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Views & Comments

Prospects for Commercial Exploitation of Deep-Sea Polymetallic Nodules: From Perspectives of Economic Benefits, Technological Feasibility, and Environmental Protection

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1. Introduction

The transition from a fossil energy economy to a green energy economy (wind energy, solar energy, and electric cars) is driving the need for new sources of critical materials, such as manganese, nickel, and cobalt [1]. It is estimated that the demand for cobalt in 2040 will be six-times higher than that in 2020 under the stated policy scenario and 21-times higher under the sustainable development scenario [2]. Deep-ocean minerals, namely polymetallic nodules (PMN), cobalt-rich ferromanganese crusts, and polymetallic sulphides (which often contain rare-earth elements), have been shown to possess far greater potential resources for many critical materials than those found on land (Table 1) [4]. The estimated cobalt reserves in the Clarion–Clipperton zone (CCZ, a deep-sea polymetallic nodule-rich region in the Pacific Ocean) are almost three-times greater than the total global terrestrial reserves [3]. Among these deep-sea mineral resources, PMN are considered the most likely to be developed commercially in the short- to medium-term owing to their potential economic value and less challenging exploration and extraction conditions.

The International Seabed Authority (ISA), mandated to regulate mineral-related activities in the Area, has issued 19 contracts for PMN exploration (each with a 15-year period covering 75 000 km^2) [5]. With the increasing number of exploration and testing activities in PMN contract areas (Fig. 1), it is possible that within one or two decades, multiple operators will exploit the seafloor for PMNs.

However, commercial exploitation of deep-sea PMN faces significant challenges, including: technological challenges; ecological and environmental impacts; regulatory uncertainties; and economic feasibility [6].

(1) **Technological challenges.** The deep-sea mining (DSM) equipment system is considered one of the largest industrial offshore systems ever developed, involving a wide range of technologies such as offshore engineering, navigation, control systems, electrical engineering, communications, and specialized vehicles. However, there are several theoretical and technological challenges [7].

- Surface supporting platform is the first technological challenge that requires high-precision positioning capability, a reliable launch and recovery system (LARS) for both the risers and collectors, and robust durability to adapt to extreme marine environments.
- Nodule collection is another critical technological challenge that requires the collector to have a high nodule pick-up efficiency with minimal seabed disturbance and strong traction performance to minimize sinks and excessive slip under a limited seabed bearing capacity.
- Vertical mineral transportation is also an important technological challenge that requires stable and efficient transportation of nodules of inhomogeneous sizes from the seabed, minimizing the blocking and abrasion of the riser and lifting system (RALS).
- Environmental disturbance is also a significant challenge for mining systems. The design of mining systems should be constrained by the seabed environment, with collection systems generating plumes, noise, and heavy metal leakage during operation, all of which significantly affect seabed ecology.

Therefore, the design of a safe, reliable, cost-effective, and low-disturbance equipment technology remains a significant challenge.

(2) **Ecological and environmental impacts.** The deep sea, which accounts for 49% of the Earth's surface area and has an average water depth > 3000 m, is an unknown area with an estimated 26.1% of the area mapped [8]. Deep-sea ecosystems are unique and fragile, the environmental impact of mining is inevitable, and environmental restoration is difficult. The ISA imposes requirements on contractors regarding environmental baseline, impact, and management. The agreement under the United Nations convention on the law of the sea on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction (BBNJ Agreement) [9] emphasizes the need for reasonable efforts to ensure that mining activities are conducted in a manner consistent with the prevention of significant adverse impacts on the marine environment. This underscores the importance of a precautionary approach to DSM in which decisions to authorize planned activities are made only after careful consideration of mitigation or

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Table 1
Deep-ocean mineral estimates [4].

Mineral	Zone	Depth (m)	Area (km^2)	Reserve	Main elements
Polymetallic nodules	Abyssal plain	3000–6500	38 million (81% in the Area*)	21 100 Mt at CCZ	Fe, Mn, Co, Ni, and Cu
Cobalt-rich ferromanganese crusts	Seamount	800–2500	1.7 million (46% in the Area*)	7533 Mt at pacific	Fe, Mn, Co, Ni, Cu, and Li
Polymetallic sulphides	Ocean ridge and volcanic arcs	1500–3500	3.2 million (58% in the Area*)	600 Mt at mid-ocean ridges	Fe, Cu, Zn, Ag, and Au

* represents the seabed beyond national jurisdictions.

