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The Future of Norwegian Deep-Sea Mining

Impacts on the Sustainability Pillars

Master's Thesis, 2024

Industrial Economics

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Acknowledgments

First and foremost, we would like to express our deepest gratitude to our wonderful supervisor, Andreea. Her support, insightful guidance, and encouragement have been invaluable throughout the process of researching and writing this thesis. Her expertise and availability to answer our questions, provide contact information, and suggest literature have significantly enhanced the quality of our work. We are profoundly thankful for her patience, constructive feedback, and dedication to our academic growth.

We also want to extend our thanks to Chiara Morfea, Håvard Carlsen, and our families. Their support, understanding, and encouragement have been our pillars of strength. They have been patient and accommodating, offering emotional and practical support that has enabled us to stay focused and motivated.

Additionally, we are deeply grateful to our classmates and A-laget for their camaraderie, assistance, and motivation throughout the semester. Their collaborative spirit, shared knowledge, and moral support have made this journey both enriching and enjoyable. The lively discussions, study sessions, and collective problem-solving efforts have greatly contributed to our learning experience. We are thankful for the sense of community and the friendships that have developed, making this academic endeavor a truly memorable one.

Abstract

The increasing demand for critical minerals, driven by the global shift towards low-carbon technologies, has intensified interest in deep-sea mining (DSM). This emerging industry presents both opportunities and challenges for Norway, which has identified valuable resources on its continental shelf. However, significant knowledge gaps exist regarding DSM's environmental, social, and economic impacts. This thesis seeks to address these gaps by answering the research questions: *What are the challenges and opportunities of deep-sea mining on the Norwegian continental shelf on the three sustainability pillars? Additionally, what management strategies can be employed to ensure viability for stakeholders?*

Previous research has highlighted some potential positive and negative risks of DSM in other parts of the world, but there remains a lack of scientific studies focusing on the Norwegian context. This thesis aims to address this gap by providing a balanced assessment of DSM's impacts, thus enabling evidence-based decision-making. To achieve this, the thesis employs a mixed-methods approach, including a cost-benefit analysis, and the development of a triple bottom line tool. This tool provides a range of metrics with relevant information for different stakeholders, such as research communities, regulators, and industry professionals. The major findings indicate that while DSM could offer benefits across all sustainability pillars, the expected costs are deemed too high, especially in the long-term and largely unknown environmental impacts. By addressing the interconnected economic, environmental, and social dimensions, the study highlights the need for sustainable practices to ensure long-term viability for all stakeholders involved.

Sammendrag

Den økende etterspørselen etter kritiske mineraler, drevet av det globale skiftet mot lavkarbonteknologi, har økt interessen for dyphavsgruvedrift. Denne fremvoksende industrien byr på både muligheter og utfordringer for Norge, som har identifisert ressurser på kontinentalsokkelen. Det er imidlertid store kunnskapshull når det gjelder de miljømessige, sosiale og økonomiske konsekvensene av dyphavsgruvedrift. Denne oppgaven ønsker å tette disse hullene ved å besvare forskningsspørsmålene: *Hvilke utfordringer og muligheter gir dyphavsgruvedrift på norsk sokkel med hensyn til bærekraftpilarene? Hvilke forvaltningsstrategier kan brukes for å sikre levedyktighet for interessentene?*

Tidligere forskning har belyst noen potensielle positive og negative risikoer ved dyphavsgruvedrift i andre deler av verden, men det mangler fortsatt forskningsstudier som fokuserer på den norske konteksten. Denne oppgaven har som mål å bidra til å tette dette gapet ved å gi en balansert vurdering av konsekvensene av dyphavsgruvedrift, slik at det blir mulig å ta evidensbaserte beslutninger. For å oppnå dette benytter oppgaven en blandet metodisk tilnærming, inkludert en kost-nytte-analyse og utviklingen av et trippel bunnlinjeverktøy. Verktøyet inneholder en rekke måleparametere med relevant informasjon for ulike interessenter, som forskningsmiljøer, myndigheter og fagfolk i bransjen. De viktigste funnene tyder på at selv om dyphavsgruvedrift kan gi fordeler på tvers av alle bærekraftpilarene, anses de forventede kostnadene å være for høye, særlig når det gjelder de langsiktige og stort sett ukjente miljøkonsekvensene. Ved å ta for seg de sammenkoblede økonomiske, miljømessige og sosiale dimensjonene understreker studien behovet for bærekraftig praksis for å sikre langsiktig levedyktighet for alle involverte.

Contents

List of Figures

List of Tables

Abbreviations

CBA	Cost-Benefit Analysis
CCZ	Clarion Clipperton Zone
CLB	Continuous line bucket
CRC	Cobalt rich crust
DSM	Deep-sea mining
DSMPI	Deep-sea mining performance indicators
EEZ	Exclusive economic zone
EU	European Union
EV	Electric vehicles
GWP	Global Warming Potential
IEA	International Energy Agency
ISA	International Seabed Authority
NCS	Norwegian continental shelf
SMS	Seafloor massive sulfides
TBL	Triple bottom line
UNCLOS	United Nations Convention on the Law of the Seas

1 Introduction

As the demand for minerals used in low-carbon technologies and modern mass-produced electronics such as electric vehicle (EV) batteries, wind turbines, solar panels, and smartphones is expected to increase in response to the green shift (IPCC, 2023), new frontiers to obtain these minerals are being explored. The deep seabed once thought to be devoid of life, has been found to contain vast mineral deposits of copper, cobalt, nickel, zinc, silver, gold, and rare earth elements (Ashford et al., 2023, p. 2). However, scientists are sounding the alarm that extracting these minerals from the ocean depths could cause irreversible harm to the deep-sea biodiversity, marine life, and the ocean's carbon cycle (Ashford et al., 2023).

In January 2024, Norway passed a bill accelerating the hunt for precious metals, making it the first country in the world to advance with the controversial practice of deep-sea mining (DSM) (Normannsen, 2024; Stallard, 2024). The Norwegian government argues that current mineral extraction is largely concentrated in a few countries and companies with lower environmental and worker rights standards than Norway. Therefore, the government should examine the possibility of Norway contributing to the global mineral supply in a responsible manner (Energidepartementet, 2024b). However, there are also plans for DSM activities outside of Norway.

In the international waters of the Pacific Ocean, the Clarion Clipperton Zone (CCZ) is an area of active debate. Here some nations are already applying to the United Nations' International Seabed Authority (ISA), also known as the Authority, for permits to begin exploration (Ashford et al., 2023). Although the ISA planned to reach an agreement on the DSM regulations in July 2023, it failed to do so (Ashford et al., 2023; Pickens et al., 2024, p. 2). The situation was further complicated by the small island state of Nauru issuing a letter notifying their intent to apply for an exploitation contract, triggering a two-year countdown for the ISA to finalize relevant regulations. The regulations serve as guidelines on how countries should pursue DSM activities in international waters (Pickens et al., 2024, pp. 1-2). These regulations will also apply to sovereign states wanting to conduct DSM activities within their waters, as national laws should be *"no less effective"* than international laws (Levin et al., 2016, p. 246). What happens before 2025 when the ISA has to finalize the regulations remains unclear (Ashford et al., 2023).

If the Norwegian government allows DSM activities in its waters based on the current impact assessment, it will likely have unforeseen impacts on the country with spillover effects on the rest of the Arctic Ocean (WWF Global Arctic Programme, 2023). Therefore, this thesis explores the potential consequences and how various stakeholders may be affected. Specifically, the study investigates the challenges and opportunities of initiating DSM activities in Norway, focusing on the three pillars of sustainability: economic, environmental, and social. This is done with an in-depth Cost-Benefit Analysis (CBA), aiming to provide transparency about what we know and what we do not know regarding the impacts of DSM.

Examining these pillars ensures a balanced approach that supports informed decision-making (Gibson, 2006, p. 260). Understanding the trade-offs and synergies between different sustainability aspects allows stakeholders to gain a clear view of the possible implications. Moreover, focusing on the sustainability pillars is crucial for the long-term viability of the DSM industry, supporting economic growth, protecting the environment, and promoting social well-being. The thesis also provides a tool for evaluating the industry's performance based on selected indicators within the sustainability pillars. This tool is designed to promote responsible management as the industry evolves.

The structure of this thesis is as follows. First, we provide background information on DSM, bringing the reader up to speed with the current state of the industry. Next, we present the current literature on DSM in Norway, identifying research gaps. Following this, we describe the methods used to address these gaps. We then present the results derived from our methodologies, and finally, we discuss the implications of our findings before concluding.

2 Background

2.1 The Main Types of Deep-Sea Mineral Deposits

This section provides a quick introduction to the different types of deep-sea mineral deposits and provides the reader with a basic understanding for the subsequent chapters. A more detailed description of these deposits and definitions of DSM can be found in Appendix A.1 and Appendix A.2.

The mineral deposits that are of commercial interest to deep-sea mining can be divided into three types: polymetallic nodules, seafloor massive sulfides (SMS), and cobalt-rich crusts (CRC). These all occur globally but are more frequent in areas with certain geological features and conditions (Childs, 2019, p. 2).

Polymetallic nodules, also known as manganese nodules, are mineral concretions typically with a diameter between 1 - 12 cm and grow by an accumulation of manganese and iron oxides around a nucleus (Hein et al., 2013, pp. 4,7). They are commonly found on sediment-covered abyssal plains at water depths of about 3,000 – 6,000 m, where sedimentation rates are less than 20 mm per thousand years (Petersen et al., 2016, p. 176). Usually, they are found within the top 20 - 30 cm of the seabed (MIDAS).

Figure 1 – Polymetallic nodule (Lavinsky, 2010)

Seafloor massive sulfides deposits form on and below the seabed from high-temperature hydrothermal water emitted by volcanoes along ridges, island arcs, and in rifted back-arc basins behind active subduction zones (Petersen et al., 2016, p. 180). Here the superheated water contains high levels of dissolved minerals, and when it encounters a physical or chemical barrier, such as cold seawater, the fluid precipitates and forms sulfide deposited on the seabed. Chimney-like structures can build up which collapse at irregular intervals and form cone-like or mound-like deposits of minerals (Meld. St. 25 (2022-2023), p. 20). Reliable size estimates of SMSs are rare because they require drilling information to judge (Petersen et al., 2016, p. 183). However, estimates range from a few tons to over 20 megatons (Hannington et al., 2011, p. 1157).

Figure 2 – An SMS where the escaping water has been colored by the minerals it contains, giving it a characterizing black "smoke". These deposits are commonly called black smokers (World Ocean Review, 2014a)

Cobalt-rich crusts, or co-rich ferromanganese crusts, are formed when dissolved metal compounds that occur naturally in seawater build up a crust directly on underwater rock formations under given conditions (Meld. St. 25 (2022-2023), p. 20). This is a slow process, where the crusts accumulate at a rate of 1 - 6 mm per million years and can reach thicknesses of up to 25 cm (MIDAS).

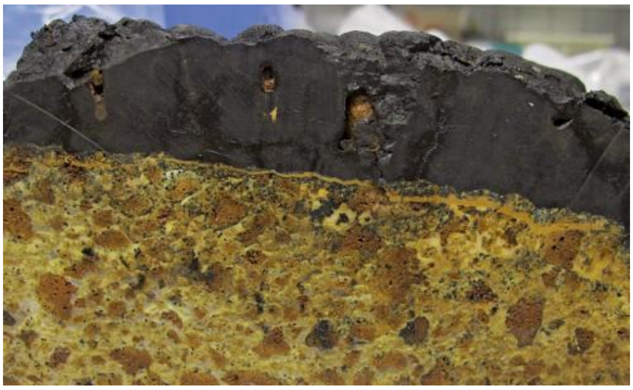

Figure 3 – Cross section of a CRC, easily recognizable on top of the volcanic rock (World Ocean Review, 2014b)

2.2 History and Technological Development of Deep-Sea Mining

The discovery of mineral deposits on the seabed is not a recent discovery. Polymetallic nodules were first found during the Challenger expedition over 140 years ago. The scientific mission took place in the 1870s and laid the foundation for modern oceanography (Scarminach, 2019). Discoveries of SMSs and CRCs happened later, with the first black smokers being discovered in 1979 in the East Pacific Rise and the presence of CRCs first being identified in 1980 in the Pacific Ocean by Germany and Britain on the "Sonne" ship (Ju et al., 2023, p. 2; World Ocean Review, 2014a). It took a long time from the discovery of polymetallic nodules to commercial interest in the resource. The first commercial interest was not seen until the mid-20th century (Scarminach, 2019).

The first trial of a polymetallic nodule mining system occurred in 1970 off the coast of Florida on the Blake Plateau. Here a 6,750 ton freighter, equipped with a derrick, lifted the nodules at a depth of 1,000 m using an airlift (International Seabed Authority, p. 5). Two years later, a Japanese vessel in a syndicate of 30 companies used a "continuous line bucket" (CLB) system (Figure 4) at a depth of 4,500 m. At this trial, an 8 km cable was equipped with buckets at regular intervals, which dredged the nodules (International Seabed Authority, p. 5; Kang & Liu, 2021, p. 2; Masuda et al., 1971).

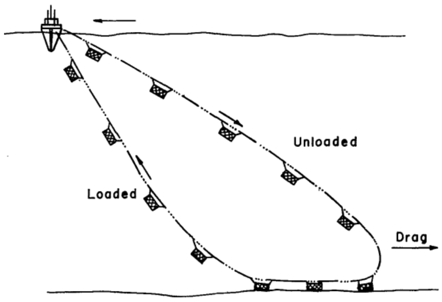

Figure 4 – Concept figure of the CLB system (Masuda et al., 1971)

In the rest of the 1970s, several consortia were active in polymetallic nodule mining, investing an amount estimated to be around USD 1.4 billion (adjusted for inflation) in projects (Carboex, 2023, p. 41). These consortia combined technology and experience derived from dredging, deep water oil and gas, near-shore underwater mining, and ore and mineral process industries (Carboex, 2023, p. 29). Notably, The Ocean Management Inc. consortium completed the first successful nodule pilot mining test in 1978 using a hydraulic system of submerged pumps and an airlift to recover nearly 1,000 tons of nodules (Kang & Liu, 2021, p. 2; OMI).

Modern Technology

For polymetallic nodules, mining companies have steered away from the CLB system. While specific plans are proprietary, all companies today plan to use a (horizontal) seafloor component moving along the seabed to collect the nodules. Connected is a (vertical) component that lifts the nodules to the ship, while a ship-based component separates the nodules from the slurry (Cuyvers et al., 2018, p. 23). As it would be an expensive procedure to transport the slurry to a tailings dam or on-land stack, it is disposed of after it is separated. It is proposed that it should be disposed of at depths of 1,000 - 1,100 m to consider light penetration, ocean turbidity, alteration of the benthic habitat, and burial of aquatic organisms (Ma et al., 2017, p. 4).

The horizontal component will be remotely operated, funneling the nodules towards the vertical component, which consists of a pipe string or riser. The equipment needs to function effectively in the high-pressure, high-acidity waters found at such great depths without clogging or stirring up too much sediment (Cuyvers et al., 2018, p. 23). As retrieval and redeployment of the equipment will be time-consuming and costly, it will also need to remain on the seabed for long periods at a time (Cuyvers et al., 2018, p. 24).

DSM in the Norwegian context is somewhat different as polymetallic nodules are not present on the Norwegian continental shelf (Meld. St. 25 (2022-2023), p. 13). The Norwegian Ministry of Energy has summarized the expected production steps for the extraction of SMSs and CRCs, as shown in Table 1 (Meld. St. 25 (2022-2023), p. 41).

Table 1 – The expected production steps for a DSM venture on the Norwegian continental shelf

1.	Mining and collection of minerals on the seabed
2.	Vertical transport of the ore from the seabed to the production unit at sea level
3.	Storage and possibly dewatering of ore at the production unit
4.	Loading from production unit to transport ship/storage system, as well as disposal of waste materials/separated seawater
5.	Transport of ore to onshore facilities for treatment and/or further processing

The mining of the different types of deposits uses similar methods, but the equipment used for extracting the minerals will differ (Jones et al., 2020, p. 10). CRCs and SMSs are difficult to extract because they stick to the steep and uneven surfaces they form on (Priyanka, 2023). A challenge here is to not collect too much rock, diluting the deposit. The collecting vehicles for these deposits use a cut-and-crush principle where the crust is first peeled off and crushed into paper clip-size fragments (Priyanka, 2023). For SMSs, the equipment is similar to what is used for terrestrial mining today (Jones et al., 2020, p. 10). See Figure 5 for an illustration of methods.

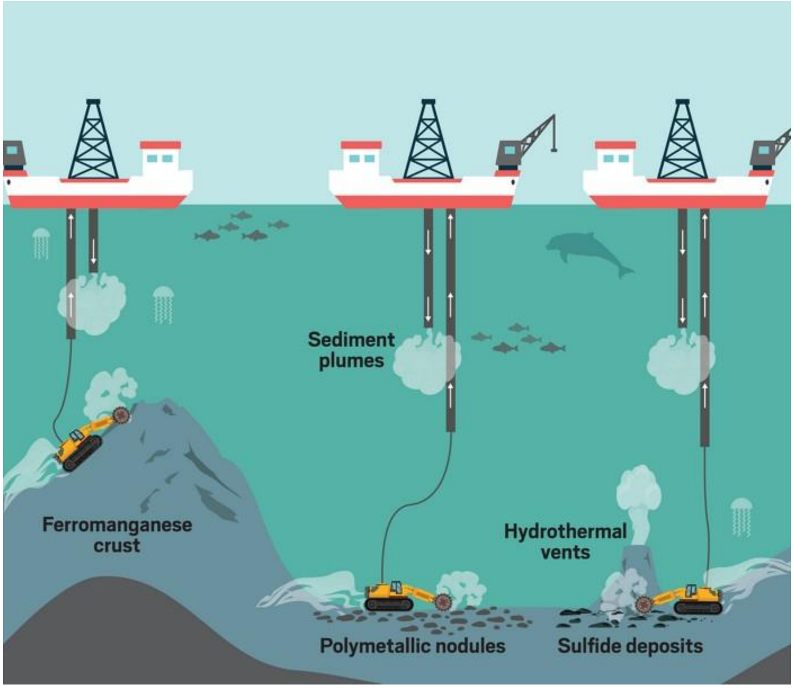

Figure 5 – Extraction methods for the three different deep-sea deposit types (Priyanka, 2023)

3 Literature review

Sustainability involves using resources to meet current needs without compromising future generations' ability to do the same, considering environmental, social, and economic aspects (Brundtland, 1987). One way to understand sustainability is to see it as an interconnected hierarchy, where environmental sustainability forms the basis for social and economic sustainability, with social considerations underpinning economic viability (Purvis et al., 2019). This emphasizes the need to assess the effects on all these pillars before undertaking DSM. The concept of the triple bottom line (TBL) is useful for situations where companies should prioritize social and environmental concerns as much as profits (Miller, 2023).

Norway has conducted an impact assessment on the expected effect DSM can have on the environment, economy, and social relations (Sokkeldirektoratet, 2024). With this assessment as a basis, the government has opened part of the Norwegian continental shelf (NCS) to mineral exploration (Brembo et al., 2023). This assessment considered a wide range of positive impacts of DSM, but only briefly touched upon the negative ones, leading to criticism from several organizations including WWF, Naturvernforbundet, Spire, as well as the European Parliament (EJF Staff, 2024; NTB, 2023). Due to this and a general lack of research on DSM in Norway, the thesis relies on international research, where the majority has been conducted in the CCZ. The information has been assessed and translated into the Norwegian context.

3.1 Environmental

There are significant concerns about the environmental impacts of DSM mining due to large scientific gaps. Reliable baseline data are necessary for establishing the pre-mining environmental conditions, which can later be used to design effective monitoring programs to detect and measure environmental changes over time (Clark et al., 2020, p. 2).

A healthy and thriving deep-sea biodiversity brings ecosystem services to humanity's benefit and plays an intricate part in a complex ecosystem keeping the oceans healthy, as it helps regulate ocean acidity and produce oxygen (Niner et al., 2018, p. 2). New research is also increasingly recognizing the role of deep-sea species and ecosystems in carbon cycling and storage (Fauna & Flora, 2023, p. 10). In the daily migration of mesopelagic[1] fish and zooplankton, they play a major role in transporting carbon from the sunlit zone to the seabed, which contains dissolved carbon stocks on a magnitude larger than terrestrial soils (Hilmi et al., 2021, p. 4).

