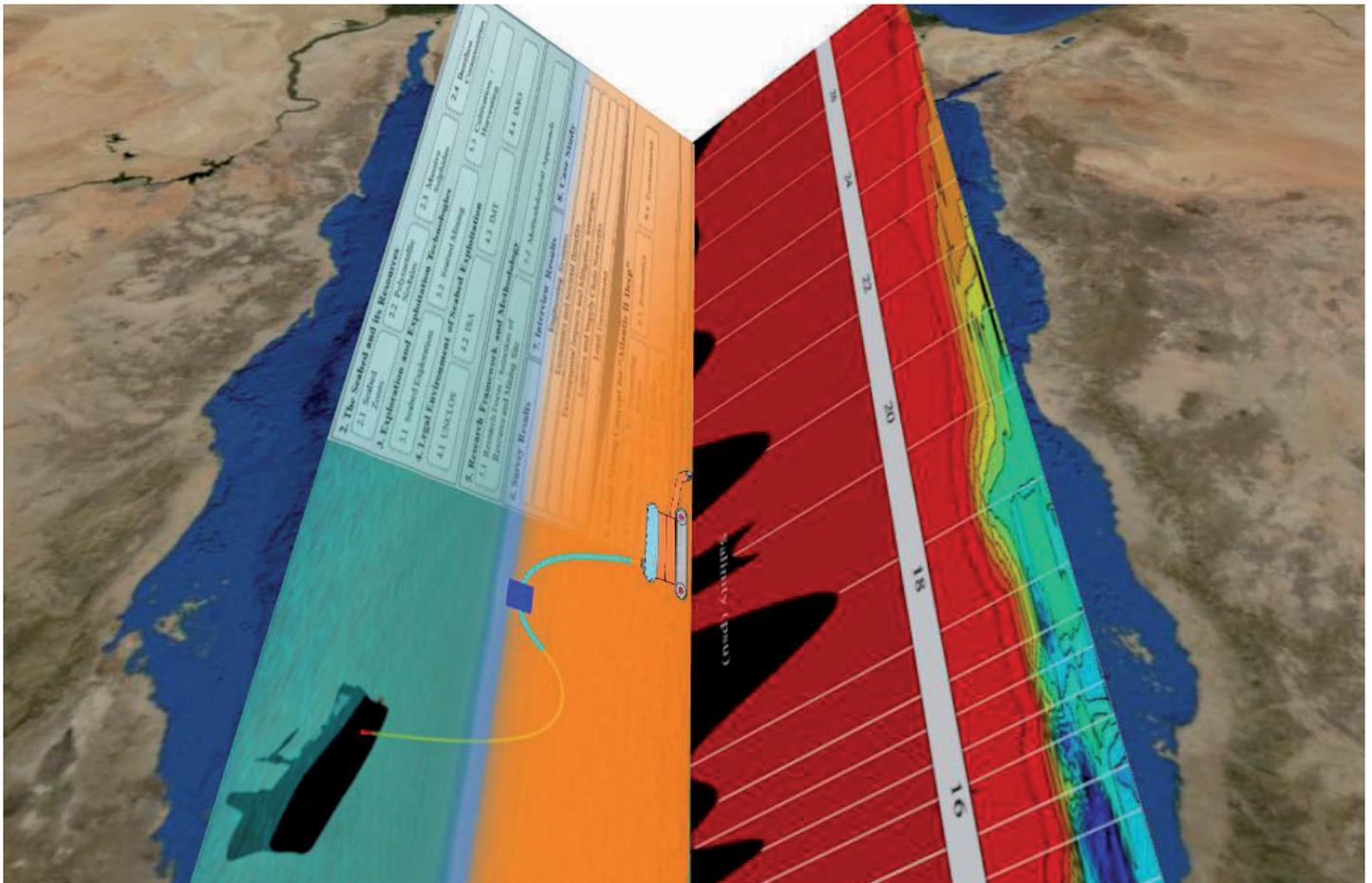


Sustainable Seabed Mining:

Guidelines and a new concept for Atlantis II Deep



Authors: **L Egorov, H Elost, N L Kudla, S Shan, KK Yang**

Series Editors: **R A Shenoi, P A Wilson, S S Bennett**

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Lev Egorov · Hany Elostá · Nicole L Kudla · Shiliang Shan · Kyung-Kyu Yang

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Foreword

The Lloyd's Register Educational Trust (The LRET) in collaboration with the University of Southampton instituted a research collegium in Advanced Ship and Maritime Systems Design in Southampton between 16 July and 7 September 2012.

This year's collegium has focused on The LRET's research-led education agenda. Successful ship and maritime systems design depends on the collaborative application of a broad range of engineering competences as the drive for improved efficiency and environmental performance places greater demand on the design community. This aspect needs to be reflected in the education of naval architects, marine engineers and others who are the active contributors to the ship design processes.

The aim of the research collegium has been to provide an environment where young people in their formative post-graduate years can learn and work in a small, mixed discipline group drawn from the maritime community to develop their skills whilst completing a project in advanced maritime systems design. The project brief that initiates each project set challenging user requirements to encourage each team to develop an imaginative solution, using individual knowledge and experience, together with learning derived from teaching to form a common element of the early part of the programme.

The collegium format provided adequate time for the participants to enhance their knowledge through a structured programme of taught modules which focussed on the design process, advanced technologies, emerging technologies and novel marine solutions, regulatory and commercial issues, design challenges (such as environmental performance and climate change mitigation and adaptation) and engineering systems integration. Lecturers were drawn from academic research and industry communities to provide a mind-broadening opportunity for participants, whatever their original specialisation.

The subject of the 2012 collegium has been systems underpinning seabed exploitation. The 25 scholars attending the 2012 collegium were teamed into five groups. The project brief included: (a) quantification of the environmental challenge; (b) understanding of the geo-political legal-social context; (c) possible techniques for harvesting or recovering resources from the seabed; (d) one engineering system to achieve seabed exploitation; (e) economics and logistics challenges. While all the groups addressed the items (a) to (c), each team focused on just one engineering system in dealing with items (d) and (e). This volume presents the findings of one of the five groups.

R A Sheno, P A Wilson, S S Bennett
Southampton
2 September 2012

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We are very grateful and truly indebted to the invited speakers for making trips to the collegium. Those lectures were very helpful and supportive. This work would not have been possible without those experts from academia and industry who provided insights into seabed exploitation during the interview process. We would also like to express our thankfulness to the participants of our large scale survey on seabed exploitation. We really appreciated their enthusiasm about the topic and thoughtful comments, concerns and suggestions.

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Lev Egorov · Hany Elost · Nicole L Kudla · Shiliang Shan · Kyung-Kyu Yang

Southampton, September 2012

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List of Abbreviations

A2D	Atlantis II Deep
AC	Alternating Current
ADCP	Acoustic Doppler Current Profiler
ALS	Accidental Limit State
API	American Petroleum Institute
ARD	Acid Rock Drainage
AUV	Autonomous Underwater Vehicle
AUX	Auxiliary Miner
BM	Bulk Miner
CAPEX	CAPital EXpenditure
CCZ	Clarion-Clipperton Zone
CM	Commercial Mining
CSEM	Controlled-Source ElectroMagnetic
DARPS	Differential, Absolute and Relative Positioning System
DC	Direct Current
DEC	Department of Environment and Conservation
DGPS	Differential Global Positioning System
DNV	Det Norske Veritas
DP	Dynamic Positioning
DPO	Dynamic Positioning Operations
DPS	Dynamic Positioning System
DSTP	Deep Sea Tailings Placement
DWP	Dewatering Plant
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
EIR	Environmental Impact Statement
EIS	Environmental Impact Statement
EMP	Environmental Management Plan
FLS	Fatigue Limit State
FPSO	Floating Production, Storage and Offloading
GM	Gathering Machine
GPS	Global Positioning System
HMS	Her Majesty's Ship
HRs	Hybird Risers
IMCA	International Marine Contractors Association

IMMS	International Marine Minerals Society
IMO	International Maritime Organisation
IMT	International Maritime Tribunal
IRR	Internal Return of Rate
ISA	International Seabed Authority
ISPS	International Ship and Port Facility Security
IUCN	International Union for Conservation of Nature
LAN	Local Area Network
LMRP	Lower Marine Riser Package
MBES	Multi-Beam Echo Sounder
MESEDA	Atlantis II Deep Metalliferous Sediments Development Program
MMF	Multi-Mode Fibers
MMS	Mineral Management Service
MPA	Marine Protected Area
MT	Magnetotelluric
NASA	National Aeronautics and Space Administration
NNW	North-northwest
OMEGA	NASA Offshore Membrane Enclosures for Growing Algae project
OPEX	OPERating EXpenditure
PE	polyethylene
PMO	Pilot Mining Operation
PNG	Papua New Guinea
PP	polypropylene
PPMT	Pre-pilot Mining Test
PRC	Pseudo-Range Correction
PSU	Practical Salinity Unit
PSV	Production Support Vessel
PU	Polyurethane
PWM	Pulse Width Modulation
RALS	Riser And Lifting System
ROV	Remotely Operated Vehicle
RQ	Research Questions
RTP	Riser Transfer Pipe
SBES	Single-Beam Echo Sounder
SCRs	Steel Catenary Risers
SLS	Serviceability Limit State
SMF	Single-Mode Fibres

SSE	South-southeast
SWOT	Strengths, Weaknesses, Opportunities and Threats
SOLAS	Safety of Life at Sea Convention
THD	Total Harmonic Distortion
TLP	Tension Leg Platform
TSJ	Taper Stress Joint
TTRs	Top-Tensioned Risers
ULS	Ultimate Limit State
UNCLOS	United Nations Convention of the Law of the Sea
UPS	Uninterruptible Power Supply
US	United States
USD	United States Dollar
VFD	Variable-Frequency Drive
VIV	Vortex-Induced Vibration

Summary

The feasibility of exploiting seabed resources is subject to the engineering solutions, and economic prospects. Due to rising metal prices, predicted mineral scarcities and unequal allocations of resources in the world, vast research programmes on the exploration and exploitation of seabed minerals are presented in 1970s. Very few studies have been published after the 1980s, when predictions were not fulfilled. The attention grew back in the last decade with marine mineral mining being in research and commercial focus again and the first seabed mining license for massive sulphides being granted in Papua New Guinea's Exclusive Economic Zone.

Research on seabed exploitation and seabed mining is a complex transdisciplinary field that demands for further attention and development. Since the field links engineering, economics, environmental, legal and supply chain research, it demands for research from a systems point of view. This implies the application of a holistic sustainability framework of to analyse the feasibility of engineering systems. The research at hand aims to close this gap by developing such a framework and providing a review of seabed resources. Based on this review it identifies a significant potential for massive sulphides in inactive hydrothermal vents and sediments to solve global resource scarcities. The research aims to provide background on seabed exploitation and to apply a holistic systems engineering approach to develop general guidelines for sustainable seabed mining of polymetallic sulphides and a new concept and solutions for the Atlantis II Deep deposit in the Red Sea.

The research methodology will start with acquiring a broader academic and industrial view on sustainable seabed mining through an online survey and expert interviews on seabed mining. In addition, the Nautilus Minerals case is reviewed for lessons learned and identification of challenges. Thereafter, a new concept for Atlantis II Deep is developed that based on a site specific assessment.

The research undertaken in this study provides a new perspective regarding sustainable seabed mining. The main contributions of this research are the development of extensive guidelines for key issues in sustainable seabed mining as well as a new concept for seabed mining involving engineering systems, environmental risk mitigation, economic feasibility, logistics and legal aspects.

1 Introduction

The research at hand aims to develop guidelines for sustainable seabed mining with a particular reference to the mining site Atlantis II Deep in the Red Sea. In the following paragraphs, the relevance of exploiting resources from the seabed is given. Beyond this, the research objectives and questions are detailed and an outline of the publication is presented.

1.1 Relevance of Seabed Exploitation

Forecasts of global trends and transformation processes in the next 25 to 50 years outline sustainable development, power and economy transitions from West to East, growth of the world's population and technological progress that lead to severe energy, mineral, food and water scarcities (National Intelligence Council (U.S.), 2008). These resource supply uncertainties lead to controversial debates on seabed exploitation. In fact 71% of world is covered by oceans with the seabed being proposed to provide significant amounts of needed minerals, bio-organisms and energy.

These resources and its environment are vastly unexplored. Experts argue life and resources of the moon are better understood than wide parts of the ocean and its seabed. For a long time it has been believed that the seabed with its extreme temperature, salinity and light conditions bears no use to mankind. The HMS Challenger expedition between 1872 and 1876 changed this view significantly and discovered mineral rich polymetallic nodules on the seafloor. Further research expeditions in the 1960s and 1970s identified thriving marine life and seafloor massive sulphides in and around hydrothermal vents in deep sea waters. Marine life on the seabed may hold future life-sciences or energy solutions. One example is macroalgae cultivation, which is now being developed for biofuel, food and fertilizer applications.

However, the feasibility of exploiting seabed resources is subject to the engineering solutions and their economic prospects. Due to rising metal prices, predicted mineral scarcities and unequal allocations of resources in the world, the 1970s presented vast research programmes on the exploration and exploitation of seabed minerals. Very few studies have been published after the 1980s, when predictions were not fulfilled (Bertram et al., 2011). The attention grew back in the last decade with marine mineral mining being in research and commercial focus again and the first seabed mining license for massive sulphides being granted in Papua New Guinea's Exclusive Economic Zone (Birney et al., 2006).

Research on seabed exploitation and seabed mining is a complex transdisciplinary field that demands for further attention and development. Since the field links engineering, economics, environmental, legal and supply chain research, it demands for research from a

systems point of view. This implies the application of a holistic sustainability framework of to analyse the feasibility of engineering systems. The research at hand aims to close this gap by developing such a framework and providing a review of seabed resources. Based on this review it identifies a significant potential for massive sulphides in inactive hydrothermal vents and sediments to solve global resource scarcities.

In the subsequent stages, the study analyses drivers and barriers for sustainable seabed mining based on a large-scale survey. It develops a concept for a high potential next mining site Atlantis II Deep in the Red Sea based on a first commercial seabed mining case study, the large scale survey and expert interviews and concludes by a derivation of guidelines for sustainable seabed mining of massive sulphides.

1.2 Research Questions and Objectives

The exploration and exploitation of seabed resources is of significant interest for commercial and scientific purposes, while it is still in an early stage of research and application. Due to this early stage and the outline of the research problem, the development of feasible concepts for seabed mining needs to consider multi-disciplinary issues of engineering, economics, the environment and society as well as legal boundaries. The objectives of the study at hand are to provide a comprehensive background on seabed exploitation and to apply a holistic systems engineering approach to develop a particular concept and guidelines for sustainable seabed mining of massive sulphides.

The research questions (*RQ*) that will be answered in the background sections are:

RQ1: How is the seabed defined?

RQ2a: What are potential resources of the seabed?

RQ2b: What is known about their economic and societal value as well as their environmental relevance?

RQ2c: What technologies are known for exploration and exploitation of seabed resources?

RQ2d: What are geo-political socio-legal constraints of seabed exploitation?

In the second part of the study, massive sulphides are analysed as high potential seafloor resources. The aim is to develop a holistic approach that leads to an engineering concept for their exploitation. As a potential mining site the Atlantis II Deep deposits in the Red Sea are contemplated. Finally, industry and academic insights into drivers and barriers for seabed mining are gathered in the various domains of the holistic approach. As a conclusion, the study produces generic guidelines for sustainable seabed mining of massive sulphides in inactive hydrothermal vents and sediments.

-
- RQ4: What are drivers and barriers for seabed exploitation from an industry and research perspective?*
- RQ5: What engineering system is feasible for sustainable exploitation of Atlantis II Deep based on expert knowledge and the Nautilus case study?*
- RQ6: What are generic guidelines for sustainable seabed mining of massive sulphides in inactive hydrothermal vents and sediments?*

1.3 Outline of the Report

The publications' outline is presented in Figure 1. The following paragraphs give a brief summary of the sections within this book.

Section 1 introduces the relevance of the problem in sciences and industry, presents the research questions and objectives and concludes by presenting the overall structure of the publication at hand.

Section 2 starts with a definition of seabed that is used throughout this book. It introduces the background information on seabed zones, relevant mineral deposits on the seabed and bio-organisms that are discussed for exploitation.

Section 3 introduces relevant technologies for the exploration and exploitation of the described resources in section 2. Inter alia it details the state-of-the-art seafloor tools and riser systems.

Section 4 presents an overview of the legal environment of seabed exploitation by introducing the legal authorities in place and their jurisdiction zones.

Section 5 defines the holistic research framework for the study and introduces the methodological steps applied. It sheds light into the selection of massive sulphides as a potential seafloor resource and outlines the selection of Atlantis II Deep as the mining site in focus of this research.

Section 6 provides the results of the large scale survey that was conducted to identify drivers and barriers for seabed mining from an academic and industry point of view.

Section 7 indicates the expert interviews that were conducted to gather knowledge on the mining site "Atlantis II Deep" as well as on environmental, legal and engineering aspects of seabed mining at that particular site.

Section 8 reviews the Nautilus Minerals Case for lessons learned for seabed mining and the presented concept in particular.

Section 9 provides the systems engineering solutions for Atlantis II Deep. The concept integrates the knowledge of the three-fold approach (Section 6 to 8).

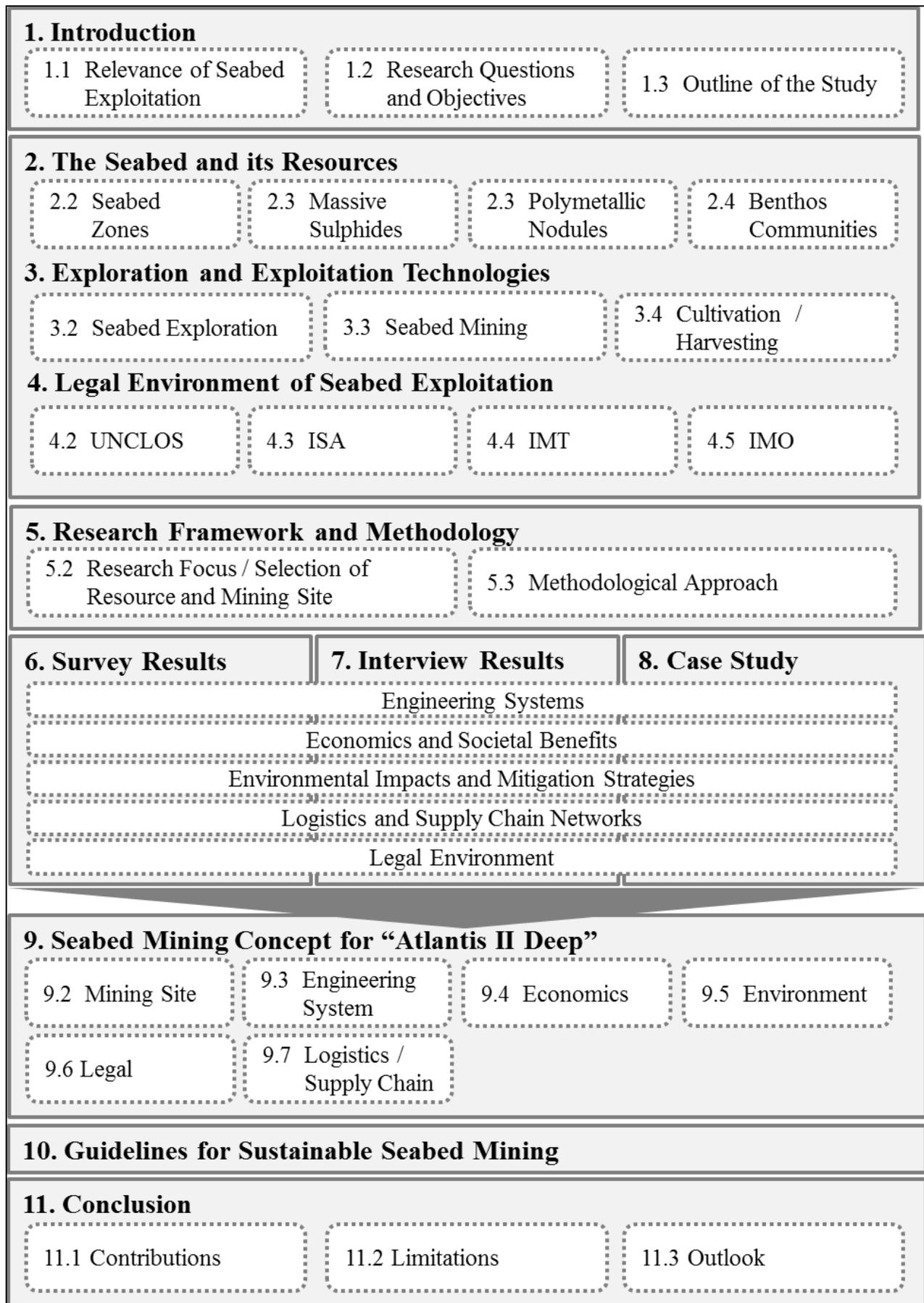


Figure 1: Outline of the Study

Section 10 derives generic guidelines and recommendations for sustainable seabed mining of massive sulphides in inactive hydrothermal vents or sediments. These guidelines integrate the study results.

Section 11 summarises the contributions and limitations of the study and concludes with opportunities for future research in the field.

1.4 Concluding Remarks

During this introductory chapter, an overview of the seabed exploitation is presented. This chapter has dwelled on clarifying the research question along with the aims and objectives of this research. The problem at hand was formulated and demonstrated. The main concept of the research focus was also revealed. It also summarised the structure outline of the study to smoothen the reading flow. In this respect, the current research study will focus on the investigation of sustainable seabed mining and providing guidelines and new concept for deepsea mining.

The next chapter will be reviewing potential seabed resources and the literature related to various aspects of their characterisation, occurrence, economic and environmental relevance.

