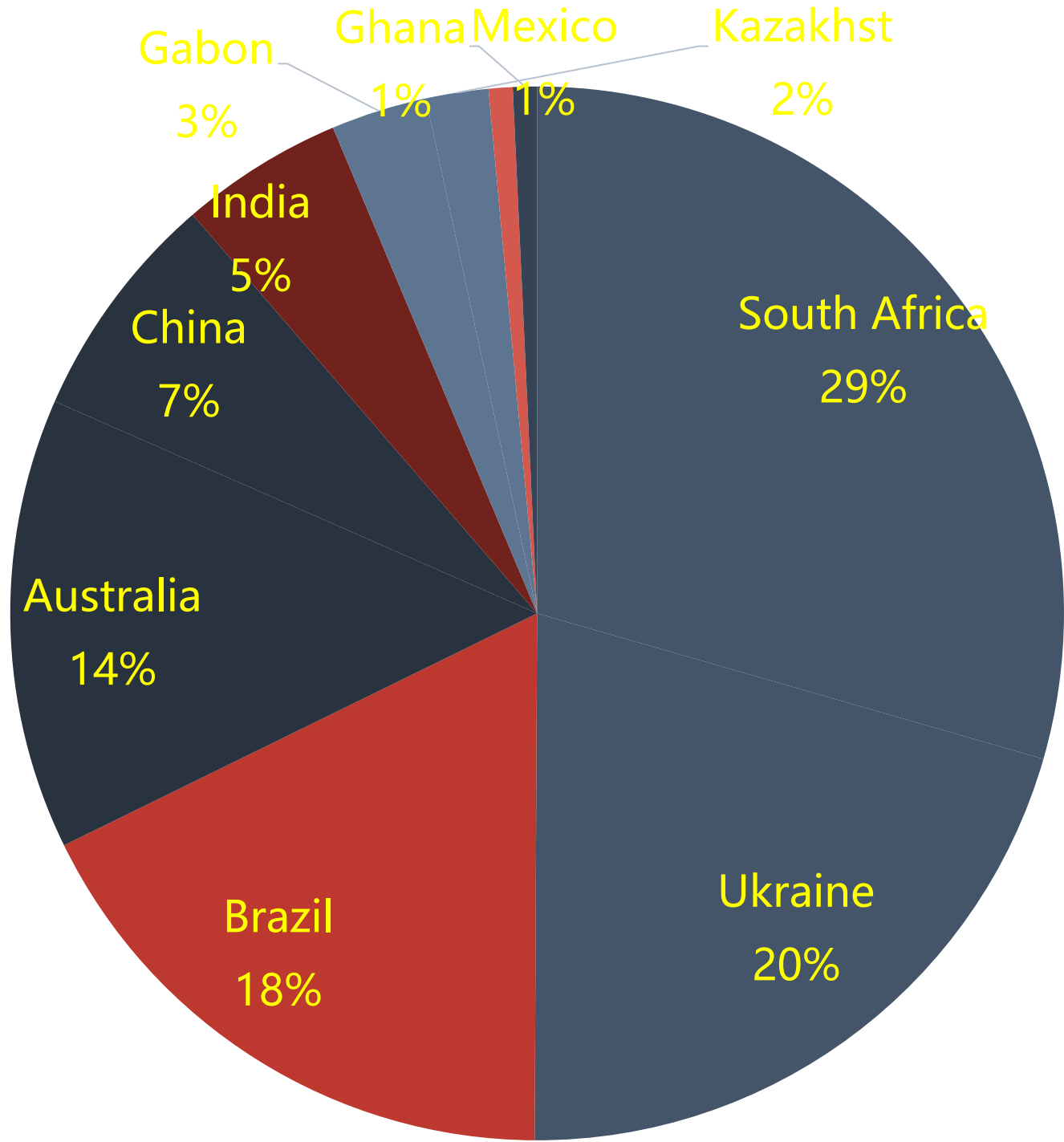
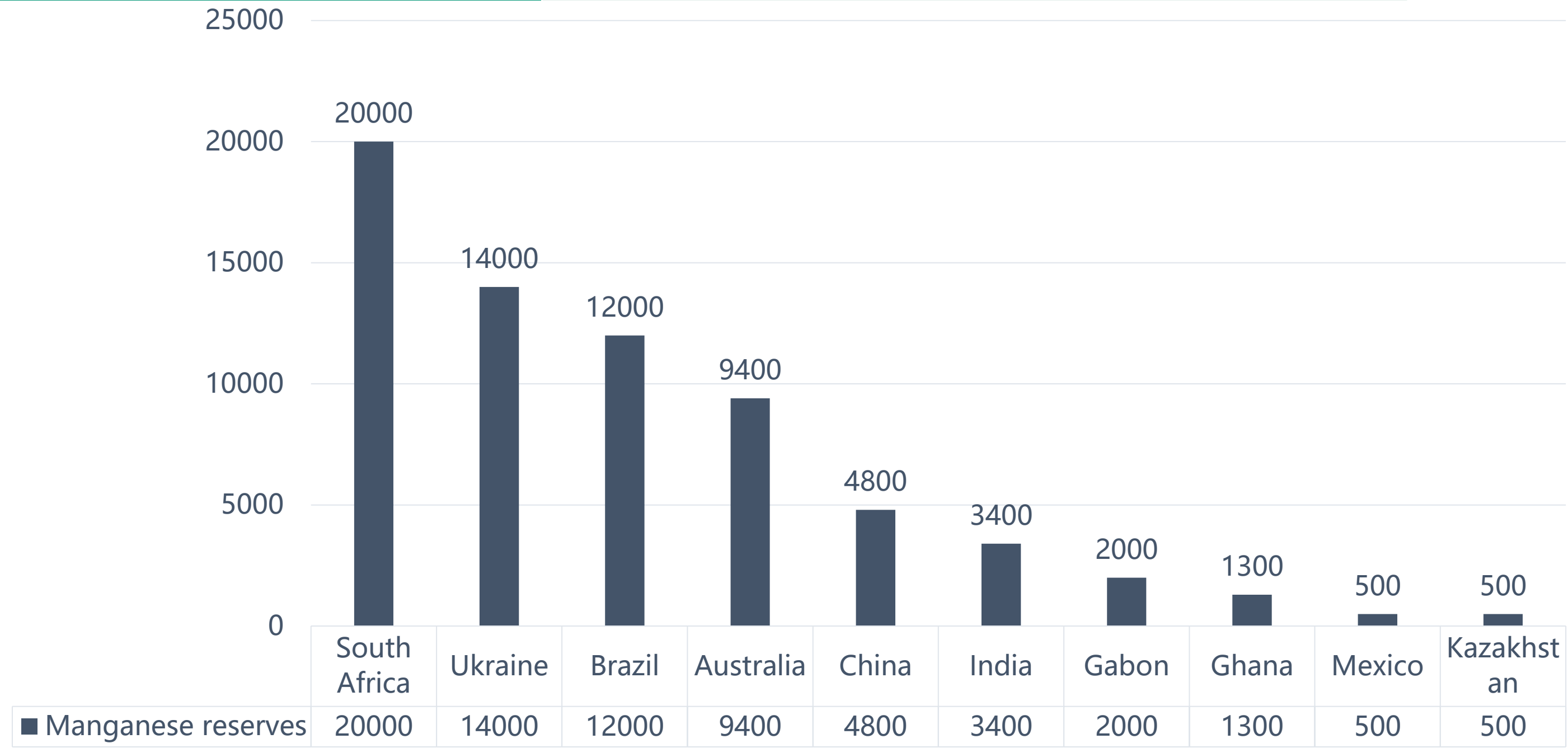


Top ten countries' reserves of cobalt (unit: 10,000 tons)