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[1] Mesopelagic organisms live in the ocean at depths between 200 – 1000 meters (Institute of Marine Research, 2023)

To date, 230,000 species in the oceans have been scientifically described, but this is expected only to be a small fraction of the total. Even in seemingly inhospitable environments, like active SMSs, life forms have evolved to thrive in extreme conditions (Fauna & Flora International, 2020, pp. 7 - 8).

The environmental baseline for nodules in the CCZ is greater than for both inactive SMSs on the Mid-Atlantic ridge and CRCs (Amon et al., 2022, p. 4). Still, in the CCZ, approximately 70 – 90 % of species collected are new to science. Additionally, it is estimated that 25 – 75 % of total species remain to be collected from sites already sampled (Amon et al., 2022, p. 3). Scientific knowledge of active SMSs on the Mid-Atlantic ridge has the greatest environmental baseline. However, SMS mining will most likely target inactive ones (Amon et al., 2022, p. 5).

Additionally, research has indicated that these species will be significantly affected. While there is little scientific knowledge about the impacts of DSM conducted in the Atlantic, there are a few studies in the CCZ that can be used to draw parallels. (Amon et al., 2022, p. 4). In the Pacific Ocean in 1989, the largest environmental impact test performed on the deep-sea floor was conducted. Since the test was performed, scientists have reported that the site never recovered, and there has been little return of life (Heffernan, 2019, p. 466). Other tests have also come to similar results. In 2020, the first test on the environmental effects of mining CRCs took place. Here, a 120 m long strip of crust was excavated and studied the following year. It was found that the density of active swimming animals, like fish and shrimp, had dropped by 43 % in the area directly affected by the sediment plume and 56 % in adjacent areas (Gilbert, 2023).

If Norway wants to reduce biological loss, the designation of Marine Protected Areas (MPAs) could be a potential solution, as these have been considered effective tools for halting the continued loss of marine species. They could therefore be a crucial instrument in helping Norway achieve its commitment to protect 30 % of its marine area by 2030 (Legrand et al., 2024, p. 4). In 2024, a study by the Institute of Marine Research put forth a proposal for an MPA network attempting to best protect biodiversity and deep-sea benthic ecosystems in the Nordic Seas (Legrand et al., 2024, p. 17). Figure 6 shows the proposed MPA network covering 30 % of the Norwegian extended continental shelf and the proposed area for DSM, illustrating a clear overlap.

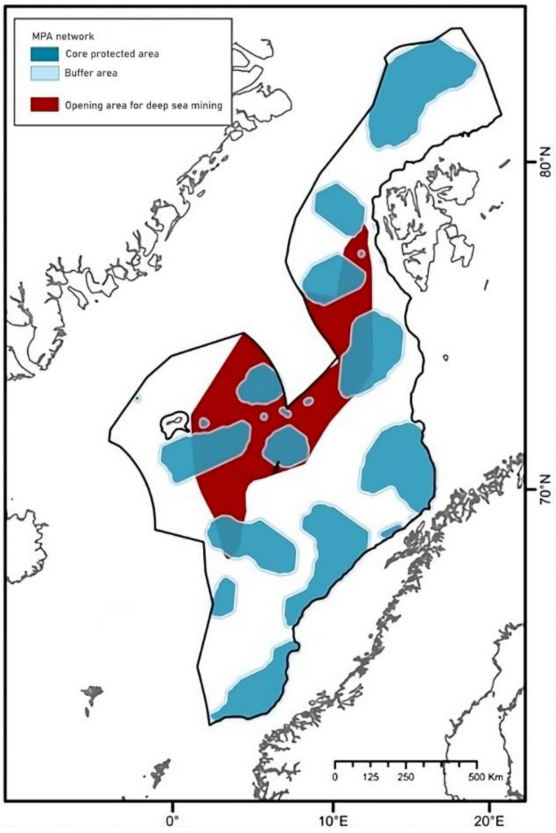

Figure 6 – MPA network with a 10 km buffer zone and the proposed area for DSM (Legrand et al., 2024)

Even though there are environmental concerns regarding DSM, the industry also brings opportunities for improvement. In 2021, the metals and mining industry accounted for approximately 4 - 7 % of worldwide greenhouse gas emissions (GlobalData). Studies have estimated that nodule mining could reduce emissions by 70 - 75 % compared to terrestrial mining (Chung et al., 2023; Paulikas et al., 2020, p. 11). It should be noted here that only three studies compare the nodule-to-commodity climate impact of nodules to terrestrial mining, showing great variation in the results (Planet Tracker, 2023, p. 3). In addition, the metallurgical processing of nodules is proposed to be similar to that of land ores. This is the biggest climate change contributor in the production process of minerals, accounting for 70 – 85 % of the total climate impact (Planet Tracker, 2023, p. 8).

3.2 Economic

In the production process of minerals, there are several challenges that DSM could help alleviate. One of these challenges is the high demand for minerals. The World Bank Group estimates that 3.5 billion tons of minerals will be required by 2050 to reach the Paris Agreement goal of keeping the global average temperatures well below 2℃ compared to pre-industrial levels (UNFCCC; World Bank Group, 2020, p. 11). This legally binding treaty necessitates a complete restructuring of the energy sector (World Ocean Review, 2021, p. 151).

Wind turbines, photovoltaic systems, and energy storage units utilize several critical minerals[2] in their construction (World Ocean Review, 2021, p. 151). Demand for these minerals is expected to increase substantially, with the International Energy Agency (IEA) estimating a nearly fourfold increase by 2030 in its Net Zero Emissions by 2050 Scenario. Meeting this demand with terrestrial mining would require the development of 164 new mines for critical minerals (International Energy Agency, 2023, p. 11).

An example of a sector with a large demand for minerals is the transportation sector. In 2022 this sector was responsible for about 20 % of global emissions (Chung et al., 2023). For EVs, the total lifecycle greenhouse gas emissions are on average around half of internal combustion cars, with the potential for a further 25 % reduction with low-carbon technologies (International Energy Agency, 2021b, p. 15). However, producing an EV is a mineral-intensive process. Compared to a conventional car powered by an internal combustion engine, producing an EV requires six times more minerals, see Figure 7 (Chung et al., 2023).

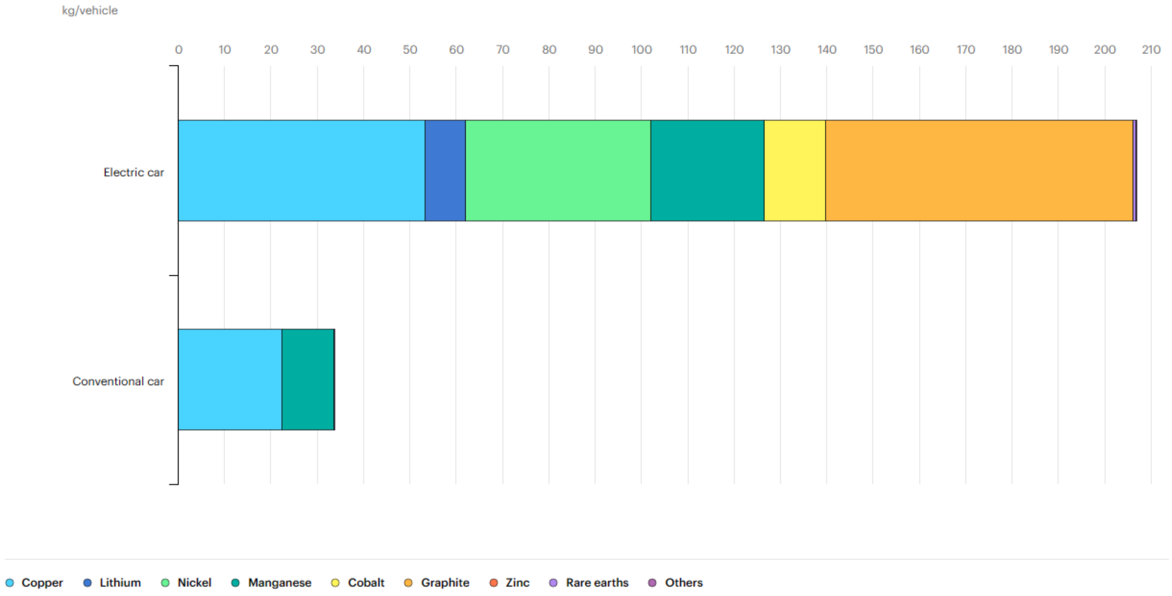

Figure 7 – Minerals used in cars, excluding steel and aluminum (International Energy Agency, 2021a)

As these low-carbon technologies are mineral intensive, it is important to look at the status of resources and reserves[3] in terrestrial mines. For both resources and reserves, there are generally no signs of shortages. Even though there has been an increase in production over the past decades, economically viable reserves for many minerals essential in the energy

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[2] Critical minerals: Minerals with significant economic importance and supply risks. Source: (SINTEF, 2022, p. 3).

[3] Resources are concentrations of metals with potential for economic extraction, while reserves are mineable resources under current conditions. Source: (International Energy Agency, 2021b, p. 130)

transition have been increasing. However, concerns about resources relate to quality rather than quantity (International Energy Agency, 2021b, p. 130). In recent years it has become increasingly difficult to mine many minerals. The ore grade[4] has decreased for many commodities over the past decade (Chung et al., 2023). As a result of the dropping ore grades, mines need to be deeper to extract the same amount of minerals, which in turn leads to higher energy consumption, production costs, greenhouse gas emissions, and waste volumes (International Energy Agency, 2021b, p. 12).

Proponents of DSM argue that if states do not meet the increasing demand for resources, it will put their economic development and the prosperity of their citizens at risk (World Ocean Review, 2021, p. 161). To ensure this demand is met, supporters of DSM say that exploiting the seabed is central (Jones, 2023). On the NCS, it is estimated to be over 300 million tons of minerals (Oljedirektoratet, 2023, pp. 1-2). Furthermore, the CCZ, which covers about 1.3 % of the world's ocean floor, contains more nickel, cobalt, and manganese than all land-based deposits. For copper, the CCZ's deposits are about equal to those on land (Chung et al., 2023).

Another approach to closing the demand gap is considering other supply sources, which could be moving to a circular economic model or an increased degree of recycling. It is projected that technological development, circular economic strategies, and recycling could reduce cumulative mineral demand by 58 % between 2022 and 2050 (EJF, 2024, p. 4). End-of-life minerals from established waste streams and emerging waste streams could in this way play a significant role in the secondary supply of minerals (International Energy Agency, 2021b, p. 177). While economic strategies and technological advancements play crucial roles in addressing mineral demand, it is equally important to consider the social implications of mining activities.

3.3 Social

Social Impacts of Terrestrial Mining

Terrestrial mining activities have given rise to a range of social implications that must be addressed in order to ensure reliable mineral supplies for the energy transition. Failing to address the concern on social impacts may cause a backlash that questions the appropriateness of using mineral-intense low-carbon technologies (World Bank Group, 2020, p. 31). In a 2021 study by the IEA, several challenges with terrestrial mining are brought up. These challenges are shown in Table 2 below.

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[4] Ore grade: the percentage of minerals that can be extracted from each metric ton of rock. Source: (Chung et al., 2023)

Table 2 – Several challenges in terrestrial mining. (International Energy Agency, 2021b, p. 40)

Governance	▪ Mineral revenues in resource-rich countries have not always been used to support economic and industrial growth and are often diverted to finance armed conflict or for private gain. ▪ Corruption and bribery pose major liability risks for companies
Health and Safety	▪ Workers face poor working conditions and workplace hazards (e.g., accidents, exposure to toxic chemicals) ▪ Workers at artisanal and small-scale mine (ASM) sites often work in unstable underground mines without access to safety equipment
Human Rights	▪ Mineral exploitation may lead to adverse impacts on the local population such as child or forced labor (e.g. children have been found to be present at about 30% of cobalt ASM sites in the DRC) ▪ Changes in the community associated with mining may also have an unequal impact on women

Even though many international mining companies have pledged to make responsible and sustainable choices when it comes to preventing harm, there is still a disparity between the voiced *"commitments"* and the effect of the practices. For example, a study found 30 companies committed to providing safe working conditions, and yet 29 of them reported workplace fatalities (RMF, 2021, p. 39). Another study of 30 extractives companies that operated in Eastern Europe and Central Asia found that *"100 % of companies with human rights policies faced allegations of abuse"* (Business & Human Rights Resource Centre, 2021, p. 4). Human rights activists mention access to information as being one of the key issues for the poor conditions. This is enabled by systematic control from politicians, poor regulations, corruption, and a lack of oversight (Business & Human Rights Resource Centre, 2021, pp. 4 - 8). These circumstances underscore the need for regulations that guarantee social responsibility.

DSM Regulatory Framework

The rules governing mining activities in the ocean are determined by whether they occur within a country's Exclusive Economic Zone (EEZ). If they do, they must adhere to the national laws of that country. For seabed areas outside these zones (the Area), the ISA manages and regulates them, as established during the United Nations Convention on the Law of the Sea (UNCLOS) (Boschen et al., 2013, pp. 61-62). These laws are meant to set a precedence and a standard for nations that want to start DSM activities and ensure that nations exploring DSM in their jurisdiction have to follow no less stringent rules and regulations (Levin et al., 2016, p. 246).

However, these regulations are not yet adopted. At the end of June 2021, Nauru sent a letter to the ISA informing that it would sponsor a contractor with plans for nodule mining in the CCZ, intending to apply for approval for their plan of work. This triggered a two-year countdown for the ISA, where they had to facilitate the approval of the plan of work (Ardito & Rovere, 2022, pp. 1-2). However, two years later, the member council decided it needed more time before giving the green light. Currently, they are working towards adopting regulations in 2025 and say that exploitation should not be allowed until a mining code is agreed upon (McVeigh, 2023). Countries such as Norway, Mexico, UK, and Nauru have pushed for a more rapid adoption of the rules (Skelly, 2023).

In Norway, alongside the regulations set by the ISA, specific national legislation, such as the *Seabed Minerals Act*, has been enacted to govern mineral extraction activities. The *Seabed Minerals Act* regulates the exploration and extraction of mineral deposits on the NCS (Energidepartementet, 2024a). Furthermore, Norway is bound by the precautionary principle through international law agreements and national laws and regulations (Jakobsen, 2021; Myhre, 2024). This principle introduces a more proactive approach entailing taking actions at an earlier stage where there might not be conclusive evidence supporting the case for harmfulness, like the current situation with DSM (Jaeckel, 2017, p. 29).

3.4 Triple Bottom Line Within the DSM Industry

When reviewing the literature, no appropriate tool for measuring the performance of the DSM industry within all the aspects of the TBL framework was found. However, the thesis was able to draw parallels to the study called *"The Fishery Performance Indicators: A Management Tool for Triple Bottom Line Outcomes"* (Anderson et al., 2015). This study developed a tool for measuring the performance of fisheries on the three pillars of sustainability: economic, social, and environmental. Similar to the fishing industry, the DSM industry extracts natural resources and will have implications on all the sustainability pillars. The TBL framework's ability to integrate these pillars may be crucial for the DSM industry, as it offers a comprehensive view of potential barriers and opportunities associated with DSM for the industry and regulators. Additionally, it provides a ramp for addressing the existing gap in scientific literature.

4 Theory

4.1 Fundamental Definitions in Risk Science

Risk can be viewed in the context of some future activity, for example, a project that wants to undertake a DSM operation on the NCS (Society for Risk Analysis, p. 4). After determining the event or activity, the risk is defined with the potential consequences (effects, implications) this event or activity has on something of identified value (Society for Risk Analysis, p. 4).

Risk can also be described as the "*consequences of the activity and associated uncertainties*". Following this definition, there are two key aspects of risk description: consequences (C) and uncertainties *(U)*. Using this denotation, risk can be simplified to *(C, U)*. In the context of the previously stated example project about DSM, there are related uncertainties about the potential consequences of pursuing the project. The consequences of the project can yield both positive and negative outcomes, where the differentiation of them may be decided by the stakeholder (Aven & Thekdi, 2022b, p. 11).

There are other ways of writing the risk term, one of which is to denote it as *(A, C, U)*. Here *(A)* indicates an event, *C* symbolizes the consequence of the event *A* has occurred, and *U* indicates the associated uncertainty (Aven & Thekdi, 2022b, p. 11). Event *A* can be defined as a *"hazard, threat or opportunity, as well as a risk source"* (Aven & Thekdi, 2022b, p. 12).

Risk Sources

Some of the most common forms of risk sources can be grouped as "*hazards, threats, and opportunities*". When risk sources are defined as hazards, the related potential consequences are injuries that can occur, both physical and psychological injuries. The term threat is often associated with security applications, while opportunities speak to something positive that stems from the risk source affecting the consequences (Aven & Thekdi, 2022b, p. 17). The likelihood of the risk source happening is given based on the probability of the event occurring.

Subjective Probability

The chosen way to judge the likelihood of an outcome is subjective probability, also known as *"knowledge-based or judgmental probability"*. Unlike the other forms of probabilities, a subjective probability can always be given as it expresses the evaluator's certainty and degree of belief for a statement to be true (Aven & Thekdi, 2022b, p. 28). If someone offers a subjective probability for an event *A* to occur, it can be compared to the probability of drawing a red ball from an urn containing X amount of red and white balls (Aven, 2021).

A subjective probability is always given with some background knowledge *(K)* that encompasses the assessors' information, beliefs, insight, and more about the given situation or subject (Aven, 2021). The knowledge is often given as a prerequisite for the event to occur and the probability is often written as:

$$P(A|K) = P(A \; given \; K) \qquad ^{5}$$

Strength of Knowledge

An important factor in the risk assessment is the Strength of Knowledge *(SoK)*. It is difficult to quantify meaningfully how much knowledge someone has on a subject. Therefore the *SoK* is often judged on an interval scale rather than a continuous scale. An example of such a scale can be *"weak knowledge, medium strong knowledge, and strong knowledge"* (Aven & Thekdi, 2022b, p. 35). Assessors who have a lot of information on a subject or are considered experts on it often possess a strong *SoK*. On the other hand, those without any prerequisite knowledge often have a weak *SoK* when assessing a situation (Aven & Thekdi, 2022b, p. 35).

Expert Judgment

Expert judgment involves the application of specialized knowledge and skills to assess and interpret data, in this thesis within the DSM context. This expertise has been sourced from available literature with the educational background and practical experience to offer valuable insights into the activity being performed. Utilizing expert judgment allows for a nuanced and informed perspective on potential outcomes, risks, and benefits associated with DSM activities (Szwed, 2016, pp. 2-3).

4.2 Cost-Benefit Analysis

4.2.1 Risk Concerns

When it comes to risk, there are two types of concerns: the need for development on one hand, and the need for protection on the other. In a quantitative Cost-Benefit Analysis (CBA), both risk and uncertainty considerations are given little attention beyond expected values. As a result, the focus is more on the development concern rather than protection (Aven & Thekdi, 2022a, pp. 220-221).

4.2.2 Qualitative Cost-Benefit Analysis

In contrast to a normal (quantitative) CBA, the qualitative CBA does not attach specific monetary values, as it is more about understanding the underlying advantages and disadvantages. This is especially useful when the cost and benefits are difficult to quantify (Alhurani, 2023).

Using a qualitative CBA helps in understanding the non-monetary effects of a decision and is particularly useful in the early stages of an assessment to identify potential costs or benefits

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[5] Source: *(Aven, 2021)*

(Alhurani, 2023). The method also has the benefit of producing a more comprehensive view of the overall costs and benefits in the short-term and longer-term (Rogers et al., 2009, p. 89).

Its limitations and disadvantages are that it may be perceived as too vague or subjective, lacking direct numerical comparisons. In decision-making, where stakeholders may want concrete figures, its influence will also be limited (Alhurani, 2023).

The process of performing both quantitative and qualitative CBAs involves three general steps, as shown in Table 3 (Stevens et al., 2008, p. 8):

Table 3 – General steps for performing CBA (Stevens et al., 2008, p. 8)

1.	**Describing** costs and benefits – identifying and describing costs and benefits
2.	**Attributing** costs and benefits – analyzing the contribution of the intervention to achieving the observed outcomes
3.	**Comparing** costs and benefits – analyzing the relationships between costs and benefits

Step 1 - Describing Costs and Benefits

The CBA includes the expended resources (both financial and non-financial) and negative outcomes that result from the project as costs. On the other hand, the benefits include all the positive outcomes resulting from the project and the negative outcomes that are avoided as a result of undertaking the project, see Table 4. Usually, it is easier to get evidence for outcomes that have been achieved than negative outcomes avoided (Stevens et al., 2008, p. 8).

