1 Introduction

The global demand for copper and other critical metals is expected to increase in the coming years, driven by the green transition (Eilu et al. 2021). This surge in demand is projected to create a substantial supply gap, particularly for minerals like copper (Crooks et al. 2024; Eilu et al. 2021), prompting interest in alternative sources such as deep-sea mining. In 2023, the Norwegian government announced the opening of parts of the Norwegian Continental Shelf (NCS) for mineral exploration, aiming to establish seabed mineral extraction in Norwegian waters (Ministry of Energy 2024). However, deep-sea mining remains commercially challenging primarily due to market uncertainties, technological challenges, unclear deposit estimates, regulatory barriers, and concerns over its potential environmental impact (Green Minerals 2020). Before extraction can begin, a better understanding of these challenges and their implications for economic feasibility, environmental sustainability, and processing capabilities is required.

This submission examines what needs to be known before deep-sea mining can commence in Norway, with a focus on the processing of extracted minerals. It explores a potential collaboration between deep-sea and onshore mining operations as a means to address key obstacles. The proposed shared value chain enables deep-sea miners to use existing onshore processing facilities, reducing capital expenditures (CAPEX) and potentially risk exposure. The onshore miner, in turn, benefits from an extended operational lifespan through the blending of high-grade deep-sea ore with onshore material. Initial testing suggests that deep-sea ore and land-based ore can be processed together (Monstad 2024). The study identifies key risks and evaluates how contractual agreements can distribute them fairly between the parties. Using Monte Carlo simulations within a discounted cash flow (DCF) model, expected net present values (NPVs) are estimated under different risk-sharing scenarios. Additionally, this study outlines some of the knowledge gaps that must be addressed before deep-sea mining can become viable, including geological uncertainties and technical feasibility for mineral processing. The findings contribute to a broader understanding of the prerequisites for deep-sea mining and provide a foundation for assessing risk factors, processing strategies, and economic sustainability.

2 Collaboration

The value chains for onshore and deep-sea mining have traditionally operated as separate processes. However, integrating these operations at the processing phase presents an opportunity for mutual benefits. The collaboration is motivated by overlapping infrastructure needs, particularly in mineral processing. Land-based mining follows a well-established sequence of exploration, development, extraction, processing, transportation, and reclamation (Dunbar 2016). Deep-sea mining is expected to follow a similar sequence but with adaptations for the offshore environment. The Norwegian Continental Shelf is estimated to hold significant seafloor massive sulfide (SMS) deposits, containing copper and other critical minerals (Norwegian Offshore Directorate 2024). These deposits share similarities with volcanogenic massive sulfide (VMS) deposits found in onshore mines, which could make blending and shared processing feasible (Monstad 2024).

An outline for the collaboration, starting from the blending and processing phases, is illustrated in Figure 1. Blending is already common in land-based mining to stabilize ore feed quality and maintain efficient processing operations (Monstad 2024). However, certain modifications to the onshore processing facilities may be required to accommodate the characteristics of deep-sea ore. Once the concentrate is produced, it continues along the shared value chain using the outbound transportation infrastructure. The final product is expected to match the quality and grade of concentrate previously produced solely by the onshore mine, meaning it can be marketed through the same sales channels and should generate similar revenue. Revenue fluctuations will likely be driven primarily by external factors such as metal prices and currency rates rather than the inclusion of deep-sea ore, provided that deep-sea ore deliveries remain consistent.

