VALUATION METHODOLOGIES UPGRADE BY TOWARD SUSTAINABLE MINING

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Abstract: The valuation methodologies for mining assets need to be improved in line with the current requirements of responsible mining, sustainable mining, and environmental and social governance. The commonly used discounted cash flow method for the valuation of mining assets and its improved Real Options method, Monte Carlo simulation analysis, have a significant impact on the factors that affect the stability of investments, and the benefits to stakeholders from obtaining social consent are required to be reflected in the investment agreement. We have studied the requirements for responsible and sustainable mining and their financial impact with the current methodology for the valuation of minerals using content analysis, and identified areas for improving the valuation methodology. This methodology has become important in incorporating good practices of companies implementing responsible and sustainable mining internationally into the methodology for the valuation of mineral assets.
Keywords: Mining assets, Valuation methodologies, Towards Sustainable Mining

ТОГТВОРТОЙ УУЛ УУРХАЙН САНААЧЛАГААР АШИГТ МАЛТМАЛЫН ХӨРӨНГИЙН ҮНЭЛГЭЭНИЙ АРГА ЗҮЙГ САЙЖРУУЛАХ НЬ

Хураангуй: Уул уурхайн хөрөнгийн үнэлгээний арга зүйг хариуцлагатай уул уурхай, тогтвортой уул уурхай, байгаль орчин, нийгмийн засаглалын өнөөгийн шаардлагад нийцүүлэн сайжруулах шаардлагатай гэж байна. Ашигт малтмалын хөрөнгийн үнэлгээнд түгээмэл хэрэглэгддэг мөнгөн урсгалыг хорогдуулах арга болон түүний сайжруулалт болох Бодит Сонголтын арга, Монте Карло симуляцийн шинжилгээнд хөрөнгө оруулалтыг тогтворжуулах гэрээ, оролцогч талуудын хүртэх үр өгөөж, нийгмийн шаардлага мэдэгдэхүйц нөлөөлөхөөр байна. Бид хариуцлагатай, тогтвортой уул уурхайн шаардлага, тэдгээрийн санхүүгийн нөлөөллийг агуулгын шинжилгээ хийж, ашиглан ашигт малтмалын үнэлгээний одоогийн арга зүйгээр судалж, үнэлгээний арга зүйг сайжруулах чиглэлүүдийг тодорхойлсон. Энэхүү арга зүй нь олон улсад хариуцлагатай, тогтвортой уул уурхайг хэрэгжүүлж буй компаниудын сайн туршлагыг ашигт малтмалын хөрөнгийн үнэлгээний арга зүйд оруулахад чухал ач холбогдолтой болсон.
Түлхүүр үгс: Ашигт малтмалын хөрөнгө, үнэлгээний аргачлал, тогтвортой уул уурхай

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1. INTRODUCTION

In Mongolia, the Mongolian Institute of Geology and Mining (MGUMI) and the Mongolian Institute of Certified Valuers (MIV), an official member of the International Valuation Standards Council (IVSC), signed a Memorandum of Understanding (MoU) on February 5, 2021, to implement the Mongolian Codecs of Valuation of Mining Assets (MONVAL).

The draft MONVAL Code currently under development is aligned with the principles and requirements of the International Mineral Asset Valuation Code (The IMVAL code,2015) and establishes the standards for preparing mineral asset valuation reports. However, the authority approves the procedures and methodologies for the valuation of mineral resources, petroleum deposits, and natural gas assets that remain vested in the Ministry of Finance, in coordination with the Minister of Industry and Mineral Resources.

The draft of the Mineral Asset Valuation Procedures currently being prepared has a regulatory content for the valuation of the asset, and the draft methodology has the disadvantage of not taking into account the type of mineral, geological conditions, mining and enrichment technology, logistics, and ESG influences.

In other words, the draft methodology reflects the requirements of the principle of selectively applying the three main approaches to asset valuation, depending on the stage of development of the common mineral asset, in accordance with International Valuation Standards (IVS).

The following are the commonly used approaches and methods for evaluating mining project phases. Let's compare their advantages and disadvantages:

Table 1. Relationship between mining stages and valuation approaches

Valuation approach		Market	Income	Cost
Early stage exploration		Not generally used	Widely used	Widely used
Advanced stage exploration		Less widely used	Widely used	Widely used
Development properties		Widely used	Less widely used	Not generally used
Production properties		Widely used	Quite widely used	Not generally used
Dormant properties	Economically viable	Widely used	Quite widely used	Not generally used
	Economically not viable	Not generally used	Widely used	Less widely used
Defunct properties		Not generally used	Widely used	Quite widely used

Best Used For	Early–mid stage assets; benchmarking	Advanced projects; producing mines	Early exploration assets with no resources
Strengths	Anchored in real transactions; simple	Captures economics and risk; most rigorous	Simple, useful baseline
Limitations	A few comparable cyclical distortions	Highly assumption-sensitive; data-intensive	Weak link to value; ignores market and geology quality

Source: Researcher's update based on SAMVAL Code, 2016

Once the exploration of a mineral deposit is complete and the reserves are confirmed by the Mineral Resources Professional Council (MRP), a feasibility study (FES) will be conducted to determine whether the deposit is economically viable. This feasibility study serves as a baseline economic and financial valuation, such as net present value, payback period, and internal rate of return.