1. Land-based proven metals reserves — Manganese

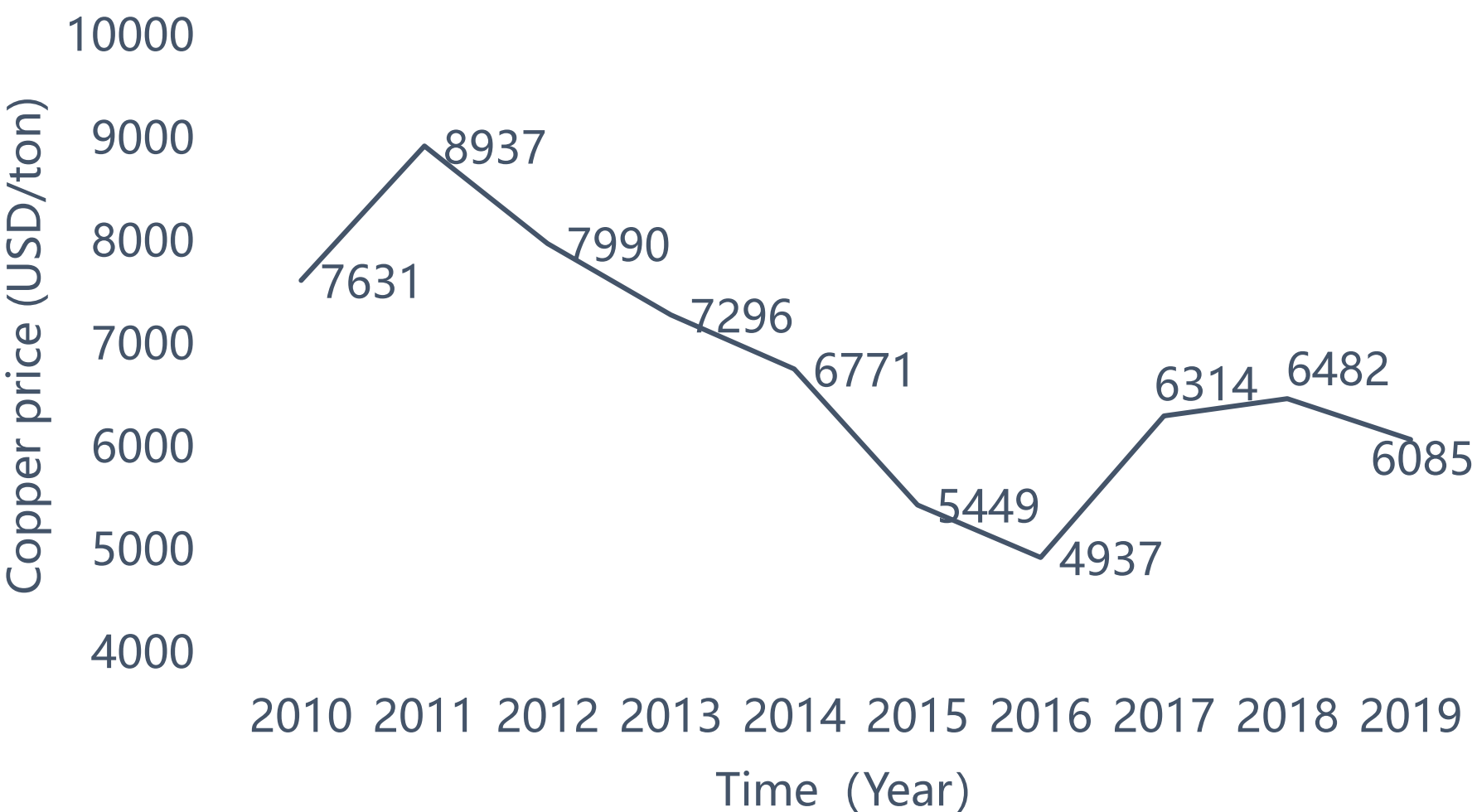
Metal Name	Global reserves (10,000 tons-metal amount)
Copper	83000
Nickel	8900
Cobalt	690
Manganese	76000

- ◆ According to the statistics of USGS, the global proven Manganese reserves in 2018 are 760 million tons.
- ◆ At present, the global manganese metal consumption (including electrolytic manganese metal, silicon manganese alloy, electrolytic manganese dioxide and other products) is about 25 million tons.
- ◆ The global proven manganese reserves have a static guarantee period of 30 years.



Top ten countries' reserves of manganese (unit: 10,000 tons)

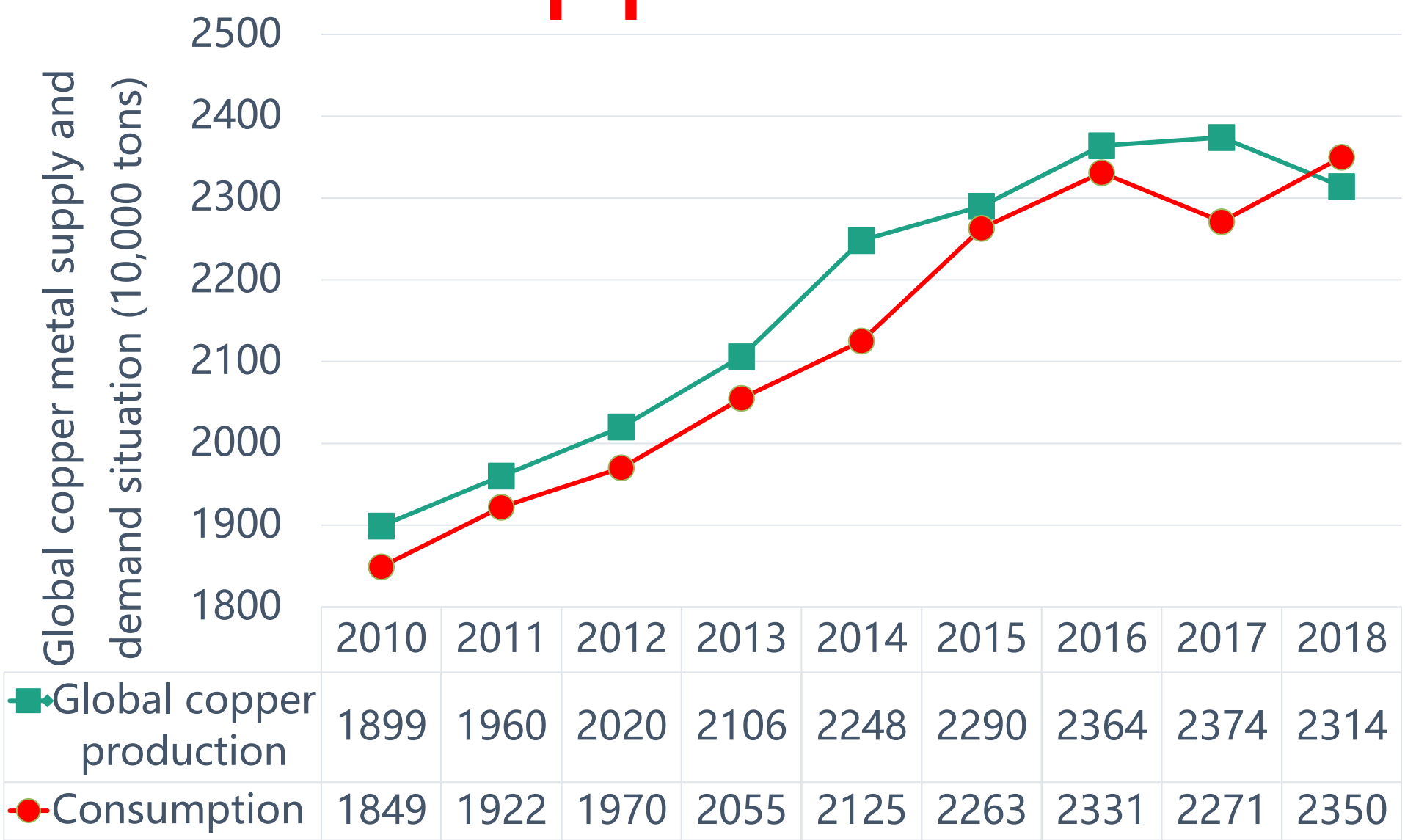
2. Supply, demand and price in Metal Market——Copper and Nickel