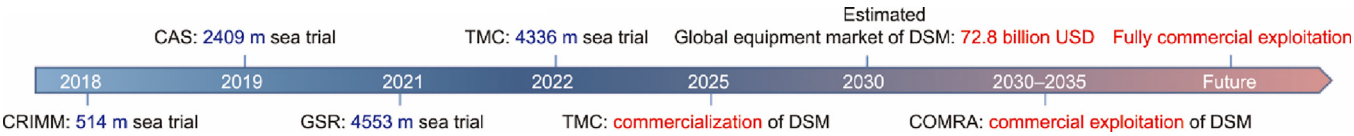

Fig. 1. Recent and future development of deep-sea mining (DSM) activities. CRIMM: Changsha Research Institute of Mining and Metallurgy (China); CAS: Chinese Academy of Sciences; GSR: Global Sea Mineral Resources NV (Belgium); TMC: The Metals Company (Canada); COMRA: China Ocean Mineral Resources R&D Association.

management measures. Therefore, scientific and comprehensive environmental impact assessments of DSM, along with environmentally friendly engineering solutions, are key to achieving a balance between environmental protection and development [10].

(3) **Regulatory uncertainties.** From a regulatory perspective, many unresolved issues remain regarding the ownership and exploitation of deep-sea minerals. The ISA planned to adopt the exploitation regulations for the PMN [11] at its 30th session in 2025, after a delay of > 2 years. Although proponents advocate the key role of deep-sea minerals in meeting the demand for critical metals to support zero-carbon initiatives, broad support exists within the international community for a moratorium on DSM until its environmental, social, and economic risks are comprehensively investigated. In the coming years, all parties will engage in intensive legal and policy debates over the focus of development "suspending" or "advancing," which will deeply affect the development process of DSM. Therefore, the potential impact of regulations on DSM should be comprehensively assessed, and the concept of sustainable development should be fully integrated into the design of the entire DSM process.

(4) **Economic feasibility.** DSM features a wide industrial chain and is closely related to many industries, such as marine scientific research, marine regulations, marine equipment manufacturing, smelting, shipping, marine environmental protection, and financial services. The exploitation of deep-sea PMN has not been commercialized globally. The initial cost is extremely high and there are high uncertainties and risks owing to unstable metal prices and uncertain nodule reserves. Therefore, it is important to innovate company-cooperation mechanisms to overcome industrial barriers. Furthermore, techno-economic analysis and risk assessment of DSM should be carried out.

Given the challenges facing DSM, the prospects for the commercial exploitation of deep-sea PMN are discussed from the perspectives of technological feasibility, environmental protection, and economic benefits.

2. Technological and engineering key factors

Various DSM systems have been proposed for PMN extraction, including submarine drag buckets, continuous line buckets, shuttle vessels, and riser-lifting systems. Based on economic viability and engineering practices, a riser-lifting system is viewed as an ideal solution for commercial PMN mining systems [12].

A riser-lifting mining system includes a surface-supporting mining vessel, a nodule collector, RALS, and LARS. The general technological concept of a riser-lifting mining system is illustrated in Fig. 2.

Deep-sea PMN mining is a complex operation that requires careful consideration of various risks. The process involves operating under extreme conditions such as high pressure, darkness, and limited visibility, which pose significant challenges to engineering systems. Breakthroughs are needed to address many theoretical and technical challenges (Figs. 3 and 4) across the mining, transportation, and mineral processing systems.

(1) **Design and analysis technology of DSM equipment.** There are various designs for deep-sea PMN mining equipment [13]. Designing DSM equipment that can withstand the harsh environmental conditions in the deep sea is challenging, and involves addressing the multifaceted challenges in engineering, environmental science, and regulatory compliance.

The key technologies include the coupling mechanism of multibody and multi-scale DSM systems, coupled dynamic model of DSM–ship–riser–mining–vehicles in complex marine environments, multi-scale safety design for ship–riser–mining vehicle systems of DSM, limit state simulation, and safety design threshold of DSM systems.

(2) **Deep-sea nodule collection technology.** A mining vehicle was designed to collect PMN from the seafloor. In ultra-deep soft-soil seabed environments, complex hydrodynamic conditions and limited seabed bearing capacity pose significant challenges to collector locomotion stability, nodule collection efficiency, and navigation control. Moreover, the sediment plumes generated during trafficking, nodule collection, and discharge pose significant environmental risks to deep-sea ecosystems.

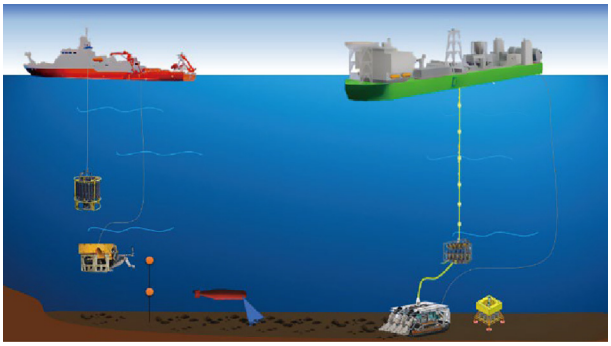

Fig. 2. General technological concept of a riser-lifting mining system.