Net present value and other financial indicators are based on Discounted Cash Flow methods (DCF, income approaches), and mineral asset valuation is being improved using methodologies such as sensitivity analysis, Real option, and Monte Carlo simulation.

Table 2. Comparisons of mineral assets methodologies

Criteria	DCF	Real Option Valuation	Monte Carlo Simulation
Level of Use	Very widely used	Moderately used	Increasingly used
Ease of Understanding	Very easy to understand	Complex	Moderate
Risk Analysis Capability	Limited	Strong	Very strong
Ability to Evaluate Flexibility	Not effective	Excellent	Moderate
Commodity Price Volatility Handling	Weak	Excellent	Strong
ESG Integration Capability	Moderate	Strong	Excellent

Complexity	Low	Very high	High
Data Requirement	Medium	High	Very high
Bank Acceptance	Very high	Moderate	High

Source: Researcher's comparison

The Discounted Cash Flow (DCF) method remains the most widely used mineral asset valuation methodology in the mining industry because of its simplicity, transparency, and strong acceptance by financial institutions and investors. DCF estimates the present value of future cash flows generated by a mining project using a discount rate that reflects project risk. Its primary advantage is that it provides a clear and standardized framework for feasibility studies, investment decisions, and project financing. However, the method has important limitations, particularly its sensitivity to assumptions related to commodity prices, production forecasts, operating costs, and discount rates. In addition, DCF assumes relatively fixed project plans and therefore struggles to adequately capture uncertainty, managerial flexibility, and changing market conditions in highly volatile mining environments. Sources: CIMVAL; (IMVAL)\

Real Option Valuation (ROV) has become increasingly important in mineral asset valuation because it incorporates strategic flexibility into project assessment. Unlike DCF, ROV recognizes that mining companies can adapt decisions over time by delaying, expanding, suspending, or abandoning projects in response to commodity price volatility, regulatory uncertainty, or operational risks. This flexibility is particularly valuable for early-stage mining projects and highly volatile commodities such as uranium, copper, lithium, and rare earth elements. The major strength of ROV lies in its ability to better represent uncertainty and managerial decision-making under changing market conditions. However, the method is highly complex and requires advanced mathematical modeling, volatility estimation, and scenario assumptions, which limit its practical use in routine valuation exercises. Furthermore, because of its complexity, ROV is less commonly accepted by banks and traditional investors compared with DCF. Sources: (SME);

Monte Carlo Simulation (MCS) is increasingly used in mineral asset valuation to analyze uncertainty and quantify project risks through probabilistic modeling. Rather than relying on single-point assumptions, MCS generates thousands of potential project outcomes by simulating variations in key variables such as commodity prices, ore grades, recovery rates, capital costs, operating costs, and ESG-related risks. The main advantage of Monte Carlo Simulation is its strong ability to evaluate multiple uncertainties simultaneously and provide a range of possible project values and risk distributions. This makes it particularly useful for ESG-sensitive projects, climate-related risk assessment, and advanced investment analysis. Nevertheless, MCS requires large volumes of high-quality data, sophisticated computational models, and technical expertise to interpret results correctly. Its output can also be difficult for non-technical stakeholders to understand, limiting its widespread application in traditional

financing contexts. Sources: Society of Petroleum Engineers;

Overall, modern mineral asset valuation increasingly relies on a combination of DCF, Real Option Valuation, and Monte Carlo Simulation methods rather than a single approach. DCF continues to serve as the industry-standard baseline valuation tool, while Real Option Valuation improves the assessment of strategic flexibility, and Monte Carlo Simulation strengthens uncertainty and ESG risk analysis. As mining projects become more exposed to commodity price volatility, climate-related risks, sustainability requirements, and geopolitical uncertainty, integrated valuation approaches are becoming essential for producing more realistic and decision-useful assessments of long-term mineral asset value. Sources: CRIRSCO; (ICMM)

2. LITERATURE REVIEW

2.1 Development of ESG Concept and Sustainable Mining

The concept of Environmental, Social, and Governance (ESG) has evolved from broader theories of sustainable development, stakeholder management, and corporate social responsibility. One of the earliest foundational studies was conducted by R. Edward Freeman in *Strategic Management: A Stakeholder Approach* (1984), where the stakeholder theory argued that corporations should not focus solely on shareholder profit maximization, but also consider the interests of employees, communities, governments, suppliers, and the environment. This theory later became one of the conceptual foundations of the social and governance dimensions of ESG.

A major milestone in sustainability studies was the publication of Our Common Future by the United Nations in 1987. The report defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This definition became the basis of modern sustainability and environmental governance frameworks.