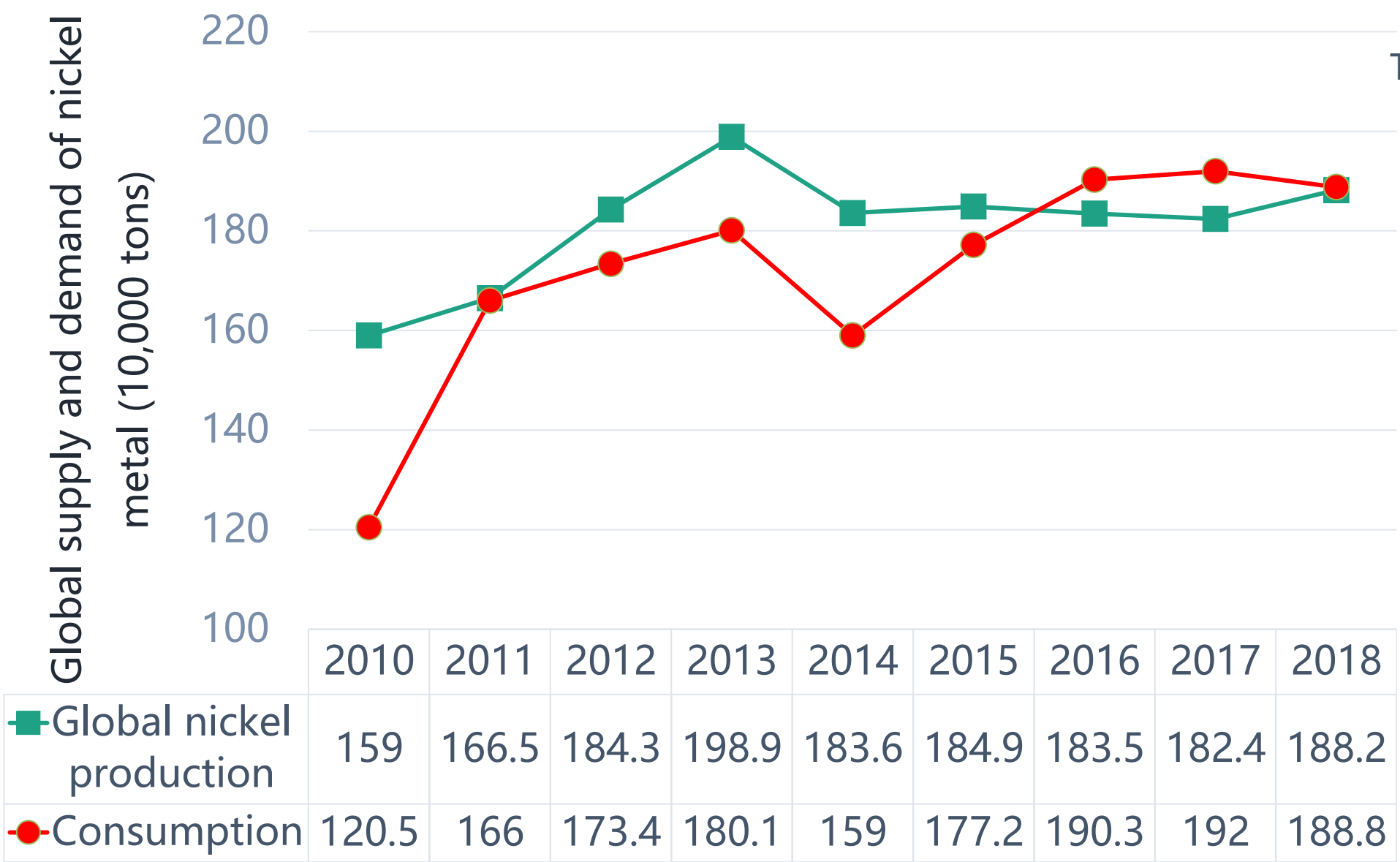
Source: London Metal Exchange (<https://www.lme.com/>)



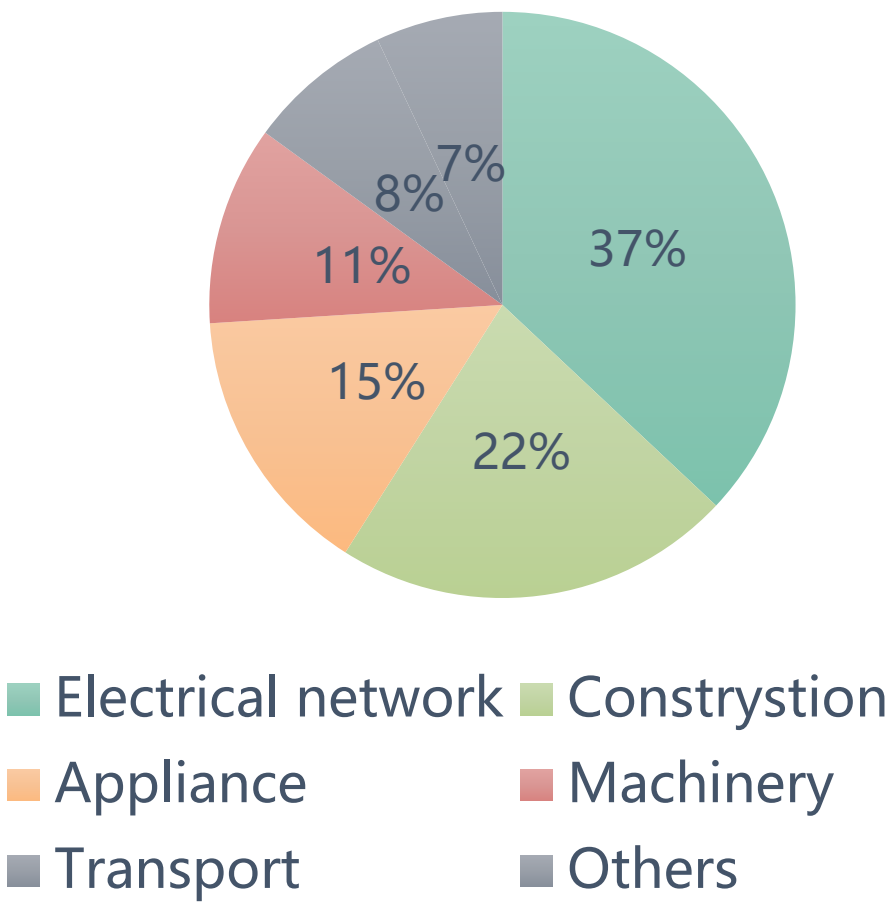
Source: London Metal Exchange (<https://www.lme.com/>)



Source: International Copper Study Group(ICSG)

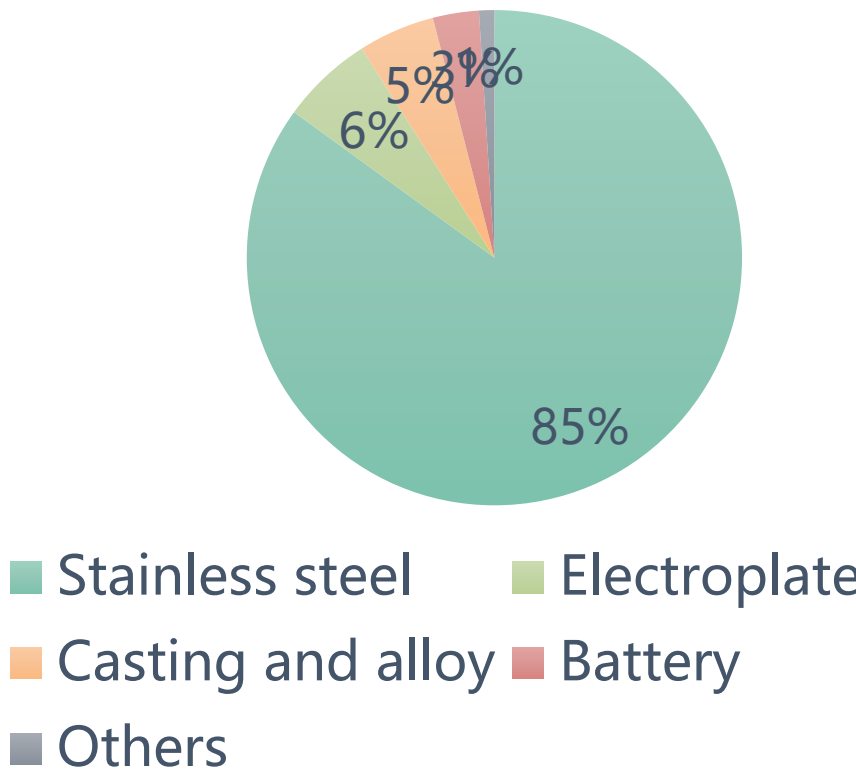


Source: CBC Metal (<http://www.cbcie.com/>)



From the perspective of demand, copper is mainly concentrated in electricity, construction and home appliances.