Table 4 – Defining benefits and costs in the CBA (Stevens et al., 2008, p. 8)

BENEFITS	**COSTS**
Positive outcomes	Resources expended
Negative outcomes avoided	Negative outcomes

Whose Benefits and Whose Costs?

A CBA is based on the perspective from whom the benefits and costs are considered. An example of this is a funding organization that receives working time from volunteers. For the organization, this is recognized as a benefit as it increases their available resources. However, for the volunteers, it is recognized as a cost, as their time cannot be used for other projects or activities. If the CBA does not recognize all costs, there is a risk of interpreting cost-shifting as if it were cost-saving (Stevens et al., 2008, p. 8).

Timeframe for Evidence of Benefits and Costs

Finding evidence of outcomes can be challenging, especially for a short-term evaluation of something whose benefits are expected to be realized over several years (Stevens et al., 2008, p. 9). Generally, the further into the future your predictions of outcomes are, the more difficult it is to make them accurate (Stobierski, 2019).

Opportunity Costs

Opportunity cost refers to the lost benefits, or opportunities, that arise when one strategy is chosen over another (Stobierski, 2019). Some CBAs consider opportunity costs. However, it might not be a valid assumption that the resources would be directed toward the specified lost opportunity (Stevens et al., 2008, p. 9).

Step 2 - Assessing the Contribution

When assessing the cost of a project, we are interested in the additional resources expended and the negative outcomes resulting from it. Similarly, for benefits, we are looking at the positive outcomes and resources leveraged as a result of undertaking the project. Separating the impacts that would have happened regardless of whether the project was initiated or not is rarely straightforward (Stevens et al., 2008, p. 9).

Step 3 - Summarizing the Relationship Between Benefits and Costs

As stated before, the qualitative CBA does not make a direct comparison in terms of monetary units. Therefore, rather than summarizing the ratio of benefits to costs, the relationships and trade-offs between different costs and benefits are analyzed (Stevens et al., 2008, p. 10).

5 Data

The data for this study were gathered from scientific literature, government reports, and international agreements and organizations. This approach provided a foundation for understanding the various aspects of DSM, including its economic viability, environmental impact, and social implications. The sources used for the CBA can be found in Appendix B.1.

6 Methodology

The CBA was selected for its ability to provide a systematic framework to compare the costs and benefits across the sustainability pillars (Abelson, 2015). This method has been applied to DSM in the Pacific Island region, as well as other extractive industries like coal mining (Cardno, 2016; NSW Government, 2015). By evaluating whether the costs outweigh the benefits, CBA offers a framework for informed decision-making. Additionally, the method provides insights into stakeholder-specific risks associated with starting DSM activities in Norway. The main objective is to offer decision-makers and stakeholders an understanding of potential economic, environmental, and social impacts.

Furthermore, the CBA is complemented by a deep-sea mining performance indicators (DSMPI) tool. This tool's setup follows the Fishery Performance Indicators (FPI), a tool used in the fishing industry (Anderson et al., 2015). Anderson et al. (2015) used this versatile tool to evaluate fisheries performance across the triple bottom line of economic, community and ecological sustainability. We chose this framework due to its comprehensive evaluation of sustainability, proven methodology, and relevance to resource extraction activities.

6.1 Qualitative Cost-Benefit Analysis

To address the issue in CBAs where the method tends to emphasize *“development concern”*, this thesis incorporates several indicators into our analysis. The qualitative CBA aims to provide a more balanced assessment that accounts for both development and protection concerns. By incorporating risk and uncertainty considerations, the analysis better addresses the potential trade-offs for stakeholders. In the CBA the uncertainty is captured by the *“certainty”* indicator. The analysis also ensures that there is transparency in the *SoK* behind the potential benefits and costs, which in turn, helps in making evidence-based decision making.

As all the consequences in the benefits part of the CBA will be beneficial for the particular stakeholders, we have therefore chosen to differentiate between *“positive risk”* and *“negative risk”*. The term *“positive risk”* might seem counterintuitive at first because risk is commonly associated with negative outcomes or adverse consequences. However, when the goal is identifying opportunities for favorable outcomes, it can be a useful concept. Thus, a high positive risk can be seen as beneficial because there is a high potential for the positive outcome to come to fruition (Hillson, 2003, p. 15). An outcome bearing a high positive risk can be the profits from taxes the government gains from DSM activity in Norway. The indicators looked at in the CBA are presented below (Table 5), and are inspired by Aven (Aven & Thekdi, 2022a, p. 287).

Table 5 – Indicators for Benefits and Costs in the CBA

Stakeholder	Outcome	Scale of Outcome	Duration of Outcome	Certainty	Positive/Negative Consequence	Strength of Knowledge	Risk Score	Positive/Negative Risk	Comment

In the CBA, we have chosen to look at the perspectives of several stakeholders. Each **stakeholder** group has distinct interests, concerns, and priorities, which can influence what is considered a benefit or a cost (Aven & Thekdi, 2022b, p. 11). The stakeholder group perspectives chosen are as follows:

- *Harvest Sector:* The harvest sector stakeholders are directly involved in exploration and extraction activities. They are concerned with regulatory compliance, environmental impact mitigation, and securing investments.
- *Norwegian Government:* As the regulatory authority and policymaker, analyzing the government's perspective helps assess impacts in a political context. Key interests include national economic growth, job creation, environmental protection, and meeting international commitments.
- *Norwegian Citizens:* The perspectives of Norwegian citizens are essential for capturing societal values and concerns regarding the potential impacts of DSM on communities.
- *Post-Harvest Sector:* Post-harvest sector stakeholders are involved in processing, manufacturing, and utilizing DSM-derived products. Their priorities include securing a reliable supply of raw materials, maintaining competitive pricing, and adhering to sustainability standards.
- *Competing Industries:* Competing industries, such as terrestrial mining and DSM in other countries, compete for resources and market share. Their concerns include potential market disruptions, the implications for resource pricing, and the comparative environmental and social impacts. They may also be interested in technological advancements and regulatory changes that could affect their operations.
- *International Governments:* The impacts of DSM in Norway are likely to have transboundary implications; therefore, analyzing international governments' perspectives helps assess the geopolitical consequences.

The **Outcome** describes how the various stakeholders are expected to be influenced/affected by the specific event that is being analyzed. This includes environmental impacts, such as changes in marine biodiversity due to mining activities, economic benefits from the extraction of valuable minerals, and social impacts, such as the creation of jobs in local communities.

The **Scale of Outcome** specifies the geographic area that the outcome would impact, and it is limited to *"Local"*, *"National"*, and *"International"* effects:

- *Local* effects refer to effects on Norwegian coastal communities and the immediate marine environment, such as job creation in the harvest sector, local government interventions, or prospecting and exploration costs.
- *National* impacts refer to the effects on a geographic area larger than a single community, such as effects on national revenue, or national regulatory frameworks.
- *International* refers to effects that will have transborder spillovers, such as the influence on international marine biodiversity or changes in international trade dynamics due to increased mineral supply.

The **Duration of Outcome** is used to specify the timeframe in which the outcome is expected to influence stakeholders. It is relevant for understanding if the outcome only applies during the program period (short term) or beyond it (long term). The program period is defined as the period beginning with exploration and lasting until the end of the decommissioning phase of the last project.

In several risk assessments, the **Certainty** is not quantified, and vague words, e.g. *"likely",* are used*.* Doing so allows for entirely different interpretations of certainty (Aven & Thekdi, 2022b, p. 275). To address this issue, we define a discrete range for the certainties of the outcomes. The certainties are then assessed based on subjective probability and expert knowledge.

- *Low certainty:* An event is deemed to have low certainty if the subjective probability of it occurring is less than 25 %. Such as the potential for a loss of tourism due to the threat of mining activities.
- *Medium certainty:* The event is given medium certainty if the likelihood of it occurring is between 25 % and 50 %. E.g. generated plumes can have an impact outside Norwegian borders.
- *High certainty:* An event is considered highly certain if it is more than 50 % likely to occur. An event that is judged with high certainty is that the spreading of plumes will have a negative impact on the environment.

We evaluate the severity of the impact if the given outcome occurs. This is done both for positive and negative **consequences** and is categorized as low, medium, or high, as follows:

- *Low consequence:* Minimal changes, such as slight increases in local employment or minor environmental disturbances.
- *Medium consequence:* Noticeable impacts, including moderate disruption to marine ecosystems or the increased need for logistic and supply chain services.
- *High consequence:* Significant changes, such as major ecological damage, substantial economic growth, or profound social changes in communities.

The **Strength of Knowledge** judges how reliable the existing knowledge is about a given outcome based on a broad consensus among experts or if sufficient data is available to analyze the event. This provides a structured and transparent framework for evaluating the reliability of information used in the assessments.

- *Weak (Low) SoK:* Limited data available, high uncertainty, and a lack of comprehensive studies, leading to low confidence in predictions. In the context of DSM, this might include the long-term social impacts on coastal communities or the cumulative environmental effects of multiple DSM operations. The weak strength of knowledge underscores the necessity for caution and the need for ongoing monitoring and research.
- *Medium SoK:* Here, the strength of knowledge is based on some data and expert opinions, but there are noticeable gaps that introduce moderate uncertainty. This category might apply to aspects of DSM where there are few studies and expert analyses, but also areas where data is sparse or conflicting. This moderate level of certainty requires careful consideration and highlights the need for further research to fill in the gaps.
- *Strong (High) SoK:* This category is characterized by extensive research, comprehensive data, and a broad consensus among experts, providing high confidence in predictions. For example, if numerous studies consistently show the same environmental impacts of DSM, the *SoK* is assessed as strong.

The **Risk Score** is used to give a consistent assessment of the positive and negative risks. The score is a weighted average of the indicators assessed in the CBA. Quantifying the differences among risks allows for them to be based on the severity of their impact and ensures transparency in the results (Halpern et al., 2007, p. 1302). Each indicator is assigned a specific weight, reflecting its perceived relative importance in determining the overall risk. The indicators and their respective weights are inspired by a study performed by Halpern, and then decided by the authors, utilizing expert judgment (Halpern et al., 2007).

In the analysis, the *SoK* is given the highest weight as it is the least subjective indicator and relies the most on scientific literature. Furthermore, long term outcomes are also given a higher weight as their impacts extend the scope of the program. Certainty is given a higher weight because it is influenced by how the facts are presented in scientific literature. However, the literature rarely states the certainty of outcomes, adding a layer of subjectivity to the evaluation. Finally, the consequence relies the most on subjective assessment of the indicators and is therefore not given a higher weight. *"Scale of Outcome"* is excluded as this indicator will not necessarily change the impact for the specific stakeholder. The weights used are shown in Table 6:

Table 6 – Weight of indicators and risk levels in CBA

Certainty	1.3
Positive/Negative Consequence	1
Strength of Knowledge	1.75
Duration of Outcome: Program duration	1
Duration of Outcome: Long term	1.5
Low	1
Medium	2
High	3

These values are then multiplied by their respective weights and summed to produce the final risk score. For example, if a beneficial outcome has a long term duration and a low value in all indicators, the following calculation is applied:

$$Risk\ Score = \frac{Long\ term\ + Certainty * Low + Consequence * Low + SoK * Low}{Number\ of\ indicators}$$

$$Risk\ Score = \frac{1.5 + 1.3 * 1 + 1 * 1 + 1.75 * 1}{4} \approx 1.4$$

As the score is below 2, the final *"Positive Risk"*, is assessed as low, in accordance with Table 7. The same process is repeated for each outcome.

Positive/Negative Risk:

Table 7 – Risk score intervals for positive and negative risk

Low positive or negative risk	Below a risk score of 2
Medium positive or negative risk	Between a risk score of 2 – 2.75
High positive or negative risk	Above a risk score of 2.75

The **comment** offers additional information and context to the result, providing further explanation or insights.

6.2 Performance Indicators

The DSMPIs diagram presented in this thesis draws inspiration from the study titled *"The Fishery Performance Indicators: A Management Tool for Triple Bottom Line Outcomes"* (Anderson et al., 2015). This study introduces a broadly applicable and flexible tool that can be used to assess the performance of fisheries on the three pillars of sustainability: economic, social, and environmental.

Through an iterative consultative process of extensive piloting and revision, the final Fishery Performance Indicators (FPI) tool consists of the TBL indicators which are captured by 14 different dimensions. These dimensions are again divided into 68 metrics of fishery performance, each coded in levels of 1 to 5, where 5 reflects better metric performance. This discrete scoring method allows experts to score the metrics – imprecisely but accurately, even when precise underlying data is not available. In the study, 61 case studies were looked at with the tool giving consistent scoring across them (Anderson et al., 2015, p. 4).

Recognizing that a lot of the indicators and metrics used to assess performance in the FPI study are also applicable in the context of DSM, we sought to adapt and extend these to specifically fit the characteristics of DSM. Our aim was to select indicators and metrics that give a comprehensive view of the industry. The chosen metrics are based on transferable metrics from the FPI study and reviewed literature.

Like in the FPIs study, rather than attempting to measure a few indicators with high precision, they are divided into dimensions of greatest interest. Following this are metrics that capture important aspects of the dimensions. Each dimension is captured by multiple metrics, ensuring robustness in scoring even when some metrics lack data or expert consensus (Anderson et al., 2015). Regular measurement of these metrics is important to track changes in DSM impacts over time.

The diagram includes four categories of people: executives, processing owners, crew, and processing workers. The executives and crew refer to the people who work in the harvesting sector, while the processing owners and workers are linked to the post-harvest sector.

The metrics presented aim to provide insights into the DSM industry's performance across environmental sustainability, economic viability, and social responsibility. By measuring and assessing these metrics, we believe the DSMPIs can offer a valuable indication of the industry's performance within the sustainability pillars. An in-depth explanation of each metric in Figure 8 can be found in Appendix C.1. All indicators, dimensions, and the insight they aim to provide are presented below.

Indicators and Dimensions

The TBL indicators on the left side of Figure 8 consist of the three sustainability pillars, after which the thesis is structured. On the right side of the figure are the Sector indicators, which are helpful for those interested in specific segments of the DSM industry. The sectors included in the figure are the environmental, the harvest, and the post-harvest sector.

TBL Indicators

To capture the *"Environmental Indicator"*, the DSMPI includes the dimension *"Ecological Health"*, which offers an overview of scientific concerns regarding environmental impacts. This guides efforts to minimize ecological disruption and conserve marine biodiversity. The *"Economic Indicator"* evaluates the financial viability and market dynamics of DSM operations through six dimensions that assess the industry's ability to generate market benefits effectively. The *"Social Indicator"* focuses on the well-being of communities and workforce dynamics, providing a comprehensive understanding of the prosperity and health of people in and around the DSM industry. Assessing the metrics will indicate the effectiveness of policies and programs aimed at improving the quality of life in affected communities. This may promote an industry where benefits and profits are equitably distributed.

Environmental Dimensions

DSM is likely to have severe impacts on the biodiversity of marine ecosystems and influence large areas (Niner et al., 2018). Therefore, five metrics are provided to capture the "Ecological Health" dimension. The first metric, *"Species Richness",* measures the biodiversity within the affected area by quantifying the number of species present. The second metric, *"Livestock Population Dynamics",* assesses the trends in species populations within the affected area, across pelagic zones such as the mesopelagic. It involves quantifying the abundance of these species and evaluating whether their populations are declining, stable, or rebuilding. Additionally, the metric *"Status of Critical Habitat"* evaluates the status of critical habitat within the affected area through expert judgment based on a critical habitat assessment. It assesses the extent to which key habitats essential for the survival and reproduction of species are intact, degraded, or under threat, providing insights into the overall health and resilience of the ecosystem. The last metrics measure the areal impact of the DSM operations, as well as their associated carbon output.

Economic Dimensions

The *"Harvest"* dimension captures how effective DSM operations are at collecting materials, and if profits are lost through operational inefficiencies or material prices. The *"Harvest Yield"* and *"Operating Efficiency"* metrics measure how much material is brought to shore in a year and the ratio of operational days compared to the theoretical maximum, respectively. *"Price Variance"* assesses the ex-vessel price[6] of harvested material by comparing it to the historical high.

The *"Harvest Assets"* dimension provides insights into the efficiency, stability, and productivity of the assets invested in harvesting activities. The metrics collectively offer an overview of how effectively capital is utilized in generating revenue, the stability of asset values, and the cost of capital. Ultimately, the dimension helps stakeholders understand the financial performance and investment attractiveness of harvesting assets.

The *"Risk"* dimension measures various sources of volatility and uncertainty that may affect the economic performance and stability of DSM. The metrics quantify the variability in revenue, landings, prices, and profitability over time, highlighting the level of uncertainty and financial risk associated with mining activities. Additionally, spatial price volatility evaluates the variability in prices across different locations, indicating the extent of market dependency and geographical risk factors. Overall, the dimension aids in understanding the economic risks inherent in DSM.

The *"Trade"* dimension offers insights into the market engagement, product value, and competitiveness of DSM operations. It comprises metrics that assess various aspects of trade and market performance, including international export value, final market wealth, and wholesale price competitiveness. These metrics quantify the value of goods exported internationally, the total value generated by products reaching end consumers, and the competitiveness of wholesale prices compared to similar products in the market (i.e., minerals from terrestrial mining). By evaluating trade dynamics, the dimension helps understand the extent of market reach and the economic contribution of DSM products.

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[6] Ex-vessel price – the price of goods where all costs are paid by the vessel until delivered at the designated port. Source: (Mindat)

The *“Product Form”* dimension offers insights into the effectiveness of the processing phase in transforming raw ore into final products. It encompasses metrics that assess various aspects of processing efficiency, including processing yield, product shrinkage, capacity utilization ratio, and value chain margins. These metrics quantify the proportion of raw material successfully transformed into usable products, the loss or shrinkage during processing, the utilization of production capacity, and the profitability at different stages of the value chain. The dimension helps to understand the efficiency of processing operations and optimize resource utilization.

The *“Post-Harvest Assets”* dimension looks at the management and performance of assets involved in the post-harvest phase of operations. Similarly to the “Harvest Assets” dimension, it helps stakeholders understand the financial performance and investment attractiveness of assets.

Social Dimensions

The *“Managerial Returns”* dimension gains insights into the compensation and returns received by managerial personnel within the industry. The metrics offer an understanding of the financial rewards and compensation levels for executives and processing owners within the industry. By evaluating managerial returns, it can gain insights into income distribution, and the attractiveness of executive positions within the industry. Additionally, this dimension helps identify any disparities in earnings relative to regional contexts.

Similar to the previous dimension, the *“Labor Returns”* dimension looks at compensation received, but for the labor force in the industry. Analyzing labor returns can provide insights into the distribution of profits, social equity, and job attractiveness.

The *“Health & Sanitation”* dimension assesses the health and safety conditions within the industry, focusing on the well-being of workers and sanitation standards. It encompasses metrics that evaluate various aspects related to health and sanitation, including harvest safety and accessibility to healthcare services for the workers. By evaluating health and sanitation standards, it can identify areas for improvement to ensure the safety, health, and well-being of all personnel involved in DSM.

The *“Community Services”* dimension evaluates how the industry interacts with and contributes to surrounding communities. The metrics provide insights into legal challenges faced and the accessibility of education opportunities for the workforce.

The *“Local Ownership”* dimension captures the level of representation and inclusion of locals in executive positions within the harvesting and post-harvest sectors. Evaluating this dimension can provide insights into how the benefits are distributed to local communities and the degree of control exercised by local stakeholders over key assets and decision-making processes.

The “*Local Labor”* metrics in this dimension evaluate different aspects related to the local labor force, such as the proportion of non-resident workers who are employed as crew members and processing workers. These metrics help understand the extent to which local workers are engaged in different positions, the reliance on non-resident labor, and the industry's contribution to local job creation over time.

The *“Career”* dimension provides insights into the workforce's experience and demographic composition. Measuring the metrics over time shows if the industry is generating stable, long-term employment for the labor force.

On the far right of Figure 8, the metrics for each indicator are classified into sector categories. These are *“Environmental Performance”*, *“Harvest Sector Performance”*, and *“Post-Harvest Sector Performance”*. This classification system helps to analyze distributional outcomes and is useful for those interested in specific segments of the DSM industry.

Sector Indicators

All the environmental metrics are mapped to the *“Environmental Performance”* indicator. The *“Harvest Sector Performance”* indicator draws metrics from both the *“Economic”* and *“Social”* indicators. Similarly, the *“Post-Harvest Performance”* indicator also draws its metrics from the *“Economic”* and *“Social”* indicators.