Later, John Elkington (1997) introduced the concept of the Triple Bottom Line in *Cannibals with Forks*, emphasizing that corporate performance should be evaluated not only by profit, but also by people and planet. This framework significantly influenced the development of ESG evaluation systems and sustainability reporting.

The term ESG itself was formally introduced in the 2004 report *Who Cares Wins*, developed by the United Nations Environment Programme Finance Initiative together with institutional investors. The report concluded that companies with stronger ESG performance may achieve superior long-term financial performance and lower investment risk. Since then, ESG has increasingly become integrated into investment analysis and corporate valuation practices.

2.2 ESG and Corporate Financial Performance

A substantial body of literature has examined the relationship between ESG performance and corporate financial performance. Michael Porter and Mark Kramer (2006), in *Strategy and Society*, argued that sustainability and corporate social responsibility should not be treated as cost, but rather as sources of competitive advantage and long-term value creation.

Similarly, a study conducted by Harvard Business School researchers Eccles, Ioannou, and Serafeim (2014) found that companies with strong sustainability practices generally outperform others in operational and stock market performance over the long term. Their research demonstrated that sustainability-oriented companies tend to adopt stronger governance systems, improved stakeholder relationships, and more resilient business strategies.

Furthermore, Friede, Busch, and Bassen (2015) conducted one of the largest meta-analyses in ESG research by reviewing more than 2,000 empirical studies. Their findings indicated that approximately 90 percent of studies identified a non-negative relationship between ESG and financial performance, while the majority reported a positive relationship. These findings strengthened the argument that ESG performance can materially influence firm value and investment attractiveness.

2.3 ESG and Sustainable Mining Studies

In the mining sector, ESG issues are particularly significant due to the industry's environmental impacts, social conflicts, and governance challenges. Previous studies have highlighted that mining sustainability depends not only on technical and financial performance, but also on environmental stewardship, community engagement, and long-term social acceptance.

Laurence (2011), in *Establishing a Sustainable Mining Operation: An Overview*, emphasized that technical success alone is insufficient for sustainable mining development. The study identified stakeholder engagement, mine closure planning, environmental management, and governance systems as critical components of sustainable mining operations.

Kemp et al. (2010) examined the relationship between mining, water governance, and human rights, concluding that water-related issues represent one of the most critical ESG risks in mining projects. Their research demonstrated that poor water management can significantly increase community conflict and project risks.

Additionally, Whitmore (2006), in *The Emperor's New Clothes: Sustainable Mining*, critically evaluated the concept of sustainable mining and argued that some sustainability reporting practices may resemble greenwashing if not supported by measurable operational improvements and transparent verification systems.

2.4 Towards Sustainable Mining (TSM) Framework

The Mining Association of Canada developed the Towards Sustainable Mining (TSM)

framework as an operational ESG management system for the mining industry. According to Jarvie-Eggart's review of the TSM program, the framework was developed between 1998 and 2004 in response to growing public concern regarding the environmental and social impacts of mining activities.

TSM evaluates mining companies through multiple protocols, including:

- tailing management,
- biodiversity conservation,
- Indigenous and community outreach,
- energy and greenhouse gas management,
- crisis management,
- safety and health.

The framework applies to a performance rating system ranging from C to AAA, where companies are encouraged to continuously improve sustainability performance and integrate ESG principles into operational and strategic decision-making. One of the unique strengths of TSM is its combination of continuous improvement and external verification mechanisms, which improve transparency, accountability, and stakeholder confidence.

Fitzpatrick, Fonseca, and McAllister (2011) concluded that TSM significantly improved transparency and stakeholder engagement within the Canadian mining industry. However, the authors also noted that TSM primarily evaluates management systems rather than direct environmental or social outcomes.

2.5 ESG Integration into Mining Asset Valuation

Recent studies increasingly focus on integrating ESG factors into mining asset valuation methodologies. Traditional valuation methods such as Discounted Cash Flow (DCF), Real Option Valuation, and Monte Carlo Simulation are now frequently adjusted to incorporate ESG-related risks and opportunities.

Table 3. Comparative Perspective of Major ESG–Valuation Studies

Authors / Study	Main ESG Focus	Research Method	Key Findings	Impact on Mining Valuation	Limitations
Michael Porter & Mark Kramer (2006) – *Strategy and Society*	Strategic ESG and CSR integration	Conceptual and strategic analysis	ESG and sustainability can create a competitive advantage rather than simply increasing costs	Strong ESG may reduce long-term operational and reputational risks, improving project value	Mainly conceptual; limited empirical mining-specific evidence
Eccles, Ioannou & Serafeim (2014) – *The Impact of Corporate Sustainability on Organizational Processes and Performance*	Corporate sustainability performance	Longitudinal empirical analysis of 180 companies	High-sustainability firms outperform low-sustainability firms over the long term in operational and stock market performance	Strong ESG governance may increase valuation stability and investor confidence	Focused on broad industries, not mining-specific
Friede, Busch & Bassen (2015) – *ESG and Financial Performance*	ESG and financial performance relationship	Meta-analysis of 2,000+ empirical studies	Approximately 90% of studies found non-negative ESG–financial relationships; majority found positive relationships	ESG integration may enhance long-term mining asset valuation and reduce investment risk	Results vary depending on region and industry
Kemp et al. (2010) – *Mining, Water and Human Rights*	Water governance and human rights	Mining case analysis	Water-related conflicts are among the largest ESG risks in mining	Poor water management may increase remediation costs, permitting risk, and project delays	Primarily focused on social-environmental conflict rather than quantitative valuation