The proportion of nickel ore consumption structure in China in 2018

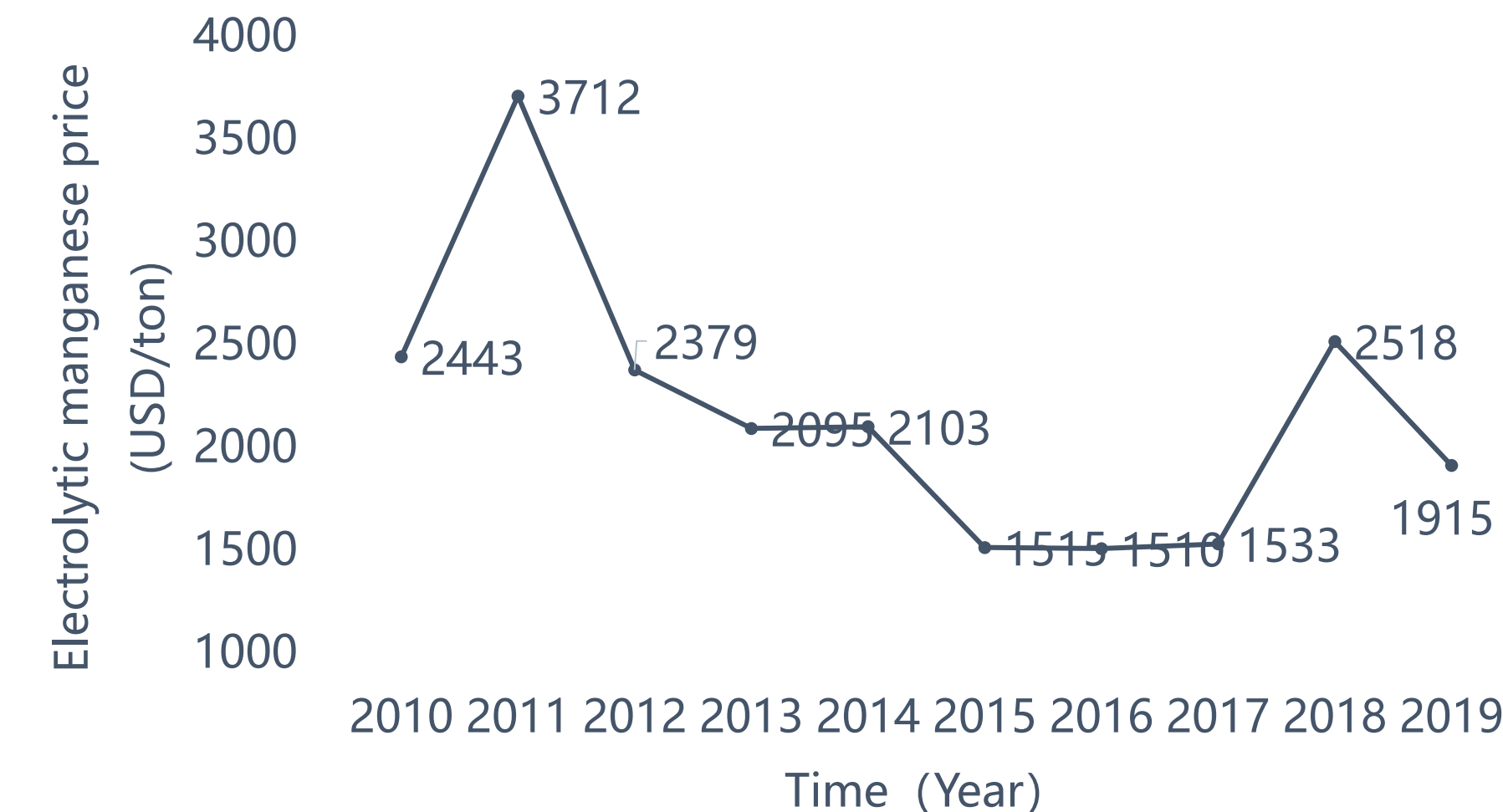


The increase in nickel used in the battery industry may push the price of nickel ore up.

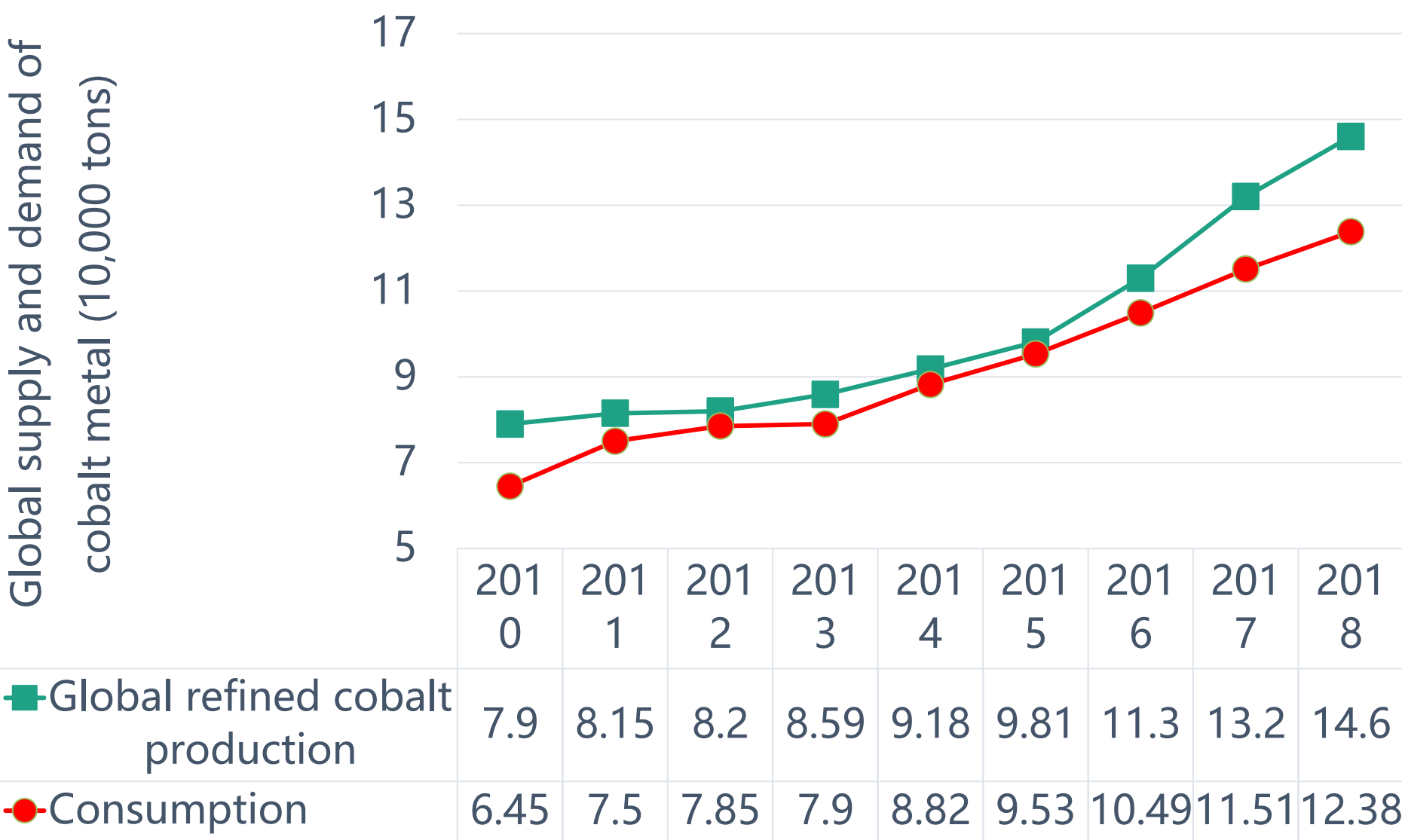
2. Supply, demand and price in Metal Market——Cobalt and Electrolytic Manganese Metal