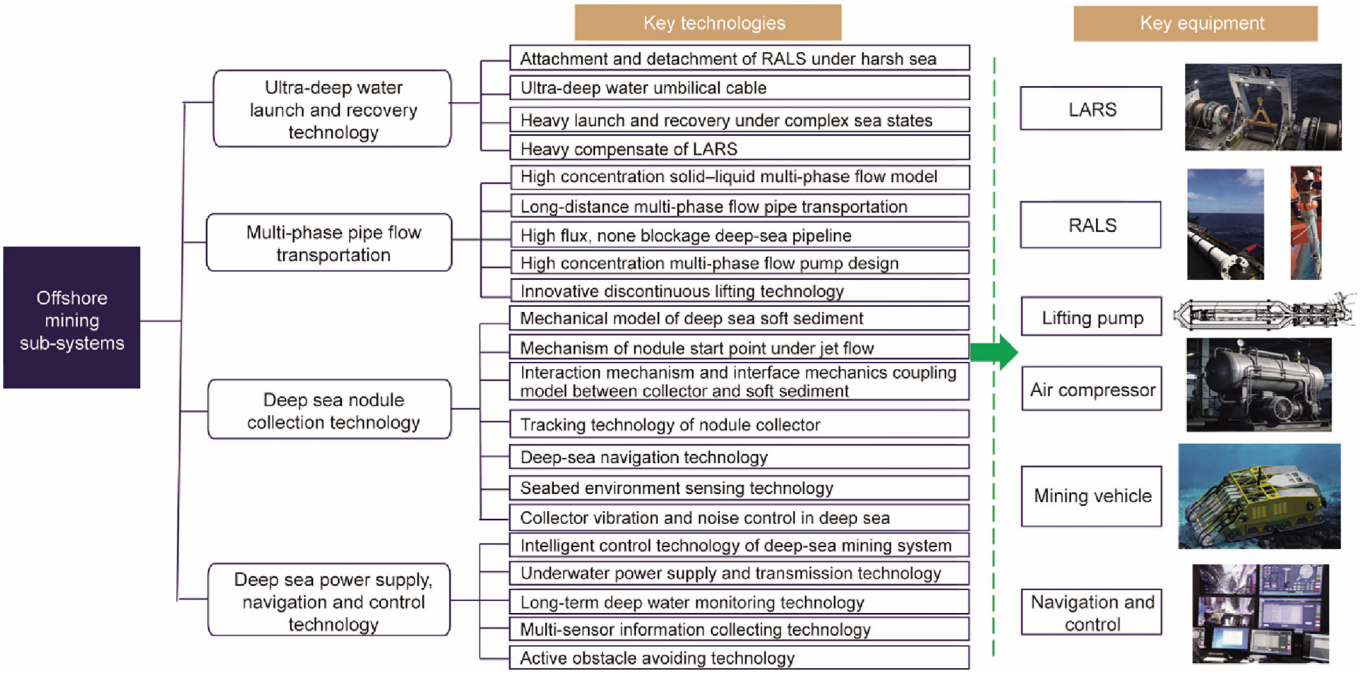

Fig. 3. Key technologies and equipment for offshore mining systems.–

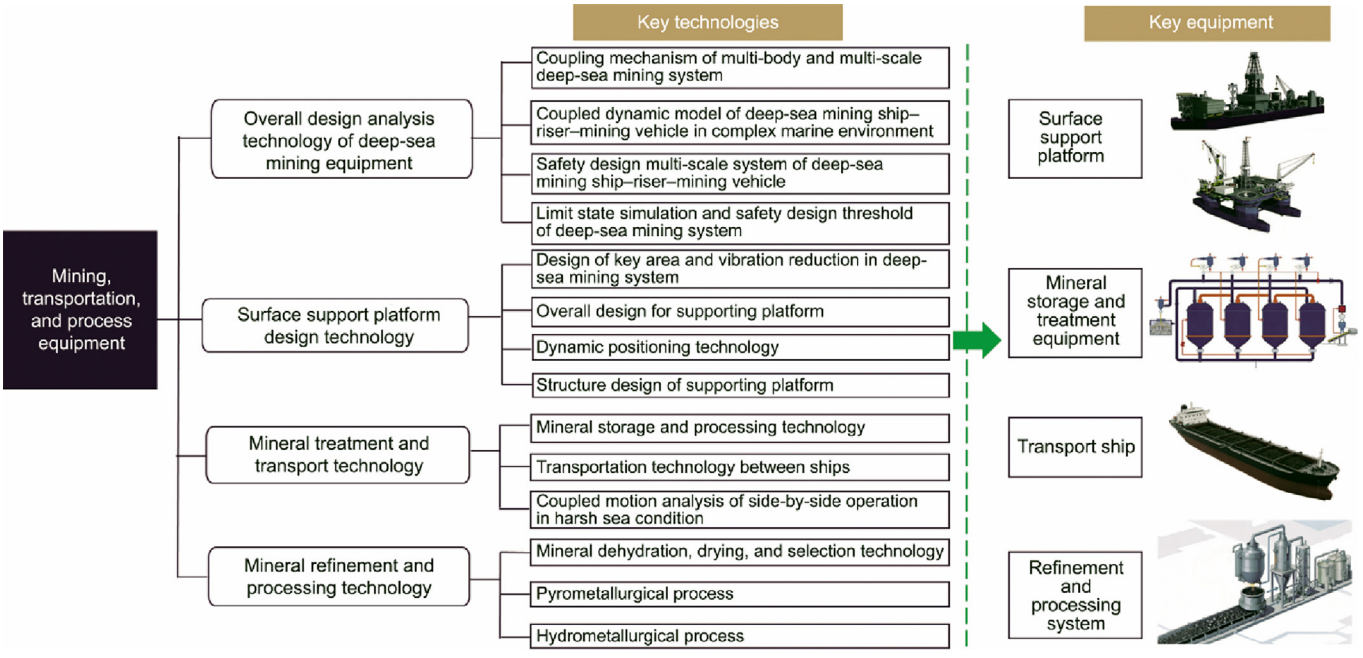

Fig. 4. Key technologies and equipment for mining, transportation and process system.

The key technologies include the mechanical model of deep-sea soft sediment, mechanism of nodule start point under jet flow, interaction mechanism and interface mechanics coupling model between the collector and soft sediment, optimal trajectory design to accomplish low seabed disturbance and minimal sink and slip, structural and suspension design for stability and maneuverability on soft seabed soil, deep-sea navigation technology, seabed environment sensing technology, and deep-sea collector vibration and noise control.

(3) **Multiphase pipe flow transportation.** Continuous transportation of high-concentration multiphase flow over a long distance while minimizing blockage and abrasion is challenging. The long-term reliable operation of the riser system and efficient transportation of ore slurry are the core bottlenecks restricting the large-scale commercialization of DSM.

The key technologies include a high concentration solid–liquid multiphase flow model, long-distance multiphase flow pipe transportation, high flux, no-blockage deep sea pipeline, high-concentration multiphase flow pump design, and innovative discontinuous lifting technology.

(4) **Ultra-deep-water launch and recovery technology.** LARS is designed for the deployment and retrieval of mineral transportation equipment and nodule collectors. LARS should be capable of handling significant forces involved in deep-sea

operations, such as the hook load and pipe tension force, and managing the storage and transfer of mining pipes, slurry pumps, and buffer stations.

The Key technologies include the attachment and detachment of the RALS in harsh ocean environments, coupling mechanisms of multi-body systems, ultra-deep-water umbilical cables, heavy launch and recovery under complex sea states, and heave compensation of LARS.

(5) **Deep sea navigation and control technology.** The navigation and control of mining vehicles are critical for accurate data transmission and coordination in strong-interference environments. The integration of various sensors and navigation systems is essential for precise control and tracking of mining vehicles.