Laurence (2011) — *Establishing a Sustainable Mining Operation*	Sustainable mining operations	Industry sustainability review	Technical success alone is insufficient; stakeholder engagement and governance are critical	ESG factors influence operational continuity and long-term mine viability	Limited quantitative financial analysis
Whitmore (2006) — *The Emperor's New Clothes: Sustainable Mining?*	Critique of sustainable mining claims	Critical sustainability analysis	Some sustainability reporting may represent greenwashing without measurable performance improvement	Weak ESG credibility may increase reputational and financing risks	Critical perspective with limited operational measurement
Fidler (2010) — *Aboriginal Engagement and Negotiated Agreements*	Indigenous engagement and social license	Community and negotiation analysis	Community acceptance significantly affects project success	Strong social license may reduce delay risk and improve valuation certainty	Focused mainly on Canadian Indigenous contexts
Mining Association of Canada — TSM Studies	Operational ESG management systems	Protocol-based operational assessment	Continuous improvement and external verification improve accountability and stakeholder trust	Better ESG systems may reduce operational, environmental, and governance risk premiums	Focuses more on management systems than direct ESG outcomes
UNEP FI (2004) — *Who Cares Wins*	ESG integration in finance	Institutional investor framework	ESG factors are material to investment analysis and long-term financial performance	ESG-adjusted discount rates and financing conditions increasingly influence mining valuation	Early-stage ESG finance framework with limited operational detail
SASB / IFRS Sustainability Studies	ESG disclosure standardization	Sustainability reporting frameworks	Standardized ESG metrics improve comparability and investor decision-making	Better ESG disclosure reduces information asymmetry and financing uncertainty	Framework-oriented rather than mine-specific analysis

Source: Researcher's summary

Researchers have argued that ESG factors affect mining valuation through:

- discount rate adjustments,
- closure liabilities,
- environmental remediation costs,
- financing conditions,
- operational continuity,
- and social license to operate.

Monte Carlo Simulation has become particularly useful for incorporating ESG uncertainty into mining project valuation because it can model multiple environmental, social, and regulatory risks simultaneously. Similarly, Real Option Valuation is increasingly applied to evaluate strategic flexibility under uncertain ESG and commodity market conditions.

Overall, the literature demonstrates that modern mining valuation is evolving from pure financial analysis toward integrated sustainability-based valuation frameworks combining financial performance, ESG quality, risk management, and long-term resilience.

3. RESEARCH METHODOLOGY

3.1 Research Methodology Framework and Design

This research aims to examine the integration of ESG factors and the TSM framework into mining asset valuation methodologies. The study particularly focuses on uranium mining projects and evaluates how sustainability-related risks and operational ESG performance influence mining project valuation.

The study applies a mixed methodological approach combining:

- Qualitative analysis was to rate implementation TSM and ESG assessment, and content analysis methods
- Quantitative financial modeling was calculated ESG integrated NPV
- Comparative analysis made NPV and ESG integrated NPV

The ESG-adjusted valuation model is expressed as

$$NPV_{ESG} = \sum_{t=0}^{n} \frac{CF_t - ESG\ Costs + ESG\ Benefits}{(1 + r + ESG\ Risk)^t}$$

Where:

- ESG Costs include remediation expenses, compliance costs, and social conflict impacts.
- ESG Benefits include lower financing costs, stronger operational continuity, and improved stakeholder trust.
- ESG Risk reflects sustainability-related risk premiums

3.2 Data Collection and Sources

Uranium exploration in Mongolia began in 1948. During the 1970s and 1980s, extensive geological surveys were carried out in eastern Mongolia in cooperation with Soviet geologists, leading to the discovery of the Mardai, Gurvanbulag, and Dornod uranium deposits. Between 1988 and 1995, uranium ore from the Mardai deposit was extracted and transported to Russia for processing.
Following the democratic revolution in 1990 and Mongolia's transition to a market-oriented economy, the country opened its mining sector to private and foreign investment, which led to the discovery of new uranium deposits. Since 1997, the French company "Areva Mongolia" (now Orano Mining, subsidiary Badrakh Energy) has conducted uranium exploration activities in Dornogovi Province, resulting in the discovery of the large uranium deposit "Zovch-Ovoo" in Zuunbayan.