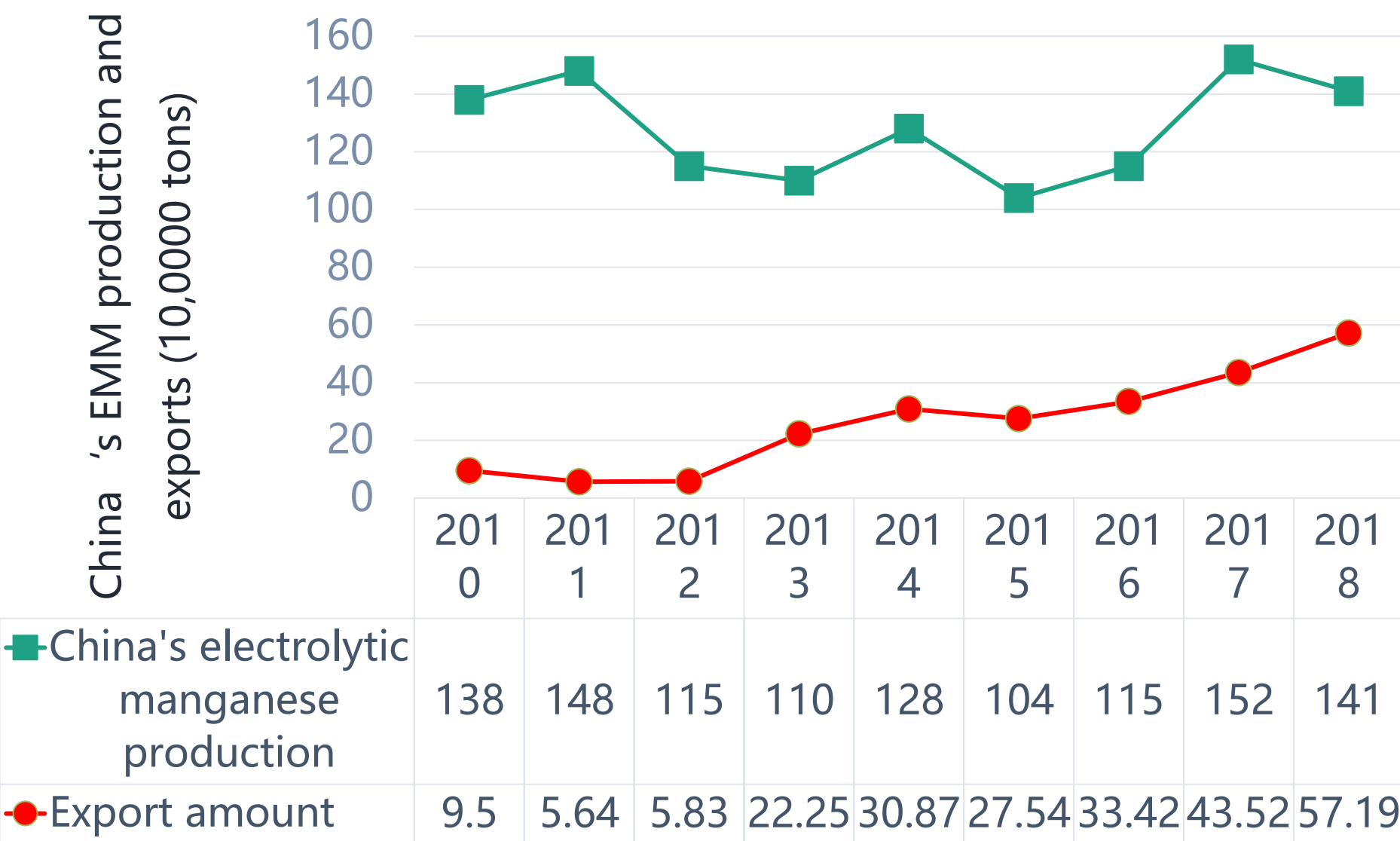
Source: London Metal Exchange (<https://www.lme.com/>)



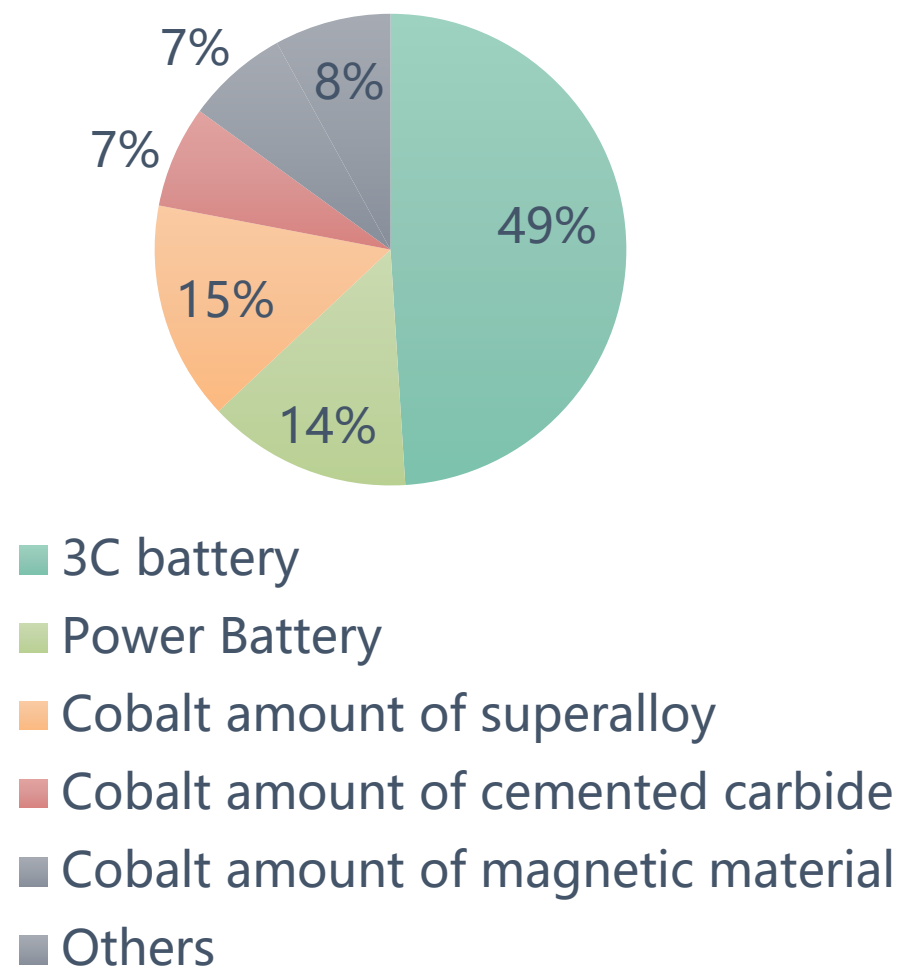
Source: China ferroalloy Market



Source: CBC Metal (<http://www.cbcie.com/>)



Source: National Manganese Industry Technical Committee



In recent years, the demand for cobalt in new energy vehicles has gradually increased.

Notes:

1. In the current cost-benefit analysis of “four metal recycling schemes”, electrolytic manganese is basically used as the analysis object. So in the chart, the relevant data of electrolytic manganese is discussed.

2. As China's electrolytic manganese production accounts for 98% of global production, the global data is replaced by China's electrolytic manganese production data.

3. Technical and economic evaluation of deep sea polymetallic nodules development — Financial model

Discounted Cash Flow Model

Net present value

$$NPV = \sum_{t=0}^n (CI_t - CO_t)(1 - i_0)^{-t}$$

Internal Rate of Return

$$NPV(IRR) = \sum_{t=0}^n (CI_t - CO_t)(1 - IRR)^{-t} = 0$$

Dynamic investment payback period

$$\sum_{t=0}^{Pt} (CI_t - CO_t)(1 - i_0)^{-t} = 0$$

$$NPV \geq 0$$

$$IRR \geq i_c$$

The project is economically feasible

■ The Discounted Cash Flow model is used for profitability assessments from a financial perspective^[1]. Three kinds of evaluation index including Net Present Value (NPV), Internal Rate of Return (IRR) and Dynamic Investment Pay-back Period are calculated.

■ If the NPV is positive and the IRR is greater than or equal to Hurdle Rate, the project is considered acceptable, otherwise the project is rejected.

Note: Hurdle Rate is the minimum rate of return on capital required by investors.

3. Technical and economic evaluation of deep sea polymetallic nodules development —The main parameters

Table3-1. Main parameters of CSU financial model

		CSU2019	
Production situation and project cycle:	Development cycle (year)	28 (incl.3 years D&B)	
	Annual production capacity (million dry tons)	3	
Analysis cycle(year):	Metal extraction type	Cu、Ni、Co、Mn	
	Manganese product program	Electrolytic manganese	
Fixed investment (millions USD):	Feasibility study	310	
	Mining system	1,210	
	Smelting system	2,000	
Operating costs(millions USD/year)	Mining and transportation	412	
	Smelting	600	
Metal grade & Metal recovery:	Metal type	Grade	Recovery
	Cobalt	0.22%	83%
	Copper	1.02%	88%
	Manganese	27.15%	90%
	Nickel	1.27%	87%
Tax	Corporate income tax	25%	
	Value added tax	8%	

The metal grade of polymetallic nodules is relatively clear and basically stable, but the prices of four metals are always changing, which will inevitably lead to change of project evaluation indicators. Therefore, three sets of metal prices were discussed in the study.

Table 3-2 Three sets of metal prices were used in the CSU model.