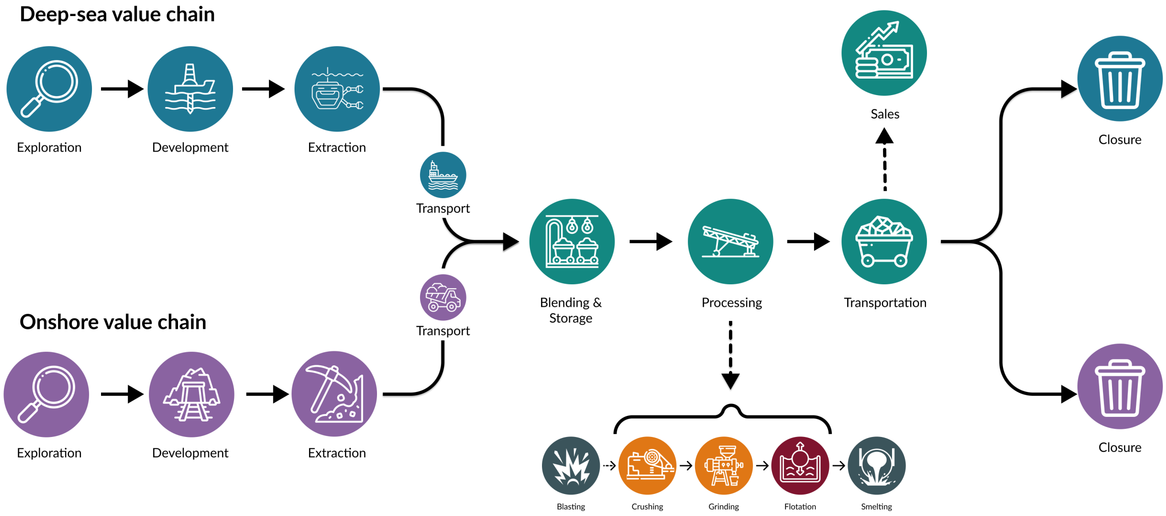

Figure 1: A potential integrated value chain

3 Risks and Framework of Collaboration

The integration of deep-sea and onshore mining introduces various uncertainties that must be addressed for a viable collaboration. Given the lack of prior examples of such partnerships and the limited research on the topic, it is necessary to first establish key risks and assumptions before conducting a quantitative analysis. This section identifies the primary risks involved and explores the framework conditions that shape the feasibility of a joint value chain. The risk analysis begins by evaluating uncertainties within each value chain separately before assessing the additional risks introduced by shared infrastructure.

Onshore mining is a mature industry with well-documented risks, including uncertainties in ore estimates, equipment reliability, regulatory challenges, and environmental concerns (Boliden AB 2023). Deep-sea mining, in contrast, remains an emerging industry with significant unknowns related to ore tonnage and grade estimation, equipment reliability in extreme conditions, and environmental risks (Lipton 2018). Many risks present in onshore operations also exist offshore, but deep-sea operations face significantly higher levels of uncertainty (Dobush and Warner 2024).

Within the shared infrastructure, several key risks emerge. Capacity limitations in stockpiling and blending systems may introduce logistical challenges, particularly if deep-sea ore deliveries are inconsistent. While initial tests indicate that deep-sea ore can be processed alongside onshore ore, uncertainties remain regarding potential modifications to the processing facility. The need for additional crushing, grinding, or flotation adjustments could impact processing efficiency and require capital investments (Monstad 2024; Shinoda et al. 2021; United States Securities and Exchange Commission (SEC) 2006).

To further assess these risks, a probability-impact matrix has been applied using the decision matrix risk-assessment (DMRA) method. This technique evaluates risks by calculating the product of severity (S) and likelihood (P), represented as $R = S \times P$ (Marhavilas et al. 2011). The DMRA framework highlights six particularly high-risk factors with risks measures ranging from 0.6 to 0.72: ore tonnage and grade variability, processing capacity constraints, metal price volatility, energy cost fluctuations, legal and regulatory challenges, and financial stability risks. These risks must be explicitly accounted for in contractual agreements to ensure financial and operational stability within the collaboration. These, and other identified risks are illustrated in Figure 2, and ore tonnage and grade variability are included in the quantitative model.