2 The Seabed and its Resources

2.1 Introductory Remarks

Nearly 71% of the earth's surface is covered by oceans. From coast to offshore, across all oceans, the seabed is divided into four distinct zones with unique environmental conditions (i.e., pressure, temperature, salinity and current), morphology and marine life. In a wider interpretation the seabed provides various types of resources, including oil and natural gas, minerals, fisheries and marine genetic life. Within the research at hand the seabed scope is defined as the solid layer at the ocean-earth interface and comprises its attached resources. Therefore, fisheries as well as oil and natural gases are excluded from the applied definition. Table 1 indicates that the properties and condition of the seabed are subject to the environmental circumstances. Whereas the Pacific Ocean has an average water depth of 4,000m, the seabed in the Arctic lies 1,100m under the sea surface. In line with the water depth and location, the salinity, temperature and currents influence the composition of the seabed. In this section, the geological features of seabed and resources will be reviewed and defined. The seabed resources include non-living and living resources. An in-depth review of massive sulphides, manganese nodules and algae cultivation will be presented.

Table 1: Overview of Ocean Characteristics
Source: Monroe et al. (2006)

Ocean	Surface Area (Million km ²)	Water Volume (Million km ³)	Average Depth (km)	Max. Depth (km)
Pacific	180	700	4.0	11.0
Atlantic	93	335	3.6	9.2
Indian	77	285	3.7	7.5
Arctic	15	17	1.1	5.2

2.2 Geological Features of the Seabed

Knowing the geological features of the sea floor is important to understand the offshore mineral deposits and design engineering systems for exploration and exploitation of their resources.

Horizontally, the seabed varies significantly from coast to open ocean. The ocean floor is not flat but contains diverse landforms including mountains, valleys, canyons, trenches and underwater volcanoes. The seabed can be categorised into four zones: continental shelf, continental slope, abyssal plain and oceanic ridge (Trujillo and Thurman, 2011).

Continental Shelf: Geologically, the continental shelf is defined as an area from the coast to water depths of 100 to 200m. The seabed on the continental shelf gently inclines seawards at an average slope of about 0.1°. Near major estuaries large amounts of sediments are deposited onto the seabed. The continental shelf is proposed to contain 80% of

resources, while the seabed beyond the continental shelf (roughly 80% of the seabed) is proposed to contain 20% of resources.

Continental Slope: The continental slope is a connection area bridging the continental shelf and abyssal ocean. The water depth changes significantly over a short distance with a steep slope of 4° . Along the continental slope there are many underwater canyons that cut into the continental shelf, which are important channels for the water exchange between the shelf and the open ocean water. Due to the accumulation of sediments, turbidity currents occur sporadically, so called underwater avalanche. Beyond the slope, the seabed is composed of sediments from the continent. The water depth descends to 3,500 to 5,500m.

Abyssal Plain: The abyssal plain is the flat seafloor area at water depths from 3,000 to 6,000m in high seas. At the sea bottom the environmental conditions are unique with high pressure, darkness and temperatures of approximately 3°C .

Oceanic Ridge: The oceanic ridge is a continuous volcanic submarine mountain chain that goes around the worlds' oceans including the Mid-Atlantic Ridge, Pacific-Antarctic Ridge, East Pacific Rise, Mid-Indian, Southeast and the Southwest Ridges.

The vertical structure and composition of the seabed are shown in Figure 2. The oceanic crust is made up of layers. As magma rises beneath the oceanic ridges, new seabed is formed. The seabed is composed of deepsea sediments, oceanic crusts and the upper mantle as the lowermost unit. The oceanic crust is thinner and denser than the continental crust. Hydrothermal vents, for instance, are commonly found along the oceanic ridge.

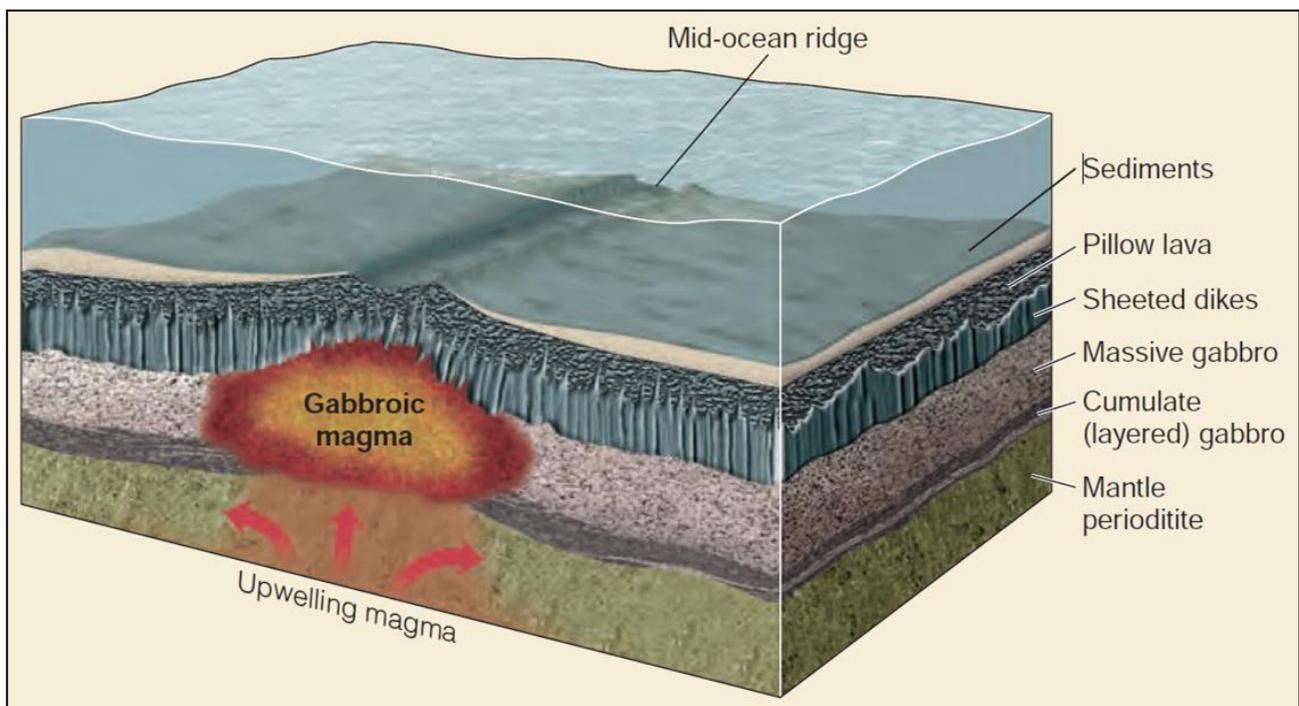


Figure 2: Composition of the Oceanic Crust
Source: Monroe et al. (2006)

The knowledge on the physical properties of sediments and rock on top of the seabed (Figure 2) is required for the estimation of resources and design of exploitation tools. Generally, the typical soils and sediments which are found in deepsea environments are soft or silt clays (Bridge and Howells, 2007; Dunlap et al., 1990). Hale et al. (1992) presented that deep ocean sediments have an overall behaviour that is similar to terrestrial soils. Figure 3 shows the distribution of sediments on the seabed. A significant percentage of seabed sediments is fine grained consisting of silt- and clay-sized particles. Most of the fine-grained sediments in the deepsea are windblown dusts and volcanic ashes from the continents and oceanic islands as well as the shells of microscopic organisms that live in the near-surface seas. Other sediment sources include cosmic dust and deposits resulting from chemical reactions in the sea water (e.g. manganese nodules).

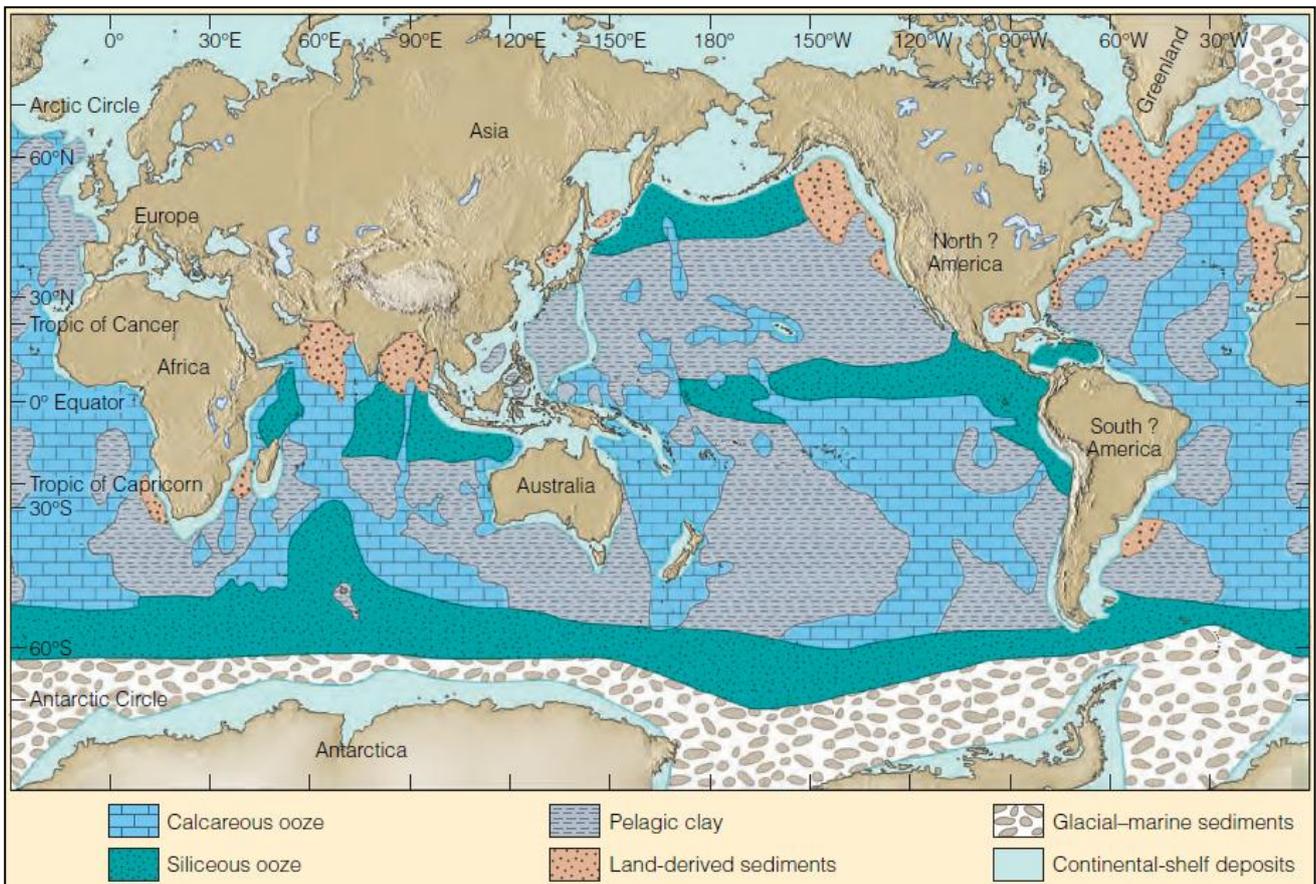


Figure 3: Sediments on the Seabeds
Source: Monroe et al. (2006)

The seabed resources also include living resources. Benthos community compositions on the seabed are varying according to water depth, reflecting environmental gradients, such as temperature, oxygen concentration, food availability and pressure (Clark et al., 2010). Among many kinds of benthos, research on algae has been widely conducted for biofuels, pharmaceuticals, fertilisers and foods. Algae are simple photosynthetic organism that have higher solar conversion efficiency and grow rapidly under suitable conditions. There are two types of algae by its size: microalgae and macroalgae. Microalgae, which are not attached to

the seabed, exist almost everywhere in the earth ecosystem. 50,000 species of microalgae are discovered, but only a limited number (around 30,000) have been studied and investigated (Mata et al., 2010). Macroalgae, which grow attached to the seabed are widely cultivated in Asian countries, Korea, Japan, and China, by net and rope type cultivation systems.

2.3 Seafloor Massive Sulphides

2.3.1 Discovery and Characterisation

Massive sulphide deposits are commonly found along oceanic ridges with hydrothermal processes. Hydrothermal vents were first discovered in 1977 on the Galapagos Rift in the Pacific. Vents are commonly associated with metal- and sulfur-rich mineralised structures such as chimneys. These chimneys are called black or white smokers and are shown in Figure 4. The vents discharge heated seawater through hot volcanic rocks and are often located where two tectonic plates are diverging and new oceanic crusts are being formed as shown in Figure 2.

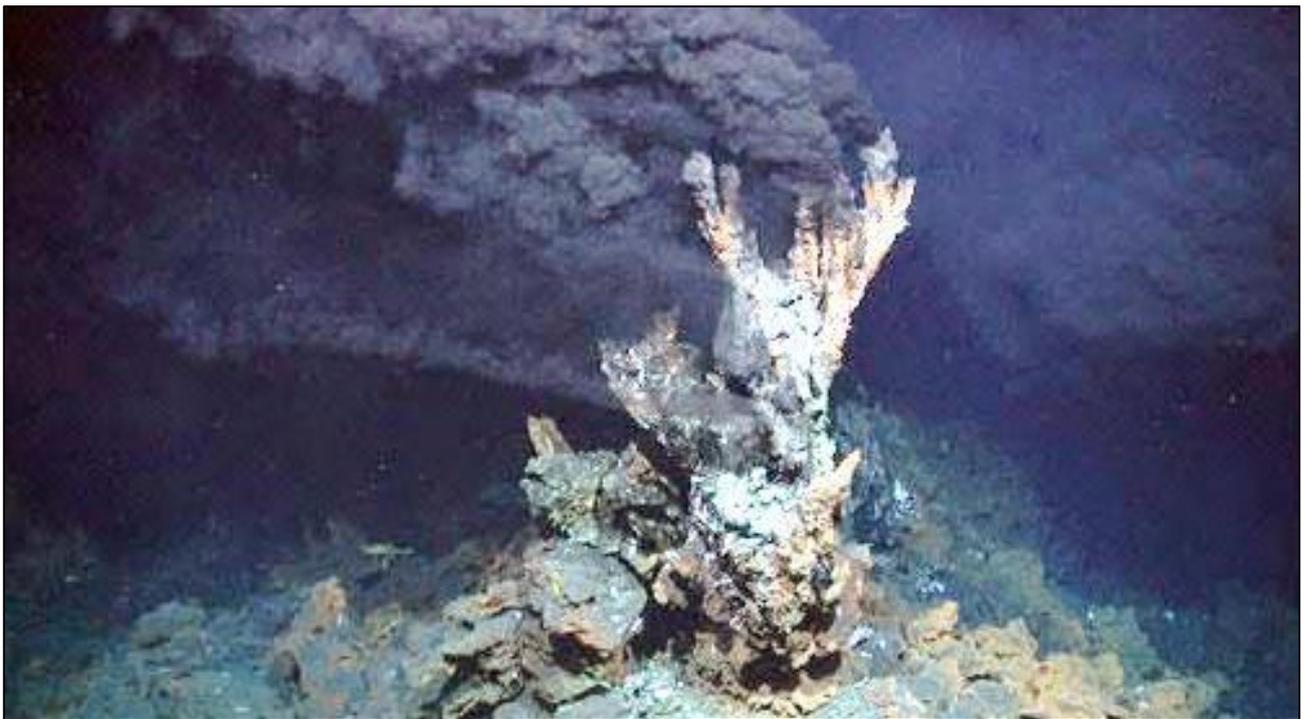


Figure 4: Active Hydrothermal Vent Site (Black Smoker)
Source: MARUM Research Center Ocean Margins, Bremen University

At the volcanic venting centers, sea water percolates down through the crust and reacts with hot rocks. At very high temperatures, the seawater and rock react chemically. The seawater often carries sulphide minerals of copper, zinc, and iron leached from the crust. When the hot vent water mixes with the cold seawater a pH and temperature change occur. The combined effect causes the metals to fall back down to the seabed to form mineral deposits.

These mineral deposits are called massive sulphides. The ore quality within these massive sulphides is quite high for certain metals such as copper, lead and zinc or even gold and silver. Figure 5 provides an overview of the chemical processes at hydrothermal vent sites. The sulphide minerals precipitated in this zone can accumulate in substantial amounts and are sometimes buried by lava flows at a later time. These deposits have commercial mining potential.

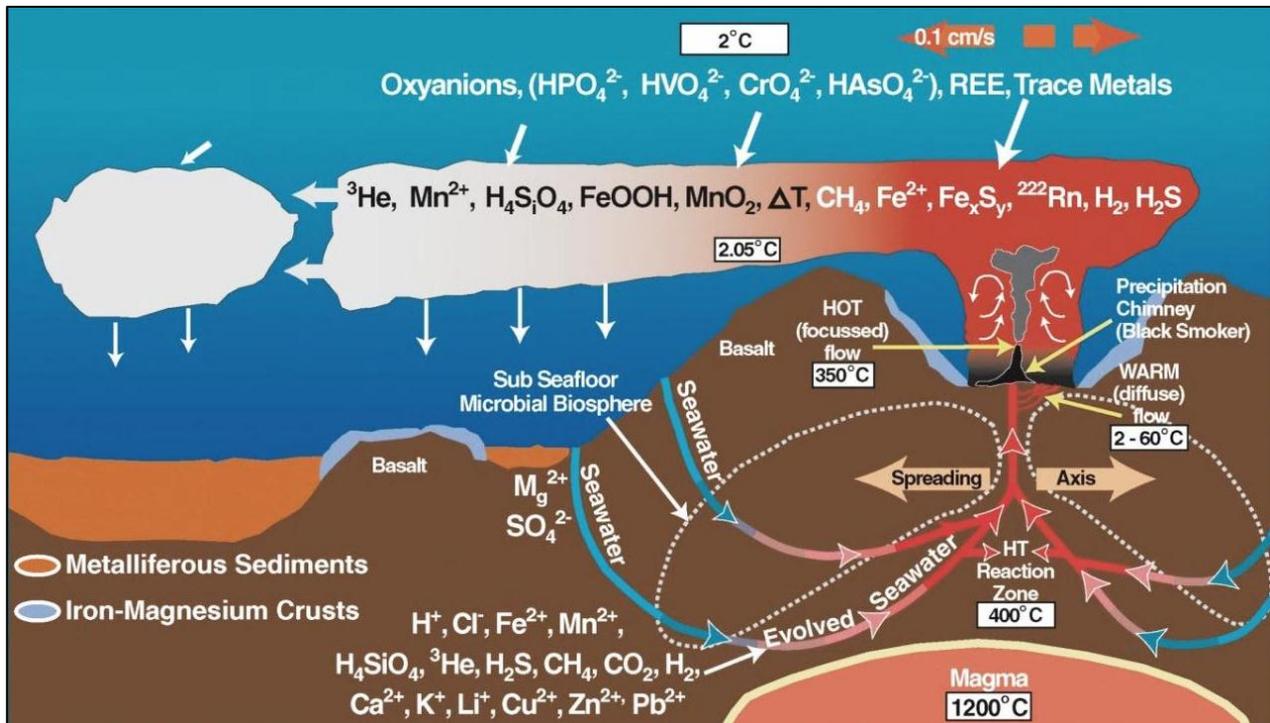


Figure 5: Chemical Processes at Hydrothermal Vents
 Source: <http://www.pmel.noaa.gov/vents/chemistry/images/vents2.gif>

2.3.2 Occurrence and Distribution

Generally, hydrothermal vents occur at the water depths ranging from 1km to 4km. The world's deepest known hydrothermal vent sites were discovered recently at depths of roughly 5km in the Mid-Cayman spreading centre in the Caribbean Sea (Connelly et al., 2012).

Hydrothermal vents are distributed along the oceanic ridges. Figure 6 shows the distribution of known hydrothermal vents in the world. Hydrothermal vents can be divided into active and inactive vents. Some vents periodically turn off and on through geological time. Due to the shut down of the hot vent fluid circulation, inactive hydrothermal vent sites are more difficult to find.

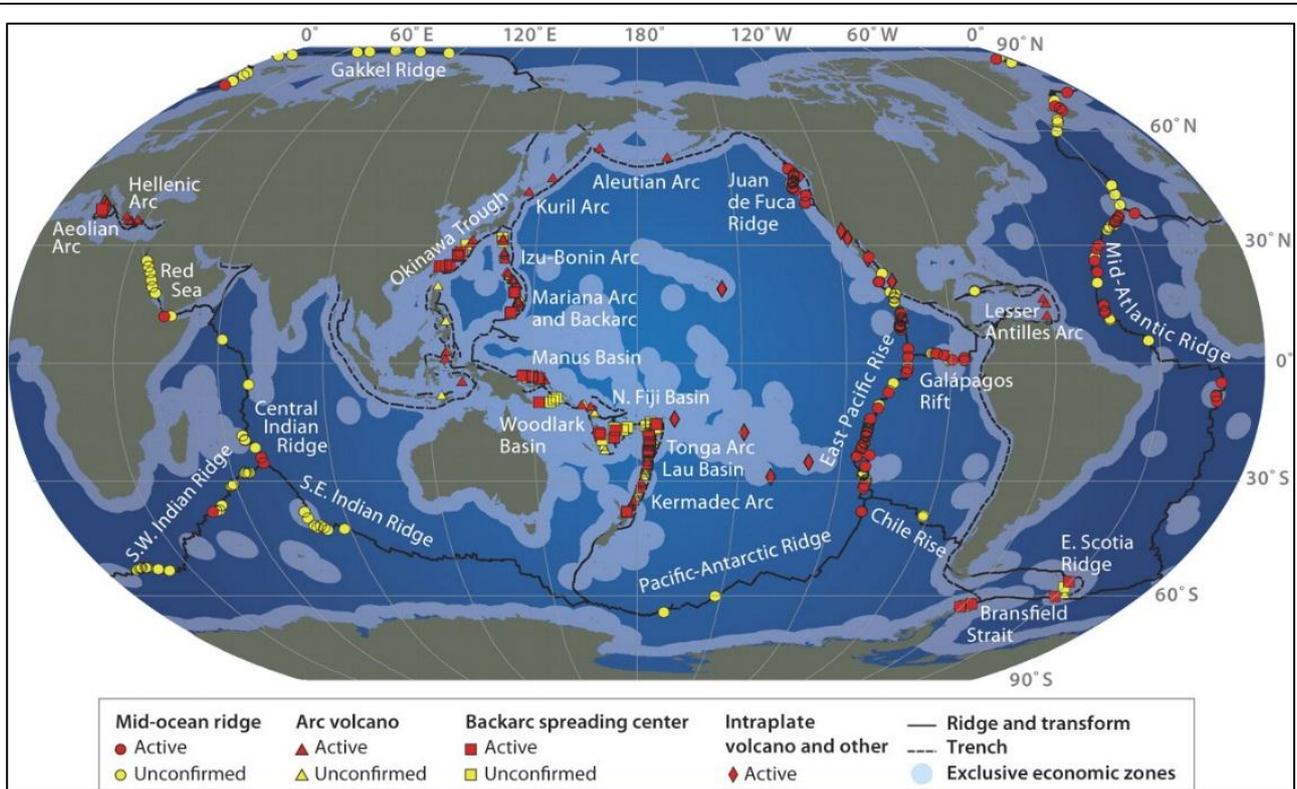


Figure 6: Global Distribution of Hydrothermal Systems and related Massive Sulphides
 Source: Hannington et al. (2011)

2.3.3 Economic and Societal Relevance of Massive Sulphides

The hydrothermal vent processes create high depositions of copper, lead, zinc, gold and silver. Detailed characteristics for each element and its societal relevance will be described in the following paragraphs.