With the Government of Mongolia signing an investment agreement with Orano Mining on January 17, 2025, the uranium project that had been stalled for 27 years is now moving into the development phase, creating a real opportunity for Mongolia to bring its uranium deposits into economic circulation.

Table 4: Selected Uranium deposits for assessment of the TSM framework.

Project, Location	Main Company/ Operator	Deposit Type	Estimated Uranium Resource	Mining Method/ Capacity	Development Status	Key Characteristics
Zovch-Ovoo, Dornogovi	Badrakh Energy/ Orano Mining	Sandstone-hosted uranium	~87,660 tU	ISR (In-Situ Recovery) 2500tU in a year	Investment agreement signed; development stage	Mongolia's largest uranium deposits; low-impact ISR technology
Dulaan Uul, Dornod	Mon-Atom	Sandstone-hosted uranium	~6,260 tU	Potential ISR	Exploration/ feasibility stage	Considered suitable for ISR mining

Mardai, Dornod	Former Soviet–Mongolian joint project	Vein-type uranium	~25,000–30,000 tU (historical estimate)	Underground mining	Previously developed during Soviet period	Mongolia's historically most developed uranium project
Gurvanbulag, Dornod	Central Asian Uranium Company	Volcanic-related uranium	~13,000 tU	Conventional mining potential	Exploration stage	Higher-grade uranium occurrence
Nemer, Dornod	Exploration license holders	Sandstone uranium	Limited public data	ISR potential	Early exploration	Small-to-medium scale potential
Kharaat, Dornogovi	Various exploration entities	Sedimentary uranium	Limited public estimate	ISR potential	Exploration stage	Located within southeastern uranium belt
Ulzit, Sukhbaatar	Exploration companies	Sandstone uranium	Limited public data	Potential ISR	Early exploration	Prospective uranium-bearing basin

Source: Sustainable development report-2020 Badrakh Energy, Researcher's summary

A preliminary review of the implementation alignment with the TSM framework, based on the contents of the Orano Mongolia Uranium Investment Agreement and Zuuvch Ovoo Project, uranium mining for sustainable future 2022, Corporate Social Responsibility Report of Badrakh energy LLC, 2022.

Table 5. Inputs on Feasibility study of Zovch-Ovoo projects.

Scenario	**Base line**	**Heigh**	**Rise**
Commodity Price $/lb	70-80$	80-90	10$
Royalty	7%	8%	1% max-14%
Discount rate	12%	12%	ESG adjusted rate-10%
Resource size	87,660 tU	2,500 тU	Capacity in year
CAPEX	USD 1.6 billion	30+ years	Mine life
Company	**OPEX**	**Technology**	**Additional**
Canada -Cameco			

Cash Cost (USD/lb U_3O_8)	~$20–30	Underground + ISR JV	High-grade ore, but underground mining costs are relatively high
AISC (USD/lb U_3O_8)	~$35–45		
Kazakhstan- Kazatomprom			
Cash Cost (USD/lb U_3O_8)	~$12–18	ISR / ISL	One of the world's lowest-cost ISR uranium producers
AISC (USD/lb U_3O_8)	~$26–27.5		
Kazakhstan, Russia, Uranium One			
Cash Cost (USD/lb U_3O_8)	$15–22	ISR	Primarily based on Kazakhstan ISR assets
AISC (USD/lb U_3O_8)	~$28–35		
China, Kazakhstan, CGN Mining			
Cash Cost (USD/lb U_3O_8)	~$18–25	ISR + Joint Ventures	Integrated overseas uranium supply model
AISC (USD/lb U_3O_8)	~$30–38		

Source: Financial performance data for use in the feasibility study

Additional: Time Series Analysis was conducted using monthly average uranium prices per pound from January 1992 to March 2026 to support Real Options Valuation and Monte Carlo Simulation for future price scenario generation.

4. RESULT

4.1 Rating on implementation ESG and TSM on Zovch-Ovoo projects

In this study, we conducted content analysis and used a qualitative scoring method to assess ESG and TSM implementation.

Table 6. ESG Implementation Rating

ESG Pillar	Assessment	Rating
Environmental	ISR mining, monitoring systems, lower surface disturbance, climate-transition alignment	7.5/10

Social	Local employment, stakeholder engagement, scholarships, livestock & community support	8/10
Governance	EITI support, anti-corruption framework, compliance systems, state partnership	8.5/10
Overall ESG Implementation	Moderate—Strong ESG implementation	8/10
TSM Alignment	Moderate—High	Approximately Level B to A
Investment ESG Attractiveness	Strong but risk-sensitive	Not measured

Source: Researchers' summary

ISR technology generally creates less land disturbance and lower carbon intensity compared with conventional uranium mining. However, uranium mining still carries environmental risks related to groundwater contamination, acid leaching, radioactive materials, and long-term site rehabilitation. Therefore, the project demonstrates relatively strong environmental management practices, but environmental sensitivity remains high.