Environmental Performance Dimension

The metrics in this dimension offer insights into the extent to which DSM companies are reducing their environmental impact, preserving biodiversity, and mitigating effects on marine ecosystems.

Harvest Sector Dimensions

The *“Harvest Performance”* dimension assesses the operational effectiveness of the DSM harvesting process, incorporating metrics such as harvesting yield and operational efficiency to evaluate DSM companies' ability to maximize material output while minimizing wasteful practices. Financial viability and safety of assets in the harvesting sector are evaluated by the *“Harvest Assets Performance”* dimension. The *“Risk Performance”* dimension measures the various risks associated with the economic aspects of DSM harvesting activities. Additionally, it examines the contestability and legal challenges, which bring risks to the industry's perception among potential investors. Ownership aspects, including executive compensation, access to healthcare for executives, and the proportion of non-resident executives, are covered in the *"Owners"* dimension. Like the previous dimension, the *"Crew"* dimension encompasses aspects related to compensation, access to healthcare, and the proportion of non-resident workers. In addition, it also examines the length of time the crew has worked in the industry in the *"Crew Experience"* metric, as well as analyzing the age structure of the crew. The metrics provide insight into the industry's retention rate and indicate whether the age of the crew leans towards a young or old labor force.

Post-Harvest Dimensions

The *"Market Performance"* dimension draws metrics from the trade, harvest, and product form dimensions to evaluate the competitiveness and economic success of DSM products in the marketplace. The *"Post-Harvest, Processing & Support Industry Performance"* dimension assesses the efficiency of processing activities in the post-harvest sector, while the *"Post-Harvest Assets Performance"* dimension examines the performance of assets used during this phase. Similar to the *"Owners"* dimension, the *"Processing Owners & Managers"* dimension evaluates aspects related to ownership, including processing owners' compensation, access to healthcare, and the involvement of non-resident owners in the DSM post-harvest sector. Lastly, the *"Processing Workers"* dimension mirrors the metrics used in the *"Crew"* dimension but applies them to the labor force in the post-harvest sector.

6.3 Limitations of the CBA

It is essential to recognize the limitations of the qualitative CBA methodology. One significant limitation is the subjective nature of the analysis. The qualitative assessment depends on expert judgment and data interpretation, which can introduce bias and variability in the results. Additionally, the *SoK* assessed in the method may be considered high relative to the available data, but it is essential to recognize that there may still be considerable uncertainty and gaps in understanding. The paucity and quality of data on certain aspects of DSM operations can limit the precision and reliability of the analysis, leading to potential overestimation or underestimation of costs and benefits.

Furthermore, the analysis does not encompass every stakeholder affected by the DSM industry. While efforts are made to include diverse perspectives, there may be stakeholders whose interests and concerns are not adequately represented in the analysis. This limitation highlights the need for ongoing stakeholder engagement and dialogue to ensure that relevant viewpoints are considered in decision-making processes related to DSM.

In our analysis, we have opted to include the outcomes only within the stakeholder group where we believe the potential benefits or costs would have the most significant impact. This is done to limit double counting. However, it is important to acknowledge the interconnectivity of the outcomes. Many of the identified outcomes are likely to influence multiple stakeholder groups to varying degrees. The result of the CBA for each stakeholder group will, therefore, vary from the result presented, which looks at the overall relationship of costs and benefits.

7 Results

7.1 Cost-Benefit Analysis

This chapter presents a selective version of the result tables, focusing on key segments of the CBA. We refer to the complete tables in Appendix B.1.

7.1.1 Benefits

Environmental Benefits

Despite widespread concerns about the environmental impacts of DSM, there are potentially beneficial outcomes. Table 8 outlines some potential outcomes and their associated positive risks. While many of the potential outcomes could have significant positive consequences for the stakeholders, the majority are characterized by low positive risk. This low positive risk assessment is largely due to the current low *SoK* and the generally low certainty of the outcomes. The only exception in the table is the outcome of *"Increased scientific research on the deep-sea ecosystems"*, which is given a high positive risk. This high positive risk assessment is based on the current research about deep-sea ecosystems, where several studies have been enabled due to the DSM industry, and the outcome is given both a high certainty and high positive consequence.

Table 8 – Potential environmental benefits

Stakeholders	**Outcome**	**Positive Risk**
Harvest Sector	The transition from terrestrial mining to DSM is projected to lower the overall Global Warming Potential (GWP).	Low
	Compared to nodule mining, CRC and SMS extraction plumes will be more localized.	Medium
Norwegian Government	Facilitates the transition to a low-emission society by increasing the availability of minerals essential for low-carbon technologies, thereby supporting the government in achieving its emissions goals.	Low
Norwegian Citizens	Shifting some mining activities to the seabed reduces the physical footprint and associated environmental degradation of terrestrial mining operations within Norway.	Low
Post-Harvest Sector	Easier access to minerals extracted with a low carbon output.	Low
	The increased availability of DSM-derived minerals could stimulate demand for metallurgical processing in countries prioritizing low-carbon industrial practices, such as Norway.	Low

Competing Industries	An increase in R&D can provide technologies that have lower emissions, which could be applicable to other industries.	Low
	If Norway becomes a large-scale mineral exporter, it could set a precedent, encouraging the international terrestrial mining industry to adopt similar standards.	Low
	DSM could pressure the metallurgical processors to reduce their GWP, as it is a major contributor to climate impact in the mineral value chain.	Medium
International Governments	DSM activities necessitate further scientific research on deep-sea ecosystems, potentially advancing understanding and contributing valuable knowledge to global environmental science.	High
	By decreasing the need for terrestrial mining, DSM can help reduce deforestation and associated habitat destruction.	Low

Economic Benefits

Table 9 presents the potential economic outcomes and associated positive risks. Notably, the economic outcomes are assessed with the highest positive risk across the three benefit tables, where most outcomes are given a medium or high positive risk. This indicates significant potential benefits, underscored by both high certainty and high positive consequences for many of the outcomes. As with the environmental outcomes, the outcomes bearing a low positive risk are generally given this assessment due to their low *SoK*. Moreover, it is important to note that almost all the benefits will only last as long as the industry operates.

Table 9 – Potential economic benefits

Stakeholders	**Outcome**	**Positive Risk**
Harvest Sector	The initiation of the DSM industry in Norway is likely to attract foreign investments by offering new opportunities for resource extraction. Coupled with Norway's robust and stable financial market, these opportunities can appeal to international investors.	Medium
	Companies will operate in an environment with higher ore grades than terrestrial mining, possibly resulting in more efficient extraction processes and lower costs per unit of mineral.	Medium

	By leveraging Norway's existing infrastructure from the maritime industries, the capital expenditures for establishing a new industry can be significantly reduced.	High
	With many firms facing resource scarcity, DSM could offer a solution by providing a fresh supply of critical minerals.	High
	Enables harvest companies, shareholders, and members of the supply chain to earn profits on the minerals sold.	High
Norwegian Government	Leveraging the experienced local workforce accustomed to working with the NCS minimizes the need for outsourcing and retains more economic value within the country.	Medium
	Revenues generated from taxes, royalties, and licenses on DSM activities can increase financing for the welfare state.	High
	Economic diversification resulting from DSM can provide the government with additional revenue streams, enhancing financial stability.	High
Norwegian Citizens	An increase in jobs directly related to DSM can have a positive ripple effect on the economy, stimulating demand for local services such as barbers and restaurants.	Medium
Post-Harvest Sector	Investments in the harvest sector can stimulate demand for logistics and supply chain services, leading to increased investments and employment opportunities in the post-harvest sector.	High
Competing Industries	Unsuccessful DSM ventures can make terrestrial mining appear as a safer investment.	Low
International Governments	Increased supply of minerals may lead to lower mineral prices, benefiting global consumers.	Low
	Diversification of the mineral supply chain reduces the risk of price squeeze providing stability and economic benefits on a global scale.	Low

Social Benefits

The social pillar encompasses a wide range of potential benefits, as shown in Table 10, which outlines the outcomes and their associated positive risks. The analysis reveals that a notable proportion of these outcomes are characterized by high positive risk, indicating substantial potential benefits for stakeholders. Generally, the stakeholders with the highest assessed positive risk are the *"Harvest Sector"* and the *"Post-Harvest Sector".* For the rest of the stakeholders, the outcomes are mostly assessed with a mix of low and medium positive risks. This variation underscores the inherent uncertainties surrounding DSM's societal implications rather than diminishing their significance.

Table 10 – Potential social benefits

Stakeholders	**Outcome**	**Positive Risk**
Harvest Sector	The sector can leverage expertise from Norway's existing maritime industry to enhance operational efficiency.	High
	The industry can increase workplaces, providing job opportunities and improving local employment rates.	High
	Norway's sustainability standards provide an opportunity for workers in the mineral industry as they can benefit from these standards, enjoying higher health and safety measures compared to those in international terrestrial mining.	High
	A stable regulatory framework in Norway ensures predictability for DSM companies.	High
	Norwegian companies can create an expertise in CRC and SMS extraction as the global focus has primarily been on nodules.	Low
Norwegian Government	The industry can contribute to increased knowledge of the deep sea for research institutions and enhance scientific understanding.	Medium
Norwegian Citizens	A strategic establishment of facilities and research centers can be used to help towns and communities create a local industry.	Low
	It enables Norwegian companies to be at the forefront of research and development for technologies to be used in the industry and beyond.	Medium
	The development of DSM in Norway has the potential to create technical and skilled job opportunities for local communities, attracting specialized workers and their families, while also incentivizing locals to stay.	High

	Based on a history of successful and effective resource management in Norway's oil and gas industry, the country is well-positioned to ensure that the financial benefits from the DSM industry are shared equitably among its citizens and preserved for the future.	High
	More job opportunities and higher paygrades for regional support businesses can increase monetary circulation and stimulate local businesses.	Medium
	The industry can create a demand for relevant educational programs.	Medium
	Funds generated from DSM can be used to improve national infrastructure, education, and healthcare services, thereby enhancing the overall quality of life in Norway.	High
Post-Harvest Sector	The industry can increase the demand for local skills and expertise in the post-harvest sector, providing job opportunities and fostering skill development.	High
	The post-harvest sector could gain easier access to high-value minerals.	High
	Increased access to minerals harvested in a socially responsible manner, reducing reliance on conflict minerals from politically unstable regions plagued by issues such as child labor and ethnic conflicts.	High
Competing Industries	There is expected to be some technological overlap between DSM and terrestrial mining, with similar equipment being used.	Low
	DSM can lead to an expertise shift and expansion of the mining workforce, broadening the skillset and experience of workers in the mining sector.	Medium
International Governments	DSM can mitigate dependence on a limited number of countries for access to critical minerals, enhancing global supply chain stability and security.	High
	The DSM industry is expected to have little direct impact on freshwater, unlike terrestrial mining.	Medium
	The Norwegian framework can be used to create intergenerational equity from non-renewable resources and avoid the resource curse.	Low
	Research associated with DSM can increase understanding of genetic resources with potential for pharmaceutical use.	Low

7.1.2 Costs

Environmental Costs

Table 11 presents the negative environmental outcomes associated with DSM on the NCS, such as the loss of biodiversity, long-lasting impacts on marine ecosystems, disruption of marine life behavior, and pollution from mining activities. Additionally, the table highlights the regulatory and compliance issues, such as non-compliance with UNCLOS obligations and premature industry initiation due to inadequate impact assessments.

In the Harvest Sector, there are significant negative outcomes, most of which are assessed as having a high negative risk. This is because there is relatively strong knowledge about the local impacts of DSM. The outcomes in this context are considered with high certainty and are predominantly seen as having a high negative consequence. On the other hand, the outcomes of international governments are mostly assessed as having a low negative risk. This is due to lower certainty and a lower level of knowledge.

Table 11 – Potential environmental costs

Stakeholders	**Outcome**	**Negative Risk**
Harvest Sector	Restoration efforts are unlikely to accurately replicate disrupted habitats, leading to a net loss of biodiversity.	High
	Removing CRCs over a large area will have significant and long-lasting environmental impacts, affecting vulnerable hard-bottom fauna and local ecosystems.	High
	Noise from DSM operations can disrupt marine life and lead to changes in behavior. Most deep-sea species have yet to be described, and sensitivities to noise have not been studied, leaving a gap in our understanding of their responses.	High
	Light pollution can occur where no natural light sources exist or where natural light is much weaker, potentially having a negative impact on deep-sea life.	High
	The mining of active SMS deposits will significantly impact unique environments and lead to the loss of species that are dependent on these habitats.	High
	Mining inactive SMS deposits can considerably impact unique environments and lead to the loss of species that are dependent on these habitats.	High

	The spread of particles and toxic metals from DSM activities can have a negative environmental impact, harming marine life and ecosystems.	Medium
	The spread of plumes can negatively impact marine life by creating a “blanket” of sediments in areas around the mining field, potentially burying benthic organisms and clogging the respiratory surfaces of filter feeders.	High
Norwegian Government	Disrupting benthic organisms and sediment-dwelling bacteria can affect climate processes, potentially exacerbating climate change impacts.	High
	Ineffective ecological compensation can lead to non-compliance with UNCLOS obligations.	High
	The government's impact assessment lacks nuanced perspectives on negative risks. This can enable the industry to start prematurely and would breach the precautionary principle.	High
	There could be an overlap between MPAs and the area opened for DSM activities.	Medium
	DSM activities could lead to a loss of transit routes and habitats for slow-moving pelagic seabirds, potentially leading to declines in their populations.	Medium
Norwegian Citizens	DSM could impact the migration patterns of fish.	Low
Post-Harvest Sector	No evidence was found supporting significant outcomes.	
Competing Industries	No evidence was found supporting significant outcomes.	
International Governments	DSM can undermine the shift to a circular economy by reducing incentives to invest in recycling and sustainable resource management.	Medium
	The impact assessment lacks sufficient attention to potential transnational impacts.	Low
	Carbon is sequestered and stored in seafloor sediment. Mining operations could risk releasing this carbon back into the ocean and the atmosphere.	Medium

Economic Costs

Table 12 outlines the negative economic outcomes and challenges posed by DSM, such as high operational costs, potential obsolescence due to technological changes, and the possible need for environmental compensation funds. Additionally, the table highlights the financial risks for investors, the potential need for government subsidies, and the broader economic implications for competing industries and international markets.

Table 12 – Potential economic costs

Stakeholders	**Outcome**	**Negative Risk**
Harvest Sector	An environmental compensation fund may be necessary to establish to cover the fees of restoring deep-sea ecosystems.	Low
	Changes in technology could lower the demand for certain minerals from DSM, impacting the economic viability of mining projects.	Low
	Prospecting and exploration costs.	Medium
	Development costs.	Medium
	Mining and extraction costs.	Medium
	Closure and reclamation costs.	Medium
	Higher recycling rates from various materials could decrease the demand for newly extracted minerals, thereby affecting the economic viability of DSM projects.	Low
	Extracting the same minerals with DSM can come at a higher cost than terrestrial mining.	Medium
	Several banks and financial institutions have distanced themselves and stated that they will not invest in the DSM industry.	High
	There is expected to be a great variation in mineral content on the NCS, which can reduce the economic viability of projects.	Medium
	Several large companies have stated that they will not buy deep-sea minerals themselves or allow them in their product value chain.	High
Norwegian Government	If the restoration costs of DSM are higher than the mining company can afford, the government may need to subsidize some of the costs.	Low
	Engaging in or regulating DSM operations that result in financial loss or third-party harm can incur costs for the state.	Low

	Adopting the Norwegian Petroleum Tax System for DSM can impose a high tax burden, impacting projects' economic feasibility.	Low
Norwegian Citizens	Disruptions to fishing activities in proximity to mining sites can lead to losses for the fishing industry.	Low
	Investors can experience economic losses by investing in unsuccessful companies.	Medium
Post-Harvest Sector	The post-harvest sector could incur economic losses from relying on minerals from a new industry with a potentially unstable supply.	Low
Competing Industries	DSM could have a lower carbon output, deterring investments in terrestrial mining.	Low
	Increased supply of metals from DSM could lead to lower prices and increased competition for land-based mining industries.	Low
	There could be a lower incentive to invest in efforts to reduce terrestrial mining impacts.	Low
	The terrestrial mining industry may incur costs trying to adapt to the ethical standards set by DSM.	Low
International Governments	A focus on DSM could lead to a lack of investment in recycling and efforts for a circular economy.	Low

Social Costs

The outcomes in Table 13 present potential social challenges posed by DSM, such as public opposition, regulatory and reputational risks, cultural and economic disruptions, and international conflicts. Like the other tables, there is a common thread – a significant portion of the negative risks are assessed as low, attributed to the current *SoK* within the field. In the context of social costs, many of the negative risks are assessed as low due to this limited knowledge.

Table 13 – Potential social costs

Stakeholders	**Outcome**	**Negative Risk**
Harvest Sector	An uproar from protestors may hinder the implementation of the industry.	Medium
	Mapping and investigating deep-sea environments is challenging and costly, requiring resource allocation to protect critical areas.	High

Norwegian Government	There is a need to develop and enforce legal and regulatory frameworks to manage environmental impacts and stakeholder interests.	High
	DSM activities in disputed waters introduce grounds for international conflicts.	High
	Norway could lose its role as co-chair of the Ocean Panel if it allows DSM in its territorial waters.	Medium
	Exploration or possible exploitation licenses granted without regard to the precautionary principle could cause reputational damages.	High
Norwegian Citizens	Norwegian citizens may experience a loss of cultural or spiritual value associated with a pristine ocean or a traditional sense of ownership of or identification with the ocean and its resources.	Low
	Disruptions to fishing in proximity to the mine site may lead to a loss of job opportunities for fishing communities.	Low
	Introducing DSM and higher pay grades to communities can strain the regional level of pay, creating income disparities.	Low
	The seafood processing industry could face increased contamination risks from pollutants released during DSM activities.	Medium
	The extraction of non-renewable minerals today reduces opportunities for the future by depleting finite resources.	Medium
Post-Harvest Sector	No evidence was found supporting significant outcomes.	
Competing Industries	Increased recycling efforts could reduce the demand for virgin minerals.	High
	A successful DSM venture may divert workers from competing industries.	Medium
International Governments	Norway could face international problems as the European Union (EU) put forward a motion requesting a resolution against Norway's seabed mining activities in the Arctic.	High
	Mining of seafloor substrates can have unknown impacts, hindering the development of future industries.	Low
	There are countries that disagree with Norway's interpretation of the Svalbard Treaty. If Norway allows exploration and exploitation activities in the areas surrounding Svalbard, it could lead to increased friction and attention regarding Norway's stance.	Medium

7.1.3 Summary of the Relationship Between Benefits and Costs

When comparing the benefits and costs presented in this study, it becomes evident that the risks associated with DSM are skewed toward higher costs than benefits. DSM promises several potential benefits, including providing critical minerals required for low-carbon technologies, economic opportunities for countries involved, and advancements in technology and research. These benefits could lead to significant economic growth and job creation, which are appealing to stakeholders. Despite the potential benefits that DSM offers to various stakeholders, the current *SoK* and the uncertainty surrounding the outcomes significantly diminish the perceived value of these positive risks. Furthermore, it is important to note that some of these benefits are contingent upon DSM effectively replacing terrestrial mining, an aspect with a low strength of knowledge in the study.

Based on our findings, it seems premature to start DSM at this stage. This is due to the scarcity of available data in the field, and the lack of a comprehensive understanding of the impacts the industry will cause in the context of the three pillars of sustainability. The limited data on the environmental, economic, and social effects of DSM operations make it challenging to fully assess the risks and benefits. This lack of data also hampers the development of effective mitigation and management strategies to address potential negative impacts.

Given the current lack of *SoK* and the high levels of uncertainty, the positive risks associated with DSM are insufficient to outweigh the potential negative risks. A cautious approach is recommended, emphasizing further research, establishing robust regulatory frameworks, and inclusive stakeholder consultations before initiating large-scale DSM operations.

7.2 Deep-Sea Mining Performance Indicators

The DSMPIs in Figure 8 shows the TBL indicators of environmental, economic, and social (on the far left), which are captured by 14 dimensions. On the right side of the diagram, the 11 dimensions are divided by whether they provide information on the environmental performance, the harvest sector performance, or the post-harvest sector performance. The braiding shows how the metrics are mapped to the dimensions.