To establish a structured framework for evaluating the onshore-deep-sea mining collaboration, a set of 13 key criteria has been identified, each representing a critical decision point or uncertainty

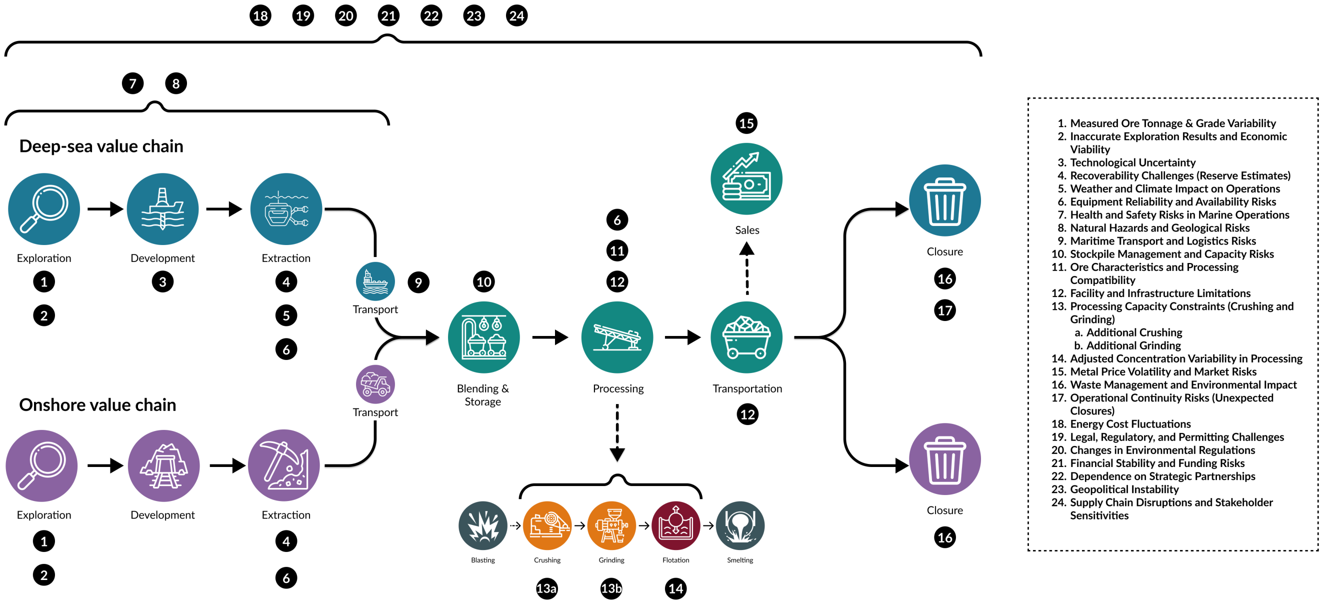

Figure 2: Shared infrastructure and risks in each phase

in the partnership. These criteria define the collaboration's operational boundaries and inform the selection of feasible scenarios for further modeling. Given the absence of prior commercial experience in deep-sea mining, the framework relies on both industry best practices and expert input. The scenarios are selected based on model simplification, data availability, and likelihood of occurrence. Figure 3 provides a visual overview of the 13 criteria and their associated scenarios, highlighting those chosen for the quantitative analysis. For each criterion, multiple scenarios were considered, including potential edge cases that could jeopardize the project if they were to materialize.

4 Quantitative Analysis

This section evaluates the financial viability of the proposed collaboration using a dynamic DCF model. Four contractual agreements are analyzed, incorporating uncertainties in ore grade and tonnage to assess risk and profitability distribution between onshore and deep-sea miners.

The contracts differ in structure and risk-sharing mechanisms. In Direct Ore Sale (Contract 1), the deep-sea miner sells unprocessed ore to the onshore miner at a fixed price with minimal risk-sharing. Direct Ore Sale with Cost Sharing and Penalty (Contract 2) introduces cost-sharing, where the deep-sea miner covers a pre-agreed portion of CAPEX, OPEX, and APEX related to processing, while also facing penalties for inconsistent deliveries. Revenue Sharing (Contract 3) splits revenues based on pre-agreed ratios, reducing supply risk for the onshore miner. Revenue Sharing with Cost Sharing and Penalty (Contract 4) combines revenue-sharing, cost-sharing, and penalty mechanisms to balance risks and rewards.