The project applies In-Situ Recovery (ISR) mining, described as a "non-destructive mining technology" with no pits, shafts, or major dust emissions. The company also reports groundwater monitoring, long-term remediation plans, and biodiversity initiatives such as planting 7,500 saxaul trees.

The company appears to prioritize local participation and social investment, which supports community acceptance and regional economic development. Programs related to education, animal health, and local infrastructure improve the project's social performance. However, uranium mining remains socially sensitive because of radiation concerns and possible future community opposition.

The reports indicate that 96% of employees are Mongolian citizens and that the company implemented scholarships, livestock support programs, local procurement, and community development funding. The project also states that it plans to create approximately 1,600 direct and indirect jobs.

Governance is the project's strongest ESG pillar, supported by formal compliance systems, international reporting standards, and oversight in both Mongolia and France. Orano's participation strengthens technical capacity and governance credibility. However, the strategic

nature of uranium mining means regulatory and political risks remain significant.

The company reports implementation of anti-corruption systems, whistleblowing mechanisms, compliance training, supplier screening, and support for the Extractive Industries Transparency Initiative (EITI). The project also follows ISO-related commitments and governance oversight through Mongolian and French state participation.

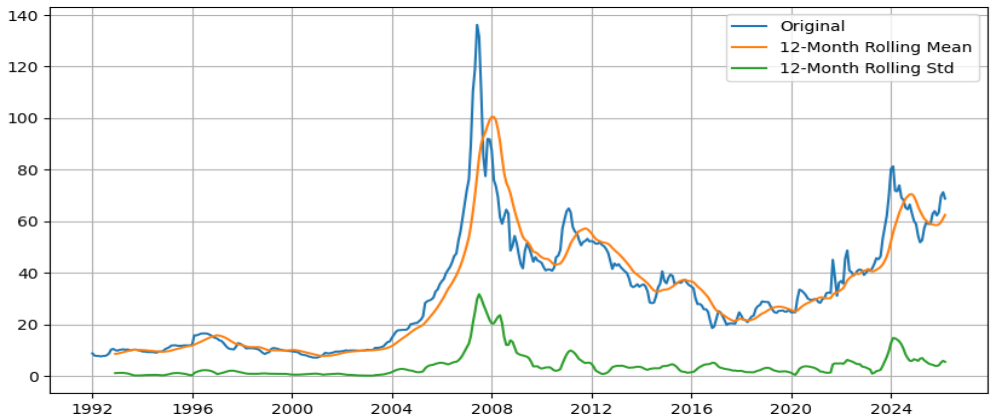
Overall, the Zuuvch Ovoo project demonstrates ESG practices that are stronger than many traditional mining projects in emerging markets. The project is aligned with global low-carbon energy trends and international mining governance practices. However, long-term ESG performance will depend on operational execution, environmental monitoring, stakeholder trust, and regulatory stability throughout the mine life.

The project combines ISR mining, ESG policies, stakeholder engagement, transparency initiatives, local participation, and climate-transition positioning.

4.2 The ESG-adjusted valuation methods

Historical uranium prices data may fluctuate across a wide range in the future, indicating substantial uncertainty and high sensitivity in the projected cash flows of mining projects. These findings demonstrate that a single deterministic forecast is insufficient and support the application of a scenario-based valuation approach.

Figure 1. Rolling Mean and Standard Deviation



Source: uranium price per pound https://www.cameco.com/invest/markets/uranium-price

We developed 2,141 future uranium price scenarios based on Monte Carlo simulation results derived from uranium price trends and cyclical time-series analysis.

Based on the uranium price forecasts, the Net Present Value (NPV) of the Zovch-Ovoo

project was estimated to use an ESG-adjusted valuation model. In this valuation, the royalty escalation rate linked to uranium price changes was incorporated in accordance with Article 20.1 of the Nuclear Energy Law of Mongolia.

The extraction unit cash cost was assumed to range between USD 12–18 per pound, reflecting the operational performance levels of benchmark uranium mining companies. The project investment was evaluated over a 35-year mine life assumption to estimate long-term capital recovery.

To assess the ESG impact, total project costs were estimated at the All-In Sustaining Cost (AISC) level of comparable benchmark companies. This approach incorporates not only direct operating costs, but also sustaining capital expenditures, environmental management costs, rehabilitation obligations, governance-related expenditures, and long-term operational sustainability factors.