	2015-2019 five-year average price (\$/ton)	2020.1-2020.4 present average price (\$/ton)	Expert estimated price (\$/ton)
Mn	1798	1547	1,685
Ni	11769	12475	12,692
Co	41999	30983	67,261
Cu	5823	5490	6,635

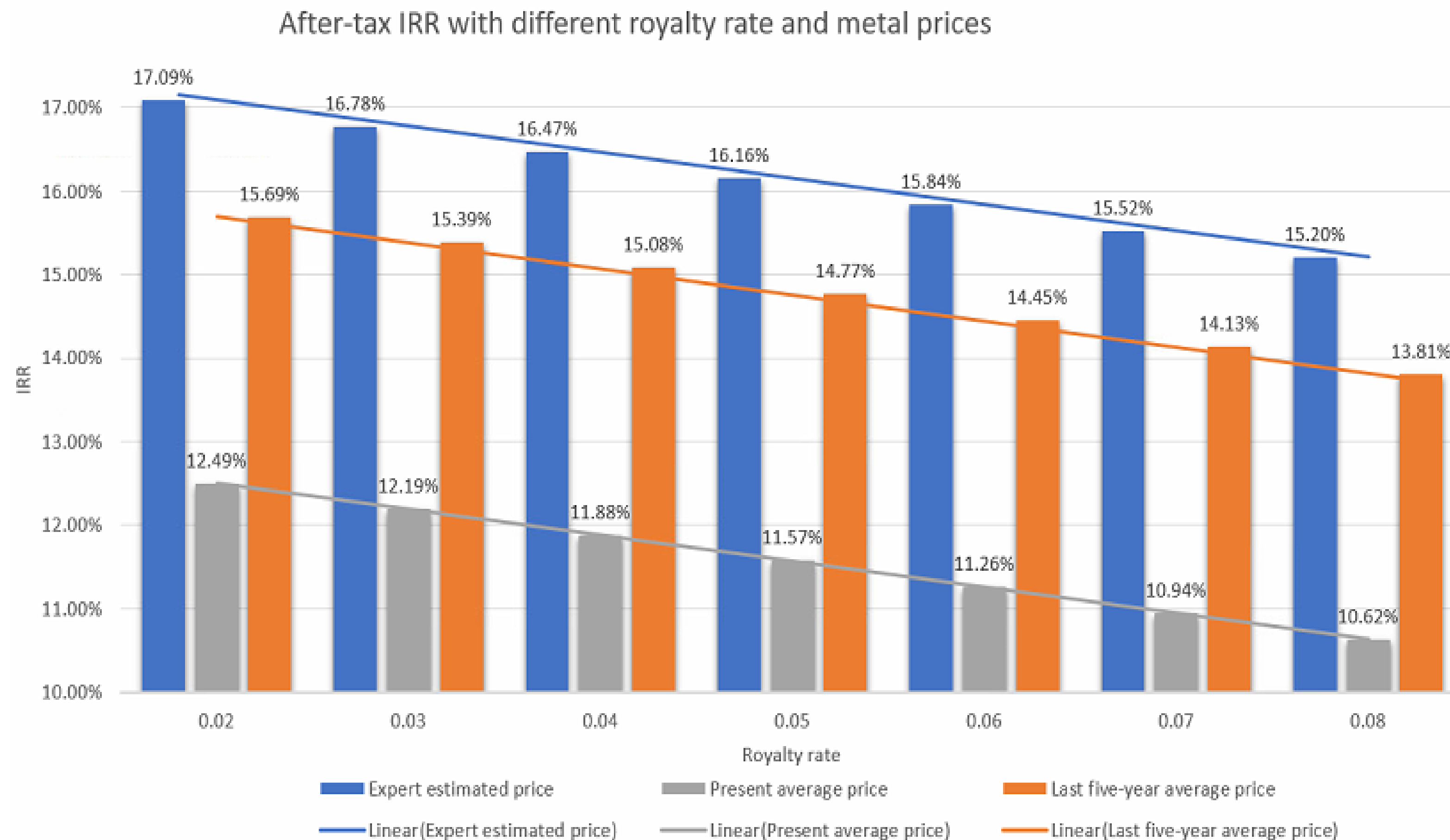
Note:1.The average price of Cu\Ni\Co are from LME. The average Mn price is from <http://www.asianmetal.cn>

2. We studied the decision tree machine-learning algorithm based on big data for metal price forecasting^[2].

3. Technical and economic evaluation of deep sea polymetallic nodules development —Analysis and Comparison of Royalty Rates

Fixed-rate ad valorem only royalty mechanism

- In this figure, three sets of metal prices in table 3-2 were discussed. The royalty rate changes from 2% to 8%.
- This figure shows that the royalty rate has a great impact on the economic evaluation index.
- According to the average price of last five years, when the ad-valorem royalty rate is equal to 4%, IRR will fall to 15.08%.
- If 15% is the threshold value of IRR, the ad-valorem royalty rate should not exceed 4% based on last five-year average price.



3. Technical and economic evaluation of deep sea polymetallic nodules development —Analysis and Comparison of Royalty Rates

Two-stage ad valorem only royalty mechanism

The basic parameter data used for calculation is from table 3-1;
Expert estimated price in table 3-2 is used for calculation.

Royalty Rate Scheme	IRR	Annual royalty (Million dollar)	Accumulative royalty (Million dollar)
AV-4%	16.5%	88.12	2203.01
AV1%5y+AV6%20y	16.5%	22.03/132.18	2753.77
AV2%5y+AV5%20y	16.5%	44.06/110.15	2423.32
AV-2.5%	17%	55.08	1376.88
AV1%5y+AV3.5%20y	17%	22.03/77.11	1652.26

- Note: E.g “AV1%5y+AV6%20y ” : It is divided into two stages of 5 years and 20 years, with 1% ad valorem royalty rate for the first 5 years and 6% ad valorem royalty rate for the next 20 years.
- When IRR is the same, considering the accumulative royalty, the “AV1%5y+AV6%20y ”is better than the “Ad-valorem 4%”.
 - The “AV1%5y+AV3.5%20y ”is better than the “Ad-valorem 2.5%”.
 - The mechanism of two-stage ad valorem only royalty is better than the mechanism of fixed-rate ad valorem only royalty.

3. Technical and economic evaluation of deep sea polymetallic nodules development —Analysis and Comparison of Royalty Rates

A combined ad valorem royalty and profit-based system

As long as minerals in the “Area” are mined and sold, ad valorem royalty model will have royalty income, which is obviously in line with the wishes of the Authority. However , the payment of profit-based royalty based on investment and production profits is beneficial to the contractor to reduce production costs and economic risks in the early stage of commercial production. Therefore, a purely profit-based or ad valorem model may be difficult to meet the requirements of both the Authority and the contractor. Based on this, if the system combined ad valorem royalty and profit-based is adopted, it is possible to balance the demands of both the Authority and the contractor to a certain extent.

The basic parameter data used for calculation is from table 3-1;
Expert estimated price in table 3-2 is used for calculation.

Payment Rate Scheme	IRR	NPV after tax (Million dollar)	Accumulative royalty (Million dollar)
AV-4%	16.5%	322.89	2203.01
AV2%+PB13%	16.5%	323.32	2519.12
AV-2.5%	17%	428.23	1376.88
AV1%+PB9%	17%	429.59	1561.92

- Note: E.g Ad valorem AV2%+PB13%: It is divided into two stages of 5 years + 20 years, with ad valorem of 2% for the first 5 years and AV2% + PB13% for the next 20 years.
- When IRR is same, considering the accumulative royalty, the AV2%+PB13% is better than the “Ad-valorem 4%”, the “AV1%+PB9% ”is better than the “Ad-valorem 2.5%”.
 - The system combined ad valorem royalty and profit-based is better than the mechanism of fixed-rate ad valorem only royalty.

3. Technical and economic evaluation of deep sea polymetallic nodules development ———Evaluation index calculation result of MIT model

- ◆ Adopt a Two-stage ad valorem recommended by MIT “AV3%5y→AV8%20y” .
- ◆ Basic parameters of MIT model^[3] (including fixed investment, operating cost, tax, ore grade, etc.) are adopted.
- ◆ Calculate five different prices in the table below. Only nickel price is revised in "revised MIT2018 value“.