The key technologies include the intelligent control technology for the DSM system, underwater power supply and transmission technology, underwater sonar positioning technology, efficient underwater wireless communication systems, long-term deep-water monitoring technology, multi-sensor information collecting technology, and active obstacle avoidance technology.

(6) **Surface support platform technology.** DSM vessels are designed to withstand harsh deep-sea conditions. They consist of a surface-supporting platform for nodule collectors and RALS, energy-supply systems, monitoring and control systems, deck-handling systems, nodule storage, processing and transport systems, launch and recovery systems, and dynamic positioning systems. The DSM vessel serve as a critical operational hub in DSM, and the reliability of the surface support systems dictate the operational safety of the entire DSM operation.

The key technologies include the key area designs and vibration reduction of surface support ships, overall design of supporting platforms, dynamic positioning technology, structural design of supporting platforms, mineral storage and processing technology, efficient dewatering and filtering of minerals, transportation technology between ships, and coupled motion analysis of side-by-side operations in harsh sea conditions.

3. Environmental monitoring and management

DSM activity may have multiple potential impacts on marine ecosystems. DSM activity not only disturbs the habitats and migration paths of marine organisms but may also be transmitted through the food chain to affect human health and economic activities [14–16]. The ISA is required to establish and periodically review environmental rules, regulations, and procedures to ensure effective protection of the marine environment from potential harm caused by activities in the area.

In addition, contracts for mineral exploration in the area require contractors to collect approximately 102 environmental parameters in various fields, including the physical oceanography, chemical oceanography, geological properties, biological communities, bioturbation, and sediment fluxes [17]. Therefore, there is increasing demand for deep-sea environmental monitoring technologies to monitor these parameters. The key monitoring parameters and techniques used in deep-sea environments are listed in Table 2. These technologies provide strong support for comprehensive monitoring and analyses of the deep-sea environment, help assess the impact of mining activities on deep-sea ecosystems, and provide a scientific basis for the protection and rational use of deep-sea resources [18].