The DCF analysis focuses on CAPEX for maintaining and extending the onshore mine, APEX and recurring OPEX, and revenue generation. Initial mine establishment costs are excluded. Revenue is estimated using the Net Smelter Return (NSR) model (Wellmer et al. 2008), incorporating deductions for smelting, refining, and transport costs into a single factor NF. Table 1 defines the key parameters. To account for the uncertainties in ore grade, production volume, and financial parameters, a Monte Carlo simulation is integrated into the analysis. The deep-sea miner's annual ore production ω_D is modeled as a normal distribution centered at 1.5 million tonnes with a standard deviation of 100,000 tonnes, reflecting expected operational variability. The ore grade of the deep-sea deposit $\bar{g}_D$ is assumed to follow a uniform distribution between 2–6%, capturing

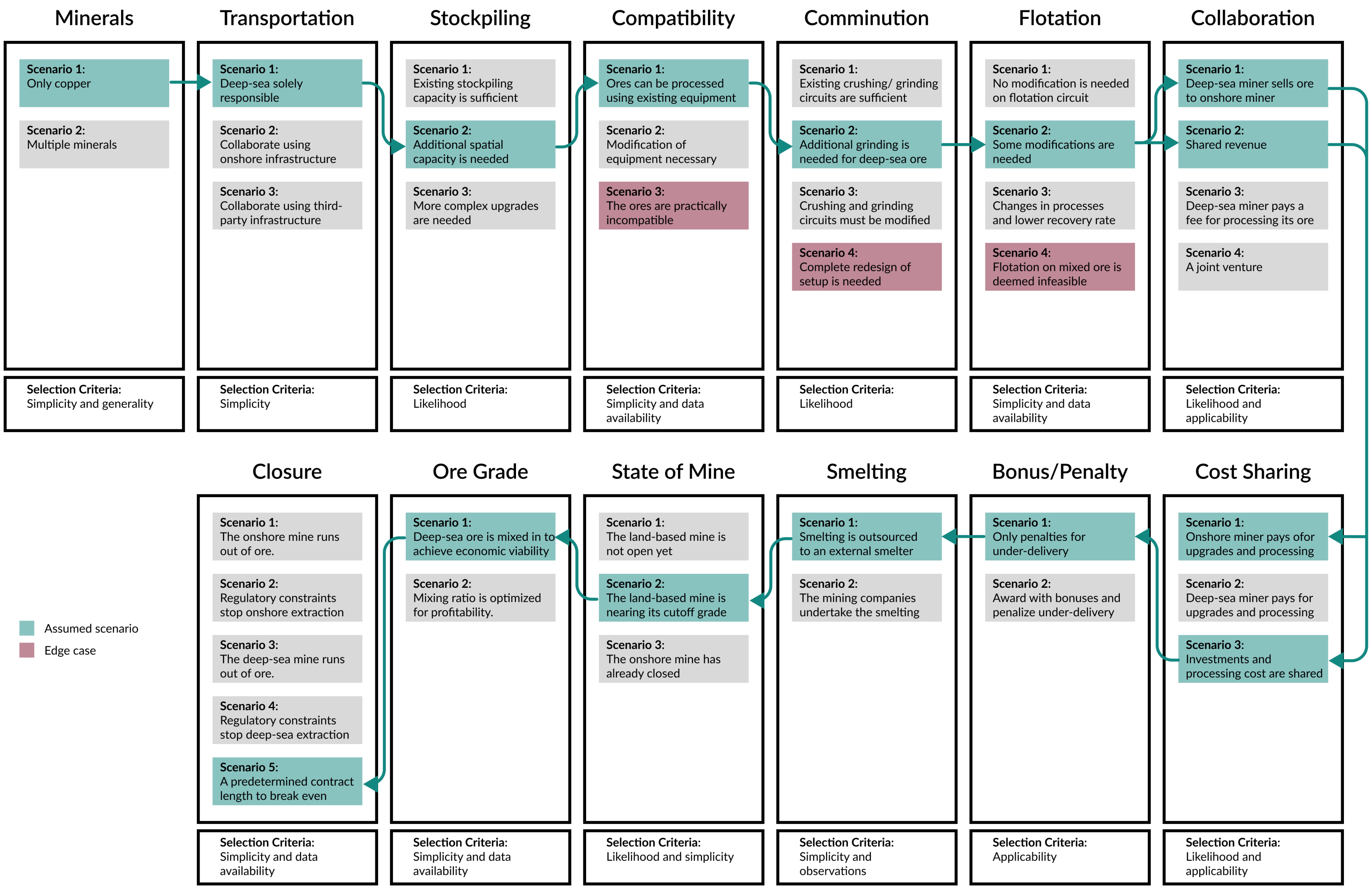

Figure 3: Overview of criteria and selected scenarios for defining the collaboration framework

geological uncertainty. The parameter values are derived from various sources, and both the data and code are available upon request.

Table 1: Symbols and Descriptions for the Model

Symbol	**Description**	**Symbol**	**Description**
ω	Annual production from mine	$\bar{g}$	Ore grade
ϵ	Processing recovery rate	P	Market price of copper
NF	Net smelter return factor	γ	Price paid for deep-sea ore
β	Revenue share for the onshore miner	δ	Penalty for low-grade ore delivery
α	Share of costs taken by deep-sea miner	Salvage Value	The residual worth of infrastructure and equipment after accounting for depreciation

The onshore revenue can be expressed under two scenarios: Direct Ore Sale and Revenue Sharing, with a subscript O denoting parameters specific to the onshore mine, while parameters with a subscript D denote those specific to the deep-sea mine.