Copper is a ductile metal with very high thermal and electrical conductivity. The major portion of copper produced in the world is used by the electronics industry, most of the remainder is combined with other metals to form alloys. Copper is among the most important industrial metals and has been used in power cables, data cables, electrical equipment, automobile radiators, cooling and refrigeration tubing, heat exchangers, artillery shell casings, small arms ammunition, water pipes and jewellery. Copper is a fairly common element, with great reserves in the Earth's crust. However, only a tiny fraction of these reserves is economically viable, given present-day prices and technologies. Various estimates of existing copper reserves available for mining vary from 25 years to 60 years, depending on core assumptions such as the growth rate. The price of copper has historically been unstable and quintupled from June 1999 to May 2006 as shown in Figure 7.

Gold has been widely used throughout the world as a vehicle for monetary exchange, investment and jewellery. It has a high malleability, ductility and resistance to corrosion and most other chemical reactions. There is little true consumption of gold in an economic

sense. Most of the gold used in manufactured goods, jewellery and works of art is eventually recovered and recycled.

Zinc is a transition metal of a light gray. It is the fourth "common" of the metals, after iron, aluminium and copper. One of the major applications for zinc is corrosion-resistancy. Other applications are in batteries and alloys, such as brass. A variety of zinc compounds are commonly used in the organic laboratory. Zinc is an essential mineral of biologic and public health importance. Zinc deficiency affects about two billion people in the developing world and is associated with many diseases (Hambidge and Krebs, 2007).

Silver is a soft, white, lustrous transition metal. It has the highest electrical and thermal conductivity. Silver is used to manufacture high-value objects such as medals, trophies, cups, cards and various decoratives. It is also widely used in dentistry for dental fillings, nuclear industry for control rods, and electronics industry for conductive material.

Given the high commercial mining potential and increasing mineral prices, many mining companies, organisations and countries are engaging in the exploration and exploitation of seafloor massive sulphide deposits.

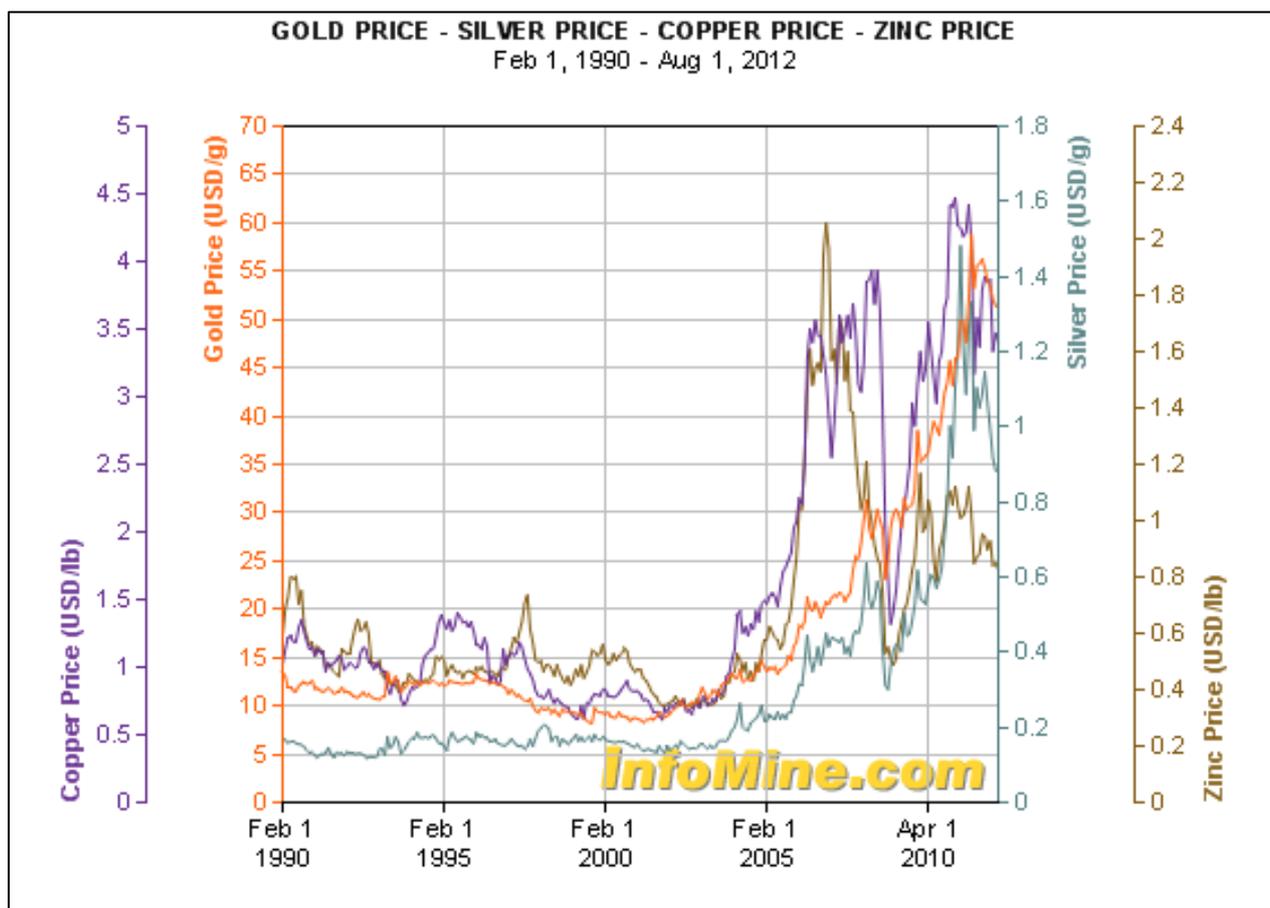


Figure 7: Mineral Price Development of Gold, Copper, Zinc and Silver (1990-2012)
Source: Adapted from www.infomine.com

2.3.4 Environmental Relevance and Impacts

Hydrothermal vents have a unique biological community. The ecosystems are dependent on chemosynthesis by sulphur-fixing bacteria, which use the chemical energy of vent fluids for the production of organic matters. At deep sea, the biomass usually exponentially declines with depth. However, in hydrothermal vent environments concentrations of cells are found 100 to 1,000 times higher than concentrations of cells in normal deep seawater.

Hydrothermal vents also have a high genetic diversity (Huber et al., 2007). New species have been continuously discovered at hydrothermal vents. The vent tubeworm (*Riftia pachyptila*) was the first animal found at the Galapagos Rift in 1977. Recently, largely unknown biological communities were discovered in the Mid-Cayman spreading centre in the Caribbean Sea (Connelly et al., 2012). Researchers have found that some hydrothermal vent systems periodically turn on and off. The biological community dies off along with the “shut down” of the vent system. When the vent system turns off, the chimneys usually get covered by sediments over time.

The emerging exploration and exploitation activities post a threat to the hydrothermal ecosystem. Mining massive sulphide deposits directly removes the habitat at the sea floor. Sediment plumes, noise and light associated with the mining operations further damage the ocean ecosystem. Assessing environmental values of the hydrothermal ecosystem is challenging. The possibility to recolonize a mining site is unknown and requires detailed environmental impact assessments.

2.4 Manganese Nodules

2.4.1 Discovery and Characterisation

Polymetallic nodules were first discovered in the Kara Sea off Sibiria and were found in all oceans of the world during the HMS Challenger expedition from 1872 to 1876 (Bender et al., 1966). They are also called manganese or ferro-manganese nodules, since they contain concentric layers of manganese and iron oxides as well as copper, nickel and cobalt concentrations around a crystallised manganese core (Scott, 2011). The nodules occur in different sizes from microscopic particles to more than 20 cm pallets as seen in Figure 8. On average the nodules have a size of 5 to 10 cm diameter similar to potatoes. Their surface is generally smooth, but can be of mammilated nature as well. Based on publications of the International Seabed Authority, manganese nodules of economic interest have an average chemical composition as stated in Table 1.

Table 2: Average Chemical Composition of Manganese Nodules
Source: ISA (2012)

Mn 29%	Fe 6%	Ni 1.4%	Cu 1.3%	Co 0.25%
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The actual chemical composition differs significantly depending on the site found. Beyond these elements, concentrations of aluminum, silicon, hydrogen, oxygen, sodium, magnesium, calcium, potassium, titanium, barium and rare earth elements, so called lanthanides, are found. Lanthanides which are found in significant concentrations within the nodules (Calvert and Cronan, 1978) are of particular economic interest due to their rare occurrence and relevance in electronic appliances. Piper (1974) analyzed the accumulations of these elements within nodules from the Pacific and Indian Ocean. He found significant differences between nodules from different depths, but no regional patterns in his sample. Moreover, the study indicated that Lanthanum and Cerium are most enriched.

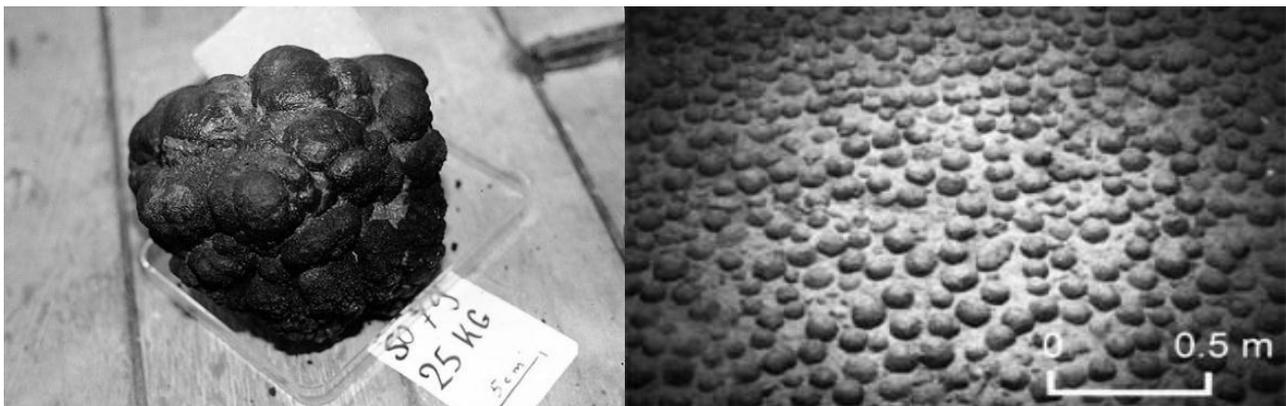


Figure 8: Sample and Seabed Images of Manganese Nodules
Source: The Federal Institute for Geosciences and Natural Resources (2012)

2.4.2 Origin, Growth and Occurrence

The origin, growth and occurrence of the nodules are specific geological phenomena that have raised controversial scientific debates. At the time the study of Bender et al. (1966) was published, there were three major theories on the origin and growth of nodules: (1) growth by slow accumulation of authigenic manganese, (2) rapid accumulation of manganese from submarine volcanic exhalates and (3) constant accumulation of manganese within deep sea sediments: “(...) Because of some unknown mechanism these hard bodies are continually rolled over the ocean floor and kept free of the depositing sediments; this process (...) continues until the hard bodies have reached a certain critical size beyond which they are too heavy to be moved: they are then covered by the sediment and preserved therein.” (p. 326)

Nowadays, the formation is believed to integrate hydrogenous, hydrothermal, diagenetic, halmyrolitic and biogenic processes. Respectively this refers to the slow precipitations of metals from the seawater, volcanic exhalates, precipitation at the interface of water and sediments, decomposition of basaltic debris in the seawater and the catalysing activity of microorganisms (ISA, 2012).

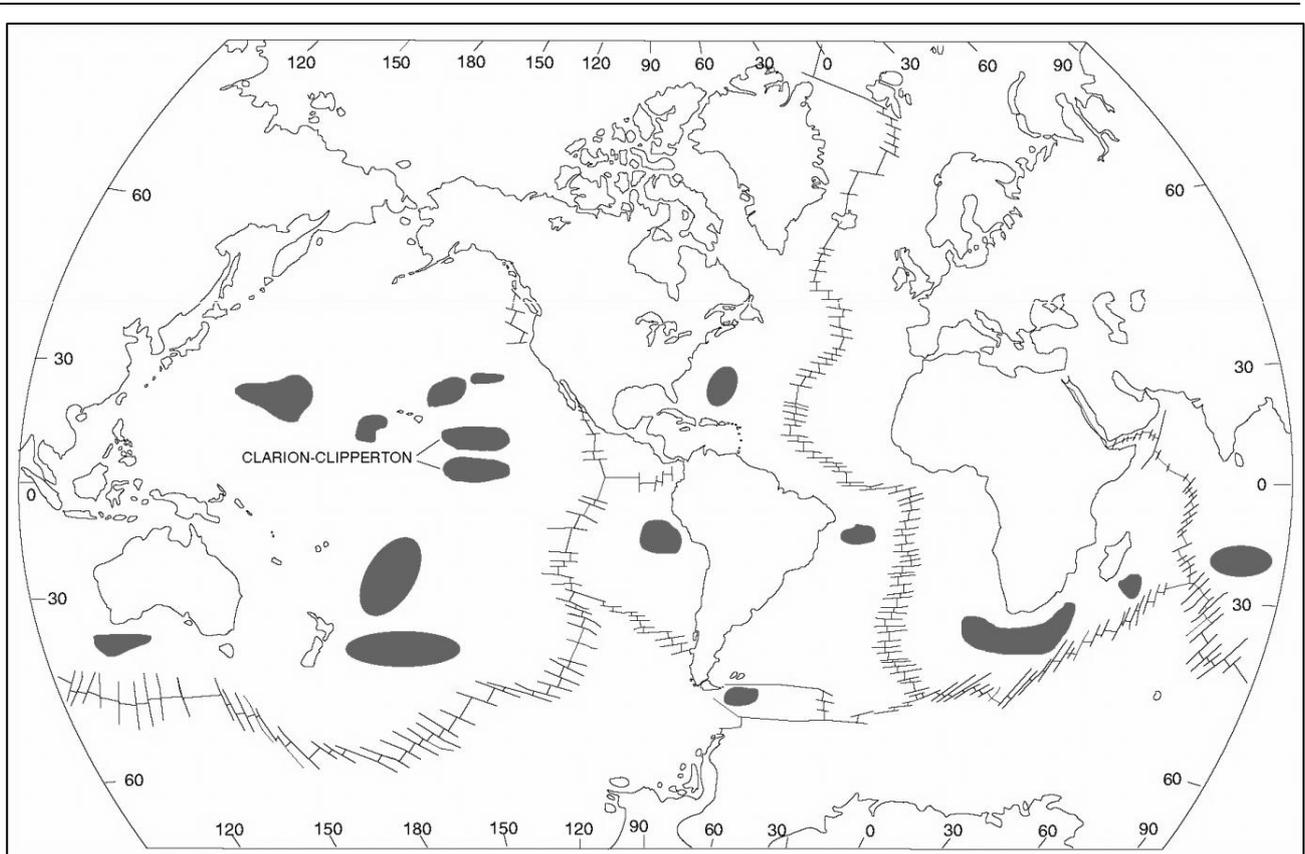


Figure 9: World Distribution of Manganese Nodules
Source: Scott (2011)

Nodules lie on or respectively slowly roll over the floor of the seabed, sometimes partly or completely covered by sediments. According to Menard (1976), the nodules appear to be growing only when they are not buried by sediments. Moreover, only one layer of nodules can be found on most sites. The estimated growth rates range between 10-40mm per 10^6 years (Heye & Marchig, 1977). Nodules are found at any depth in the sea or in lakes (Calvert & Price, 1970). However, largest concentrations with sea floor sites covered by up to 70% were discovered in the abyssal zone between 4,000 and 6,000m. Nodules of economic interest have been found predominantly in three areas of the north central Pacific Ocean, the Peru Basin in the southeast Pacific and the center of the Indian Ocean. Most promising deposits in terms of nodule concentration and chemical composition are supposed to be in the Clipperton Fracture Zone highlighted in Figure 9.

2.4.3 Economic and Societal Relevance

Since the 1960s various studies have addressed the economic feasibility of manganese nodule exploitation. Earlier studies concluded the break-even concentration of nodules per m^2 is 10 kg of nodules with a nickel and copper ratio of around 3% (Menard & Frazer, 1978). However, the feasibility is largely dependent on market price developments. Metal and mineral prices are highly volatile and sensitive both to market demands and supplies (see Figure 10 and Figure 11). Moreover, technological developments, the political

environment and other factors may affect the prices. The figures below present prices of manganese, cobalt, copper and nickel for publically available timescales.



Figure 10: Mineral Price Development of Nickel and Copper (1989-2012)
 Source: Adapted from www.infomine.com

In particular copper and nickel as well as lanthanide prices are the major drivers for economic feasibility. However, rare earth elements are not exchange-traded but sold on private markets, which are harder to monitor. Based on these developments, a recent study by Martino and Parson (2012) predicted a 15% internal return rate by exploitation of manganese nodules and concluded: “This low rate clarifies why the ISA has issued only licences for exploration, not production” at the moment (p.797).



Figure 11: Mineral Price Development of Manganese and Cobalt (2005-2012)
 Source: Adapted from www.infomine.com

The manganese nodules are rich in manganese, nickel, copper, cobalt and rare earth elements. Manganese is mainly applied in iron and steel production. Hence, products contain manganese are found in the construction or transportation industry. Manganese ores are used in animal nutrition or as a fertiliser. Nickel is primarily used as refined metal or ferronickel. According to the US Geological Survey, 65% is consumed by developed countries to produce stainless steel and 12% is used for superalloys or nonferrous alloys. Due to its corrosion preventive characteristics, the aerospace industry is one of the largest consumers of superalloys. Further applications are rechargeable batteries, catalysts, coinage, foundry products and plating. The predominant uses of cobalt are in rechargeable battery electrodes and superalloys. Finally, rare earth elements are of particular interest to electronic manufacturers, since their chemical characteristics have shown relevance in batteries, telecommunication, television and further electronic products.

2.4.4 Environmental Relevance and Impacts

The deep sea environment is still vastly unexplored in terms of the benthos communities and their interplay. It is known that the upper levels of sediments and the water-sediment interface have high species quantities and their bacterial populations sustain submarine life. The environmental impacts of manganese nodule exploitation are therefore largely dependent on understanding the biodiversity, regeneration rates and interplay with ocean currents (Clark and Neutra, 1983).

The ISA discussed environmental impacts by nodule exploitation in numerous workshops. Liu and Yang (2001) allocated the environmental impacts to three schematic zones indicated by Figure 12.

First the transport vessel and processing platforms disturb the sea surface and water column by noises, vibrations and emission of fuels and processing waste materials and liquids. The water column is affected by discharges and plumes that might occur during the transport of nodules and sediments to the surface. Discharges refer to waste waters and materials as well as the exchange of oligotrophic, low nutrient, deep-sea water and sediments with other zones. Especially, the deep-sea environment might be affected by rapid environmental changes. Sediment plumes can transport benthic communities and sediments over far distances and can have significant impacts on filter-feeding animals (Bluhm, 1994). Finally, the seabed is affected directly and indirectly by the collector machinery. The collection process disperses sediment dusts whilst removing nodules, infauna and epifauna. Beyond this, the machinery disturbs and compresses the soils underneath. The infauna and epifauna refers to the benthos community living on and around the nodules. Bluhm (1994) found that the abundance of benthos communities varies largely between 300 and 1,600 megabenthos/ha depending on the size and abundance of nodules.

In an long-term disturbance and recolonisation experiment of megabenthos-communities in the Peru Basin, Bluhm (2001) identified various long-term developments: (1) the fauna attached to the nodules disappeared after the disturbance, (2) the soft-bottom community recovered in some parts during the seven years, but total abundance was still lower than prior impact, (3) the repopulation started shortly after the area was ploughed. Seven years later hemisessile animals had returned, (4) nearby reference areas showed changes in animal densities, which might be a result of resettled sediment plumes. In these not directly impacted areas animal densities declined after the ploughing, but appeared to be greater than prior impact after seven years.