The DSMPI tool is designed to offer flexibility in analysis, allowing stakeholders to read and interpret the data both from left to right and from right to left. When read from left to right, the tool provides a sequential view starting from the TBL indicators across the sustainability pillars, followed by a further subdivision of their dimension. Conversely, reading from right to left allows users to trace the metrics back to the sector indicators, offering insights into how specific metrics relate to sector performance.

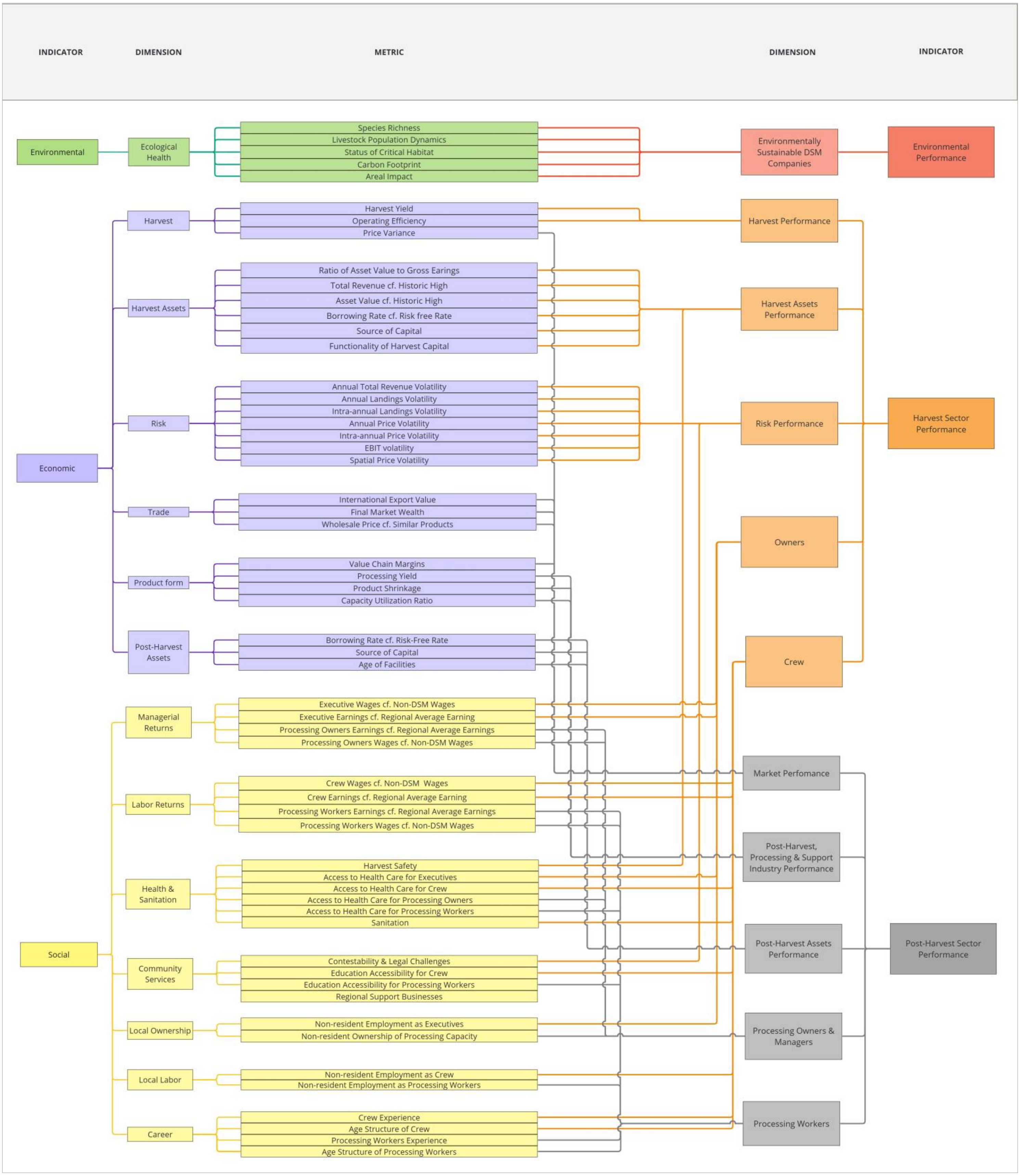

Figure 8 – DSM Performance Indicators

8 Discussion

The CBA and DSMPI tool used in this study provide a comprehensive framework to evaluate the potential impacts of DSM across the pillars of economic, environmental, and social dimensions. It is important to remember that the thesis is centered around a complex and evolving topic, where the situation is dynamic and constantly changing. Therefore, it is important to keep in mind that what is presented in the thesis will change in the future once new scientific research, regulatory policies, technological improvements, or stakeholder opinions become available. A way to think about the presented information is as a snapshot of the situation at the time of writing.

By providing both the DSMPI tool and the CBA, stakeholders and decision-makers gain insight into relevant negative and positive risks associated with DSM today, as well as have a tool that aids sustainable management for the future. By combining these methods, stakeholders can assess some potential pitfalls for the entire industry or specific companies. Additionally, they can measure how it will impact relevant indicators. All in all, the thesis provides some groundwork for deciding if a DSM industry can be viable in Norway.

CBA

The CBA reveals a nuanced picture of DSM, characterized by substantial potential benefits and significant risks. Economically, the industry promises job creation, revenue generation, and investment, particularly in coastal regions with existing and relevant infrastructure. Environmentally, it could offer a lower greenhouse gas emissions alternative to terrestrial mining, contributing to global emissions reduction targets. DSM could also reduce the need for terrestrial mining and lower the associated deforestation, soil erosion, and habitat destruction. Socially, it has the potential to supply minerals from non-conflict areas, enhancing ethical sourcing and reducing the risk of human rights abuses associated with terrestrial mining.

However, the analysis also underscores the high levels of uncertainty and potential negative impacts associated with DSM. Economically, the high operational costs and the possible cost of environmental compensation funds pose substantial downsides. Environmental impacts include significant habitat degradation, biodiversity loss, and long-term disruptions to marine life. Socially, potential income disparities, cultural disruptions, and reputational damage are critical concerns. Some of the groundwork prepared for the Norwegian government's impact assessment has been used for the benefits of the CBA, but it has been critically assessed in this thesis.

A major drawback to the benefits of DSM is that it will not necessarily impact terrestrial mines significantly. Terrestrial mining operations might continue with business as usual due to the established infrastructure, extensive experience, and ongoing demand for minerals. The existing market dynamics and the scale of terrestrial mining operations mean that DSM is unlikely to displace or substantially disrupt traditional mining activities (Gilbert, 2023; Priyanka, 2023). Instead, DSM may complement terrestrial mining by providing additional sources of critical minerals without altering the primary operations of established land-based mines (Ackerman, 2020). This undermines some of the anticipated environmental and economic benefits, as it might not reduce the worldwide mining environmental footprint or create a significant shift in the global supply chain dynamics.

The application of the precautionary principle, various international treaties, and designated safe zones presents challenges to the approval and implementation of DSM. Given the high levels of uncertainty and limited knowledge regarding the environmental and social impacts, regulators may impose stringent restrictions or bans to prevent potentially irreversible damage to marine ecosystems. Treaties such as the UNCLOS and the ISA Mining Code require rigorous environmental impact assessments and measures to minimize harm, aligning with the precautionary principle and potentially delaying or preventing DSM permits (Legrand et al., 2024, p. 22).

Moreover, designated safe zones like MPAs and areas of particular environmental interest further restrict available areas for DSM. These zones aim to preserve biodiversity and protect vulnerable marine habitats, adding regulatory complexity when DSM sites overlap with protected areas. The establishment of extensive MPAs, with buffer zones to protect ecosystems, highlights marine conservation commitments that could conflict with DSM interests (Legrand et al., 2024, pp. 7,24). As shown in Figure 6, there is a clear overlap between the proposed MPAs on the NCS and the area opened for DSM, an important challenge for policymakers to address.

The findings suggest that while DSM has potential, its successful implementation depends on addressing the high levels of uncertainty and negative risk. The limited *SoK* in many areas calls for comprehensive and long-term research to better understand the consequences on the economic, environmental, and social pillars. The current lack of data and high uncertainty make it difficult to adopt fully informed decisions. For future research, we recommend reassessing the risks of outcomes as new research in the field is added. In addition, the CBA assesses the risks with broad levels, aiming for accuracy in the analysis rather than precision. With more resources and data available, precision could be captured to a greater extent and could be complimented with a sensitivity analysis to find the most impactful outcomes.

DSMPI

While this thesis suggests that initiating DSM at the present time might be premature, it emphasizes the need to prepare for a future where the industry becomes operational. The thesis introduces the DSMPI tool, which offers guiding parameters for the industry. Measuring these parameters and metrics should give grounds for assessing the performance in all sustainability pillars of a DSM company/industry. Overall, DSMPIs could serve as a tool for measuring the performance of the DSM industry, both in Norway and worldwide. The metrics highlight aspects within the pillars that are viable for this emerging industry. It ensures that no single dimension is overlooked, offering an overview of the industry.

For policymakers, there is a clear need to develop robust regulatory frameworks that incorporate precautionary principles and adaptive regulations. These frameworks should be flexible enough to adjust to new information and changing conditions, ensuring sustainable growth for the industry. Continuous stakeholder engagement and transparent decision-making processes are necessary to gain broad acceptance and compliance (Menini et al., 2022, p. 1). Comprehensive environmental and social impact assessments have been shown to be promising tools for acknowledging the social and biophysical impacts of programs, and they could be crucial for the industry (Dendena & Corsi, 2015). Companies should prioritize sustainable practices and actively engage with local communities to address potential social disruptions and ensure equitable distribution of benefits.

The DSMPI can serve several roles and cater to various audiences. Harvesters and processors within DSM companies can utilize the indicators to compare their performance with similar companies globally, helping to identify specific sources of foregone wealth and establishing predicates for improvement. Suppliers and retailers engaged in international mineral trade can leverage the indicators to identify companies that are not only environmentally sustainable but also promote sustainable social practices. Additionally, the indicators offer a framework for investors and bankers to pinpoint companies with high potential for return and low risk associated with improper management or dysfunctional communities.

For international bodies, the indicators can help identify companies that are not meeting their potential, thereby providing insight useful for supporting local economic development. This support might improve standards of living or alleviate poverty. Research communities worldwide can use the tool to assess mining companies' impacts on the affected communities, environment, and economy.

One significant limitation is the lack of real-world case studies to test the tool on, as commercial DSM has not yet commenced. The robustness and applicability of the tool are, therefore, not validated. Given this, the initial application of the tool should be considered a preliminary step, requiring further testing and refinement. Moreover, this report does not look into input metrics, management approaches, and enabling factors due to time constraints. In the FPI study, these are included to help explain the variation among outcomes (Anderson et al., 2015, p. 2). Future research should focus on long-term environmental monitoring, detailed economic impact assessments, and thorough social evaluations. Furthermore, improvements can be made by examining the enabling factors of the industry. These factors can be utilized to connect different views of success with specific measures.

9 Conclusion

As of January 2024, the Norwegian government passed a bill to allow the exploration of minerals on the Norwegian continental shelf. The nascent DSM industry is expected to impact all three pillars of sustainability: environmental, economic, and social (Cardno, 2016). However, there remain large scientific gaps surrounding the field (Amon et al., 2022, p. 4).

In this thesis, a cost-benefit analysis is conducted to investigate the potential outcomes of DSM in Norway and to identify associated risks within these pillars. Our findings indicate that the negative risks of starting the DSM industry in Norway outweigh the positive risks. Although there are several positive outcomes linked to the industry, the current strength of knowledge is too weak. The uncertainty surrounding the potential benefits, due to limited real-world data and incomplete understanding of DSM's impacts, diminishes confidence in these positive outcomes. This highlights the need for further research to support more accurate risk assessments.

Furthermore, to ensure sustainable management within the pillars, we noted the dimensions that contribute insight into the effects of DSM on the triple bottom line. These dimensions were connected under the DSMPI tool, following a similar framework from another resource extractive industry, fisheries (Anderson et al., 2015).

Policymakers should consider the substantial uncertainties and potential environmental, economic, and social risks associated with DSM. Implementing the DSMPI tool could address some of these concerns by ensuring continuous monitoring of the industry, giving insights into their performance. Regulators could in this way adapt the regulatory frameworks to better ensure sustainable management.

The outcome of this study is constrained by the lack of relevant real-world DSM case studies. Future research should reassess the outcomes of the CBA as new data become available. If DSM operations commence, the reliability and accuracy of the DSMPI tool should be tested through practical case studies. This will allow testing the tool's robustness and determine whether it is a useful resource for evaluating the sustainability of DSM activities.

AI Disclosure

To write the thesis, we have utilized AI tools such as ChatGPT-4, Research Rabbit, and Grammarly for inspiration and writing suggestions. These tools have been used to refine the language, enhance clarity, and improve the overall structure of the document. AI was used critically as a tool, and we assessed all suggestions and made the final decisions regarding content.

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Appendices

Appendix A.1

Definitions of Deep-Sea Mining

Sea mining is the process of extracting resources from the ocean floor. The mining happens at the surface layer of the seabed which can be rich in mineral deposits (Chen et al., 2023, p. 276). In the literature, there is a vast range of terms used for underwater mining operations. There are several terms used to refer to mining activities in the ocean, including subsea mining, seafloor mining, seabed mining, ocean mining, offshore mining, and marine mining. However, there is a difference between these terms and deep-sea mining, as subsea mining may occur at any depth (Frimanslund, 2016, p. 1). For example, explorations and exploitations off the coast of Namibia are described as seabed mining and exist within the territorial sea (12 nautical miles) and in the Exclusive Economic Zone (EEZ, up to 200 nautical miles) from the West African country's coast – but these deposits are not deep (Chen et al., 2023, p. 276). Deep-sea mining refers to retrieving mineral deposits from the deep sea – the ocean below 200 m (IUCN, 2022).

Appendix A.2

Formation and Distribution of Polymetallic Nodules

Distribution

Polymetallic nodules cover vast areas of the seabed in several marine regions across the world, where occurrences of economic interest are found in deep basins of 3,500 to 6,500 m. Nodules can be found in all oceans, but only four regions have a great enough nodule density for industrial exploitation (World Ocean Review, 2014c, p. 67). The four regions are the CCZ, Peru basin, Penrhyn basin, and the Indian Ocean (World Ocean Review, 2014c, p. 67).

Formation

Polymetallic nodules are created in specific sedimentary and chemical processes that typically take place in the abyssal plains. In this environment the sedimentation rate is slow, in part because of its distance from land, and in part because of the low primary productivity[7].

The structure of a polymetallic nodule is typically layered like an onion (World Ocean Review, 2021, p. 155). Layers start to form when precipitation occurs concentrically around a pre-existing hard nucleus (e.g. shark tooth or lithic fragment) (Tilot et al., 2021, p. 620; World Ocean Review, 2021, p. 155). Nodules can be divided into three different groups depending on the origin of their materials. The precipitation of their constituent materials occurs from two

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[7] Primary productivity measures how fast photosynthetic producers convert energy (from the sun) to organic substances. Source: (Britannica, 2022)

sources: the water column above, or the interstitial (pore) water that circulates through the upper sediments of the seabed. Nodules formed by the overlying seawater are considered hydrogenetic nodules, while the latter is considered diagenetic (Verlaan & Cronan, 2022, pp. 6,7; World Ocean Review, 2021, p. 153). The third group, and the most common, is called "*mixed nodules*" or "*mixed hydrogenetic-diagenetic nodules*", and originate from both formation types (Cuyvers et al., 2018, p. 8; Verlaan & Cronan, 2022, p. 3). The different groups of nodules have different chemical compositions and accretion rates. Hydrogenetic nodules accrete at a rate of 1 - 10 mm per million years, while diagenetic nodules at 1 - 300 mm per million years (Tilot et al., 2021, p. 620; World Ocean Review, 2014c, p. 68).

Formation and Distribution of Cobalt-Rich Crusts

Distribution

Cobalt-rich crusts that have sufficient mineral content to have economic interest occur at depths between 800 - 2,500 m on seamounts and are estimated to cover an area of 1.7 million km^2 (Amon et al., 2022, p. 7; Hein, 2013, p. 8). About two-thirds of occurrences significant for mining are in the Pacific Ocean, 23 % in the Atlantic Ocean, and 11 % in the Indian Ocean (World Ocean Review, 2021, p. 155).

In the Norwegian context, suitable rock formations for CRCs are found in the majority of the deep-sea area of the NCS. These underwater formations can be found for 200 - 300 km on both flanks of the mid-Atlantic ridge. In addition, there are also prominent structures in the Vøring-ridge and the Jan Mayen-ridge (Meld. St. 25 (2022-2023), p. 24). The Norwegian government has estimated there to be over 226 megatons of metals in CRCs, with over 80 % of this being manganese, within their area of exploration for seabed minerals (Meld. St. 25 (2022-2023), p. 24).

Formation

CRCs form in a similar way to hydrogenetic polymetallic nodules, gaining most of their metals from the surrounding seawater column. However, unlike in the deep-sea flat plains, no sediments are deposited on the slopes of the seamounts (World Ocean Review, 2021, p. 154). A defining feature is the presence of strong currents carrying away the fine sediments and keeping the rock exposed (Hein, 2013, p. 9; MIDAS; World Ocean Review, 2014c, p. 76; 2021, p. 154).

CRCs are formed when metal ions in the water react with oxygen to create oxides, which get deposited on the surface of seamounts. These crusts can only form in areas where there's sufficient oxygen in the water (GEOMAR; World Ocean Review, 2014c, p. 76). However, there's a contradiction since the thickest CRCs are found in the water zone that has the least amount of oxygen. The oxygen minimum zone is at around 1,000 m depth with a range of several hundred meters (World Ocean Review, 2014c, p. 76). The zone is a result of bacterial breakdown of sinking dead biomass, a process that consumes oxygen. Because the water at this depth is not mixed by storms and waves, very little oxygen reaches it (Fauna & Flora International, 2020, p. 107; World Ocean Review, 2014c, p. 76).

The reason behind the formation is that in the oxygen minimum zone, the free metal ions tend to accumulate in the oxygen-poor water. However, at seamounts, oxygen-rich water flows up from the seabed, creating a mixing zone where metal oxides can form. Over time, these metal oxides precipitate on the rock surfaces and form crusts (GEOMAR; World Ocean Review, 2014c, p. 76). See Figure 9 for illustration of formation process.

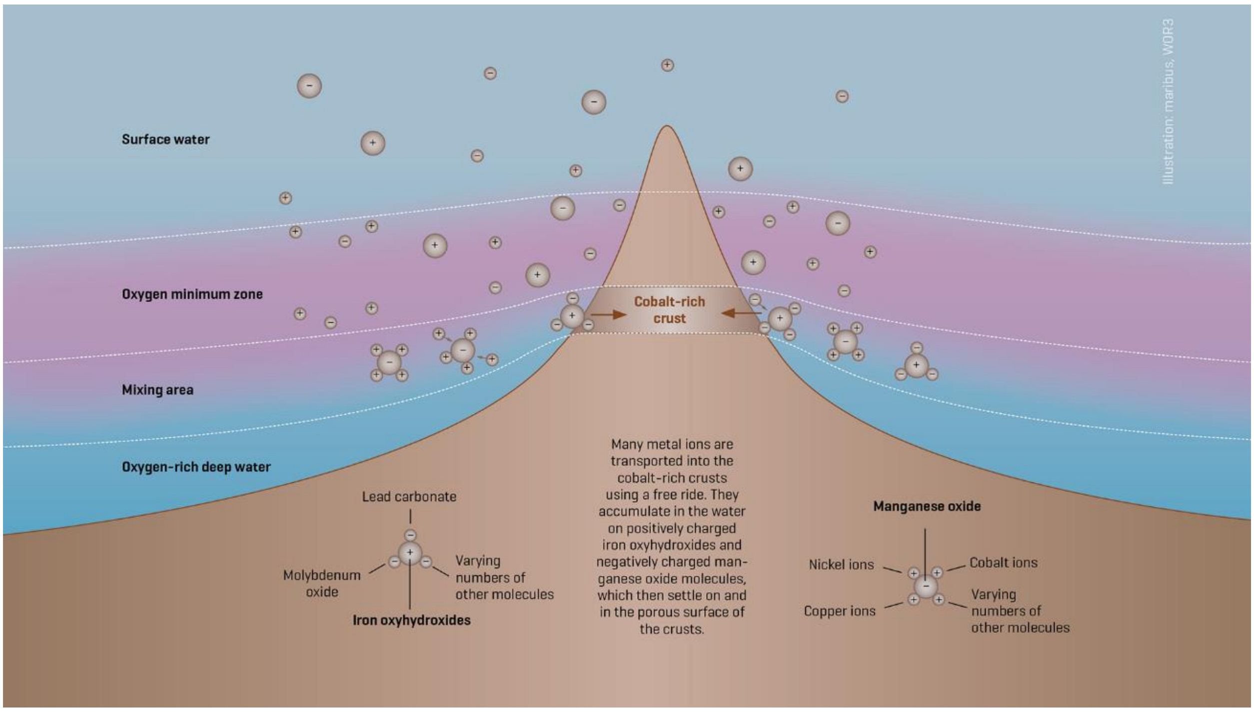

Figure 9 – Formation process of CRCs (GEOMAR)

Formation and Distribution of Seafloor Massive Sulfide Deposits

Distribution

Most seafloor massive sulfides can be found near mid-ocean ridges and back-arc basins, in water depths of 1,600 - 4,000 m (World Ocean Review, 2021, p. 155). Based on the current understanding of the formation of SMS deposits, two major regions have been identified as having the potential for commercially viable deposits. These areas are the western Pacific, which has many back-arc basins, and the slow-spreading Mid-Atlantic Ridge (Cuyvers et al., 2018, p. 12). Mining exploration contracts targeting sulfides have been granted in both of these regions (Amon et al., 2022, p. 5; Cuyvers et al., 2018, p. 12).