$$\text{Revenue}_{\text{O}} = \underbrace{((\omega_O \times \bar{g}_O + \omega_D \times \bar{g}_D) \times \epsilon)}_{\text{Annual Concentrate}} \times \text{NF} \times P - \underbrace{(\omega_D \times \bar{g}_D \times \gamma)}_{\text{Deep-Sea Ore Cost}} + \delta \quad \text{(Direct Ore Sale)} \tag{1}$$

$$\text{Revenue}_{\text{O}} = \underbrace{((\omega_O \times \bar{g}_O + \omega_D \times \bar{g}_D) \times \epsilon)}_{\text{Annual Concentrate}} \times \text{NF} \times P \times \beta + \delta \quad \text{(Revenue Sharing)} \tag{2}$$

The deep-sea revenue can similarly be expressed as:

$$\text{Revenue}_{\text{D}} = \underbrace{(\omega_D \times \bar{g}_D \times \gamma)}_{\text{Deep-Sea Ore Sale}} - \delta \quad \text{(Direct Ore Sale)} \tag{3}$$

$$\text{Revenue}_{\text{D}} = \underbrace{((\omega_O \times \bar{g}_O + \omega_D \times \bar{g}_D) \times \epsilon)}_{\text{Annual Concentrate}} \times \text{NF} \times P \times (1-\beta) - \delta \quad \text{(Revenue Sharing)} \tag{4}$$

The Free Cash Flow (FCF) for both the onshore and deep-sea operations is calculated as follows:

$$\text{FCF}_{O,t} = \begin{cases} \text{Revenue}_O - (\text{OPEX}_O + \text{CAPEX}_O + \text{Tax}_O), & \text{for } t = 0 \\ \text{Revenue}_{O,t} - (\text{OPEX}_O + \text{Tax}_O) + \text{Salvage Value}, & \text{for } 0 < t < T \\ \text{Revenue}_{O,T} - (\text{OPEX}_O + \text{Tax}_O + \text{APEX}_O), & \text{for } t = T \end{cases} \tag{5}$$

$$\text{FCF}_{D,t} = \begin{cases} \text{Revenue}_D - (\text{OPEX}_D + \text{CAPEX}_D + \text{Tax}_D), & \text{for } t = 0 \\ \text{Revenue}_{D,t} - (\text{OPEX}_D + \text{Tax}_D), & \text{for } 0 < t < T \\ \text{Revenue}_{D,T} - (\text{OPEX}_D + \text{Tax}_D + \text{APEX}_D), & \text{for } t = T \end{cases} \tag{6}$$