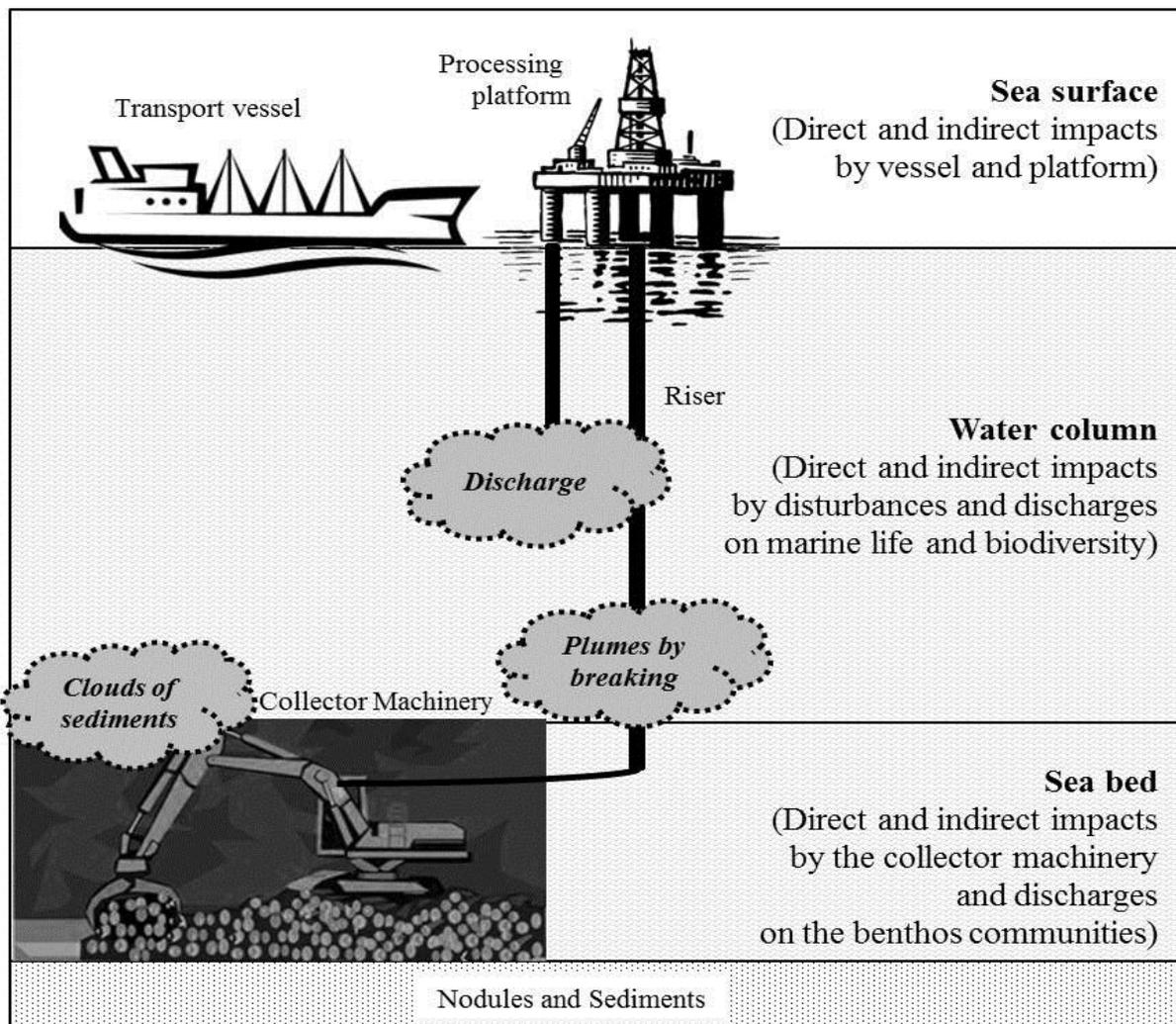


Figure 12: Environmental Impacts of Nodule Exploitation
 Source: Adapted from Liu and Yang (2001)

The outlined study used a photo/video system for the assessments and thus, concentrated on megabenthos only. Therefore, impact and recolonisation studies on meio- and microbenthos communities within and on sediments are still lacking. These are essential to understand and assess the environmental impacts of nodules exploitation fully. Further factor are the different ocean currents, depths and climates that make impact assessments specific to any site.

2.5 Benthos Community: Algae and Biofuel

The seabed resources include non-living and living resources. In the previous section, mineral deposits as the major part of the non-living resources on the seabed were reviewed. In the following section, the living resources, especially the algae will be reviewed.

2.5.1 Discovery and Characterisation

Algae have emerged as a promising way to produce biofuels from biomass. More than 50 years of research have demonstrated the potential of various microalgae to produce several chemical intermediates and hydrocarbons that can be converted into biofuels. A schematic overview of this conversion from environmental components such as sunlight, CO₂, water, minerals, and nitrogen to biofuels is presented in Figure 13. Lipids, carbohydrates, and proteins are the three major components that can be used to produce biofuels. According to the chemical characteristics of these components the types of biofuel can be determined (Darzins et al., 2010).

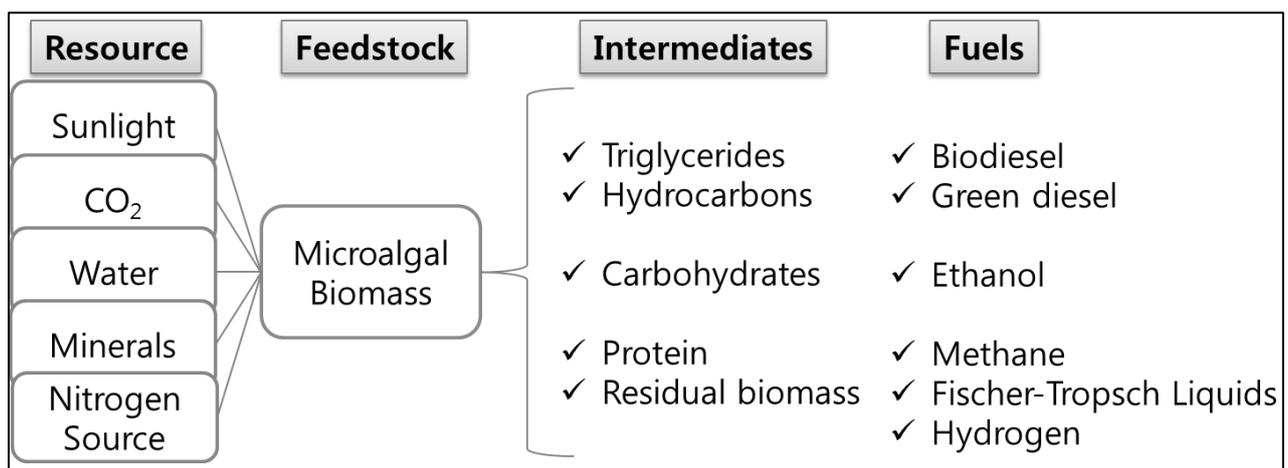


Figure 13: Pathway for Conversion of Environmental Resources to Biofuels
Source: Adapted from Darzins et al. (2010)

2.5.2 Algae Production and Cultivation Methods

Algae can grow very rapidly under suitable conditions, sufficient amounts of sunlight, water, CO₂ and especially nitrogen. In order to establish economic feasibility biofuel has to be produced at low costs. It means that the production rate of biomass should be enhanced as much as possible. Thus, maintenance of aforementioned resources in a certain level is crucial to obtain sufficient amounts of biomass. Optimal sites of large scale algae biofuel production facilities require that the resources exist close to the site and that climate remains almost at same conditions. However, much more effort is required to develop a more complete picture of ideal locations for algae growth (Darzins et al., 2010).

There are three different methods for large scale cultivation of algae biofuels: wastewater high-rate ponds, raceway ponds and photobioreactors. A wastewater high-rate pond is a relatively cheap, low-technology approach. However, increasing water depths have limited sunlight penetration and result in lower production rates for biomass than are achievable with the other methods. A raceway pond is a closed-loop recirculation open pond.

These can be constructed as individual ponds or groups of connected ponds as shown in Figure 14. The pond contents are maintained in a well-mixed status by a paddlewheel actions. In photobioreactors algae are grown in plastic bags or tubes in a closed-system. They have the advantage that the bags or tubes can prevent the system from invasion of other species and keep the CO₂ and nitrogen in the system. Also, it can generate higher biomass concentrations compared to open ponds systems.

When algae grow in closed photobioreactors oxygen is produced. This may be taken off periodically. The high construction and operating costs of closed systems are a limitation for large scale cultivation. In a recent algae project (OMEGA), NASA suggested new types of floating photobioreactors with offshore membrane enclosures for growing. The OMEGA system consists of flexible plastic enclosures with reinforced plastic on the underside and clear plastic on the upper sunny-side. An internal gas-permeable membrane provides a constant supply of CO₂ and regions of forward osmosis membranes concentrate nutrients to stimulate growth and dewater the algae to facilitate harvesting (Iersel and Flammini, 2010). Its technical and economic feasibility has not yet been determined. An economic analysis concluded that raceways ponds are likely the most feasible configuration of large-scale algal cultivation (Wiley et al., 2011).

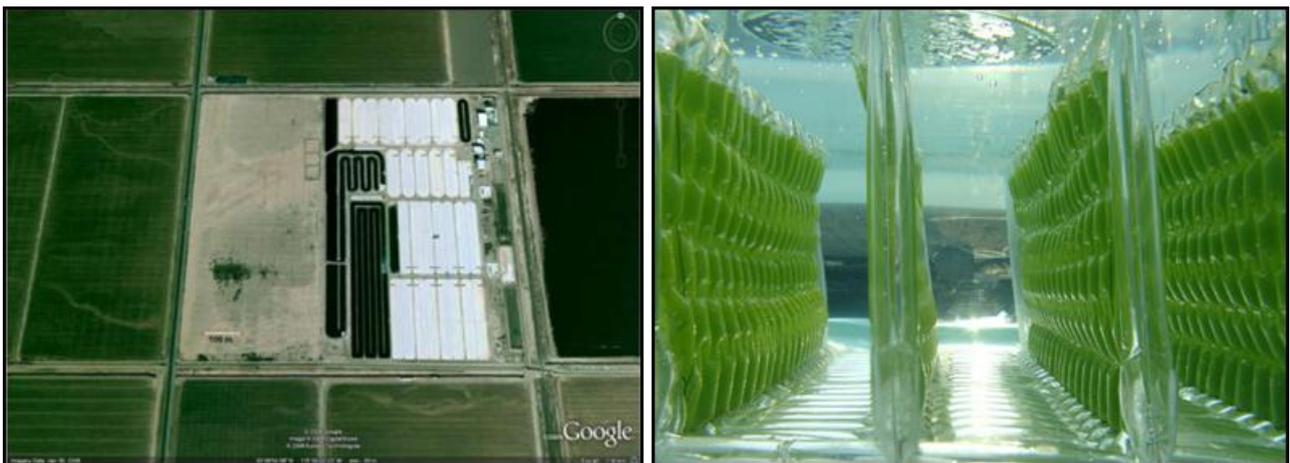


Figure 14: Cultivation Methods for Algae Biofuels
(open raceway ponds (left) and closed photobioreactor (right))

Source: Darzins et al. (2010)

2.5.3 Economic and Societal Relevance

Current production of biofuel depends on crops such as corn, soybean, sunflower, and oil palm. The main reason of development of biofuel based on algae is higher photosynthetic efficiency and higher production per unit areas compared to conventional landbased crops.

Biodiesel production rates for various plant sources are compared in Table 3. It shows that significant variations in biodiesel production even though oil contents are similar to each other. Microalgae provide high biodiesel production rates despite small land consumption (Mata et al., 2010).

Based on different scenarios of biofuel production, production costs between open raceway ponds and closed photobioreactors are compared by Darzins et al. (2010). Although there is great uncertainty in prediction of economics for future algae production, their conclusion is that open raceway pond systems are more effective than closed photobioreactors. However, current production costs of algae biofuel are two or three times higher than that of fossil fuels. In order to establish economic feasibility of algae biofuel, the most important factor is to increase the annual production rate of biofuel from algae. The production rate strongly depends on environmental and nutritional conditions. Cost of maintenance of growing conditions significantly affects the production costs of algae biofuel. Especially, costs of providing water during the whole production process will be a crucially important parameters.

Table 3: Comparisons of Biodiesel Production Rates from different Sources
Source: Mata et al. (2010)

Plant source	Seed oil content (%)	Oil yield (L/ha yr)	Land use (m ² yr / kg)	Biodiesel productivity (kg/ha yr)
Corn/Maize (<i>Zea mays</i> L.)	44	172	66	152
Hemp (<i>Cannabis sativa</i> L.)	33	363	31	321
Soybean (<i>Glycine max</i> L.)	18	636	18	562
Jatropha (<i>Jatropha curcas</i> L.)	28	741	15	656
Canola/Rapeseed (<i>Brassica napus</i> L.)	41	974	12	862
Sunflower (<i>Helianthus annuus</i> L.)	40	1,070	11	946
Castor (<i>Ricinus communis</i>)	48	1,307	9	1,156
Palm oil (<i>Elaeis guineensis</i>)	36	5,366	2	4,747
Microalgae (low oil content)	30	58,700	0.2	51,927
Microalgae (medium oil content)	50	97,800	0.1	86,515
Microalgae (high oil content)	70	136,900	0.1	121,104

Algae can be used not only as biofuels but also in various areas such as pharmaceuticals, nutrition, fertilisers and food. The application areas of algae are presented in Figure 15. Medicines and nutraceuticals are most feasible applications of microalgae. The second field is agriculture and environment. In this field, algae are used as feed for animals and environmental monitoring. Microalgae consume carbon dioxide dissolved in sea water by photosynthesis. It can be used as a monitoring system for the sea environment by measuring the sea colour (Sumi, 2009).

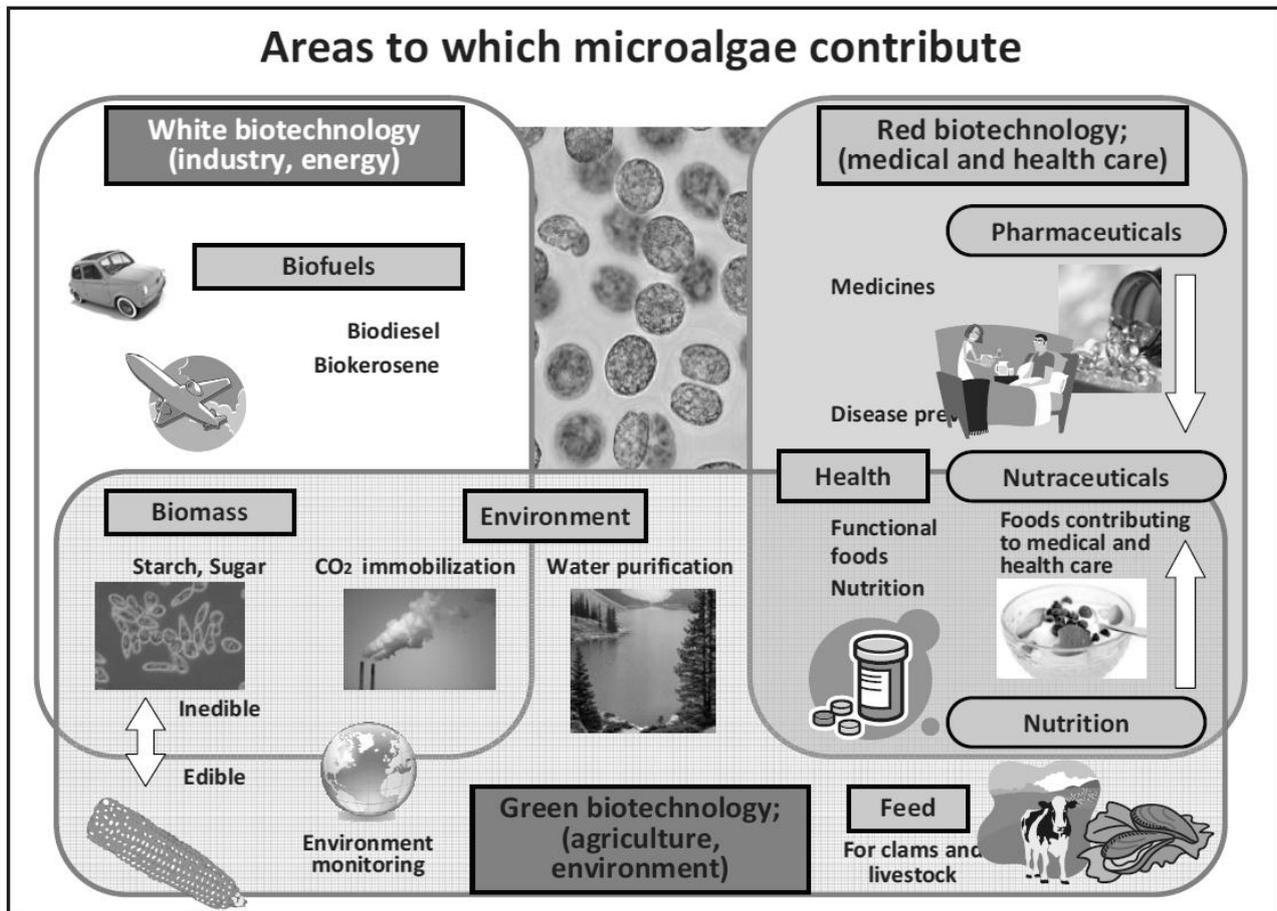


Figure 15: Application Areas of Microalgae
Source: Sumi (2009)

2.5.4 Environmental Impact of Algae Cultivation

Biological communities on seabed face a number of threats from human activities, fishing, especially trawling, exploitation of mineral resources (Clark et al., 2010).

Cultivating microalgae in open ponds has advantages in sustainability point of view. The greenhouse gas emission is balanced with consumption of carbon dioxide and the biomass production has no impact on biodiversity. Ground water is not depleted and water quality is maintained or improved. Air quality is also maintained or improved (Darzins et al., 2010).

On the other hand, the environmental impacts of macroalgae cultivation largely depend on the cultivation methods. According to the cultivation or harvesting method, the size of affected area and seaweed population are determined. Considering the carbon emissions in processing stage, total greenhouse gas reductions in lifecycle of macroalgae are 78-91%. However, if the cultivation area is large, it changes current and wave characteristics. Consequently, it affects the local ecosystem vicinity of the cultivation region. Only limited research has been done on the environmental impacts of the cultivation of macroalgae. It is essential that a precautionary approach is adopted regardless of the method used (Roberts and Upham, 2012).

2.6 Concluding Remarks

Within this chapter the scope of the seabed was defined integrating the geological features and relevant seabed resources. Both non-living and living resources were reviewed regarding their characteristics, economic and societal relevance as well as their environmental relevance. Against this background insights into massive sulphides, manganese nodules and algae cultivation were gained.

Within the next chapter the focus will lie on the technologies for exploration and exploitation of the presented resources.

3 Exploration and Exploitation Technologies

3.1 Introductory Remarks

This chapter comprehensively reviews relevant technologies for the exploration and exploitation of the different seabed resources. The review starts by looking at mapping and exploration of the seabed involving echo sounders, remotely operating vehicles (ROV) and autonomous underwater vehicles (AUV). Thereafter, the focus moves to the review of the critical engineering components of seabed mining systems. These components have been utilised directly from the offshore oil and gas industry where these items are field proven in similar applications. In addition, the review presents cultivation and harvesting technologies for algae.

3.2 Seabed Exploration and Mapping

The assessment of seabed resources needs an investigation of the geographical and geological conditions of the seafloor to obtain comprehensive information. Different types of equipment and techniques have been developed for this investigation, which will be reviewed in the following paragraphs.

3.2.1 Echo Sounding Exploration Technologies

The water depth and seabed data in deep water ocean can be measured using echo sounder technologies.

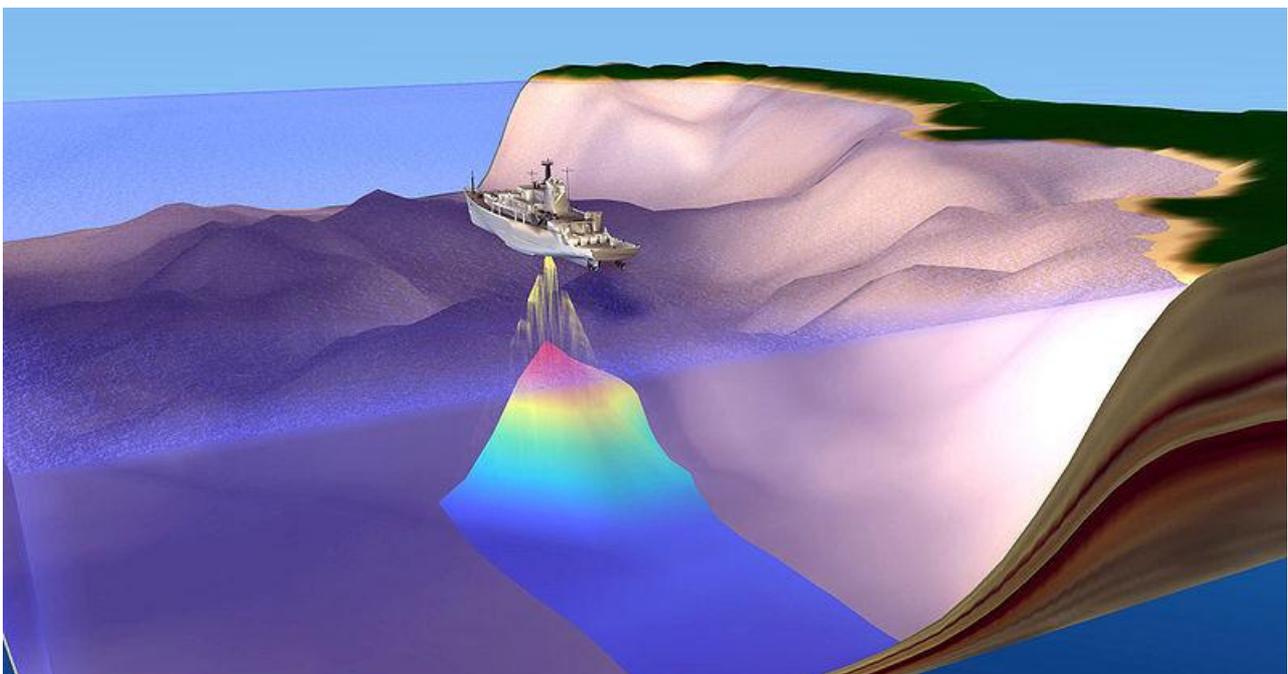


Figure 16: Illustration of Echo Sounding using a Multi-Beam Echo Sounder
Source: www.coml.org

Echo sounders use sound pulses to assess the water depth. The interval from the emission of a pulse to reception of its echo is recorded and the water depth is calculated from the known speed of propagation of sound through water. There are two main types of echo sounders for such purposes: Single-Beam Echo Sounder (SBES) and Multi-Beam Echo Sounder (MBES). An illustration can be seen in Figure 16. SBES is usually used to determine the water depth and it has one transceiver that emits and detects echo time series at normal incidence to the seabed. MBES has multiple transceivers sending sound waves at various angles towards the seabed. It should be noted that MBES can provide comprehensive information on the bottom surface.