On the Norwegian continental shelf, several locations are prospective for SMSs. These include the Knipovich-ridge, Mohns-ridge, and the northern part of the Kolbeinsey-ridge (Oljedirektoratet, 2023, p. 28). There are nine proven occurrences of SMSs in the Mohns-ridge, however, there is expected to be twice the amount along this ridge (Oljedirektoratet, 2023, p. 39).

SMSs are generated at active hydrothermal vents and are retained at inactive or extinct vents after hydrothermal activity ends. At extinct vents, hydrothermal activity has permanently stopped, whereas at inactive vents the cease in activity is temporary. It can be difficult to classify these vents, as conclusions of inactivity can be premature (Amon et al., 2022, p. 5). Worldwide, it is believed to be more inactive sites than active sites, but these are much more difficult to find (SPC, 2013, p. 11; World Ocean Review, 2021, p. 156).

Formation

There are conflicting views on the formation rate of SMSs in scientific literature. Some researchers state that SMS deposits require a hydrothermal system ranging in timescales from several million to several hundred million years to form (Tilot et al., 2021, p. 623). Others claim that the lifespan of hydrothermal systems that form SMSs is around 50,000 years, after which the magmatic heat-source migrates or the deposition field is covered by a lava-flow (Bang & Trellevik, 2022, p. 6).

They form as the result of seawater circulating through the upper three kilometers of the seabed. The seawater is then heated by a heat source, such as a magma chamber, and transformed into a hot (around 400 ℃), acidic, and highly concentrated solution. This solution then dissolves metals from the volcanic rocks surrounding it. Due to the lower density of the now metal-enriched water, it rises rapidly to the sea floor. Most of it is expelled into the water column above as a focused flow at chimney vent sites. When the water eventually reacts with the cold seawater, the dissolved metals are precipitated as metal sulfides, producing black and white smoker chimneys (SPC, 2013, p. 8; World Ocean Review, 2021, pp. 155,156). Figure 10 below illustrates the formation process of SMSs.

When the chimneys reach a certain height, at times more than 30 meters, it collapses over itself. Another chimney then starts to form, and the process is repeated. As a result, sulfide mounds are formed at the seafloor, sometimes several hundred meters wide and several tens of meters thick (Cuyvers et al., 2018, pp. 11-12; World Ocean Review, 2021, p. 156).

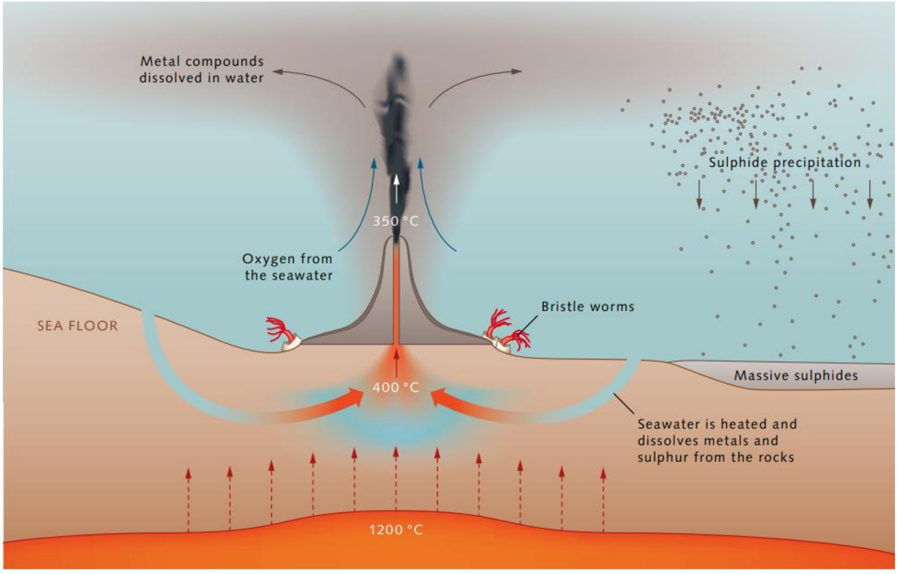

Figure 10 – Formation process of SMSs (World Ocean Review, 2014c, p. 83)

Appendix B.1

Full tables CBA

Environmental Benefits

ENVIRONMENTAL										
Stakeholders	Outcome	Scale of Outcome	Duration of Outcome	Certainty	Positive Consequence	Strength of Knowledge	Positive Risk	Risk Score	Comment	Sources
Harvest Sector	The transition from terrestrial mining to DSM is projected to lower the overall GWP.	International	Long term	Low	High	Low	Low	1.14	It is estimated that the CO2-equivalent emissions related to extracting minerals from DSM can be as low as ¼ compared to terrestrial mining. However, there are few estimates and large discrepancies among them.	(Paulikas et al., 2020, pp. 10 -11; Planet Tracker, 2023)
	Compared to nodule mining, CRC and SMS extraction plumes will be more localized.	National	Program duration	Medium	High	Medium	Medium	2.28	Studies suggest the horizontal spread of plumes from SMS and CRC mining will be less extensive.	(Fauna & Flora, 2023)
Norwegian Government	Facilitates the transition to a low-emission society by increasing the availability of minerals essential for low-carbon technologies, thereby supporting the Government in achieving its emissions goals.	National	Long term	Medium	High	Low	Low	1.96	Norway's target is to reduce emissions by at least 55% by 2030. The increase in mineral supply can further boost the production of low-carbon technologies, making them more accessible to Norwegian citizens and aiding the transition to a low-emission society	(Statsministerens kontor, 2022).

Norwegian Citizens	Shifting some mining activities to the seabed reduces the physical footprint and associated environmental degradation of terrestrial mining operations within Norway.	National	Program duration	Low	Medium	Low	Low	1.01	If the minerals can be extracted from DSM, it may reduce the demand for terrestrial mines on land in Norway. An example could be the planned "Norge Mineraler" mine in Rogaland, covering over 32 square kilometers and affecting 204 landowners. Several more mines are proposed on Norwegian land, some mining the same minerals targeted with DSM.	(Bogen & Høyland, 2024)
Post-Harvest Sector	Easier access to minerals extracted with a low carbon output.	International	Program duration	Medium	High	Low	Low	1.84	As stated, it is estimated DSM may have a lower carbon output than terrestrial mining. If DSM starts, it enables the post-harvest sector to buy minerals with a lower carbon output.	(Chung et al., 2023; Paulikas et al., 2020; Planet Tracker, 2023)
	The increased availability of DSM-derived minerals could stimulate demand for metallurgical processing in countries prioritizing low-carbon industrial practices, such as Norway.	International	Program duration	Low	High	Low	Low	1.01	70 – 85 % of the total climate impact from the value chain of metals comes from metallurgical processing which is the same for both terrestrial and DSM. Initiating DSM in Norway, which has a relatively large focus on low-carbon solutions, might increase the demand for metallurgical processing with lower emissions. Currently, there is little evidence for this.	(Planet Tracker, 2023) (Lyle, 2023)
Competing Industries	An increase in R&D can provide technologies that have lower emissions, which could be	International	Long term	Low	High	Low	Low	1.14	R&D in DSM might produce technologies with a lower carbon output that could be applicable for terrestrial mining.	(Levin et al., 2020)

	applicable to other industries.									
	If Norway becomes a large-scale mineral exporter, it could set a precedent, encouraging the international terrestrial mining industry to adopt similar standards.	International	Long term	Medium	High	Low	Low	1.96	If Norway become a large-scale mineral exporter, it could pressure the international mining sector to adopt more environmentally friendly practices. Either directly by offering reduced emissions linked to mineral extraction or indirectly by setting regulatory precedence for emission	(EY, 2022)
	DSM could pressure the of metallurgical processors to reduce their GWP, as it is a major contributor in the mineral value chain.	International	Long term	Low	High	Low	Low	1.14		Authors judgment
International Governments	DSM activities necessitate further scientific research on deep-sea ecosystems, potentially advancing understanding and contributing valuable knowledge to global environmental science.	International	Long term	High	High	Low	Medium	2.53	A representative for the Norwegian government states that DSM at this stage involves research and exploration of deep-sea habitats, that will increase our understanding of them. The plan is to get more information before exploration commences	(Brembo et al., 2023)

	By decreasing the need for terrestrial mining, DSM can help reduce deforestation and associated habitat destruction.	International	Program duration	Low	High	Low	Low	1.01	If terrestrial mining is replaced with DSM, it will reduce deforestation from terrestrial mining-related activities. There is little evidence to suggest this will happen.	(Amadi & Mosnier, 2023)

Economic Benefits

ECONOMIC										
Stakeholders	Outcome	Scale of Outcome	Duration of outcome	Certainty	Positive Consequence	Strength of Knowledge	Positive Risk	Risk Score	Comment	Sources
Harvest Sector	The initiation of the DSM industry in Norway is likely to attract foreign investments by offering new opportunities for resource extraction. Coupled with Norway's robust and stable financial market, these opportunities can appeal to international investors.	National	Program duration	Medium	High	Medium	Medium	2.23	Access to capital is necessary for any project and Norway has different public funding schemes for the industrial sector. This in combination with robust and liquid financial institutions can lower the barrier of entry for possible companies.	(Norwegian Ministry of Trade, 2023, p. 45)
	Companies will operate in an environment with higher ore grades than terrestrial mining, resulting in more efficient extraction processes and lower costs per unit of mineral.	National	Program duration	Medium	Medium	High	Medium	2.71	The ore grades in the deep sea are measured to be much higher than that of terrestrial mining today.	(Green Minerals, 2020; Rystad Energy, 2020, p. 21

	By leveraging Norway's existing infrastructure from the maritime industries, the capital expenditures for establishing a new industry can be significantly reduced.	Local	Program duration	High	High	Medium	High	2.85	The oil and gas, shipping, and fishing industries all have existing infrastructure and a workforce with extensive experience from the NCS allocated along the coast. This could significantly reduce the capital expenditures of establishing a new industry. EY had talks with various technology and innovation clusters spread out in Norway who were very positive about facilitating the industry.	(EY, 2022, pp. 19 - 21) (Asplan Viak, 2022, p. 39).
	With many firms facing resource scarcity, DSM could offer a solution by providing a fresh supply of critical minerals.	International	Program duration	High	High	High	High	3.29	ABB did a survey with 3, 304 respondents around the globe, where 91 % said they are experiencing resource scarcity.	(ABB, 2024, p. 6).
	Enables harvest companies, shareholders, and members of the supply chain to earn profits on the minerals sold.	Local	Program duration	High	High	High	High	3.29		(Levin et al., 2020)
Norwegian Government	Leveraging the experienced local workforce accustomed to working with the NCS minimizes the need for outsourcing and retains more	National	Long term	High	Low	Low	Medium	2.04	The oil and gas, shipping, and fishing industries all have existing infrastructure and a workforce with extensive experience from the NCS allocated along the coast. This could significantly reduce the capital expenditures of establishing a new industry. EY had talks with various	(EY, 2022, pp. 19 - 21; Rystad Energy, 2020, p. 39)

	economic value within the country.								technology and innovation clusters spread out in Norway who were very positive about facilitating the industry	
	Revenues generated from taxes, royalties, and licenses on DSM activities can increase financing for the welfare state.	National	Program duration	High	High	High	High	3.29		(Levin et al., 2020)
	Economic diversification resulting from DSM can provide the government with additional revenue streams, enhancing financial stability.	National	Program duration	High	Medium	High	High	3.29		(Levin et al., 2020, p. 7)
Norwegian Citizens	An increase in jobs directly related to DSM can have a positive ripple effect on the economy, stimulating demand for local services such as barbers and restaurants.	National	Program duration	Medium	High	Medium	Medium	2.3	Financial investments in an industry are bound to have an economic multiplier effect, where the DSM industry can stimulate economic growth in related sectors such as equipment supply and increase demand for local services such as barbers	(Asplan Viak et al., 2022, p. 38; Cardno, 2016).
Post-Harvest Sector	Investments in the harvest sector can stimulate demand for logistics and supply chain services, leading	International	Program duration	High	Medium	Medium	High	2.85		(Asplan Viak et al., 2022; Levin et al., 2020)

	to increased investments and employment opportunities in the post-harvest sector.									
Competing Industries	Unsuccessful DSM ventures can make terrestrial mining appear as a safer investment.	International	Program duration	Medium	High	Low	Low	1.84	An example of an unsuccessful venture is the Solwara 1. Similar projects can deter investments from DSM, and investors might look at other investment opportunities more favorably. The source advocates that financial institutions should stay away from experimental DSM projects.	(BankTrack)
International Governments	Increased supply of minerals may lead to lower mineral prices, benefiting global consumers.	International	Program duration	Medium	High	Low	Low	1.84	With demand being the same and with increased supply the expected effect on price is that it will be lower.	Authors judgment
	Diversification of the mineral supply chain reduces the risk of price squeeze providing stability and economic benefits on a global scale.	International	Program duration	Medium	High	Low	Low	1.84	If Norway can provide a steady and enhanced supply of critical materials it can undermine the global pressure preventing or blocking access to materials. Major countries and the EU are trying to position themselves strategically to deal with uncertainty relating to access to raw materials	(Norwegian Ministry of Trade, 2023, p. 19)

Social Benefits

SOCIAL										
Stakeholders	Outcome	Scale of Outcome	Duration of outcome	Certainty	Positive Consequence	Strength of Knowledge	Positive Risk	Risk Score	Comment	Sources
Harvest Sector	The sector can leverage expertise from Norway's existing maritime industry to enhance operational efficiency.	National	Program duration	High	High	Medium	High	2.85	As stated under economic benefits, Norway can build on its extensive experience in the maritime industry, particularly in oil and gas, fishing, and shipping. These industries can provide a solid foundation with their established coastal facilities, supply bases, and workers	(EY, 2022, pp. 19 - 21) (Rystad Energy, 2020, p. 39).
	The industry can increase workplaces, providing job opportunities and improving local employment rates.	National	Long term	High	High	High	High	3.41	There are expected to be 21,000 new jobs related to the DSM industry	(Lorentsen, 2020)
	Norway's sustainability standards provide an opportunity for workers in the mineral industry as they can benefit from these standards, enjoying higher health and safety measures compared to	International	Program duration	High	High	Medium	High	2.85		(Norwegian Ministry of Trade, 2023)

	those in international terrestrial mining.									
	A stable regulatory framework in Norway ensures predictability for DSM companies.	National	Program duration	High	High	Medium	High	2.85	Norway has extensive experience in deepwater operations acquired over decades of offshore activity, coupled with a stable regulatory framework. These factors position the NCS as a globally competitive area for DSM.	(Green Minerals)
	Norwegian companies can create an expertise in CRC and SMS extraction as the global focus has primarily been on nodules.	International	Long term	Medium	High	Low	Low	1.96	Among the three types of mineral deposits considered for deep-sea mining, CRCs have received the least attention in terms of scientific study. Globally, only a small percentage of total large seamounts (over 1,000 m in height) have been directly sampled for scientific purposes, with the range falling between 0.4 – 4 % (or 200 - 300 globally) (Amon et al., 2022, p. 7). In the NCS the expected mineral deposits are SMS and CRC. Globally, the technology for extracting these deposits is underdeveloped, as the world has focused on nodules. This could provide possibilities for Norway to develop expertise that could be valuable around the world	(Asplan Viak et al., 2022, pp. 55 - 58). (Amon et al., 2022, p. 7).
Norwegian Government	The industry can contribute to increased knowledge of the deep sea for research institutions and	National	Long term	High	High	Low	Medium	2.54	This can be achieved through research centers, technology clusters, and specialized university programs, strengthening Norway's position in the global maritime and mining industries	Authors judgment

	enhance scientific understanding.									
Norwegian Citizens	A strategic establishment of facilities and research centers can be used to help towns and communities create a local industry.	Local	Program duration	Low	Low	Low	Low	1.26	Establishing facilities related to DSM and research centers can be used strategically to help local towns and communities become hubs for innovation and development	(Asplan Viak et al., 2022, pp. 21 - 23).
	It enables Norwegian companies to be at the forefront of research and development for technologies to be used in the industry and beyond.	National	Long term	High	Medium	Low	Medium	2.54	In the NCS the expected mineral deposits are SMS and CRC. Globally, the technology for extracting these deposits is underdeveloped, as the world has focused on nodules. This could provide possibilities for Norway to develop expertise that could be valuable around the world	(Asplan Viak et al., 2022, pp. 55 - 58).
	The development of DSM in Norway has the potential to create technical and skilled job opportunities for local communities, attracting specialized workers and their families, while also incentivizing locals to stay.	National	Program duration	High	Medium	Medium	High	2.85	This approach can help in attracting specialized workers and their families, while also providing incentives for locals to remain in the communities. This can lead to direct benefits, as individuals will experience greater purchasing power, as well as indirect benefits through the increased demand for supplies from subcontractors. Additionally, this can also lead to consumer effects, as people will use their salaries to purchase goods and services.	(Asplan Viak et al., 2022, pp. 21 - 23).