Table 7. NPV vs ESG NPV-Statistics by Price Interval

Price Range (USD/lb)	Scenario (Number of Simulations)	NPV (USD)				ESG NPV (USD)			
		Min of NPV (USD)	Average of NPV (USD)	Max of NPV (USD)	StdDev of NPV (USD)	Min of ESG NPV (USD)	Average of ESG NPV (USD)	Max of ESG NPV (USD)	StdDev of ESG NPV (USD)
to 30	48	(1,619,200,118)	(1,423,604,461)	(1,236,994,493)	127,313,849	(1,939,090,882)	(1,650,839,697)	(1,355,826,305)	190,034,359
30 to 40	67	(1,235,326,260)	(1,101,434,964)	(980,421,842)	81,066,188	(1,352,584,220)	(1,117,691,113)	(930,251,243)	132,448,537
40 to 50	143	(975,339,644)	(821,133,463)	(718,268,468)	74,586,192	(922,843,589)	(698,077,469)	(548,144,661)	108,714,507
50 to 60	510	(715,833,797)	(580,659,474)	(457,468,598)	75,821,819	(544,595,960)	(347,570,083)	(168,010,904)	110,515,519
60 to 70	430	(471,803,923)	(337,334,130)	(215,619,529)	74,506,715	(188,905,627)	7,093,349	184,500,756	108,598,664
70 to 80	308	(234,535,367)	(119,845,627)	18,798,848	71,408,524	156,929,620	324,097,808	526,181,670	104,082,837
80 to 90	190	(1,459,216)	125,600,098	248,986,881	75,546,496	496,654,148	681,851,841	861,696,569	110,114,216
90 to 100	164	225,577,007	344,324,847	473,483,578	69,964,272	827,575,065	1,000,658,213	1,188,915,952	101,977,741
100 to 110	164	447,519,221	565,133,356	691,295,688	68,655,217	1,151,071,115	1,322,501,811	1,506,392,090	100,069,703
110 to 120	114	664,631,244	774,867,326	902,994,254	71,939,684	1,467,526,829	1,628,203,504	1,814,957,318	104,857,040
120 to 130	86	876,320,977	1,004,464,854	1,111,085,151	63,959,911	1,776,079,181	1,962,857,700	2,118,264,119	93,225,971
130 to 140	69	1,080,203,259	1,187,308,754	1,305,257,133	61,706,170	2,073,251,637	2,229,365,265	2,401,283,144	89,940,989
over 140	48	1,279,351,367	1,396,965,592	1,511,579,236	74,591,946	2,363,523,708	2,534,954,534	2,702,011,807	108,722,894
Total / Overall	**2,141**	**(1,619,200,118)**	**(58,294,787)**	**1,511,579,236**	**633,328,951**	**(1,939,090,882)**	**411,793,521**	**2,702,011,807**	**927,435,908**

Notes

- **Scenario (Number of Simulations):** Number of Monte Carlo simulation results within each price interval (NPV scenarios).
- Values are in USD.
- Negative values are shown in red, positive values in green.
- NPV and ESG NPV are calculated using the same simulation scenarios.

Variation (Var %) Formula

Var (%) = (Average − Previous Average) / |Previous Average| × 100

Coefficient of Variation (Varp) Formula

Varp = StdDev / |Average|

A higher Varp indicates greater relative volatility.

Source: Researcher's calculation.

The Coefficient of Variation (CV) is a statistical measure that evaluates the degree of variability relative to the mean value of a dataset and is widely used to assess the relative level of risk.

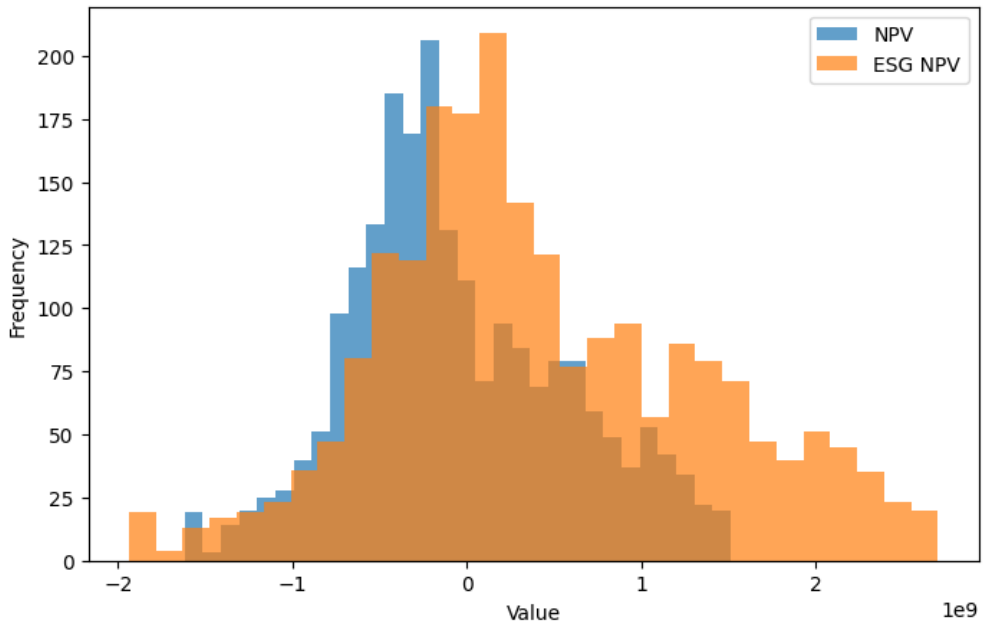
The CV of the conventional NPV is 10.86, indicating extremely high volatility and instability relative to its average value. In contrast, the CV of the ESG-adjusted NPV is 2.25, suggesting comparatively lower risk and a more stable financial structure.