Table 2
Key technologies for deep-sea environmental monitoring and management.

Category	Key techniques and monitoring parameters
Marine physical, chemical, and geological monitoring	Key techniques: full water column profile monitoring technology, long-term full-profile monitoring technology, near-bottom measuring technology based on autonomous underwater vehicle/remote operated vehicle, deep-sea multi-beam bathymetry technology, deep-sea high-resolution current profile acoustic Doppler measurement technology, *in-situ* testing technology for deep-sea sediment mechanics, and so on Monitoring parameters: pressure, current, temperature, salinity, turbidity, light, noise; water column and seabed chemical properties, pH, carbonate system, geomorphological and geological characteristics, sediment characteristics, and so on
Biological monitoring	Key techniques: deep-sea biological monitoring, identification and measurement technology, deep-sea resource environment sampling technology, *in-situ* rapid analysis technology of indicator organisms in DSM areas, *in-situ* monitoring technology of biological communities in DSM areas, *in-situ* monitoring technology of metabolic indicators of seabed biological communities, omics sensors (environmental DNA, eDNA), *in-situ* monitoring technology of seabed habitat and toxicological effects, and so on Monitoring parameters: microorganisms, protozoa, metazoan, oxygen consumption of sediment communities, and so on
Plume monitoring	Key techniques: plume monitoring equipment development technology, plume numerical model, ocean geological deposition and plume migration and sedimentation monitoring technology, mining plume dispersion simulation and sedimentation mechanism analysis technology, and environmental impact analysis technology Monitoring parameters: particle thickness, depth, concentration, composition, dispersion path, dispersion range, dispersion time, and so on
Simulation of deep-sea environment	Key techniques: deep-sea high-resolution current profile numerical simulation technology, DSM site bottom current measurement and numerical forecasting technology, construction of *in-situ* long-term monitoring network, full-process numerical simulation technology of deep-sea exploration, and so on

4. Economic benefits based on a case study

Currently, deep-sea mineral resource development is not commercialized globally and international research on DSM economic analysis remains in its developmental stage. Several preliminary economic models have been proposed [19]. Based on these models, an economic evaluation of PMN mining in a contract area located in the West Pacific Ocean was conducted to demonstrate the economic feasibility of DSM.

The total contract area was 74 052 km^2 and included four blocks: M-1 (12 903 km^2), M-2 (23 667 km^2), C-1 (26 112 km^2), and C-2 (11 370 km^2) [20]. This section presents an economic evaluation of the commercial exploitation of blocks M-1 and M-2. Similar to a previous study [9], a preliminary mining plan was made for 34 years starting in 2025, including a 4-year research and development (R&D) period and a 30-year production ramp-up and production period for commercial mining. In this section, the income and cost of mining in the contract area were evaluated based on a mining plan.

First, as shown in Table 3 [20,21], the nodule reserves in contract areas M-1 and M-2 were estimated based on exploration data

Table 3
Nodule reserve estimation in contract area.

Contract areas	Area (km^2)	Mining area (km^2)	Abundance ($kg·m^{-2}$)	Wet nodule (Mt)	Dry nodule (Mt)	Mn (Mt)	Cu (Mt)	Co (Mt)	Ni (Mt)
M-1 and M-2 [20]	36 570	24 631.07	15.05	370.70	281.73	65.61	0.41	1.30	1.19
TMC NORI-D [21]	25 160	—	16.90	356.00	270.56	78.74	2.79	0.36	3.56

[20]. The nodule abundance in this area was estimated at 15.05 $kg·m^{-2}$, resulting in a total wet nodule reserve of 370.70 Mt, or a dry nodule reserve of 281.73 Mt with a 24% nodule moisture content. The estimated nodule reserve of the NORI-D contract area of the Metals Company (TMC, Canada) [21] is also presented for comparison.

Based on the analysis of the samples obtained from the preliminary exploration, the metal element grades are listed as followed [22]. In the contract area, the Mn content was 17.7%, whereas Fe constituted 18.3% of the nodules. The manganese-to-iron ratio (Mn/Fe) was 0.97, the Co content was 0.35%, the Ni content was 0.32%, and the Cu content was 0.11%. The combined concentration of Co, Ni, and Cu was 0.78%. Additionally, Al comprised 2.16% of the nodules, and Si was present at 6.44%. Therefore, in terms of metal content, the combined resources in the M-1 and M-2 areas were estimated to contain total amounts of Mn, Cu, Co, and Ni 65.61, 0.41, 1.30, and 1.19 Mt, respectively (Table 3).

To estimate the total income, the metal recovery rates and predicted prices were assumed based on the technical report of TMC, as shown in Tables 4 and 5 [21].

Table 4
Assumed recovery rate.

Contract area	Recovery rate (%)			
	Mn	Cu	Co	Ni
TMC NORI-D [21]	98.9	86.2	77.2	94.6

Table 5
Price of metal elements.