3.2.2 Electromagnetic Exploration Technologies

Offshore deepwater electromagnetic exploration technologies as shown in Figure 17 include: controlled-source electromagnetic (CSEM) surveying and magnetotelluric (MT) surveying.

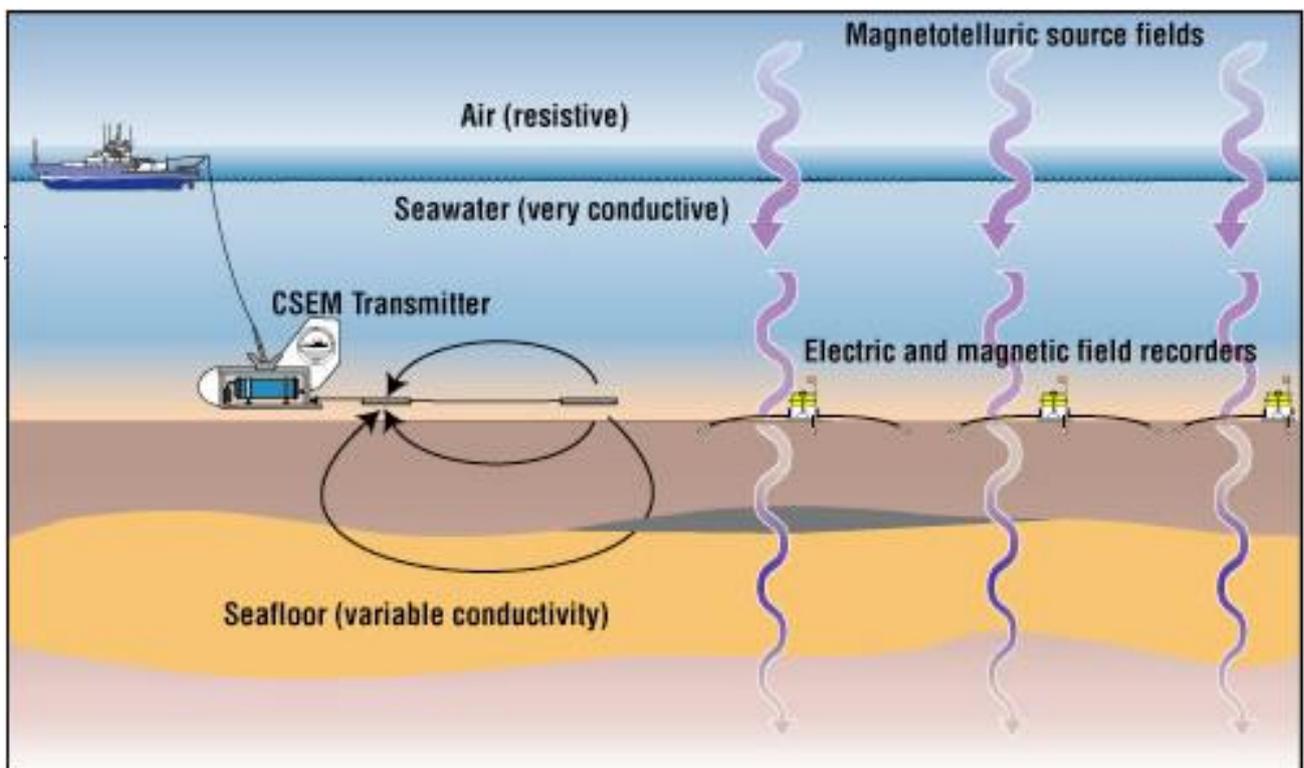


Figure 17: Illustration of Electromagnetic Surveying (CSEM and MT)

Source: www.searchanddiscovery.com

In CSEM surveying, a powerful horizontal electric dipole is towed about 30m above the seafloor. The dipole source transmits a carefully designed, low-frequency electromagnetic signal into the subsurface. Grids of seabed receivers measure the energy that has propagated through the sea and the subsurface. Data processing, post-modelling and inversion are performed to produce 3D resistivity volumes. These datasets are integrated with other

subsurface information to enable to make important drilling decisions with greater confidence.

In a similar way to CSEM surveying, the MT technique is sensitive to resistive bodies in the subsurface. Marine MT surveys map subsurface resistivity variations by measuring naturally occurring electric and magnetic fields on the seabed. The sensitivity of receivers enables to acquire high-quality MT data inherently as part of a CSEM survey when the controlled source is inactive. The naturally occurring electric and magnetic fields are generated by the interactions of solar wind with the Earth's magnetic field, which when strong, are known as geomagnetic storms. The source fields are very low frequency, which offers excellent depth penetration.

The low-frequency, deep-sensing nature of MT surveying makes the technique excellent for mapping and interpreting regional geology. MT technology does not have the same sensitivity towards thin horizontal resistors as the CSEM technique; rather it can penetrate the thicker resistive layers that might otherwise be challenging for CSEM and seismic techniques. (Sinha et al., 1990)

3.2.3 Remotely Operated Vehicles

A remotely operated vehicle (ROV) is a tethered underwater vehicle. ROVs are unoccupied, highly manoeuvrable and operated by a person aboard a vessel shown in Figure 18. They are linked to the ship by a tether (sometimes referred to as an umbilical cable), which is a group of cables that carry electrical power, video and data signals back and forth between the operator and the vehicle. High power applications will often use hydraulics in addition to electrical cabling. Most ROVs are equipped with at least a video camera and lights. Additional equipment is commonly added to expand the vehicle's capabilities. These may include sonars, magnetometers, a still camera, a manipulator or cutting arm, grabbing arms, water samplers, and instruments that measure water clarity, light penetration and temperature.

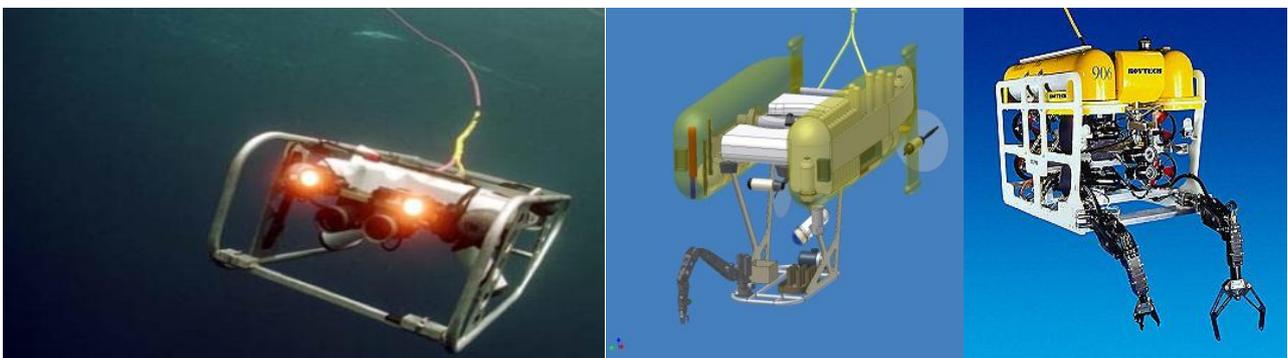


Figure 18: Types of Remotely Operated Vehicles

Source: <http://uncw.edu/nurc/systems/rov.htm> <http://www.sub-find.com/panther.htm>
<http://krafttelerobotics.com/news/abyss/abyss.html>

3.2.4 Autonomous Underwater Vehicles

An autonomous underwater vehicle (AUV) is a robot which travels underwater without requiring input from an operator. They are equipped with echo sounders and various measurement sensors to measure the concentration of various elements or compounds, the absorption or reflection of light, and the presence of microscopic life. Additionally, AUVs can be configured as tow-vehicles to deliver customized sensor packages to specific locations, and return to the ship after a deployment of about 20 hours. Nautilus Minerals Inc. conducted a proof of concept evaluation of AUV technology for seabed massive sulphites chimney field mapping applications over Nautilus Minerals' tenements in the northeast Lau Basin, Tonga in November 2011. This experiment demonstrated AUVs can provide higher resolution mapping than the conventional deep tow technology and offer significant operational productivity gains over ROVs (Stevenson and Plunkett, 2012).

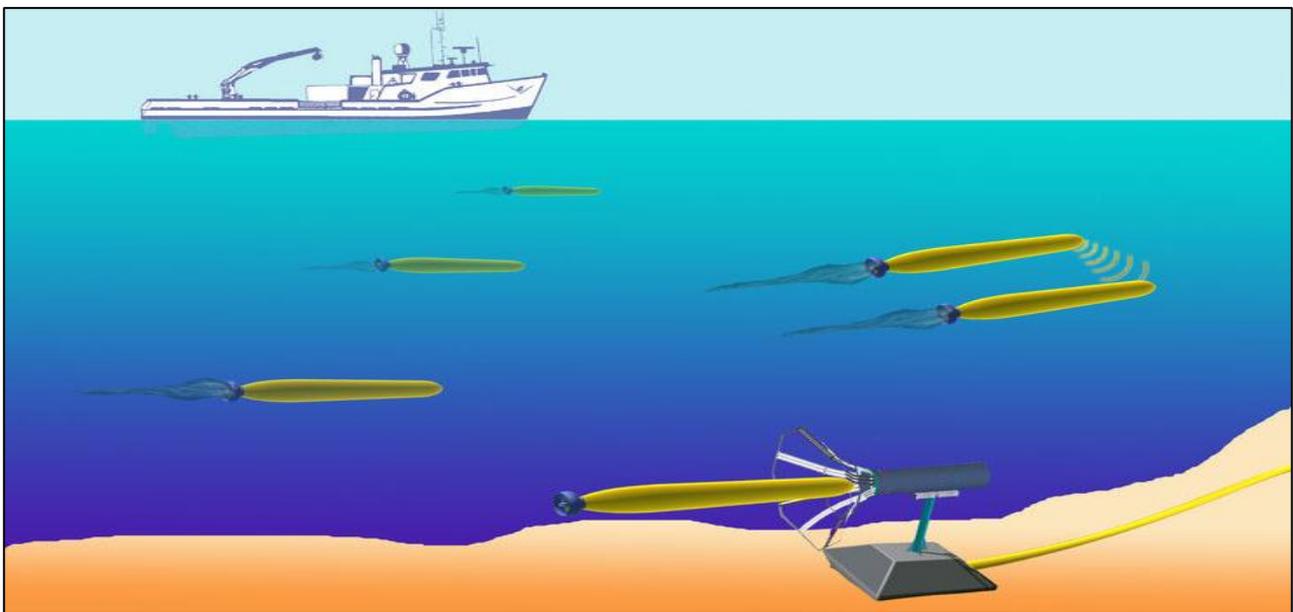


Figure 19: Illustration of Autonomous Underwater Vehicles
Source: www.mbari.org

3.3 Deepsea Mining Technology

Since deepsea mining technology is still in an early stage, wide parts of engineering systems are or may be transferred from the oil and gas as well as dredging industries. This refers particularly to the floaters and risers. For seabed mining new types of seafloor tools need to be taken into consideration. Seafloor tools will be described and evaluated in detail in Chapters 8 and 9.

3.3.1 Floater Types

As depicted in Figure 20 various deepwater floaters including Spar, Tension Leg Platform (TLP), Semisubmersible and Floating Production, Storage and Offloading (FPSO) are applied in offshore industries. These floater types have distinct application areas that are subject to water depths and facility payloads (Bell et al., 2005).

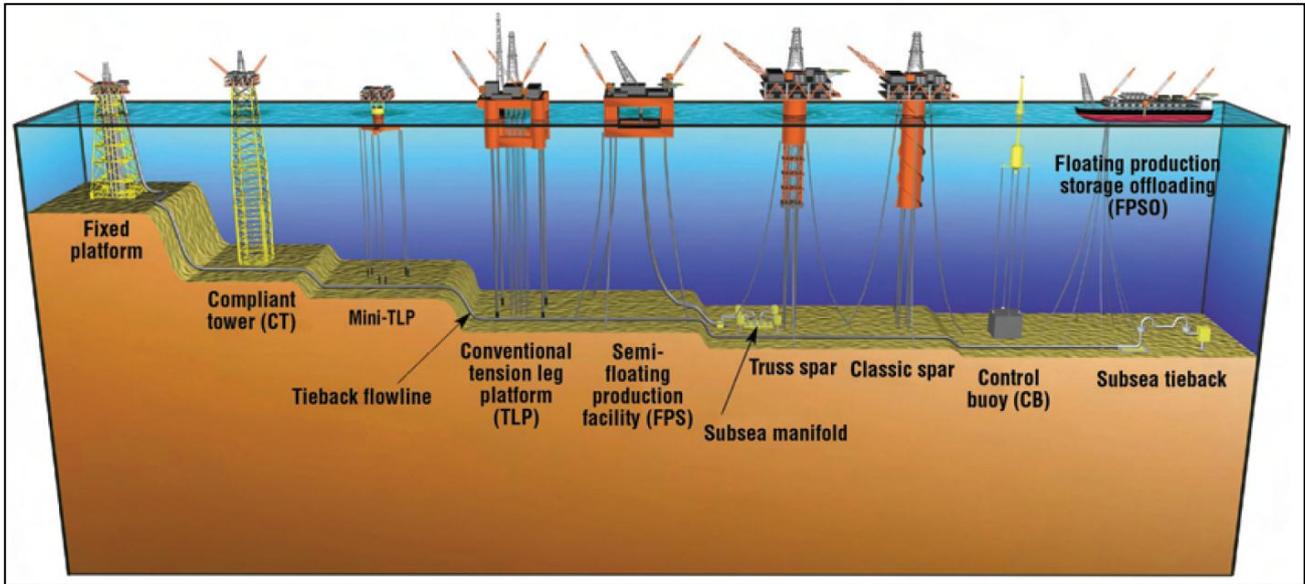


Figure 20: Floater Types
Source: Arnold (2007)

3.3.2 Marine Risers

Marine risers are the structure systems that connect the subsea fields to the production and drilling units. Risers are pipes transferring hydrocarbons and production materials such as injection fluids between the wells and the platforms. During a drilling operation, risers are used to provide transportation of necessary fluids, like drilling mud, to and from the well. They also support drilling strings, guide tools and auxiliary lines. Production and export risers are used to transfer produced oil and gas to the floating unit. Risers are normally made of steel or titanium with the pipe having a wall thickness of less than one inch with an outer diameter of less than thirty inches. The length of the risers depends on the seabed depth. Therefore, a riser is considered as a vital element for offshore production, as a failure in the riser will result in the stoppage of production and can also lead to pollution and spillage as well as very high economic and political consequences.

The selection of a riser system type depends on the meta-ocean data and water depth. As shown in Figure 21. Several types of risers are available extending from the flexible riser, SCR, and free-standing hybrid riser to the top-tensioned rigid riser

Primarily there are two main types of riser: rigid risers and flexible risers. A hybrid riser is a combination of these two (Bai, 2001; Bai, Y. and Bai, Q., 2005). However, the most popular marine riser used in deepwater is the Steel Catenary Riser which presents major merits over the conventional flexible or freestanding hybrid risers.

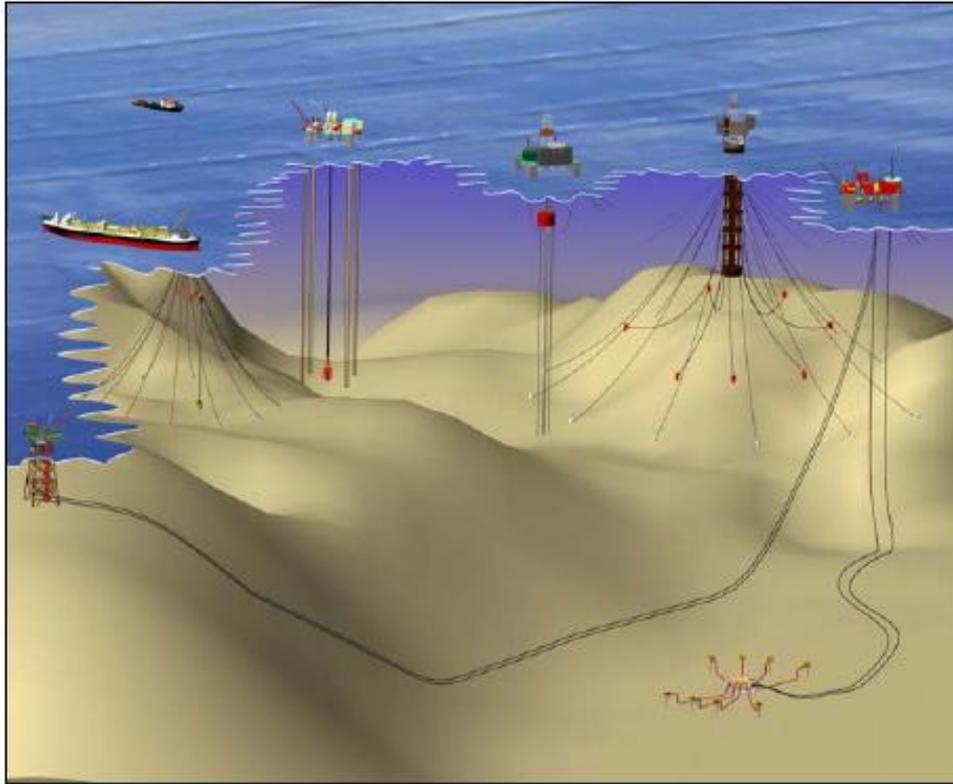


Figure 21: Types of Riser Systems
Source: Song and Stanton (2007)

Flexible risers

A flexible riser provides flexibility to cope with the floating unit motions. Flexible risers were found to be appropriate for offshore applications in the form of production and export risers. The application of a flexible riser has been decided since the 1970s. The crucial characteristic of a flexible riser is its axial stiffness and relative bending. Flexible risers are characterised by their wall structure.

The structure of the flexible riser, as illustrated in Figure 22, is made up of several different layers: an inner metallic carcass for collapse resistance; a plastic pressure sheath fluid containment that is leak-proof; a zeta and flat steel spiral for resisting internal pressure, external crushing loads and hoop stress resistance; steel armours to resist axial tensile loads; anti-wear layer to avoid friction; and a plastic outer sheath to prevent seawater penetration (Sparks, 2007).

The flexibility system of a flexible riser is sustained by arranging the riser in a number of different standard configurations: Steep Wave, Lazy Wave, Free Hanging, Steep S, Lazy S, and Chinese Lantern as shown in

Figure 23.

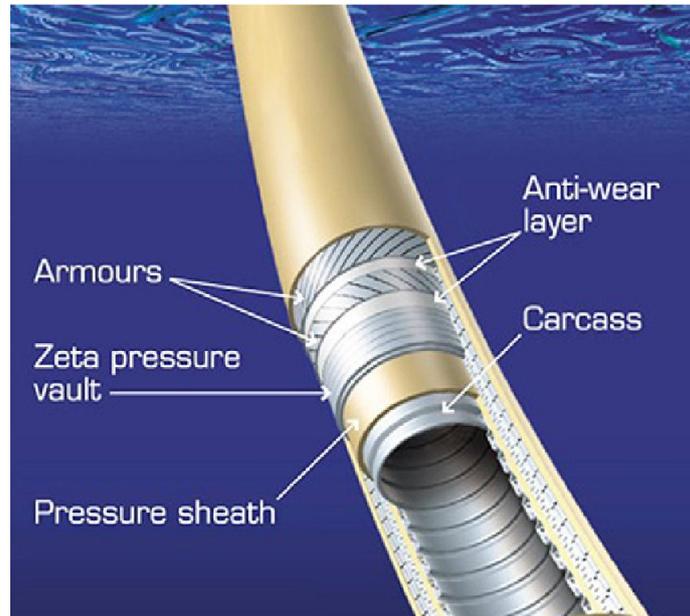


Figure 22: Typical Cross Section of a Flexible Riser
Source: Bai, Y. and Bai, Q. (2010)

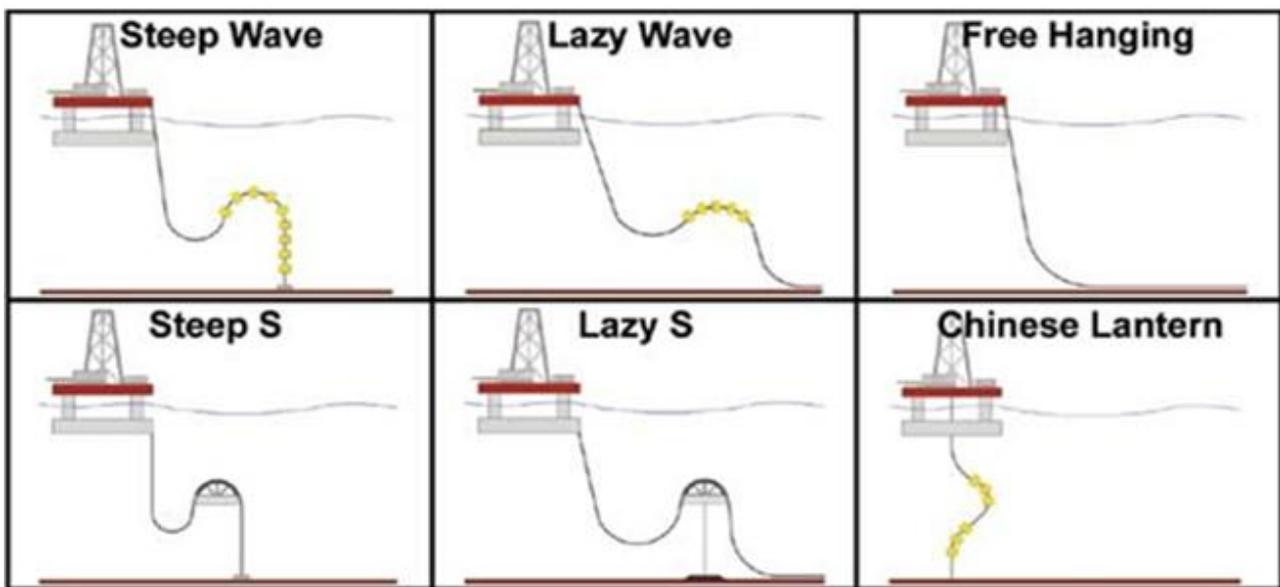


Figure 23: Standard Flexible Riser Configurations
Source: www.pennenergy.com

Steel Catenary Risers (SCRs)

Recently, SCRs have joined the riser family building on the catenary equation that has assisted in creating bridges across the world. SCRs are commonly used with TLPs, FPSOs, semisubmersibles and spars, as well as fixed structures, compliant towers and gravity

structures (Mekha, 2001 and SPARKS, 2007). The number of SCRs is increasing quickly due to simplicity, economic effectiveness, and well-known material properties. They can be hanged in longer lengths, eliminating the need for mid-depth arches or buoys due to the dead weight of its sag-bend. As shown in Figure 24, an SCR is a freely hanging pipe connected to a floating production vessel; it hangs at a prescribed top angle (8° - 20°) and gradually extends down to the seabed at the touch down zone. An SCR consists of a steel pipe, with or without insulation and casing (Kenny, 2007). In deeper waters, be it 800 metres and deeper, it can be more economical to install catenary-shaped risers. They can be suspended in longer lengths, removing the need for mid-depth arches or buoys due to the dead weight of its sag-bend.