	Based a history of successful and effective resource management from Norway's oil and gas industry, the country is well-positioned to ensure that the financial benefits from the DSM industry are shared equitably among its citizens and preserved for the future.								Norway have previously avoided the “resource curse” with Oil and Gas, and using the existing framework for equitable distribution of wealth can benefit the industry. The source speaks to the problem of the resource curse.	(Levin et al., 2020; Meld. St. 25 (2012–2013))
	More job opportunities and higher paygrades for regional support businesses can increase monetary circulation and stimulate local businesses.	Local	Program duration	High	High	Low	Medium	2.41	This can attract specialized workers and their families while also incentivizing locals to stay. This can lead to direct impacts as people experience a higher purchasing power, and indirect impacts by an increased demand for supplies from subcontractors. All of which can have ripple effects on the economy and have a positive effect on areas that might otherwise face decline	(Asplan Viak et al., 2022, pp. 21 - 23).
	The industry can create a demand for relevant educational programs.	International	Long term	High	Medium	Low	Medium	2.53		Authors judgment
	Funds generated from DSM can be used to improve national	National	Long term	High	High	Low	Medium	2.41		Authors judgment

	infrastructure, education, and healthcare services, thereby enhancing the overall quality of life in Norway.									
Post-Harvest Sector	The industry can increase the demand for local skills and expertise in the post-harvest sector, providing job opportunities and fostering skill development.	National	Program duration	High	High	Medium	High	2.85		(EY, 2022)
	The post-harvest sector could gain easier access to high-value minerals	International	Program duration	High	High	Medium	High	2.85		Authors judgment
	Increased access to minerals harvested in a socially responsible manner, reducing reliance on conflict minerals from politically unstable regions plagued by issues such as child labor and ethnic conflicts.	International	Program duration	High	High	Medium	High	2.85	The world's largest suppliers of cobalt and copper face significant ethical and humanitarian challenges. By developing its own DSM industry, Norway could provide a stable and ethical supply of these critical minerals, supporting global sustainability and ethical practices DSM can provide materials needed for renewable energy infrastructure, reducing reliance on conflict minerals from politically unstable regions plagued by issues like child labor and ethnic conflicts.	(Rystad Energy, 2020, pp. 17 - 21). (Norwegian Ministry of Trade, 2023)

Competing Industries	There is expected to be some technological overlap between DSM and terrestrial mining, with similar equipment being used.	International	Program duration	Low	Medium	Low	Low	1.01	There can be an overlap of subcontractors and special equipment previously used for terrestrial mining, whereby terrestrial mining companies can sell equipment and have an available workforce for both, at least in the short term.	(Jones, 2023, p. 10)
	DSM can lead to an expertise shift and expansion of the mining workforce, broadening the skillset and experience of workers in the mining sector.	International	Long term	High	High	Low	Medium	2.54		Authors judgment
International Governments	DSM can mitigate dependence on a limited number of countries for access to critical minerals, enhancing global supply chain stability and security.	International	Program duration	High	High	High	High	3.29	Norway could provide a supply of these minerals, reducing reliance on a few current countries	(Rystad Energy, 2020, pp. 17 - 21). (Norwegian Ministry of Trade, 2023)
	The DSM industry is expected to have little direct impact on freshwater,	International	Program duration	High	High	Low	Medium	2.41		(Paulikas et al., 2020, p. 4)

	unlike terrestrial mining.									
	The Norwegian framework can be used to create intergenerational equity from non-renewable resources and avoid the resource curse.	International	Long term	Low	High	Low	Low	1.14	The ISA can use the Norwegian model of a sovereign wealth fund to ensure that the non-renewable resources can benefit future generations as well. Propper and sustainable managed wealth can improve living standards and create economic opportunities for both current and future generations. The source speaks to the importance of sustainable and transparent management of a sovereign wealth fund and the complexities of implementing it.	(Ovesen et al., 2018)
	Research associated with DSM can increase understanding of genetic resources with potential for pharmaceutical use.	International	Long term	Low	High	Low	Low	1.14		(Levin et al., 2020)

Environmental Costs

ENVIRONMENTAL										
Stakeholders	Outcome	Scale of Outcome	Duration of outcome	Certainty	Negative Consequence	Strength of Knowledge	Negative Risk	Risk Score	Comment	Source
Harvest Sector	Restoration efforts are unlikely to accurately replicate disrupted habitats, leading to a net loss of biodiversity.	National	Long term	High	High	Medium	High	2.97	Given the complexity of deep-sea ecosystems and our limited understanding of the interdependencies between species, achieving “like for like habitat restoration” can be difficult. This challenge is compounded by a lack of data and proven methods for effective restoration. Efforts to restore biodiversity might not accurately replicate the ecological characteristics and functions of habitats disrupted by DSM, leading to irreversible damage and a net loss of biodiversity.	(Niner et al., 2018, p. 7)
	Removing CRCs over a large area will have significant and long-lasting environmental impacts, affecting vulnerable hard-bottom fauna and local ecosystems.	National	Long term	High	High	High	High	3.41		(Koschinsky et al., 2018, p. 677; Miljødirektoratet, 2023, pp. 7 - 8)
	Noise from DSM operations can disrupt marine life and lead to changes in	International	Program duration	High	High	High	High	3.03	Many species rely on sound and vibrations in the absence of sunlight, making them potentially vulnerable to noise from human activities.	(Williams et al., 2022)

	behavior. Most deep-sea species have yet to be described, and sensitivities to noise have not been studied, leaving a gap in our understanding of their responses.									
	Light pollution can occur where no natural light sources exist or where natural light is much weaker, potentially having a negative impact on deep-sea life.	International	Program duration	High	High	High	High	3.03	Light pollution occurs where no natural light sources exist or where natural light is much weaker. There can be taken steps to reduce the light emission, but it is unlikely to be completely avoided. The impact this will have on marine life is unclear	(Leal Filho et al., 2021)
	The mining of active SMS deposits will significantly impact unique environments and lead to the loss of species that are dependent on these habitats.	National	Long term	High	High	High	High	3.41	Mining will most likely not occur at these deposits.	(Koschinsky et al., 2018, pp. 677 - 678; Miljødirektoratet, 2023, pp. 7 - 8)
	Mining inactive SMS deposits can considerably	National	Long term	High	Medium	High	High	3.41	Inactive SMSs are considered less critical to the local ecosystem, especially if they only host soft bottom fauna. Recently, however,	(Koschinsky et al., 2018, pp. 677 - 678;

	impact unique environments and lead to the loss of species that are dependent on these habitats.								inactive vents have been considered to host a different set of sediments and need to be assessed closer to understand the potential impact they might have on life around them. Assessing the difference between inactive vents and dormant vents is considered to be quite a challenge.	Miljødirektoratet, 2023, pp. 7 - 8)
	The spread of particles and toxic metals from DSM activities can have a negative environmental impact, harming marine life and ecosystems.	International	Program duration	High	High	Medium	Medium	2.6		(Filho et al., 2021; Miljødirektoratet, 2023, pp. 7 - 8; Niner et al., 2018, p. 4)
	The spread of plumes can negatively impact marine life by creating a “blanket” of sediments in areas around the mining field, potentially burying benthic organisms and clogging the respiratory surfaces of filter feeders.	International	Long term	High	High	Medium	High	3.03	Environmental concerns regarding sediment removal and discharges from DSM are centered on the re-deposition of these sediments from the plume, as it can create a cover of sediments in areas surrounding the mining field. This can bury benthic organisms and clog the respiratory surfaces of filter feeders. The plumes could contain toxic substances, reduced metals, and unstable organic matter, leading to oxygen depletion. Furthermore, there are concerns about their effects on midwater fauna.	(Fauna & Flora International, 2020; Filho et al., 2021)
Norwegian Government	Disrupting benthic organisms and	International	Long term	High	High	Medium	High	2.97	Some deep-sea sediments act as a carbon sink. Certain benthic organisms regulate organic	(Cardno, 2016; United Nations Environment

	sediment-dwelling bacteria can affect climate processes, potentially exacerbating climate change impacts.								decomposition, influencing CO2 sequestration and water purification.	Programme Finance Initiative, 2022)
	Ineffective ecological compensation can lead to non-compliance with UNCLOS obligations.	International	Long term	Medium	High	High	High	2.83	The UNCLOS states that nations exploring DSM in their jurisdiction have to follow no less stringent rules and regulations, than they provide	(Advokatfirmaet Wikborg Rein, 2023) (Levin et al., 2016)
	The impact assessment performed by the government is lacking nuanced perspectives on negative risks. This can enable the premature start of the industry and would be in breach with the precautionary principle.	National	Program duration	High	High	High	High	3.03	The Norwegian Environment Agency states that allowing for exploitation of minerals based on the current impact assessment would breach with the precautionary principle	(Miljødirektoratet, 2023)
	There could be an overlap between MPAs and the area opened for DSM activities.	National	Program duration	High	High	Medium	Medium	2.6		(Legrand et al., 2024)

	DSM activities could lead to a loss of transit routes and habitats for slow-moving pelagic seabirds, potentially leading to declines in their populations.	National	Program duration	Medium	Medium	Low	Low	1.58	There could be established resource bases on land that could disturb the habitats of the birds, furthermore some of their transit routes are expected to overlap with the proposed area	(Rystad Energy, 2020; Strøm et al., 2021)
Norwegian Citizens	DSM could impact the migration patterns of fish.	International	Program duration	Medium	High	Low	Low	1.58	Due to increased sea temperatures, species are migrating northwards. In the CCZ, new migration patterns for fish have been reported, driving them into the deeper part of the CCZ, which overlaps with the proposed mining area, possibly affecting the fishing industry.	(Matthijsen et al., 2018) (Yirka, 2023).
Post-Harvest Sector	No evidence was found supporting significant outcomes.									
Competing Industries	No evidence was found supporting significant outcomes.									
International Governments	DSM can undermine the shift to a circular economy by reducing	International	Program duration	High	High	Medium	Medium	2.6	Supporting the transition toward a circular economy Promoting efforts toward a circular economy such as increased recycling and the reuse of components from products at the end of their life cycle, ensuring that raw materials are fed back into the	(United Nations Environment Programme Finance Initiative, 2022) (EJF, 2024)

	incentives to invest in recycling and sustainable resource management.								economy. Can lead to reducing current mineral demand and setting us on a path to a sustainable, circular resource economy.	
	The impact assessment lacks sufficient attention to potential transnational impacts.	International	Program duration	Medium	Medium	Low	Low	1.58	Norway is required to notify neighboring states about possible transboundary impacts through certain conventions. Giving notification based on a lacking impact assessment can be in conflict with the conventions intention.	(Advokatfirmaet Wikborg Rein, 2023)
	Carbon is sequestered and stored in seafloor sediment. Mining operations could risk releasing this carbon back into the ocean and the atmosphere.	International	Long term	Medium	High	Low	Low	1.96	DSM activity can disturb the carbon sequestering process, negatively affect climate change, and increase ocean acidification.	(Cherry, 2024)

Economic Costs

ECONOMIC										
Stakeholders	Outcome	Scale of Outcome	Duration of outcome	Certainty	Negative Consequence	Strength of Knowledge	Negative Risk	Risk Score	Comment	Sources
Harvest Sector	An environmental compensation fund can be necessary to establish to cover the fees of restoring deep-sea ecosystems.	National	Long term	Medium	Medium	Low	Low	1.96	If Norway empose a similar approach as the ISA to govrenannce, they could implement an environmental compensationfund to restore potential disturbances caused. It is however, unlikely that the fund as proposed by the ISA will actually cover the restoration costs. There has been assessments made on restoring nodule sites with artificial nodules, that have estimated a higher cost of restoration than expected revenue per km^2 If implemented it would impose financial burdens on the harvest sector due to contributions required for the fund.	(Amadi & Mosnier, 2023)
	Changes in technology could lower the demand for certain minerals from DSM, impacting the economic viability of mining projects.	National	Program duration	Medium	High	Low	Low	1.58	Changes in technology could reduce demand for certain DSM minerals. An example is the change to LFP EV batteries, which do not require expensive cobalt and nickel.	(EJF, 2024; Frik, 2024)
	Prospecting and exploration costs.	Local	Program duration	High	High	Medium	Medium	2.6	USD 20 million	(Ma et al., 2022)

	Development costs.	Local	Program duration	High	High	Medium	Medium	2.6	USD 1 billion to manufacture (capital cost)	(Ma et al., 2022)
	Mining and extraction costs.	Local	Program duration	High	High	Medium	Medium	2.6	<USD 1 billion per year (operation cost)	(Ma et al., 2022)
	Closure and reclamation costs.	Local	Program duration	High	High	Low	Medium	2.16	Unknown economic costs	(Ma et al., 2022)
	Higher recycling rates from various materials could decrease the demand for newly extracted minerals, thereby affecting the economic viability of DSM projects.	International	Program duration	Medium	High	Medium	Medium	2.05	Point N in the EU resolution argues that we should be less dependent on raw materials and we can meet demand through other forms, such as substitution of materials, recycling, and various circular economy measures. Another approach to closing the demand gap is considering other supply sources, which could be moving to a circular economic model or an increased degree of recycling. It is projected that technological development, circular economic strategies, and recycling could reduce cumulative mineral demand by 58 % between 2022 and 2050	(Bentele et al., 2024; EJF, 2024)
	Extracting the same minerals with DSM can come at a higher cost than terrestrial mining.	International	Program duration	High	High	Medium	Medium	2.6	The Norwegian Environmental Agency says that minerals. The future cost landscape is uncertain and will depend on technological advancements. Consequently, substantial investment will likely be required to develop adequate extraction technology, a topic that is only briefly touched upon in the impact assessment.	(Miljødirektoratet, 2023)

	Several banks and financial institutions have distanced themselves and stated that they will not invest in the DSM industry.	International	Program duration	High	High	High	High	3.03	Outside the automotive industry, some financial institutions have expressed their support for a DSM moratorium or have explicitly distanced themselves from investing in the DSM industry. This includes banks and financial institutions such as Storebrand, ABN AMRO, BBVA, Cooperative Bank, Lloyds Banking Group, NatWest (previously Bank of Scotland), Standard Chartered Bank, Triodos Bank, and the European Investment Bank.	(Deep Sea Conservation Coalition, 2024)

	There is expected to be great variation in mineral contents on the NCS which can reduce the economic viability of projects.	National	Program duration	Medium	Medium	Medium	Medium	2.02	By looking at analysis made by the Norwegian Petroleum Directorate, Swedish, and Russian researchers on SMS and CRC shows that there is a high variation in minerals, and some samples suggests that it is lower metal content than what is considered viable for terrestrial mines.	(Miljødirektoratet, 2023)

	Several large companies have stated that they will not buy deep-sea minerals themselves or allow them in their product value chain.	International	Program duration	High	High	High	High	3.03	A strong signal that DSM is unnecessary comes from the sector that is expected to need a surge in metals. EV manufacturers such as BMW Group, Renault Group, Rivian and Volkswagen Group have all committed not to use Deep Sea Metals in their production chain and have stated their support for a DSM moratorium There are also companies that have expressed their support for a DSM moratorium or have explicitly distanced themselves from deep-sea metals. These include tech companies like Google, Samsung SDI, and Philips.	(Deep Sea Conservation Coalition, 2024)
Norwegian Government	If the restoration costs of DSM are higher than the mining company can afford, the government may need to subsidize some of the costs.	National	Program duration	Low	High	Low	Low	0.76	Linked to an earlier point, maybe the government has to provide subsidies to achieve a worthy restoration.	(Amadi & Mosnier, 2023)
	Engaging in or regulating DSM operations that results in financial loss or third-party harm can incur costs for the state.	National	Program duration	Medium	High	Low	Low	1.58	Papua New Guinea said it was unlikely that their joint venture in Solwara 1 project was set to turn out net positive for the government, as Nautilus Minerals went bankrupt	(DSM Observer, 2018)

	Adopting the Norwegian Petroleum Tax System for DSM can impose a high tax burden, impacting projects' economic feasibility.	National	Program duration	Medium	Medium	Low	Low	1.58	The Norwegian Government has proposed to use a similar tax regime to that of the petroleum industry. Which can impact the profitability of mining operations	(Finansdepartementet, 2022) (Jonsbråten & Minge, 2023)
Norwegian Citizens	Disruptions to fishing in proximity to the mining site can lead to losses for the fishing industry	National	Program duration	Medium	High	Low	Low	1.58		(Koschinsky et al., 2018)
	Investors can experience economic losses by investing in unsuccessful companies.	International	Program duration	High	Medium	Low	Medium	2.16	As Nautilus Minerals went into administration, there are expected to be some financial losses for its investors, such as the Papua New Guinea government	(DSM Observer, 2018) (BankTrack)
Post-Harvest Sector	The post-harvest sector could incur economic losses from relying on minerals from a new industry with a potentially unstable supply.	International	Program duration	Low	High	Low	Low	0.76		Authors judgment
Competing Industries	DSM could have a lower carbon output, deterring investments in terrestrial mining.	International	Program duration	Medium	High	Low	Low	1.58	The source shows some examples for GWP for terrestrial and deep sea mining	(Paulikas et al., 2020)

	Increased supply of metals from DSM could lead to lower prices and increased competition for land-based mining industries.	International	Program duration	Medium	High	Low	Low	1.58		Authors judgment
	There can be a lower incentive to invest in efforts to reduce terrestrial mining impacts.	International	Program duration	Medium	High	Low	Low	1.58		Authors judgment
	The terrestrial mining industry may incur costs trying to adapt to the ethical standards set by DSM	International	Long term	Low	Low	Low	Low	1.38		Authors judgment
International Governments	A focus on DSM could lead to a lack of investment in recycling and efforts for a circular economy.	International	Program duration	Medium	Medium	Low	Low	1.58	Investing in efforts to close the lifecycle loop for minerals is an effective way to address the growing demand. Specifically, investing in circular economy initiatives offers a practical and viable solution.	(United Nations Environment Programme Finance Initiative, 2022)

Social Costs

SOCIAL										
Stakeholders	Outcome	Scale of Outcome	Duration of Outcome	Certainty	Negative Consequence	SoK	Negative Risk	Risk Score	Comment	Source
Harvest Sector	An uproar from protestors may hinder the implementation of the industry.	National	Program duration	High	High	Low	Medium	2.16	Currently, over 2 million people are calling governments to vote for a moratorium on the industry. Protesters have already been taken to court for delaying DSM operations.	(Greenpeace International; Young)
	Mapping and investigating deep-sea environments is challenging and costly, requiring resource allocation to protect critical areas.	Local	Program duration	High	Medium	High	High	3.03	Mapping deep-sea areas is difficult and expensive, and it is important to obtain sufficient knowledge to protect vulnerable areas. MAREANO is recommended to be given national responsibility for the mapping, with the necessary resources prioritized corresponding to those used for investigations of mineral resources.	(Miljødirektoratet, 2023, p. 14)
Norwegian Government	There is a need to develop and enforce legal and regulatory frameworks to manage environmental impacts and stakeholder interests.	National	Program duration	High	High	High	High	3.03	The need to develop and enforce robust legal and regulatory frameworks to manage environmental impacts and stakeholder interests (Source 3: Levin).	(Levin et al., 2020)
	DSM activities in disputed waters introduce grounds for international conflicts.	International	Long term	High	High	Medium	High	2.97	The resolution argues that the water column on the extended continental shelf is considered the High Sea which limits Norway's sovereignty	(Advokatfirmaet Wikborg Rein, 2023; Bentele et al., 2024)

	Norway could lose its role as co-chair of the Ocean Panel if it allows DSM in its territorial waters.	International	Program duration	High	Medium	Medium	Medium	2.6	The ocean panel aims to manage EEZ sustainably, and allowing DSM activities goes against this. The ocean panel scientists say they know too little about the possible impact to support this decision.	(Nature, 2024)
	Exploration or possible exploitation licenses granted without regard to the precautionary principle could cause reputational damages.	International	Long term	High	High	Medium	High	2.97	DSM does introduce reputational risks. The Norwegian Environment Agency believes that the draft decision does not have a sufficient professional and legal basis because the principles of knowledge base, precaution, and overall burden in the Natural Diversity Act §§ 8-10 have not been followed, which is necessary according to the Natural Diversity Act § 7 and the Seabed Minerals Act § 2- 2.	(Amadi & Mosnier, 2023; Miljødirektoratet, 2023)
Norwegian Citizens	Norwegian citizens may experience a loss of cultural or spiritual value associated with a pristine ocean or a traditional sense of ownership of or identification with the ocean and its resources.	Local	Long term	Low	Low	Low	Low	1.38	There may be a degradation of cultural values recognized by communities because of the development of a possibly destructive industry.	(United Nations Environment Programme Finance Initiative, 2022)
	Disruptions to fishing in proximity to the mine site may lead to a loss of	Local	Program duration	Medium	High	Low	Low	1.58	Noise, light, sediment plumes, and contaminants can pose a threat to both commercial and subsistence fisheries.	(Cardno, 2016; Levin et al., 2020)

	job opportunities for fishing communities.									
	Introducing DSM and higher paygrades to communities can strain the regional level of pay, creating income disparities	Local	Program duration	Low	Medium	Low	Low	0.76	High unemployment locally indicates a good supply of labor in the short term, and if many unemployed people have relevant skills, the region can meet increased demand for labor, but this can in the long run lead to a labor shortage and wage pressure.	(Asplan Viak et al., 2022)
	The seafood processing industry could face increased contamination risks from pollutants released during DSM activities	National	Long term	Medium	High	Medium	Medium	2.4	This can lead to higher costs for ensuring product safety and a potential loss of market confidence in Norwegian seafood.	(Levin et al., 2020; Sousa, 2021)
	The extraction of non-renewable minerals today reduces opportunities for the future by depleting finite resources	National	Long term	High	Medium	Low	Medium	2.53		Authors judgment
Post-Harvest Sector	No evidence was found supporting significant outcomes.									

Competing Industries	A successful DSM venture may divert workers from competing industries	International	Program duration	High	Medium	Low	Medium	2.16	If DSM becomes successful in Norway, it could entice workers to start in this industry rather than competing ones.	Authors judgment
International Governments	Norway could face international problems as the EU put forward a motion requesting a resolution against Norway's seabed mining activities in the Arctic.	International	Long term	High	High	High	High	3.41	The EU proposed a resolution expressing its concerns against the opening decision, they further claim that Norway has obligations as a signatory to various treaties that they could be in conflict with.	(Bentele et al., 2024)
	Mining of seafloor substrates can have unknown impacts, hindering the development of future industries.	National	Long term	Low	High	Low	Low	1.13	It is also possible that mining could prevent future use of the mining site for other purposes. Seafloor substrates targeted for mining may hold genetic resources that could be lost.	(Levin et al., 2020)
	There are countries that disagree with Norway's interpretation of the Svalbard Treaty. If Norway allows exploration and exploitation activities in the areas	International	Long term	Medium	High	Medium	Medium	2.4	Part of the area opened for exploration are located under the fishery protection zone of Svalbard. There has been a case surrounding crab fishing, where the Norwegian supreme court concluded that the Svalbard treaty only applies on land and no further out than the territorial sea. However, not all states and international expert communities agree with Norway's interpretation and application of the Treaty.	(Jones, 2023) (Advokatfirma et Wikborg Rein, 2023; Bentele et al., 2024)

	surrounding Svalbard, it could lead to increased friction and attention regarding Norway's stance.									