The financial feasibility of each contract is evaluated using the NPV, calculated by discounting FCF over the project duration T at a risk-adjusted discount rate r:

$$\text{NPV}_{\text{O}} = \sum_{t=0}^{T} \frac{\text{FCF}_{\text{O},t}}{(1+r)^t} \tag{7}$$

$$\text{NPV}_{\text{D}} = \sum_{t=0}^{T} \frac{\text{FCF}_{\text{D},t}}{(1+r)^t} \tag{8}$$

5 Results

This section presents the results of the dynamic DCF analysis, evaluating the financial viability of the proposed collaboration. The analysis assesses the profitability and risk distribution under the four explored contracts. Table 2 summarizes the main insights regarding project profitability, risk distribution, and sensitivity of NPV to key variables.

Table 2: Main findings from the dynamic DCF analysis

	Explanation	**Supporting Evidence**
1	The project remains profitable under modeled risks.	All expected NPV values and 95% confidence interval lower bounds are positive.
2	Cost sharing increases the deep-sea miner's risk but also potential reward.	Contracts with cost sharing show higher expected NPV and standard deviation for the deep-sea miner.
3	Contract 1 is unfavorable for the deep-sea miner when market risk is excluded.	The deep-sea miner faces higher variability, a greater standard deviation, and a lower P10 compared to the onshore miner.
4	Contracts can be tailored to match risk preferences.	Contracts 2, 3, and 4 offer better alignment of risk exposure and expected returns.
5	Key NPV drivers include copper price, NSR factor, ore grade, and project duration.	Sensitivity analysis confirms these factors have the largest influence on profitability.
6	Revenue-sharing contracts reduce NPV sensitivity.	These contracts exhibit smaller fluctuations in NPV compared to direct sale contracts.
7	Incorrect parameter selection may misalign incentives.	In Contracts 3 and 4, increased onshore production negatively impacts the onshore miner's NPV.

Our results show that, under appropriate contractual terms, the project remains profitable for both parties, even at the lower bound of the 95% confidence interval. A key insight is that the proposed contracts offer flexibility to tailor terms to align with the risk preferences of both the onshore and deep-sea miners. Cost-sharing mechanisms effectively redistribute risks, with Contracts 2-4 offering a more balanced risk-return trade off compared to Contract 1. Sensitivity analysis highlights that market risks, particularly fluctuations in NF and copper price, have the most significant impact on NPV, reinforcing the importance of revenue-sharing mechanisms for mitigating risk exposure.

Cost-sharing shifts financial risk to the deep-sea miner, particularly in Contract 2, where increased CAPEX and OPEX contributions are offset by higher expected returns. Contract 3 balances revenue distribution, though the onshore miner faces higher variability due to processing facility costs. Contract 4 mitigates this variability by redistributing costs to the deep-sea miner, improving overall alignment of risk and reward. Excluding market risks makes Contract 1 less favorable for the deep-sea miner, as it bears significant uncertainty without proportional compensation. The sensitivity analysis further reveals that incorrect parameter selection, particularly in Contracts 3 and 4, can lead to misaligned incentives, where increased production reduces the onshore miner's profitability. Adjusting revenue-sharing terms could help optimize contract fairness.

This submission has explored the knowledge needed before launching deep-sea mining, focusing on the processing of extracted minerals. It proposes a collaboration between deep-sea and onshore mining operations as a way to reduce capital requirements for deep-sea mining while extending the operational lifespan of onshore mines. Given the assumptions and necessary simplifications due to uncertainties, the financial analysis indicates that, under well-structured contracts, both parties can achieve positive NPVs, with revenue-sharing reducing volatility and cost-sharing promoting a fairer distribution of risk. However, market risks, permitting challenges, and technical uncertainties remain significant obstacles. Future research should refine risk assessments, optimize contractual terms, and explore alternative processing strategies to advance the viability of deep-sea mineral extraction.

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