Contract area	Price ($USD·t^{-1}$)			
	Mn	Cu	Co	Ni
TMC NORI-D [21]	453	6 872	46 333	16 472

Based on the grade, recovery rate, and predicted price of the metal elements Mn, Cu, Co, and Ni, the total income of the contract area was estimated according to the following equation and is presented in Table 6 [21].

$$\text{Total income} = \text{dry nodule reserve} \times \text{grade of metal elements} \times \text{recovery rate} \times \text{price}$$

The estimated total income of the TMC NORI-D contract area is presented for comparison. The total estimated income from the mining operations in the contract area was 73 495 million USD over the 34-year period.

Moreover, based on the development plan of 34 years starting from 2025, including a 4-year R&D period and a 30-year production ramp-up and production period for commercial mining, the annual mining plan was designed to ramp up to an annual production capacity of 12 Mt wet nodules after 2036 (Table 7). The estimated annual income is presented in Fig. 5, according to the metal prices shown in Table 5. Fig. 5 shows that the annual income stabilized at approximately 16 890 million CNY after 2036, reaching the full production capacity of 12 Mt wet nodules per year.

Furthermore, the capital expenditure (CAPEX) and operational expenditure (OPEX) were estimated on a per-tonne basis. The total CAPEX in the nodule collection, transportation, and refinery stages was estimated to be 7000 CNY per tonnage, and the total OPEX was estimated at 2100 CNY per tonne [23]. According to the annual mining plan shown in Fig. 6, the CAPEX will reach its peak in 2034 with the construction of an onshore mineral processing facility. The annual OPEX stabilizes at approximately 12 100 million CNY after 2036, reaching a steady full production capacity of 12 Mt wet nodules per year. An economic analysis was conducted based on the estimated income and cost, and the annual undiscounted cash flow was calculated and is presented in Fig. 6.

Although a relatively conservative value of nodule abundance and a 20% contingency on cost were used in the economic analysis, the calculated internal rate of return can still reach approximately 9.33% for the proposed development plan in the contract area, which is promising. Further sensitivity analyses on grade,

Table 6
Estimated total income.

Contract areas	Income (million USD)				
	Mn	Cu	Co	Ni	Total
M-1 and M-2 [20]	22 341	1 836	35 270	14 048	73 495
TMC NORI-D [21]	26 785	12 682	11 077	44 109	94 653

Table 7
Annual mining plan.

Item	2025–2029	2030	2031	2032	2033	2034	2035	2036–2058	2059	Total
Annual wet nodule (Mt)	0.003	0.70	1.00	3.00	4.00	6.00	10.00	12.00	6.00	306.703
Annual dry nodule (Mt)	0.002	0.532	0.760	2.280	3.040	4.560	7.600	9.120	4.56	233.094
Mining capability ($t·h^{-1}$ × units)	150 × 1	150 × 1	150 × 2	150 × 4	150 × 4	150 × 4 + 300 × 4	150 × 4 + 300 × 4	150 × 4 + 300 × 4	150 × 4 + 300 × 4	—
Annual number of working days	1	200	140	280	280	280	280	280	140	—
Annual mining area (km^2)	0.20	46.51	66.45	199.336	265.781	398.67	664.45	797.34	398.67	20378.94

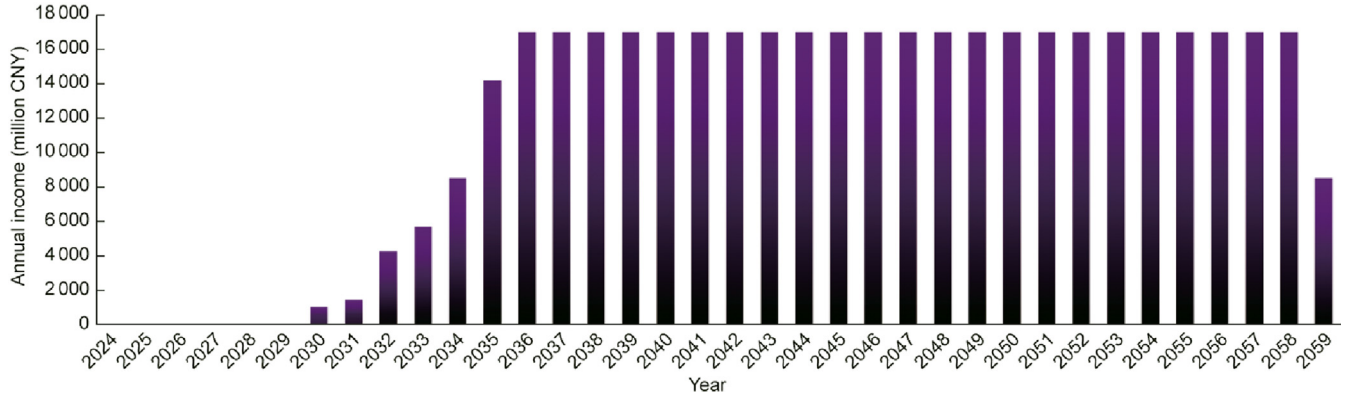

Fig. 5. Estimated annual income.