	2015-2019 five-year average price	2020.1-2020.4 present average price	CSU2019 values	MIT2018 values (from the MIT2019 model)	Revised MIT2018 value (only revised nickel price)
Mn	1798	1547	1,685	1,640	1,640
Ni	11769	12475	12,692	22962	12,692
Co	41999	30983	67,261	55535	55,535
Cu	5823	5490	6,635	6965	6,965

	2015-2019 five-year average price	2020.1-2020.4 present average price	CSU2019 values	MIT2018 values (from the MIT2019 model)	Revised MIT2018 value (only revised nickel price)
IRR	13.25%	10.93%	14.19%	17.00% (from MIT report)	13.40%
NPV (millions of US dollars)	-94	-205	-47	114 (from MIT model)	-87

3. Technical and economic evaluation of deep sea polymetallic nodules development ——Risk Analysis

- ◆ Adopt a royalty rate recommended by MIT “AV3%5y→AV8%20y”
- ◆ The basic parameters of MIT model were adopted (including fixed investment, operating costs, taxes, ore grade, etc)
- ◆ Metal price adopts "revised MIT2018 value"

Distribution type and distribution interval of risk variables

Risk variables		Distribution type	Expectation	Distribution range	Range
Annual ore output (10,000 tons)		Triangular distribution	300	[250,315]	[-17%, +5%]
Annual operating cost (millions of US dollars)		Triangular distribution	1037	[778,1296]	+/-25%
Fixed investment (millions of US dollars)		Triangular distribution	4116	[3087,5145]	+/-25%
Metal grade	Mn	Triangular distribution	28.4%	[26.98%,29.82%]	+/-5%
	Co	Triangular distribution	0.2%	[0.19%,0.21%]	+/-5%
	Ni	Triangular distribution	1.3%	[1.235%,1.365%]	+/-5%
	Cu	Triangular distribution	1.1%	[1.045%,1.155%]	+/-5%
The price of the metal(USD/ton)	Mn	Triangular distribution	1640	[1230,2050]	+/-25%
	Co	Triangular distribution	55535	[41651.25,69418.75]	+/-25%
	Ni	Triangular distribution	12692	[9519,15865]	+/-25%
	Cu	Triangular distribution	6965	[5223.75,8706.25]	+/-25%

3. Technical and economic evaluation of deep sea polymetallic nodules development ———Risk Analysis

(1) Value added tax 8% is considered in risk analysis

Risk analysis process

Determine the probability distribution of risk variables



Construct the objective function of risk analysis



Random sampling multiple times for **montecarlo simulation**



Analyze the risk and economic feasibility of the project

➤If the net present value is more than \$0 million, the internal rate of return is more than 0.15, and the dynamic payback period is less than 25 years, then the investment risk of this project is about 78%.

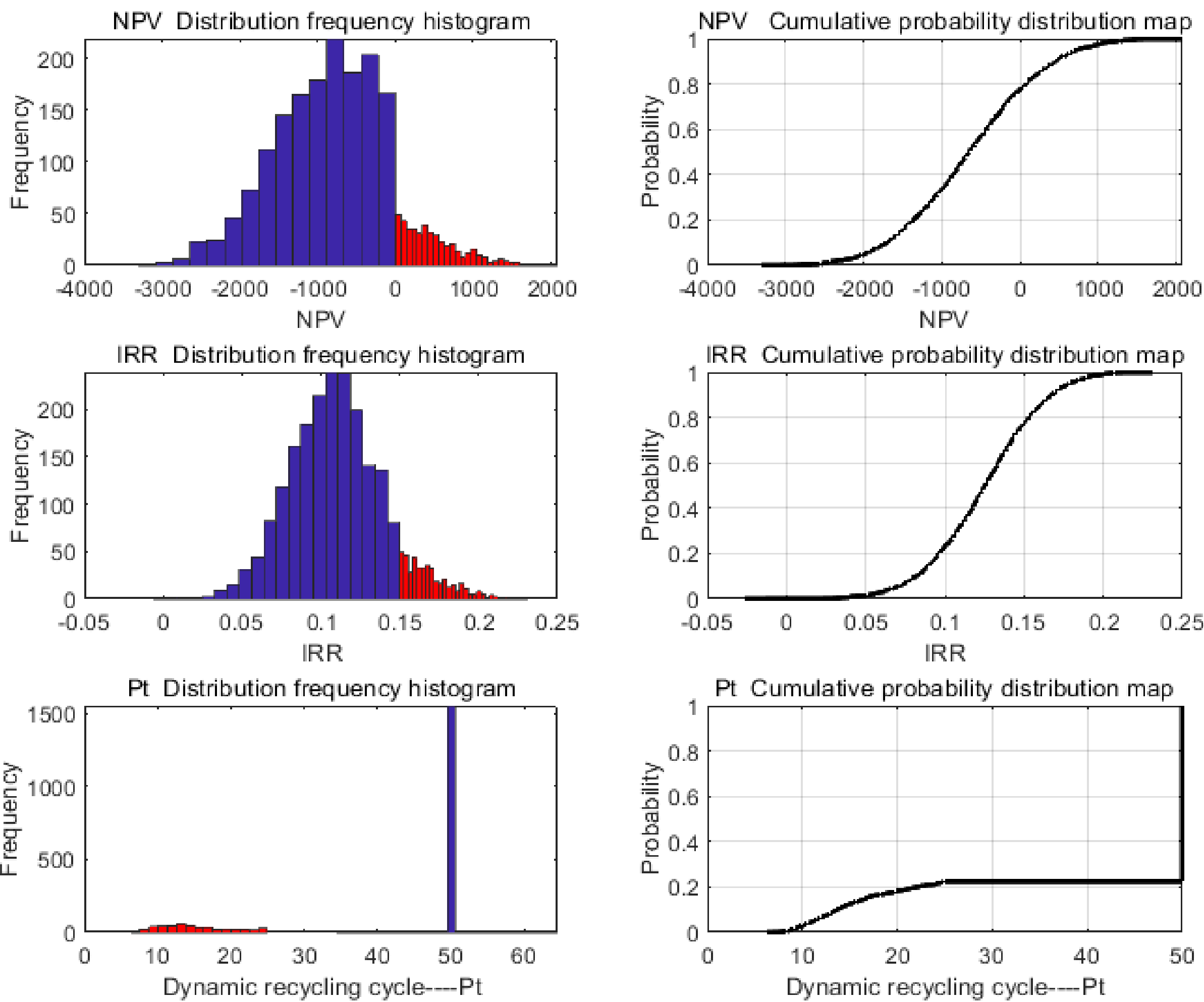


Fig.3 Distribution frequency histogram and cumulative probability distribution diagram of each evaluation index after tax

3. Technical and economic evaluation of deep sea polymetallic nodules development ———Risk Analysis

(2) Value added tax 8% is not considered in risk analysis

Risk analysis process

Determine the probability distribution of risk variables

Construct the objective function of risk analysis

Random sampling multiple times for **montecarlo simulation**

Analyze the risk and economic feasibility of the project

➤If the net present value is more than \$0 million, the internal rate of return is more than 0.15, and the dynamic payback period is less than 25 years, then the investment risk of this project is about 66%.