The ESG-adjusted NPV exhibits a wider distribution and greater variability in values. This suggests that incorporating ESG factors into the valuation framework may enhance

the project's long-term value potential, although it may also increase short-term costs and investment pressures.

The distribution of the conventional NPV is relatively more concentrated, indicating comparatively stable financial returns; however, it primarily reflects a valuation approach based solely on projected cash flows. In contrast, the ESG-adjusted NPV incorporates environmental, social, and governance considerations, thereby better capturing long-term benefits such as reduced regulatory risk, improved social license to operate, and enhanced access to sustainable financing opportunities.

Figure 2. NPV vs ESG NPV Distribution



DISCUSSION

ESG considerations are increasingly demonstrating substantial implications for asset valuation, particularly within the mining sector. This necessitates an explicit integration of ESG factors into established valuation methodologies, including their underlying assumptions and the data employed throughout the valuation process.

The findings derived from this study align with previous research, suggesting that the incorporation of ESG factors into project valuation can significantly contribute to the long-term viability and resilience of value creation.

An examination of the distribution profiles for both conventional Net Present Value (NPV) and ESG-adjusted NPV indicates that both metrics exhibit sensitivity to fluctuations in uranium prices. However, a comparative analysis of risk levels reveals

that the higher standard deviation associated with NPV_{ESG} implies a heightened responsiveness to shifts in both broader market conditions and ESG-specific criteria. Despite this amplified sensitivity, the consistently positive average value of NPV_{ESG} suggests that projects meticulously aligned with sustainable development principles hold the potential to generate superior long-term value.

Consequently, an exclusive reliance on traditional NPV may prove insufficient for comprehensive investment decision-making in mining. The application of ESG-integrated valuation approaches, such as the ESG-adjusted NPV, is therefore proposed as a more appropriate and robust methodology for strategic evaluation and for guiding investment analysis toward sustainable development objectives in mining projects.

Conclusion

This study indicates that ESG requirements and sustainable mining standards are evolving into critical elements within mineral asset valuation. This is particularly pertinent to the mining sector, where projects inherently face substantial environmental, social, regulatory, and market-related exposures. While traditional valuation methods, such as Discounted Cash Flow (DCF), retain their fundamental role for baseline project assessment due to their inherent simplicity, transparency, and established industry acceptance, they are proving insufficient on their own. These conventional approaches are limited in their capacity to comprehensively address the complexities of contemporary mining projects, which operate amidst commodity price volatility, climate-related uncertainties, evolving ESG expectations, and increasing stakeholder scrutiny.

Further analysis reveals that incorporating ESG considerations into valuation methodologies can notably refine the assessment of long-term project sustainability and the stability of value. A comparative examination between traditional Net Present Value (NPV) and ESG-adjusted NPV suggests that, although ESG NPV may exhibit heightened sensitivity and volatility, attributable to the inclusion of additional sustainability-related variables, its long-term valuation outcomes are often positive. This implies that responsible mining projects, those aligned with sustainable development principles, are poised to generate more robust and resilient economic value over extended periods.

The research also confirms that advanced valuation methodologies, specifically Real Option Valuation (ROV) and Monte Carlo Simulation, offer distinct advantages when evaluating uncertainty, operational flexibility, and ESG-related risks. ROV enhances the capacity to appraise strategic managerial decisions within volatile market conditions, while Monte Carlo Simulation facilitates the probabilistic modeling of a range of uncertainties, encompassing commodity prices, environmental liabilities, climate risks, and factors related to social license to operate. Consequently, integrated valuation frameworks that combine DCF, ESG-adjusted NPV, ROV, and Monte Carlo Simulation present a more holistic and realistic approach to the valuation of mining assets.

The case study involving the Mongolia—Orano uranium project provides empirical evidence of how the adoption of international responsible mining frameworks, such as Towards Sustainable Mining (TSM), alongside robust ESG reporting practices, In-Situ Recovery (ISR) mining technology, advanced groundwater protection systems, proactive stakeholder engagement mechanisms, and local economic development initiatives, can positively influence long-term project value, investment appeal, and financial resilience. This project demonstrates a strong degree of alignment with international sustainable mining principles, notably in areas such as environmental stewardship, community engagement, governance transparency, occupational safety, and contributions to climate transition.

In summation, this study concludes that the future trajectory of mineral asset valuation is increasingly contingent upon the integration of sustainability considerations into financial evaluation models. ESG-related risks and opportunities are no longer peripheral concerns; rather, they are becoming fundamental determinants of mining project value, access to financing, regulatory approval, and long-term competitiveness. Therefore, mining companies, investors, regulatory bodies, and valuation professionals should progressively adopt integrated, ESG-oriented valuation methodologies to support more informed, resilient, and sustainable investment decisions within the mining industry.

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