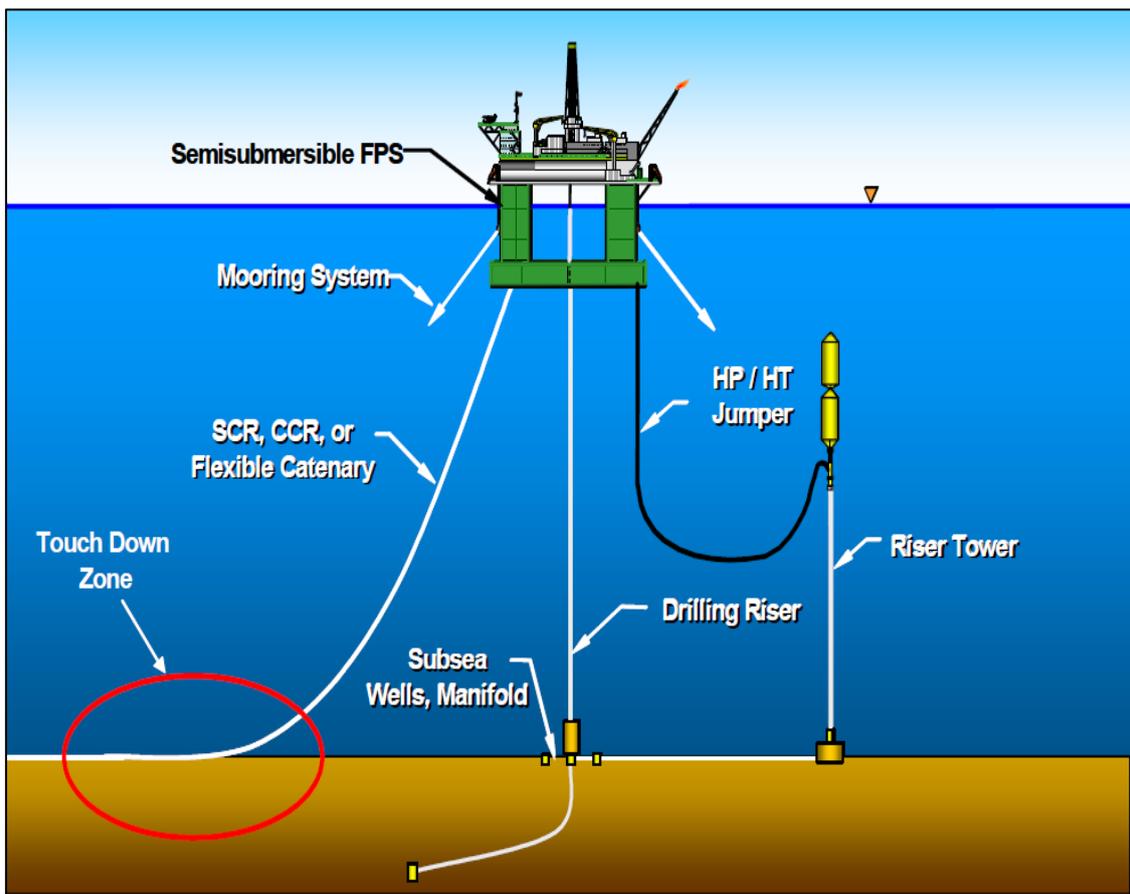


Figure 24: Steel Catenary Riser connected to Semisubmersible

Hybrid Risers (HRs)

A hybrid riser is the combination of rigid and flexible risers. The fundamental of a hybrid riser was developed based on the top-tensioned risers (Bai, Y. and Bai, Q., 2010). A typical configuration of an HR consists of a vertical bundle of steel pipes supported by external buoyancy and flexible jumpers, connecting the top of the riser and the floating unit. It is used to accommodate relative motion between the floater and riser bundle as shown in Figure 25.

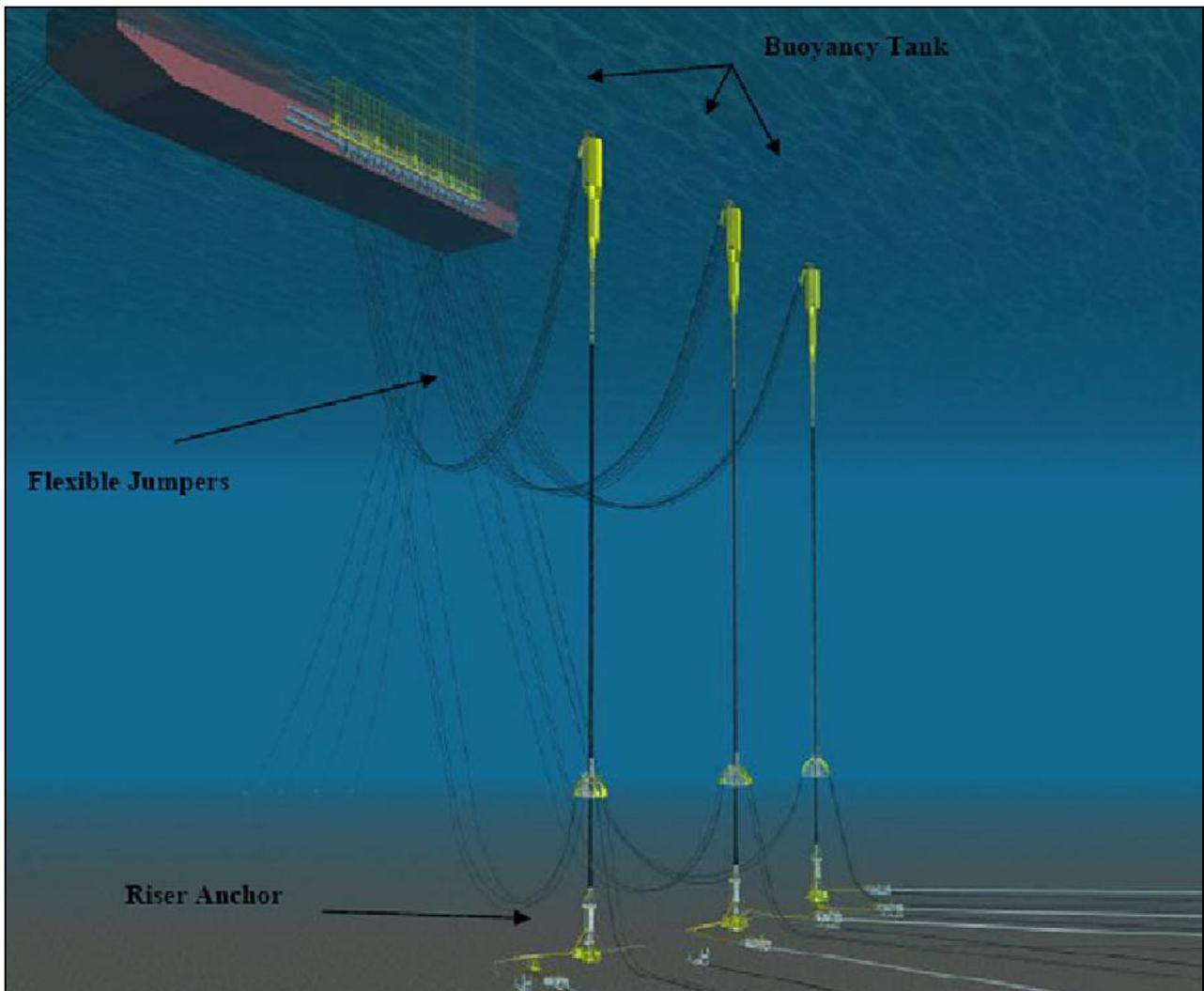


Figure 25: Hybrid riser system
Source: Bai, Y. and Bai, Q. (2010)

Top-Tensioned Risers (TTRs)

TTRs are a completely vertical riser system that terminates directly below the surface unit, such as TLPs and spars (see Figure 26). These floating units are able to move laterally with wind, waves and current even though they are moored.

While TTRs are fixed to the seabed, vertical displacement was introduced between the top of the riser and its connection point on the floating unit. Therefore, the common solution for these issues is a motion compensator that can be included in the top-tensioning riser system. It can maintain constant tension on the riser by expanding and contracting with the motions of the floating unit and buoyancy cans which can be extended around the outside of the riser to keep it afloat. Also, the top of the rigid vertical top-tensioned riser is connected to the floating unit by a flexible pipe in order to accommodate the motions of the floating unit.

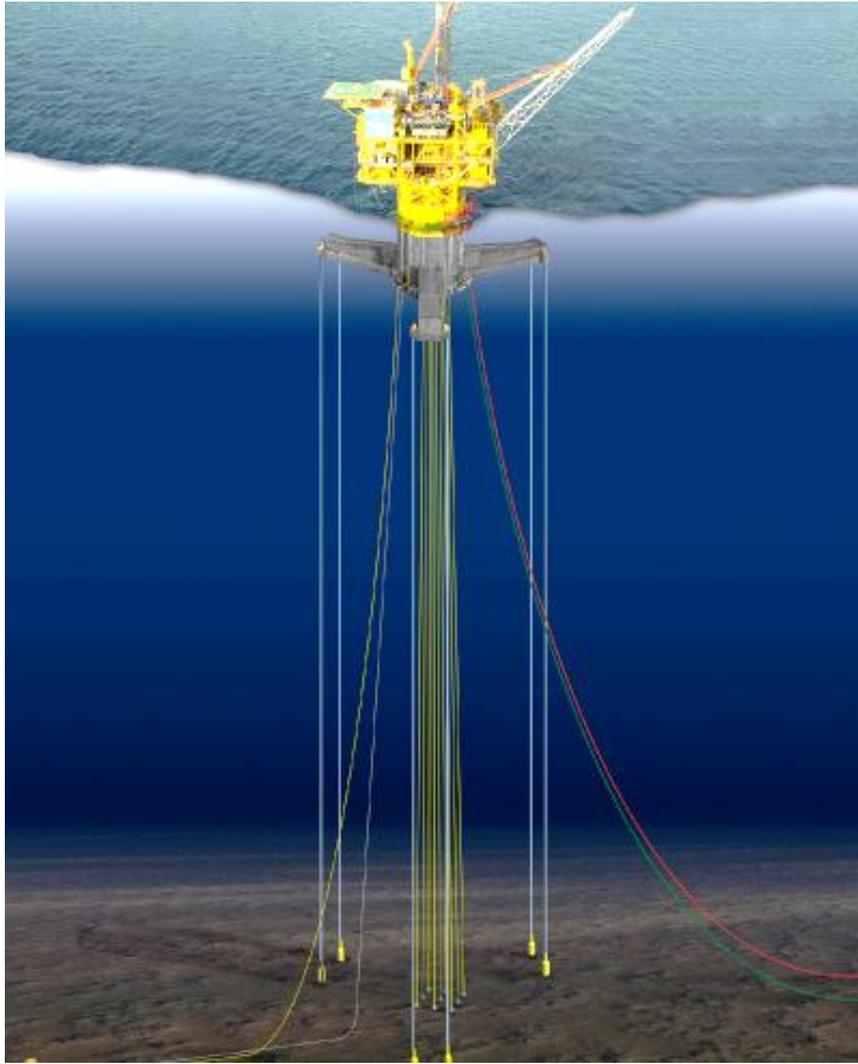


Figure 26: Top-Tensioned Risers
Source: www.rigzone.com

3.4 Cultivation and Harvesting Technologies

Renewable fuels require development of a large domestic supply of diverse biomass feedstocks. Macroalgae, also known as seaweed, could be a potential contributor towards renewable fuels (Carlsson and Bowles, 2007).

Advances in cultivation technology could potentially increase the production rate by three to ten folds with a corresponding decrease in the area needed for cultivation to meet specified production goals. A detailed assessment of environmental resources, cultivation and harvesting technology, conversion to fuels, connectivity with existing energy supply chains, and the associated economic and life cycle analyses will facilitate evaluation of this potentially important biomass resource.

To improve the offshore cultivation of marine macroalgae an offshore ring system has been designed and successfully been tested on a kelp type (*Laminaria saccharina*) in the North Sea. The macroalgae grow on the newly invented ring-structure presented in , which seems

to be beneficial not only in meeting rough weather conditions (strong current velocities and wave heights), but also in permitting easy handling when compared to other constructions (Roesijadi et al., 2010). This construction allows adjustment of the culture lines to an appropriate depth between 1 and 1.5m, which is important to avoid physical harm of the young plants, while simultaneously providing sufficient light intensity for photosynthesis. In addition, the ring management is rather simple as it can be assembled onshore with the respective culture line and harvesting or sampling can be accomplished by heaving the entire ring up via a ships crane or even by hauling the whole structure onshore.

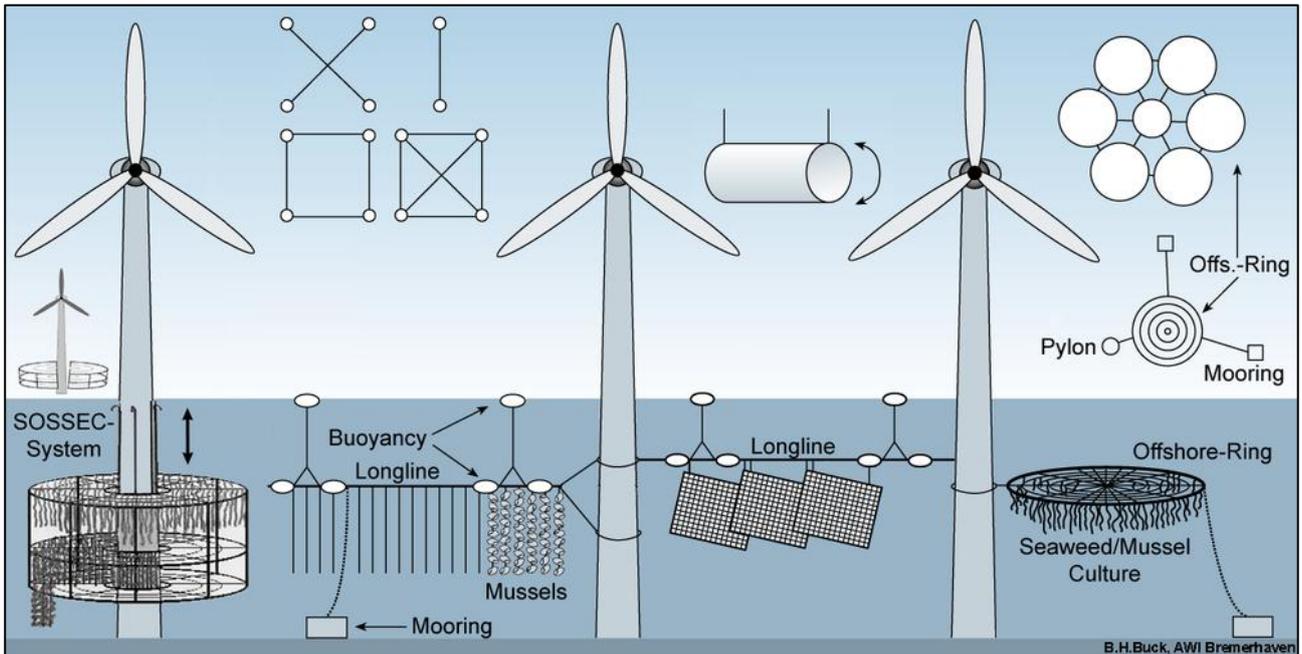


Figure 27: Illustration of Offshore Wind Farms with Seaweed Ring Construction
Source: www.awi.de

Mechanized harvesting methods, which can involve mowing with rotating blades, suction, or dredging with cutters, have been developed. The harvested seaweeds are pumped through a pipe directly onto adjacent barges, which are transported directly to a processing plant by tugboats. Modern seaweed harvesting vessels can be equipped with pumps to direct harvest seaweeds into nets or other containment structures as illustrated in Figure 28.



Figure 28: Illustration of Algae Harvesting Process
Source: www.dnrec.state.de.us

3.5 Concluding Remarks

After reviewing the different parts of engineering technologies relevant to exploration and exploitation of seabed resources, some of the required knowledge to be used in this research is acquired and other existing engineering technology challenges are identified. This chapter presented a review of the state-of-the-art technologies for potential seabed mining as well as cultivation and harvesting. It also discussed the different floater types and marine riser systems as well as seabed exploration tools.

The next chapter outlines the legal environment for seabed exploitation.

4 Legal Environment

4.1 Introductory Remarks

Seabed exploitation refers to seabeds in national and international waters. Therefore, the exploitation of marine resources demands for a thorough analysis of the geo-political and socio-legal context. Against the background of the seabed definition within this report (see Chapter 2), this section presents relevant legal authorities and regulations.

4.2 United Nations Convention on the Law of the Sea

The United Nations Conventions on the Law of the Sea (UNCLOS) is an international agreement that defines the guidelines, rights and responsibilities of nations regarding the worlds' oceans and its marine environments. The UNCLOS III, which is the current Law of the Sea treaty, replaced the four UNCLOS I agreements from 1958. UNCLOS III came into force in 1994 and is signed by 162 nations and the European Community up to day. The convention contains 320 articles that specify ocean space borders, environmental issues, marine research, commercial activities, technology collaborations and dispute instruments. Figure 29 gives an overview of the zones and definitions detailed in the following. Relevant to the research at hand are the territorial seas, contiguous zone, exclusive economic zones and the continental shelf as well as the high sea legislations.

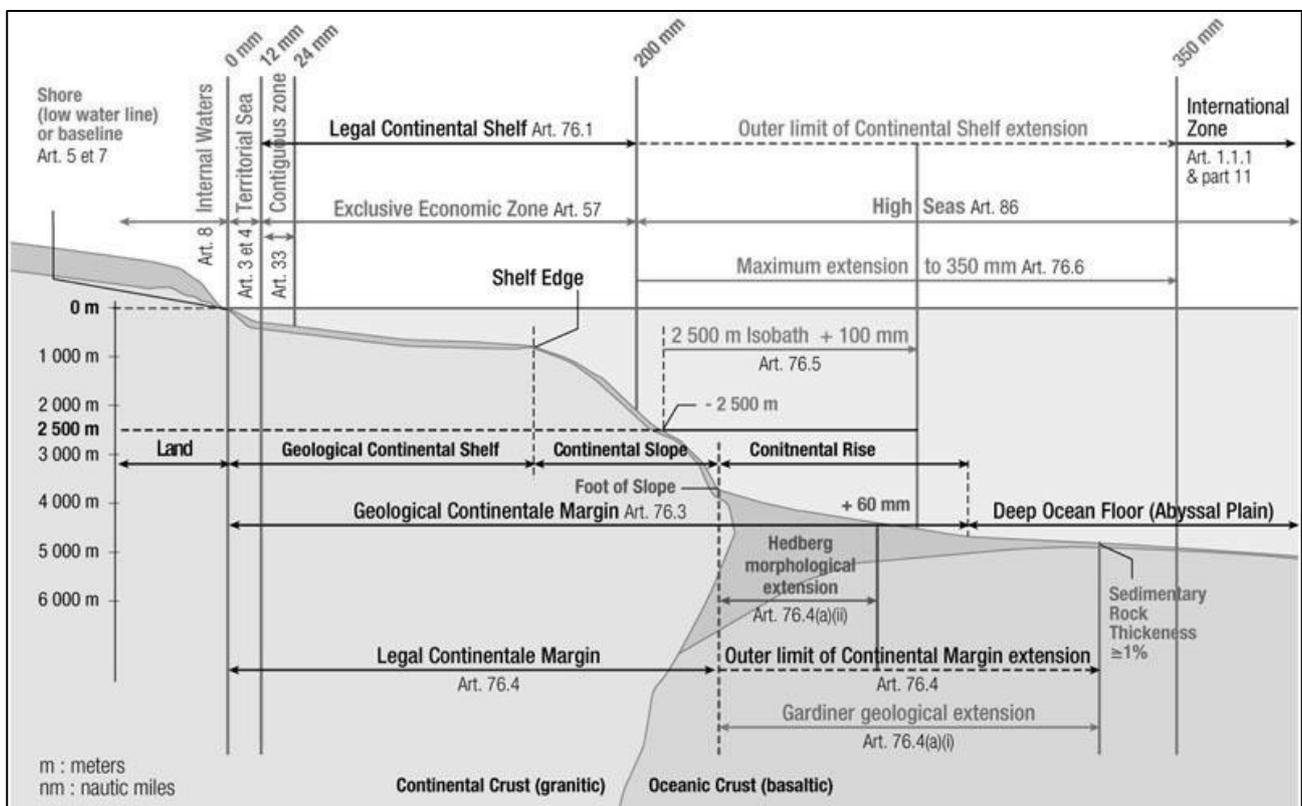


Figure 29: Marine Legal Environment

Source: www.lecerclepolaire.com/images/articles/Pratt/LimitesMer_En-800.jpg

4.2.1 Territorial Waters and Contiguous Zone

Territorial waters (Art. 3 ff) reach out to 12 nautical miles from the low-water mark or so called baseline. The coastal state is allowed to define laws and regulate the exploitation of its resources within these waters. Foreign vessels are given rights to “innocent” passage, whereas fisheries, environmental jurisdiction and commercial activities are subject to state policies. The contiguous zone (Art. 33) may extend the territorial waters line to another 12 nautical miles. Within this zone states can enforce policies on customs, taxes, migration and the environment.