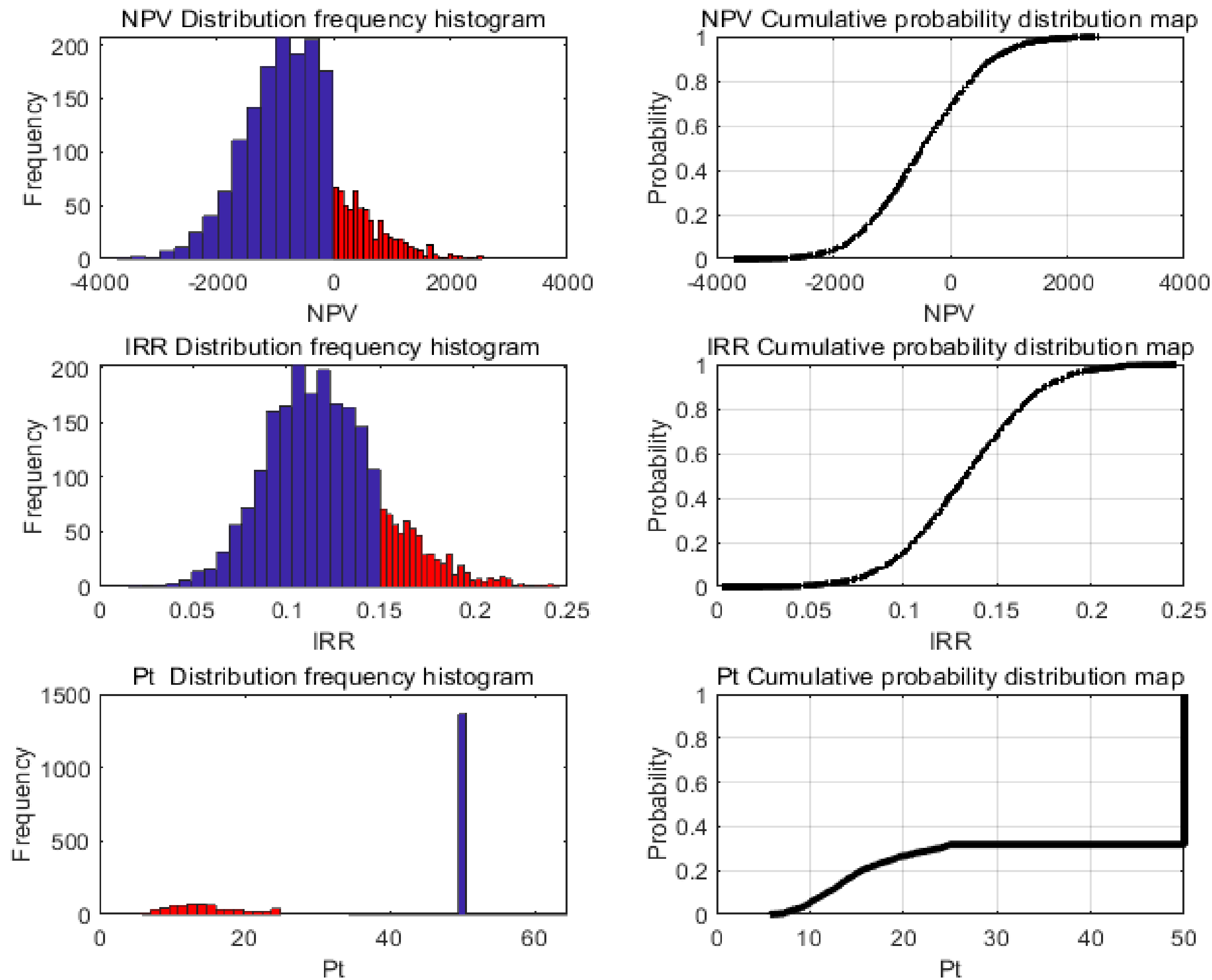


Fig.4 Distribution frequency histogram and cumulative probability distribution diagram of each evaluation index after tax

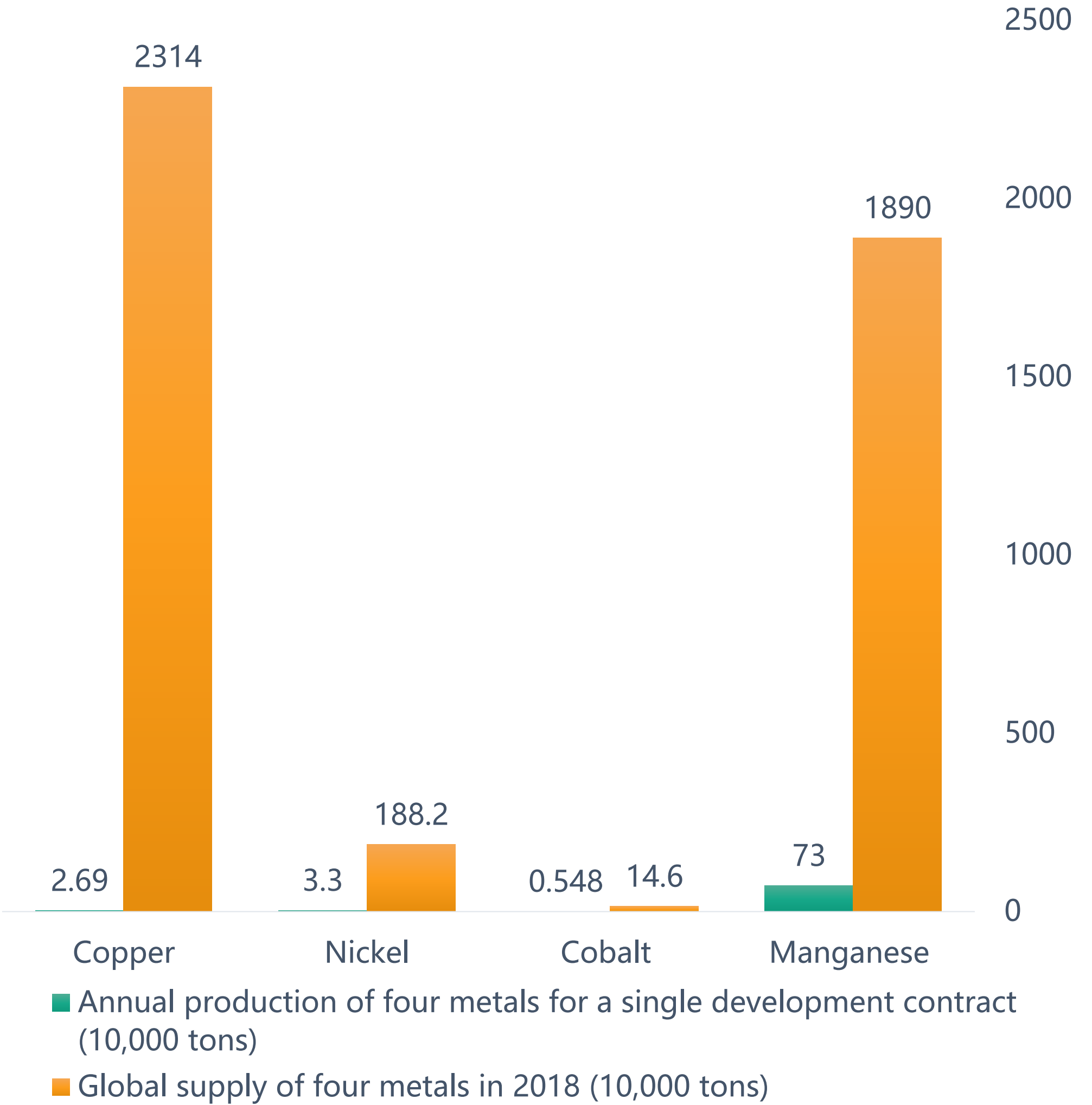
4. Possible impact of deep sea polymetallic nodules development on the metal market ——Individual development contracts account for global production

Assume that the annual production capacity of polymetallic nodules in a single development contract is 3 million tons. The metal grade and recovery rate are as follows.

Metal	Copper	Nickel	Cobalt	Manganese
Metal grade	1.02%	1.27%	0.22%	27.15%
Metal recovery	88%	87%	83%	90%

Metal	Copper	Nickel	Cobalt	Manganese
Annual production of four metals for a single development contract (10,000 tons)	2.69	3.3	0.548	73
Global supply of four metals in 2018 (10,000 tons)	2314	188.2	14.6	1890
Proportion	0.116%	1.75%	3.75%	3.86%

The prediction of metal price in the above economic evaluation analysis is based on the current land mining production conditions, while some metals in deep sea mineral resources have huge capacity relative to current market demand or land mining production, especially manganese and cobalt.



4. Possible impact of deep sea polymetallic nodules development on the metal market ——Manganese and Cobalt Market

Manganese Market

- The global production of manganese metal in 2018 is about 18.9 million tons. Calculated on 3 million tons of Polymetallic nodules per year in each mining area, the annual output of manganese in a single mining area is 730,000 tons. Assuming 10 mining areas are simultaneously mined, manganese metal production can reach 7.3 million tons, accounting for about 38.6% of the global manganese market supply. **Such structural changes in market supply and demand can lead to changes in metal prices that can be difficult to predict mathematically.**
- Each ton of electrolytic manganese consumes 7,000 kWh. Calculated on the annual output of 3 million tons, the annual electricity consumption is 5.1 billion kWh. At present, the installed capacity of China's medium-sized thermal power station is 1000MW, with 35% loss, and the annual generating capacity is 5.694 billion KWH. **The annual electricity consumption of electrolytic manganese in a mining area is almost equal to the annual power generation of a medium-sized thermal power station, and the energy consumption is too large.**



Electrolytic manganese is clearly not suitable as the sole product, and it is necessary to consider silicon-manganese alloy and manganese-rich slag as products, or in various product forms.

Cobalt Market

- The global supply of cobalt in 2018 is about 146,000 tons. Calculated on an annual output of 3 million tons of dry nodules, 0.21% of cobalt grade and 85% of smelting recovery rate, the production of cobalt metal in a single mining area can reach 0.54 million tons, accounting for 3.75% of the global market supply.
- **Assuming 10 mining areas are simultaneously mined, cobalt metal production can reach 54,000 tons, accounting for about 37.5% of the global market supply.**



If polymetallic nodules in the “Area” really enter large-scale mining, such a large increase in the production of cobalt metal may also have a huge impact on the global cobalt market capacity and the price of cobalt metal market.

reference

- [1] Chang L, Yan L, Liang Z, et al. Study on technical and economic evaluation model of seabed mineral resources exploitation[J]. China Mining Magazine. 2016. 25(8): 69-73.
- [3] Chang L, Zhenhua H, Yan L, et al. Forecasting copper prices by decision tree learning[J]. Resources Policy. 2017, 52: 427–434.
- [2] Randolph K, Richard R, Frank R, et al. Report to the International Seabed Authority on the Development of an economic Model and System of Payments for the Exploitation of Polymetallic Nodules in the Area[R]. 2019. Technical Report.