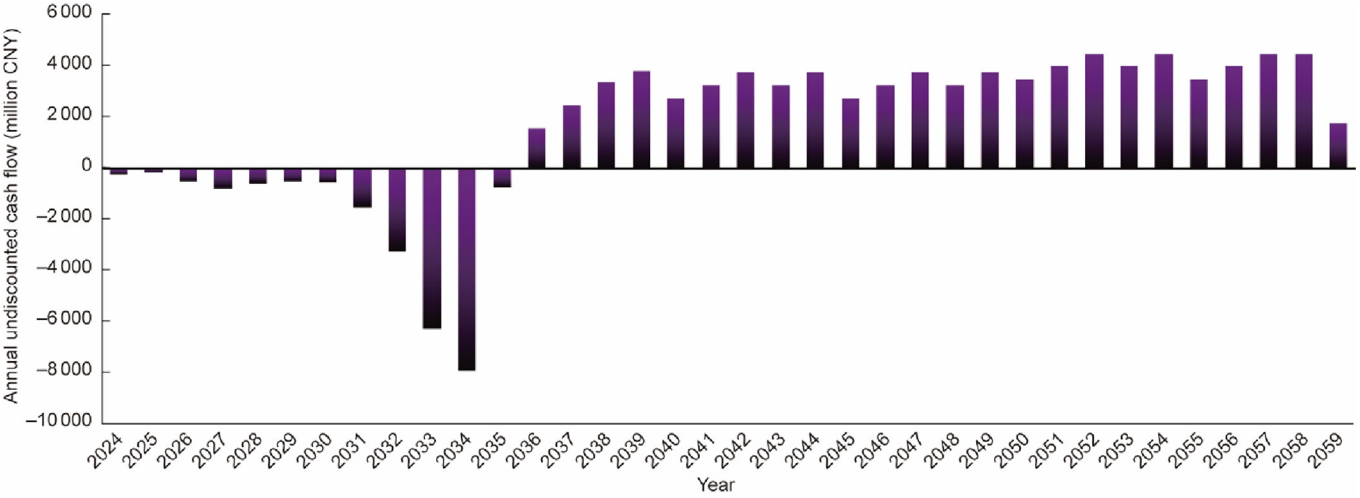

Fig. 6. Annual undiscounted cash flow.

abundance, price, recovery, CAPEX, and OPEX should be considered, which can help analyze different mining scenarios and contribute to a more accurate assessment of the economic risks of DSM.

5. Conclusions and suggestions

DSM is a complex endeavor that requires a strategic approach that combines commercialization, project-driven collaboration, extensive market engagement, and a strong focus on environmental research. Industry must navigate legal frameworks, conduct thorough environmental impact assessments, and foster international cooperation to address the challenges of resource extraction from the ocean floor. The following suggestions are proposed for the development of possible commercial exploitation of PMN.

(1) **Commercialization and engineering-driven test mining.** Aiming at commercial mining, a development plan and roadmap for commercial mining of PMN, which prioritizes sustainability and environmentally friendly practices, should be developed. Detailed technical assessments and economic analyses should be completed and implementation should be phased in with test mining to reduce risks and investments. To ensure the safety and reliability of operations, DSM should be driven by the needs of engineering projects and cooperate with market-oriented, professional, and international enterprises for their advantages in key equipment R&D, manufacturing, and deep-sea engineering operations.

(2) **Science-driven environmental protection and efficient exploration.** Collaboration among multiple international research institutions should be promoted for comprehensive DSM environmental impact assessment, and environmentally friendly engineering solutions. Advanced techniques and equipment tailored to deep-sea conditions are critical for commercial development of deep-sea minerals. An exploration roadmap should be strategically designed to efficiently identify and assess mineral deposits, and development of estimation models for deep-sea mineral deposits is crucial for accurate resource assessment and guiding future mining decisions.

(3) **Stakeholder participation and international cooperation.** DSM involves multiple stakeholders, including nations that have exploration contracts, countries with deep-sea mineral deposits, countries that mine the same minerals on land, mining companies, research institutions and scientific networks, environmental advocacy groups, intergovernmental organizations and non-governmental organizations. Thus, DSM should create a multi-area participation environment. Moreover, DSM is difficult to be completed independently by a single country or region across regulations, resource exploration, environment, and technical equipment. Diverse international cooperation and coordination are required to accelerate its implementation.

CRediT authorship contribution statement

Huajun Li: Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Jiancheng Liu:** Writing – review & editing, Validation, Resources. **Lei Li:** Writing – review & editing, Project administration, Investigation. **Xiuzhan Zhang:** Investigation, Formal analysis, Data curation. **Liwei Yu:** Writing – original draft, Visualization, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The author is an Editorial Board Member/Editor-in-Chief/Associate Editor/Guest Editor for Engineering journal and was not involved in the editorial review or the decision to publish this article.