4.2.2 Archipelagic Waters

For a group of islands, the baseline is drawn between the outermost points of the territories. The waters in-between these points are defined as archipelagic waters and are in the sovereignty of the state but allow “innocent” passage.

4.2.3 Exclusive Economic Zones (EEZs)

EEZs (Art. 57) define the waters 200 nautical miles from the baseline. Coastal states have the sovereignty to exploit the natural resources and exercise jurisdiction within this area. Foreign nations and vessels have the freedom of navigation and over flight. Land-locked or so called geographically disadvantaged nations have the right to participate in the revenues of exploited living resources of the EEZ's of coastal states in the same region. Figure 30 indicates the global allocation of EEZ's.

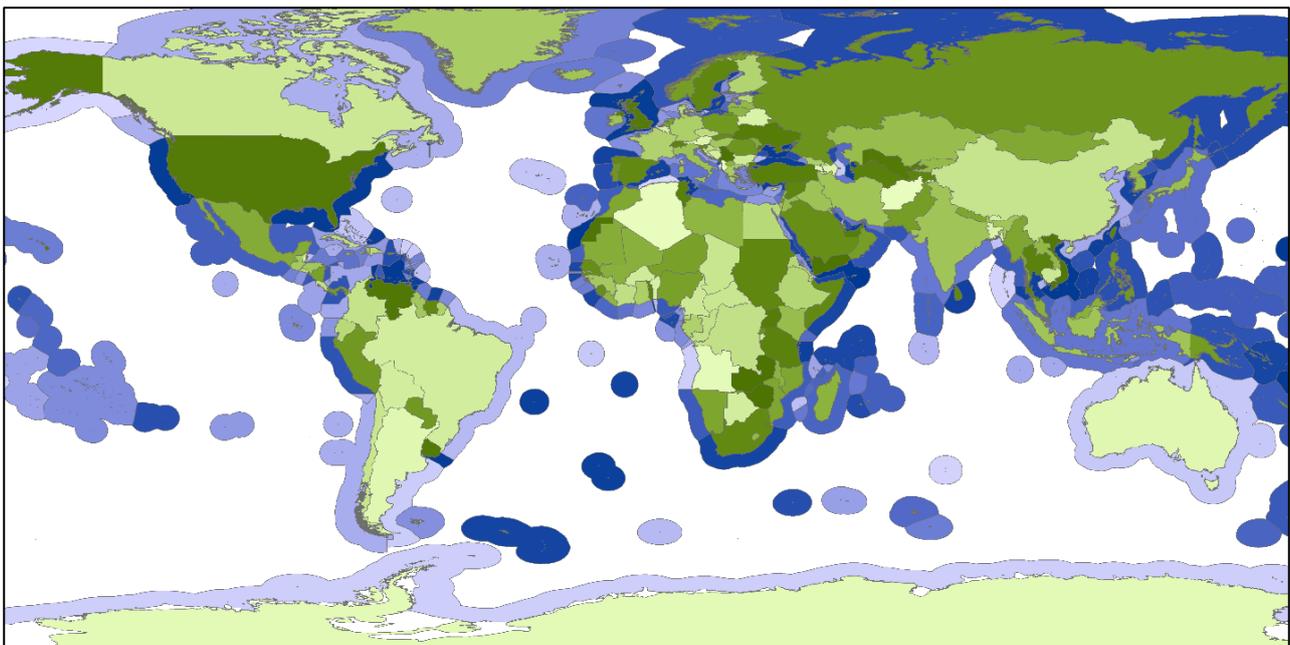


Figure 30: Exclusive Economic Zones (EEZs)
Source: Based on Maritime Boundaries Geodatabase, version 6.1,
<http://www.vliz.be/vmdcdata/marbound>

4.2.4 Continental Shelf

The continental shelf (Art. 76) was given a legal definition as the stretch of the seabed adjacent to the shores of a particular country to which it belongs. The continental shelf is defined as the natural prolongation of the land territory to the continental margin's outer edge, or 200 nautical miles from the coastal state's baseline, whichever is greater. It may never exceed 350 nautical miles from the baseline; or it may never exceed 100 nautical miles beyond the 2,500 meter.

Coastal states have exclusive rights to resources located within the continental shelf. Coastal states have the exclusive right to harvest minerals and non-living materials in the subsoil of its continental shelf and also have exclusive control over living resources "attached" to the continental shelf, but not to creatures living in the water column beyond the exclusive economic zone.

4.2.5 High Seas

Outside of the continental shelf boundaries and thus beyond the limits of national jurisdiction, the protection of the marine environment, navigation, research and resource exploitation is regulated by the International Seabed Authority (ISA). The high seas (Art. 1) follow the common heritage of mankind principle. This principle ensures the conservation of resources for future generations and regulates exploration and exploitation by the international community.

4.3 International Seabed Authority (ISA)

The ISA is an autonomous international organisation that was established as part of the Law of the Sea Treaty in 1994. Its major obligation is the regulation and administration of natural resources in the world's oceans. The headquarters are located in Kingston, Jamaica.

The ISA regulates granting of exploration and exploitation licenses in high seas. Nowadays, exploration licenses are granted to contractors for the Clarion-Clipperton Zone and the Central Indian Basin. The exploration areas are limited to 150,000 km². Contractors are required to report their activities annually and abandon half of the areas after eight years. Since, exploitation licenses have not been awarded yet, commercial activities have not started in high seas.

In addition to the regulative works on the exploration and exploitation of polymetallic nodules, sulphides and crusts, the ISA works on standards for environmental impact assessments for the marine environment. However, deep-sea mining activities up to date are operational only in national zones under national jurisdiction (e.g. Papua New Guinea).

4.4 International Maritime Tribunal (IMT)

The International Tribunal for the Law of the Sea is an independent body established by the United Nations to solve legal issues that arise out of the application of the Convention. It is located in Hamburg, Germany and consists of 21 independent members with expertise in the fields of the law of the sea.

The IMT has jurisdiction over all disputes concerning the interpretation and application of boundaries and obligations. Disputes can be submitted by states that have ratified the convention as well as inter-governmental organisations.

4.5 International Maritime Organisation (IMO)

The International Maritime Organisation (IMO) was established by the United Nations in Geneva in 1948 and is headquartered in London. It operates a regulatory framework for shipping its safety, environmental concerns, legal matters, technical co-operation, maritime security and the efficiency of shipping. This regulatory framework is implemented by several notable conventions such as the Safety of Life at Sea Convention (SOLAS), which was first adopted in 1914 after the Titanic disaster and has been modified and updated by the IMO since. Second, IMO operates the International Convention for the Prevention of Pollution of the Sea by Oil (OILPOL). Besides this, the regulatory work of IMO covers a wide range of maritime issues such as safe navigation, search and rescue, wreck removal, tonnage measurement, liability and compensation, ship recycling, the training and certification of seafarers, emission measurement and piracy. The latter is related to the most recent developments of maritime security by the International Ship and Port Facility Security Code.

4.6 Concluding Remarks

The relevant legal authorities and regulations of the exploration and exploitation of marine resources were presented. The guidelines, rights and responsibilities of nations regarding the sea are specifically defined by UNCLOS. The seabed resources in national water are subject to national laws and regulations. Outside the national water, the seabed resources in the International water are regulated and administrated by the ISA.

The seabed resources and their associated exploitation technologies and legal regulations were extensively reviewed in the previous chapters. Using this review as foundation, we will introduce the research framework and methodology in the following chapter.

5 Research Framework and Methodology

5.1 Introductory Remarks

Based on the review of seabed resources, the legal background and exploitation technologies, this section aims to provide the reasoning for the research focus on developing guidelines and a new concept for sustainable mining of seafloor massive sulphides in inactive hydrothermal vents and sediments respectively. In a second step Atlantis II Deep is chosen as an example site with prospects for future exploitation that shall be dealt with for concept development. It introduces the concept of sustainability and presents an overall assessment of seabed resources as well as the research framework and methodology for the study at hand.

5.2 Focus “Sustainable Seabed Mining of Polymetallic Sulphides”

The marine resources presented in Chapter 2 lead to minerals and uses that are not unique or different from resources exploited onshore. They must compete for price, quality and supply reliability with other sources. Therefore, marine minerals must either prove to exist in large, high-quality deposits and/or to be mined and processed more sustainably than their onshore counterparts in order to be competitive.

Sustainability or sustainable development are terms of common use in business, media, societal and political debates nowadays. The underlying traditional understanding of sustainability is defined by the triple bottom line concept (Elkington, 1997) as the balance of "(...) economic development, environmental stewardship and social equity" ((Sikdar 2003), p. 1928).

Research on the viability of seabed exploitation demands comprehensive analyses of multidisciplinary determinants such as economics of resources and their exploitation, environmental effects, societal benefits and legal constraints. Hence, this research aims to apply the holistic triple bottom line understanding of sustainability to seabed exploitation. Figure 31 presents this understanding and indicates sustainability in the centre of the three dimensions.

- **Economic dimension:** *"Economic prosperity involves the creation and distribution of goods and services that will help to raise the standard of living around the world. Open, competitive, international markets that encourage innovation, efficiency, and wealth creation are fundamental aspects of sustainable development"* ((Bansal, 2005), p. 198).
- **Environmental dimension:** *"Ecologically sustainable companies use only natural resources that are consumed at a rate below the natural reproduction, or at a rate below the development of substitutes. They do not cause emissions that accumulate in*

the environment at a rate beyond the capacity of the natural system to absorb and assimilate these emissions. Finally they do not engage in activities that degrade ecosystem service" ((Dyllick and Hockerts, 2002), p. 133).

- **Societal dimension:** *"The social equity principle ensures that all members of society have equal access to resources and opportunities. (...) Human needs not only include basic needs such as food, clothing, and shelter, but also include a good quality of life such as health care, education, and political freedom" ((Bansal, 2005), p. 198).*

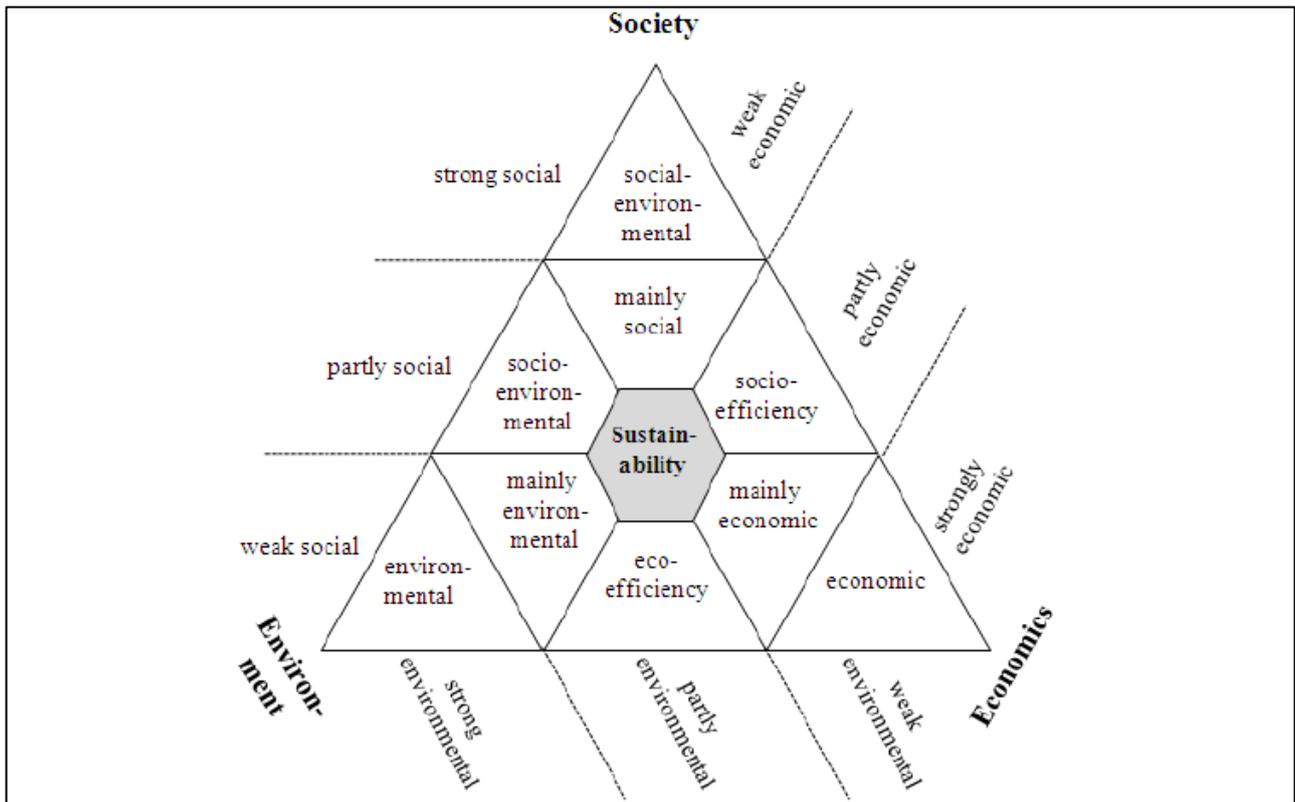


Figure 31: The Triple Bottom Line Concept of Sustainability
 Source: Adapted from Dyllick & Hockerts (2002); Bansa (2005)

For the selection of the seabed resource in focus of this research, the sustainability dimensions are considered as supportive lenses. Table 4 presents a selection matrix that summarises the findings of Chapter 2 for massive sulphides in active and inactive vents (as well as sediments), manganese nodules and macroalgae.

Seafloor massive sulphide deposits are rich in multi minerals such as Copper, Zinc, Lead, Silver and Gold. Nearly all of these minerals are considered as scarce, with reserve/consumption rates of 10 to 25 years (see Figure 32). They occur in water depths of 1000 to 4000m, which is in scope of current technology developments. The economic feasibility strongly depends on the deposit composition and concentrations. Moreover, the ability to minimise and mitigate environmental impacts plays a predominant role. Active hydrothermal vents are known as sources of life due to chemosynthetic processes, whereas inactive hydrothermal vents are shut-off sites with assumed lower biodiversity levels.

Manganese nodules are highly concentrated polymetallic deposits that occur in deep sea and hold manganese, copper, nickel and cobalt. These elements show higher reserve/consumption rates of 25 to 100 years. The economic feasibility is strongly dependent on the concentration of nodules in certain areas and the comparability to land sources. From an environmental perspective, the growth and occurrence is subject to very slow reproduction processes. Environmental effect assessments of their exploitation are still in an early stage. Legally, the exploitation is subject to international laws.

Macroalgae are proposed to be a future solution to mass production of biofuels. Engineering solutions are currently majorly tested in pond and lab environments. The economic feasibility depends on the product mix of uses in biofuels, food products and fertilisers. Due to the shallow water depths that allow macroalgae growth and the high related biodiversity, environmental impacts need thorough investigation.

Table 4: Selection Matrix of Seabed Resources

Massive Sulphides (Active Vents)	Massive Sulphides (Inactive Vents/ Sediments)	Manganese Nodules	Benthos: Algae and Biofuel
<i>Economics</i>			
<ul style="list-style-type: none"> ▪ Mineral rich deposits (e.g. Cu, Zn, Ag, Au) ▪ Water depths: ~1000 – 4000m 	<ul style="list-style-type: none"> ▪ Mineral rich deposits (e.g. Cu, Zn, Ag, Au) ▪ Water depths: ~1000 – 4000m 	<ul style="list-style-type: none"> ▪ Highly-concentrated polymetallic nodules (e.g. Mn, Co, Ni, Cu) ▪ Water depths: ~4000 - 6000m 	<ul style="list-style-type: none"> ▪ Multiple uses of algae as biofuels, fertilisers and food ▪ High production rate compared to landbased biofuels ▪ Water depths: 0 – 50m
<i>Environment</i>			
<ul style="list-style-type: none"> ▪ Chemosynthesis: High biodiversity 	<ul style="list-style-type: none"> ▪ Shut-off active chemosynthesis: lower biodiversity 	<ul style="list-style-type: none"> ▪ Growth and occurrence unclear ▪ Deep seawater biodiversity in early exploration state 	<ul style="list-style-type: none"> ▪ High biodiversity related to algae growth ▪ Limited research and knowledge on mass algae cultivation on the seabed
<i>Society / Legal</i>			
<ul style="list-style-type: none"> ▪ EEZ and High Seas (Intl. Waters) 	<ul style="list-style-type: none"> ▪ EEZ and High Seas (Intl. Waters) 	<ul style="list-style-type: none"> ▪ High seas, CCZ and Indian Ocean 	<ul style="list-style-type: none"> ▪ EEZ

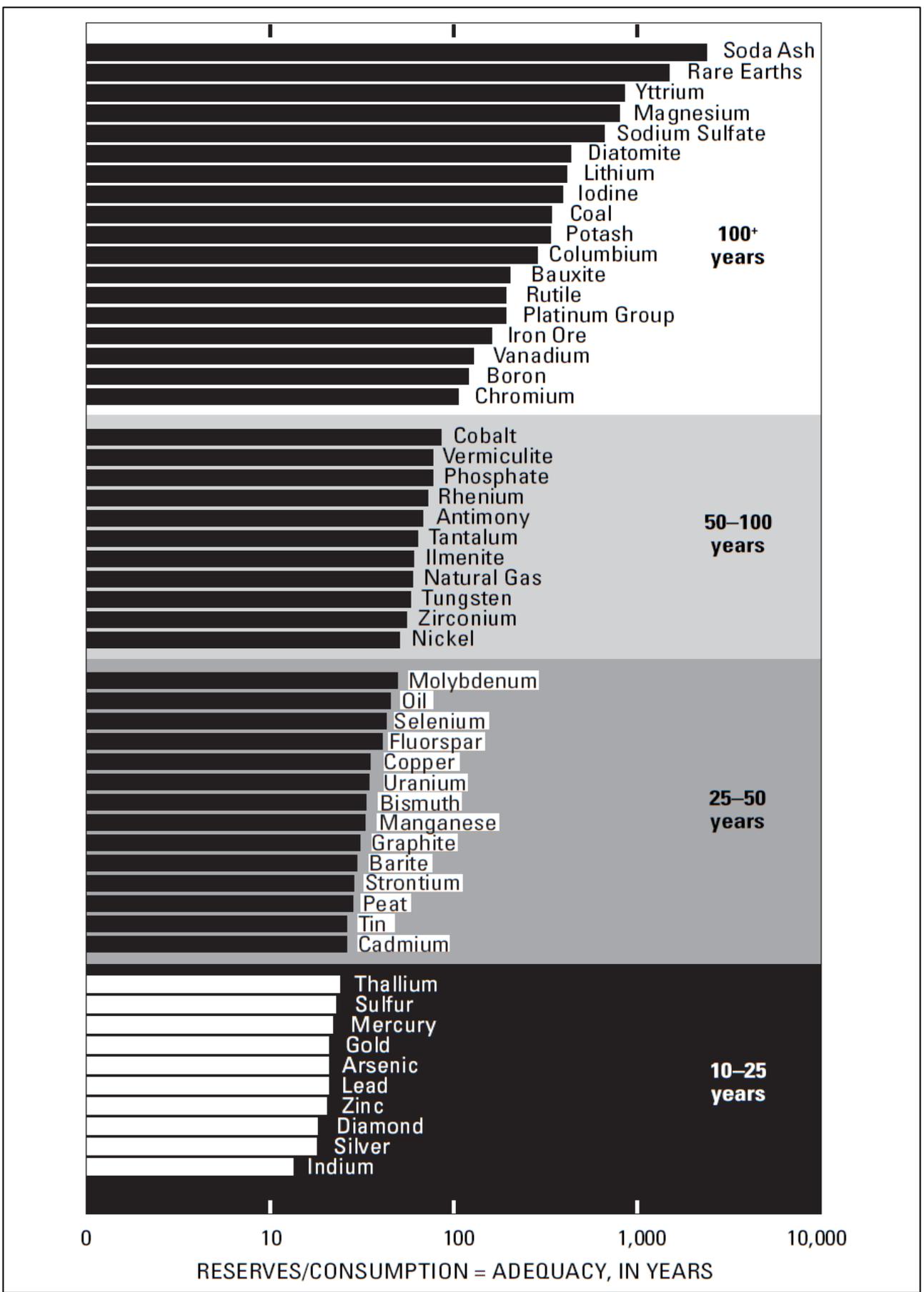


Figure 32: Global Reserves and Annual Global Consumption of Selected Minerals
 Source: Kesler (1994)

As a conclusion, mining of massive sulphides in inactive hydrothermal vents or sediments is chosen as a research focus. In contrast to manganese nodules, the legal environment and engineering technologies seem to be more likely to allow a short- to mid-term commercialisation. Furthermore, the natural reproduction rate of massive sulphides is higher than in nodules. The environmental impacts in inactive vent environments are assumed to allow for mitigation strategies in contrast to active vent sites. Macroalgae and the mass production of biofuels are proposed to be of high economic and societal interest. Currently macroalgae are mostly investigated and commercialised in pond environments. Alternative concepts in the sea cultivate microalgae, which are not attached to the seafloor. Since the business case for algae cultivation and harvesting might go beyond the seabed environment, algae are proposed as a topic for future research to exploit harsh environments.