Appendix C.1

Explanation of DSM Performance Indicator Diagram Metrics

Environmental Metrics

Dimension: Ecological Health

Metric:	**Explanation:**	**Suggestion for scoring:**
Species Richness	Measures the biodiversity within the affected area by quantifying the number of species present.	5 – Same as baseline level 4 – Below 10% difference from baseline 3 – Between 10 – 30% below baseline 2 – Between 30 – 50% below baseline 1 – More than 50% below baseline
Livestock Population Dynamics	Assesses the trends in species populations within the affected area, across various pelagic zones. It involves quantifying the abundance of these species and evaluating whether their populations are declining, stable, or showing signs of recovery.	5 – Livestock populations are rapidly rebuilding 4 – Livestock populations are rebuilding 3 – Livestock populations are stable 2 – Livestock populations are declining 1 – Livestock populations are rapidly declining
Status of Critical Habitat	Evaluates the status of critical habitat within the affected area through expert judgment based on a critical habitat assessment. It assesses the extent to which key habitats essential for the survival and reproduction of species are intact, degraded, or under threat, providing insights into the overall health and resilience of the ecosystem.	5 – Critical habitat is healthy 4 – Critical habitat is less than 25% degraded 3 – Critical habitat is less than 50% degraded/destroyed 2 – Critical habitat is less than 75% destroyed 1 – Nearly all critical habitat is destroyed
Carbon Footprint	Assess the CO_2-equivalent emissions from DSM operations.	No suggestion given
Areal Impact	Measures the areal impact of DSM operations.	No suggestion given

Economic Metrics

Dimension: Harvest

Metric:	**Explanation:**	**Suggestion for scoring:**
Harvest Yield	Quantifies the amount of sellable material brought to shore, reflecting the landings level within the harvest indicator, comparing it to the historical high in the past 10 years.	No suggestion given
Operational Efficiency	Measures the efficiency of operations by comparing the actual days at sea (operating days) with the theoretical maximum of operation. It provides insight into the utilization of time and resources in harvesting activities.	5 – Over 95 % operational days compared to the theoretical maximum 4 – 95 – 85 % 3 – 85 – 50 % 2 – 50 – 25 % 1 – Less than 25 %
Price Variance	Assesses the ex-vessel price of harvested material by comparing it to the historical high in the past 10 years. It quantifies the deviation ratio from the historical price benchmarks, indicating market performance and potential economic fluctuations.	5 – Above 95 % 4 – 95 – 85 % 3 – 85 – 70 % 2 – 70 – 50 % 1 – Below 50 %

Dimension: Harvest Assets

Metric:	**Explanation:**	**Suggestion for scoring:**
Ratio of Asset Value to Gross Earnings	Assesses the efficiency of harvest assets by calculating the ratio of asset value to gross earnings. It quantifies the productivity of invested assets in generating revenue within the harvest assets indicator.	No suggestion given

Total Revenue cf. Historic High	Compares the total revenue generated from harvesting activities to historical highs. It provides insight into the deviation from past revenue benchmarks, indicating the performance of the harvest assets in generating income.	5 – Above 95 % 4 – 95 – 85 % 3 – 85 – 70 % 2 – 70 – 50 % 1 – Below 50 %
Asset Value cf. Historic High	Evaluates the fluctuation of asset value by comparing it to historical highs. It quantifies the deviation from past asset value benchmarks, providing an indication of asset stability.	5 – Above 95 % 4 – 95 – 85 % 3 – 85 – 70 % 2 – 70 – 50 % 1 – Below 50 %
Borrowing Rate cf. Risk-Free Rate	Compares the borrowing rate associated with harvest operations to the risk-free rate (US 10-year Treasury Bill might be an appropriate comparison). It assesses the cost of capital relative to a risk-free investment, providing insights into the financial risk and investment attractiveness of harvest assets.	5 – Less than 1.75 4 – Less than 2.5 3 – Less than 4 2 – Less than 7 1 – Greater than 7
Source of Capital	Evaluates where the funding for the harvest assets is coming from. This indicator gives an insight into the risk profile and gives insights into potential control dynamics for the harvest assets.	5 – Unsecured loans from banks or venture capital 4 – Secured loans or public stock offerings 3 – Loans secured by personal assets 2 – Family/Community loans 1 – No available capital

Functionality of Harvest Capital	Measures the proportion of harvested material that is usable or sellable. It quantifies the efficiency of which resources are managed and converted to sellable material. A higher score indicates better resource utilization and reduced waste.	No suggestion given

Dimension: Risk

Metric:	**Explanation**	**Suggestion for scoring:**
Annual Total Revenue Volatility	Measures the variability or fluctuations in total revenue on an annual basis, providing insights into the stability or risk associated with revenue generation. The ratio is the standard deviation from the mean in the last 10 years.	5 – Less than 10 % 4 – 10 – 20 % 3 – 20 – 35 % 2 – 35 – 50 % 1 – Over 50 %
Annual Landings Volatility	Measures the variability in annual landings, indicating the level of uncertainty in harvested quantities and its impact on economic performance. The ratio is the standard deviation from the mean in the last 10 years.	5 – Less than 15 % 4 – 15 – 25 % 3 – 25 – 40 % 2 – 40 – 100 % 1 – Over 100 %
Intra-annual Landings Volatility	Assesses the variability in landings within a single year,	5 – Less than 15 % 4 – 15 – 25 %

	providing insights into seasonal fluctuations and their implications for economic risk.	3 – 25 – 40 % 2 – 40 – 100 % 1 – Over 100 %
Annual Price Volatility	Quantifies the variability in prices of harvested material on an annual basis, reflecting market fluctuations and their influence on economic outcomes. The ratio is the standard deviation from the mean in the last 10 years.	5 – Less than 15 % 4 – 15 – 25 % 3 – 25 – 40 % 2 – 40 – 100 % 1 – Over 100 %
Intra-annual Price Volatility	Evaluates the variability in prices of harvested material within a single year, providing insights into short-term market dynamics and their impact on economic risk.	5 – Less than 15 % 4 - 15 – 25 % 3 – 25 – 40 % 2 – 40 – 100 % 1 – Over 100 %
EBIT Volatility	Measures the volatility of earnings before interest and taxes (EBIT), reflecting fluctuations in profitability and their implications for economic risk management. The ratio is the standard deviation from the mean in the last 10 years.	5 – Less than 15 % 4 - 15 – 25 % 3 – 25 – 40 % 2 – 40 – 100 % 1 – Over 100 %
Spatial Price Volatility	Assesses the variability in prices of harvested material across different locations, indicating the extent of location dependency in market dynamics and its impact on economic risk.	5 – Less than 15 % 4 - 15 – 25 % 3 – 25 – 40 % 2 – 40 – 100 % 1 – Over 100 %

	The ratio is the standard deviation from the mean in the last 10 years.	

Dimension: Trade

Metric:	**Explanation**	**Suggestion for scoring:**
International Export Value	Quantifies the value of goods or materials exported internationally to higher-value markets.	No suggestion given.
Final Market Wealth	Measures the total value or wealth generated by a product or service once it reaches the end consumer in the market. It provides insights into the economic contribution of the product throughout the supply chain.	No suggestion given.
Wholesale Price cf. Similar Products	Compares the wholesale price of the product to similar products in the market, i.e. metals from terrestrial mining. It assesses the pricing competitiveness and market positioning of the product relative to its counterparts, providing insights into economic performance within the trade indicator. Compared to the global average price.	5 – Above 20 % of global average 4 - Between 10 – 20 % above global average. 3 – Within 10 % of global average 2 – Between 10 – 50 % below global average 1 – Less than half of global average

Dimension: Product Form

Metric:	**Explanation**	**Suggestion for scoring:**

Processing Yield	Assesses the efficiency of converting raw ore at landings to final product through processing. It quantifies the proportion of raw material successfully transformed into usable products, providing insights into the economic efficiency of production within the product form indicator.	5 – Over 95 % 4 – 95 – 80 % 3 – 80 – 50 % 2 – 50 – 25 % 1 – Less than 25 %
Product Shrinkage	Measures the shrinkage or loss of usable products during processing. It quantifies the proportion of material that becomes unusable or is lost during the production process, reflecting the efficiency of resource utilization and potential economic losses.	5 – Less than 5 % 4 - 5 – 10 % 3 – 10 – 25 % 2 – 25 – 50 % 1 – Over 50 %
Capacity Utilization Ratio	Evaluates the utilization of production capacity within the processing facilities. It compares the actual output of usable products to the maximum capacity of the facilities, providing insights into operational efficiency and resource optimization within the product form indicator.	No suggestion given.
Value Chain Margins	Examines the margins at each step of the value chain, from ex-vessel to wholesale markets. It measures the	No suggestion given.

	profitability and value-added contributions at different stages of product distribution, providing insights into economic performance and market dynamics within the product form indicator.	

Dimension: Post-Harvest Assets Performance

Metric:	**Explanation**	**Suggestion for scoring:**
Borrowing Rate cf. Risk-free rate	Compares the borrowing rate associated with post-harvest assets to the risk-free rate. It assesses the cost of capital relative to a risk-free investment, providing insights into the financial risk and investment attractiveness of post-harvest assets within the economic dimension.	5 – Less than 1.75 4 – Less than 2.5 3 – Less than 4 2 – Less than 7 1 – Greater than 7
Source of Capital	Evaluates where the funding for the post-harvest assets is coming from. This indicator gives an insight into the risk profile and gives insights into potential control dynamics for the harvest assets.	5 - Unsecured loans from banks or venture capital 4 - Secured loans or public stock offerings 3 - Loans secured by personal assets 2 - Family/Community loans 1 – No available capital
Age of Facilities	Measures the age of post-harvest facilities, reflecting the longevity and potential depreciation of infrastructure assets. It provides insights into the maintenance	5 – In the first quarter of the expected life of the facility 4 – Second quarter 3 – Third quarter 2 – Fourth quarter 1 – Exceeding expected life

	requirements, technological obsolescence, and overall performance of post-harvest assets over time.	

Social Metrics

Dimension: Managerial Returns

Metric:	**Explanation**	**Suggestion for scoring:**
Executive Wages cf. Non-DSM Wages	Compares the wages of executives in DSM to those in other industries. It assesses the level of executive compensation relative to comparable positions in different sectors, providing insights into social equity and managerial returns within the social dimension.	5 – More than 50 % above alternative industry wage 4 - Between 50 – 10 % 3 - Within 10 % 2 – Below 10 - 50 % 1 – Below 50 %
Executive Earnings cf. Regional Average Earnings	Evaluates the earnings of executives in DSM compared to the regional average earnings. It highlights any disparities in executive compensation relative to the broader regional socioeconomic context, offering insights into income equality and social justice.	5 – More than 50 % above regional average earning 4 - Between 50 – 10 % 3 - Within 10 % 2 – Below 10 - 50 % 1 – Below 50 %
Processing Owners Wages cf. Non-DSM Wages	Compares the wages of processing owners in DSM to wages in other industries. It assesses the level of compensation for processing owners relative	5 – More than 50 % above alternative industry wage 4 - Between 50 – 10 % 3 - Within 10 % 2 – Below 10 - 50 % 1 – Below 50 %

	to comparable positions outside of the industry, providing insights into wage fairness and social mobility.	
Processing Owners Earnings cf. Regional Average Earnings	Compares the earnings of processing owners in DSM to regional average earnings. It identifies any discrepancies in earnings among processing owners relative to the regional socioeconomic context, shedding light on income disparities and social inclusivity within the industry.	5 – More than 50 % above regional average earning 4 – Between 50 – 10 % 3 – Within 10 % 2 – Below 10 - 50 % 1 – Below 50 %-

Dimension: Labor Returns

Metric:	**Explanation**	**Suggestion for scoring:**
Crew Wages cf. Non-DSM Wages	Compares the wages of crew members in the DSM industry to those in other industries. It provides insights into the relative compensation levels and equity considerations within the social dimension of labor returns.	5 – More than 50 % above alternative industry wage 4 – Between 50 – 10 % 3 – Within 10 % 2 – Below 10 - 50 % 1 – Below 50 %
Crew Earnings cf. Regional Average Earnings	Assesses crew earnings in relation to the regional average earning level. It provides insights into income distribution and fairness considerations within the regional context.	5 – More than 50 % above regional average earning 4 - Between 50 – 10 % 3 - Within 10 % 2 – Below 10 - 50 % 1 – Below 50 %

Processing Workers Wages cf. Non-DSM Wages	Compares the wages of processing workers in the DSM industry to those in other industries. It provides insights into the relative compensation levels and equity considerations within the social dimension of labor returns.	5 – More than 50 % above alternative industry wage 4 - Between 50 – 10 % 3 - Within 10 % 2 – Below 10 - 50 % 1 – Below 50 %
Processing Workers Earnings cf. Regional Average Earnings	Compares the earnings of processing workers to the regional average earning level. It provides insights into income distribution and equity considerations within the regional context.	5 – More than 50 % above regional average earning 4 - Between 50 – 10 % 3 - Within 10 % 2 – Below 10 - 50 % 1 – Below 50 %

Dimension: Health & Sanitation

Metric:	**Explanation**	**Suggestion for scoring:**
Harvest Safety	Assesses the safety record within harvesting operations, considering incidents of loss of life. It provides insights into the effectiveness of safety protocols and practices within the harvesting process.	5 - Less than 0.1 deaths per thousand per year 4 - Less than 0.5 deaths 3 - Less than 1 2 - Less than 5 1 – More than 5 deaths per thousand per year
Executive Health Care Access	Evaluates the access to healthcare services for executives within the DSM industry. It considers factors such as availability, affordability, and quality of healthcare services to ensure the well-being of executives.	5 - Global standard treatment for illness is accessible 4 – Licensed practitioners provide surgical and drug treatments 3 – Emergency treatment is available

		2 – Basic medical treatment is available 1 – No medical treatment is available
Crew Health Care Access	Assesses the access to healthcare services for crew members involved in harvesting operations. It evaluates factors such as medical facilities availability, emergency response systems, and healthcare coverage to promote the health and safety of crew members.	5 - Global standard treatment for illness is accessible 4 – Licensed practitioners provide surgical and drug treatments 3 – Emergency treatment is available 2 – Basic medical treatment is available 1 – No medical treatment is available
Processing Owners Health Care Access	Evaluates the access to healthcare services for processing owners within the DSM industry. It considers factors such as healthcare infrastructure, medical insurance coverage, and preventive healthcare programs to support the health and well-being of processing owners.	5 - Global standard treatment for illness is accessible 4 – Licensed practitioners provide surgical and drug treatments 3 – Emergency treatment is available 2 – Basic medical treatment is available 1 – No medical treatment is available
Processing Workers' Health Care Access	The access to healthcare services for workers involved in processing activities. It evaluates factors such as healthcare facility proximity, occupational health services, and health	5 - Global standard treatment for illness is accessible 4 – Licensed practitioners provide surgical and drug treatments 3 – Emergency treatment is available

	insurance coverage to ensure the health and safety of processing workers.	2 – Basic medical treatment is available 1 – No medical treatment is available
Sanitation	Measures the sanitation conditions in the harvest areas. This measure is scored relative to global standards, not local standards.	5 – Sanitation meets global health standards 4 – Basic sanitation needs met 3 – Inadequate sanitation, workers are exposed to some lack of sanitation 2 – Workers are exposed to considerable lack of sanitation 1 – No measures for sanitation implemented

Dimension: Community Services

Metric:	**Explanation**	**Suggestion for scoring:**
Contestability & Legal Challenges	Evaluates the extent of contestability and legal challenges faced by the DSM industry, and to which degree they limit the ability to implement effective regulations for the industry. It considers factors such as legal disputes, regulatory compliance, and stakeholder engagement, providing insights into the industry's legal and social impact on the community.	5 - No significant legal challenges, civil actions, or protests regarding industry. 4 - Minor legal challenges that slow implementation. 3 - Legal challenges, civil actions, or protests that impede some management measures. 2 - Legal challenges, civil actions, or protests that suspend major elements of the management system. 1 - Legal challenges, civil actions, or protests that suspend or prohibit implementation of key

		management reforms and regulation certification.
Education Accessibility for Crew	Measures the accessibility of education opportunities for crew members involved in DSM operations. It considers the availability of educational institutions and availability of technical training programs.	5 – Higher education is available 4 - High school and technical education are available 3 – Middle school education is available 2 – Basic literacy and mathematics education is available 1 – No formal education is available
Education Accessibility for Processing Workers	Evaluates the accessibility of education opportunities for processing workers employed in DSM facilities. It considers the availability of educational institutions and availability of technical training programs.	5 – Higher education is available 4 - High school and technical education are available 3 – Middle school education is available 2 – Basic literacy and mathematics education is available 1 – No formal education is available
Regional Support Businesses	Support businesses are businesses that provide critical inputs (e.g. vessel maintenance) or post-harvest functions (e.g. brokering, logistics).	5 - All types of support are readily available 4 - Some types of support are limited by capacity or unavailable 3 - Most types of support are limited by capacity or unavailable 2 - Support is limited to variable inputs

		1 - Industry support is not available locally

Dimension: Local Ownership

Metric:	Explanation	Suggestion for scoring:
Non-Resident Employment as Executives	Quantifies the proportion of executives in DSM operations who are non-residents. It provides insights into the level of local representation and inclusion in executive positions within the social dimension of local ownership.	5 – Above 70 % local executives 4 – 70 – 50 % 3 – 50 – 30 % 2 – Below 30 % 1 – No local executives
Non-Resident Employment as Processing Owners	Measures the extent of nonresident ownership of processing capacity within the DSM industry. It provides insights into the distribution of ownership and control over critical infrastructure assets, highlighting potential implications for local economic development and social dynamics.	5 – Above 70 % local ownership 4 – 70 – 50 % 3 – 50 – 30 % 2 – Below 30 % 1 – No local ownership

Dimension: Local Labor

Metric:	Explanation	Suggestion for scoring:
Non-Resident Employment as Crew	Quantifies the proportion of nonresident workers employed as crew members within the local labor context. It provides insights into the extent of reliance on nonresident labor in DSM	5 – Above 70 % local employment 4 – 70 – 50 % 3 – 50 – 30 % 2 – Below 30 % 1 – No local employment

	operations, contributing to the understanding of social dynamics and labor practices	
Non-Resident Employment as Processing Workers	Quantifies the proportion of processing workers employed in deep sea mining operations who are nonresidents. It provides insights into the extent to which local labor is engaged in processing positions within the social dimension of local labor.	5 – Above 70 % local employment 4 – 70 – 50 % 3 – 50 – 30 % 2 – Below 30 % 1 – No local employment

Dimension: Career

Metric:	**Explanation**	**Suggestion for scoring:**
Crew Experience	Evaluates the work experience of the crew involved in harvesting operations. Measures average years of experience.	5 – Above 7 years of experience 4 - 7 – 5 years 3 – 5 – 2 years 2 – 2 – 1 years 1 – Below 1 year
Age Structure of Crew	Examines the age structure of harvesters, providing insights into the demographic composition of the workforce. It analyzes the distribution of workers across different age groups, identifying trends and potential implications for workforce management.	5 - All working ages are represented 4 – Slight skewed older or younger 3 - Skewed older or younger 2 – Considerable skew towards older or younger 1 – Almost entirely skewed younger or older
Processing Workers Experience	Evaluates the work experience of processing	5 – Above 7 years of experience 4 - 7 – 5 years

	workers. Measures average years of experience.	3 – 5 – 2 years 2 – 2 – 1 years 1 – Below 1 year
Age Structure of Processing Workers	Examines the age structure of processing workers, providing insights into the demographic composition of the workforce. It analyzes the distribution of workers across different age groups, identifying trends and potential implications for workforce management.	5 - All working ages are represented 4 – Slight skewed older or younger 3 - Skewed older or younger 2 – Considerable skew towards older or younger 1 – Almost entirely skewed younger or older

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