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References

[1] Hein JR, Mizell K, Koschinsky A, Conrad TA. Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: comparison with land-based resources. Ore Geol Rev 2013;51:1–14.
[2] International Energy Agency (IEA). The role of critical minerals in clean energy transitions-analysis. Report. Paris: IEA; 2021.
[3] Heffernan O. Seabed mining is coming—bringing mineral riches and fears of epic extinctions. Nature 2019;571(7766):465–8.
[4] Petersen S, Krätschell A, Augustin N, Jamieson J, Hein JR, Hannington MD. News from the seabed—geological characteristics and resource potential of deep-sea mineral resources. Mar Policy 2016;70:175–87.
[5] International Seabed Authority (ISA). DeepData [Internet]. Kingston: ISA; [cited 2025 Feb 28]. Available from: https://data.isa.org.jm/isa/map/.
[6] Miller KA, Thompson KF, Johnston P, Santillo D. An overview of seabed mining including the current state of development, environmental impacts, and knowledge gaps. Front Mar Sci 2018;4:418.
[7] Li JB, Wang Y, Liu L, Xu X. Current status and prospect of deep-sea mining technology. Sci Technol Foresight 2022;1:92–102 [Chinese].
[8] Our mission [Internet]. Dillenburgsingel: Seabed 2030; [cited 2025 Feb 18]. Available from: https://seabed2030.org/our-mission/.
[9] United Nations. The agreement under the United Nations convention on the law of the sea on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction. Geneva: United Nations; 2023.
[10] Muñoz-Royo C, Ouillon R, El Mousadik S, Alford MH, Peacock T. An *in situ* study of abyssal turbidity—current sediment plumes generated by a deep seabed polymetallic nodule mining preprototype collector vehicle. Sci Adv 2022;8(38):eabn1219.
[11] Brown KA. The Draft regulations on exploitation of mineral resources in the area. In: Ascencio-Herrera A, Nordquist MH, editors. The United Nations convention on the law of the sea, part XI regime and the international seabed authority: a twenty-five year journey. Boston: Brill Nijhoff; 2022. p. 303–52.
[12] Liu Z, Liu K, Chen X, Ma Z, Lv R, Wei C, et al. Deep-sea rock mechanics and mining technology: state of the art and perspectives. Int J Min Sci Technol 2023;33(9):1083–115.
[13] Sitlhou L, Chakraborty P. Comparing deep-sea polymetallic nodule mining technologies and evaluating their probable impacts on deep-sea pollution. Mar Pollut Bull 2024;206:116762.
[14] Levin LA, Amon DJ, Lily H. Challenges to the sustainability of deep-seabed mining. Nat Sustain 2020;3(10):784–94.
[15] Van Dover CL, Ardron JA, Escobar E, Gianni M, Gjerde KM, Jaeckel A, et al. Biodiversity loss from deep-sea mining. Nat Geosci 2017;10(7):464–5.
[16] Levin LA, Mengerink K, Gjerde KM, Rowden AA, Van Dover CL, Clark MR, et al. Defining "serious harm" to the marine environment in the context of deep-seabed mining. Mar Policy 2016;74:245–59.
[17] International Seabed Authority (ISA); Legal and Technical Commission. Recommendations for the guidance of contractors for the assessment of the possible environmental impacts arising from exploration for marine minerals in the Area. Geneva: ISA; 2019.
[18] Levin LA, Bett BJ, Gates AR, Heimbach P, Howe BM, Janssen F, et al. Global observing needs in the deep ocean. Front Mar Sci 2019;6:241.
[19] Roth R, Kirchain R, Field F, Peacock T. Understanding the economics of seabed mining for polymetallic nodules. Geneva: International Seabed Authority (ISA); 2018.
[20] Beijing Pioneer Hi-Tech Development Co., Ltd. Environmental impact statement joint test of deep-sea miner and buffer station in Beijing Pioneer Polymetallic Nodule Contract Area. Report. Beijing: Beijing Pioneer Hi-Tech Development Co., Ltd.; 2024.
[21] Deep Green Metals Inc. Initial Assessment of the NORI Property, Clarion–Clipperton Zone. Report. Sydney: Deep Green Metals Inc.; 2021.
[22] Cheng Y. Occurrence characteristics of elements and paleoenvironmental records in polymetallic nodules from Parece Vela Basin, East Philippine Sea [dissertation]. Xiamen: Third Institute of Oceanography, Ministry of Natural Resources, PRC; 2022 [Chinese].
[23] Li Y, Liu C, Su S, Li M, Liu S. Analysis of the effect of payment mechanism on exploitation of polymetallic nodules in the area. Minerals 2021;11(2):221.