Based on this decision, the research aims to investigate the critical issues for sustainable seabed mining of massive sulphides in inactive hydrothermal vents based on a real-world example. The second step for the research focus is thus, to define a potential mining site. The International Seabed Authority published a review of the 10 most likely massive sulphide mining sites. Atlantis II Deep is one of the more explored ones that has a land mine comparable deposit size. Moreover, its jurisdiction and legal environment in Saudi Arabia and Sudan is seen as supportive for seabed mining. Against this background, Atlantis II Deep is chosen as an example study context for sustainable seabed mining.

Table 5: Potential Mining Sites of Massive Sulphides at Inactive Hydrothermal Vents
Source: ISA (2010)

Potential Deposit Sites	Water Depth	Jurisdiction	Country
Atlantis II Deep	2,000-2,200 m	EEZ	Saudi Arabia, Sudan
Middle Valley Northeast Pacific	2,400-2,500 m	EEZ	Canada
Explorer Ridge Northeast Pacific	1,750-2,600 m	EEZ	Canada
Lau Basin Southwest Pacific	1,700-2,000 m	EEZ	Tonga
North Fiji Basin Southwest Pacific	1,900-2,000 m	EEZ	Fiji
Eastern Manus Basin Southwest Pacific	1,450-1,650 m	EEZ	Papua New Guinea
Central Manus Basin Southwest Pacific	2,450-2,500 m	EEZ	Papua New Guinea
Conical Seamount Southwest Pacific	1,050-1,650 m	EEZ	Papua New Guinea
Okinawa Trough West Pacific	1,250-1,610 m	EEZ	Japan
Galapagos Rift East Pacific	2,600-2,850 m	EEZ	Ecuador
EPR 13°N East Pacific	2,500-2,600 m	International	International
TAG Central Atlantic	3,650-3,700 m	International	International

5.3 Research Framework and Methodology

The research aims to develop general guidelines for sustainable seabed mining of polymetallic sulphides and a new concept for the Atlantis II Deep deposit in the Red Sea. As outlined in the previous subchapter the approach is based on the triple bottom line concept of sustainability. The holistic approach thus covers the economics and societal benefits, the environmental impacts and mitigation strategies as well as the engineering system, logistics and legal environment for seabed mining.

Due to the early stage of seabed exploitation research, the knowledge on sustainable mining is planned to be gathered by an action research approach (Checkland and Holwell, 1998) in three interrelated stages of data collection and analysis. As shown in Figure 33, a broader academic and industrial view on sustainable seabed mining shall be gained by a large scale survey. Specific knowledge on seabed mining based on lessons learned and expert knowledge will be gathered from expert interviews and a case study on the first commercial seabed mining operation. This triangulation of quantitative and qualitative datasets supports understanding and designing systems and shall be applied as the basis of the new concept and general guidelines (Jick, 1979).

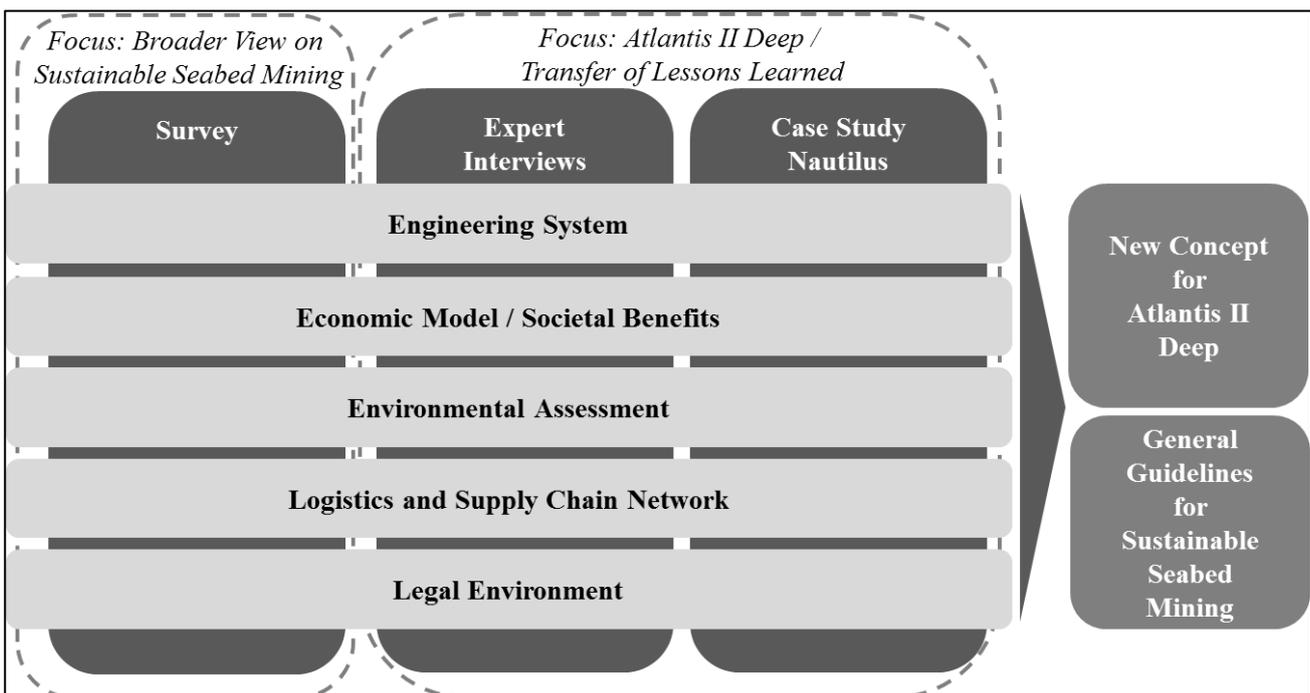


Figure 33: Research Framework

5.3.1 Survey

The large scale survey is developed as an exploratory study to quantitatively describe academic and industrial perceptions of seabed mining from related disciplines. A random sampling method was chosen to generate an equal or known probability of participation for the various disciplines (Bamberger, 2000). For the survey distribution, university networks,

individual industrial partners, organisations and institutions with relation to seabed mining were addressed. The quantitative datasets are of subjective nature but aim to be aggregated and generalised for all dimensions of the research framework. The online questionnaire covered 15 questions along the dimensions of the research framework (see Appendix A.1).

5.3.2 Expert Interviews

The expert interviews aim at gaining in-depth knowledge on the subject of seabed mining. The experts were chosen according to their knowledge in one or more of the dimensions introduced in the research framework. All interviews were conducted in person or as telephone interviews with durations of 60 to 120 minutes and followed a semi-structured guideline (Flick, 2009). The gained qualitative datasets extend the quantitatively available knowledge of the survey and provide insights on specifics of Atlantis II Deep and critical issues for the concept development and guideline design.

5.3.3 Single Case Study

As a third dataset, a single case study on the first commercial seabed mining operation in Papua New Guinea is chosen. Single case studies provide deep information on the dynamics of a system (Eisenhardt, 1989). The aim of the presentation of the Nautilus Minerals case is to identify solutions and lessons learned for sustainable seabed mining from a first mover viewpoint. The datasets in focus are publically available on the website and include technical and economic feasibility studies, specifications, annual reports and news feeds. The units of analysis refer to the proposed research framework above.

5.3.4 Concept Proposal and Guideline Development

Based on the three folded approach considering quantitative and qualitative datasets of the public, subject matter experts and a real-world example, the new concept for Atlantis II Deep is developed and guidelines are derived. The new concept transfers the gathered knowledge to the Atlantis II Deep environment and proposes solutions for site specific critical issues and seafloor massive sulphide mining in general.

6 Survey Results

6.1 Introductory Remarks

One of the three pillars of the research at hand was an online survey on the perceptions of industry and academia on seabed mining. The survey was conducted in August 2012 and was sent out to numerous universities, research institutions as well as industry partners. Its objective was to bring together expertise and views of various disciplines relevant to seabed mining. The questionnaire, which can be seen in Appendix A.1, comprised 15 mandatory questions and 5 expert questions in the following structure:

- a) Participant information (5 questions)
- b) Societal benefits of seabed resources (2 multiple choice questions)
- c) Economics of seabed mining (2 multiple choice questions)
- d) Environmental effects of seabed mining (2 multiple choice and 1 open question)
- e) Engineering systems and technologies for seabed mining (1 multiple choice question)
- f) General drivers and barriers for seabed mining (2 multiple choice questions)
- g) Expert questions regarding the feasibility of seabed mining in general and specific to Atlantis II Deep

6.2 Survey Overview

The survey was completed by 147 participants from Europe (~60%), North America (~16%), Asia (~13%) and the Middle East (~11%). The actual response rates from residents and nationals of world's regions is indicated in Figure 34 and may partly explained by the wide-spread distribution of the survey at the University of Southampton, Strathclyde University, Imperial College London, Seoul University and Dalhousie University.

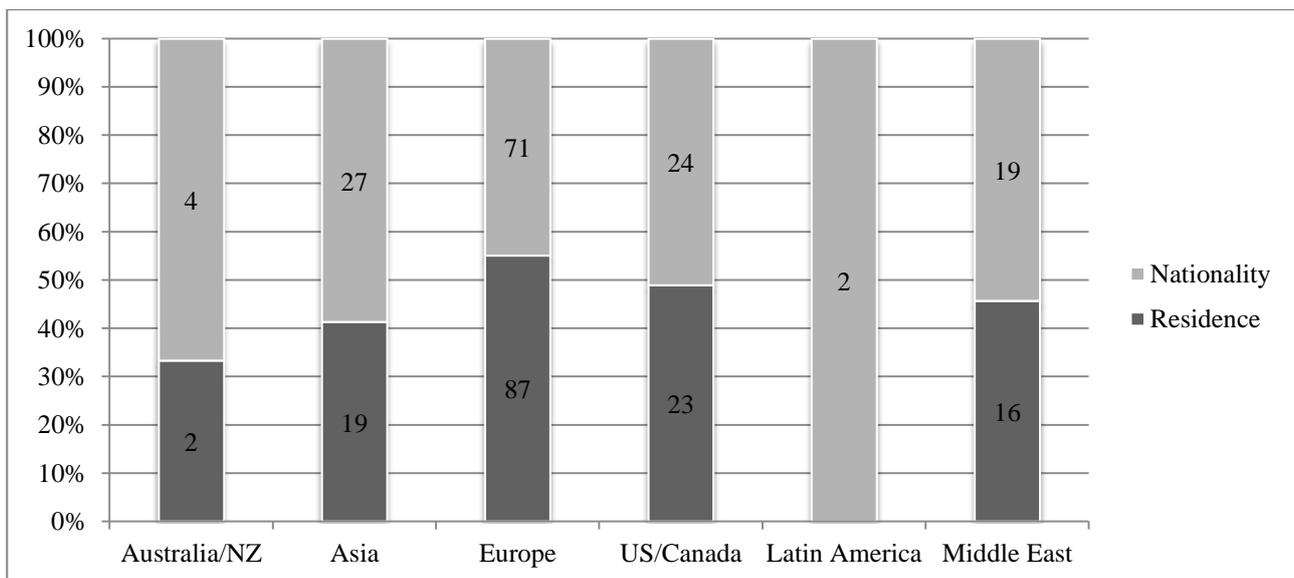


Figure 34: Overview of Survey Participant Origin

Figure 35 presents the affiliation and gender distribution of the survey participants. It indicates a high response rate and interest in seabed mining by experts in the fields of maritime engineering / naval architecture (32.7%) and earth sciences (~17.6%). 80% of the responses came from academia and 20% from industry, with largest amount working as managers and engineers in the maritime industry. 30.6% of the respondents were female.

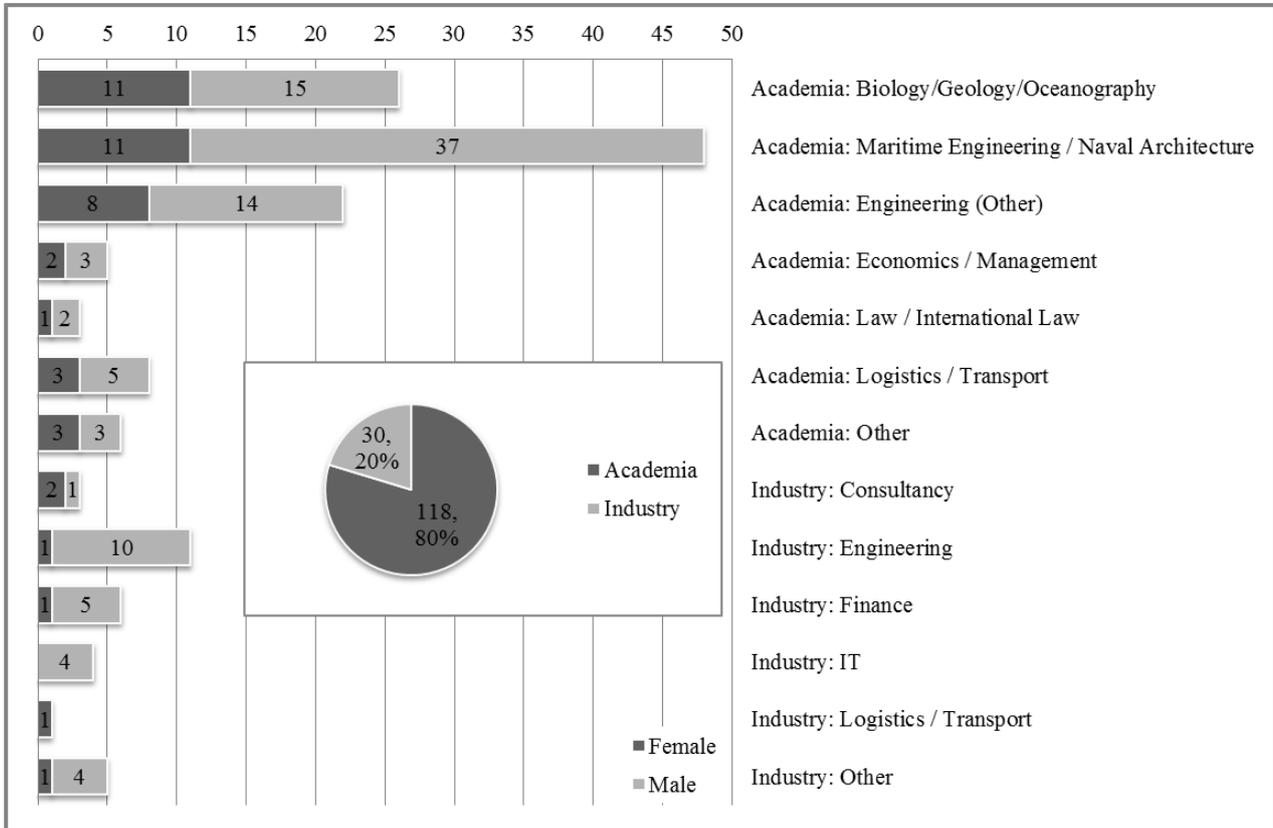


Figure 35: Affiliation of Survey Participants (Absolute / Percentage)

As shown in Figure 36, 32.2% of the survey participants from academia were academic and research staff and 38.1% PhD students. From the industry participants 46.7% were in management positions and 38.9% in operations.

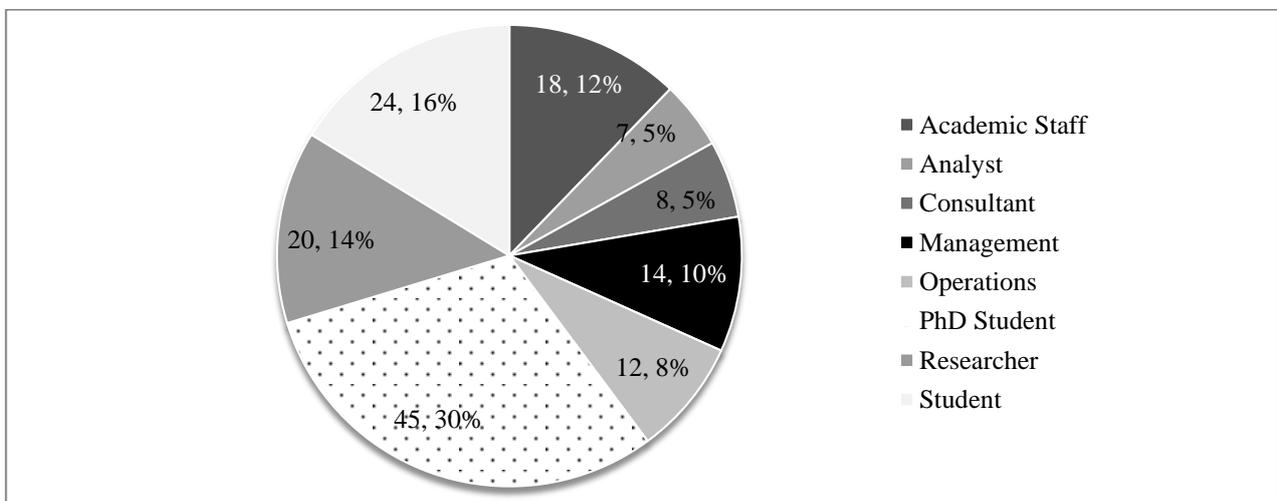


Figure 36: Position of Survey Participants

6.3 Economics

The economic section of the survey aimed at identifying the views of the participants on the largest economic barriers for seabed mining. The majority of participants selected the costs of operations on sea (84.9%) and the research and development costs for engineering systems (66.6%) as high and very high barriers, whereas a lack of customers was identified as very or low barrier (68.2%). The volatility of mineral prices, lack of investors and licensing costs were chosen as mediocre barriers.

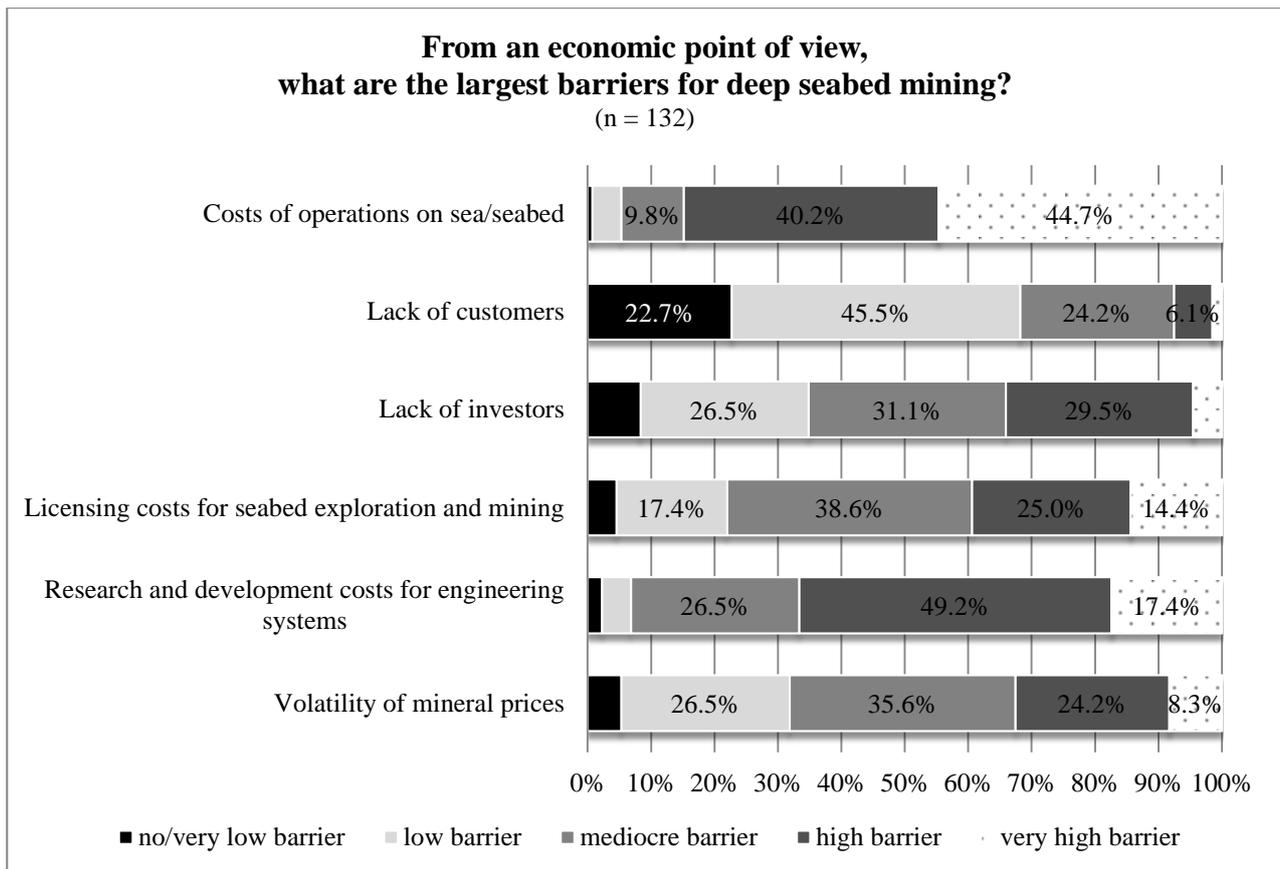


Figure 37: Economic Barriers for Seabed Mining

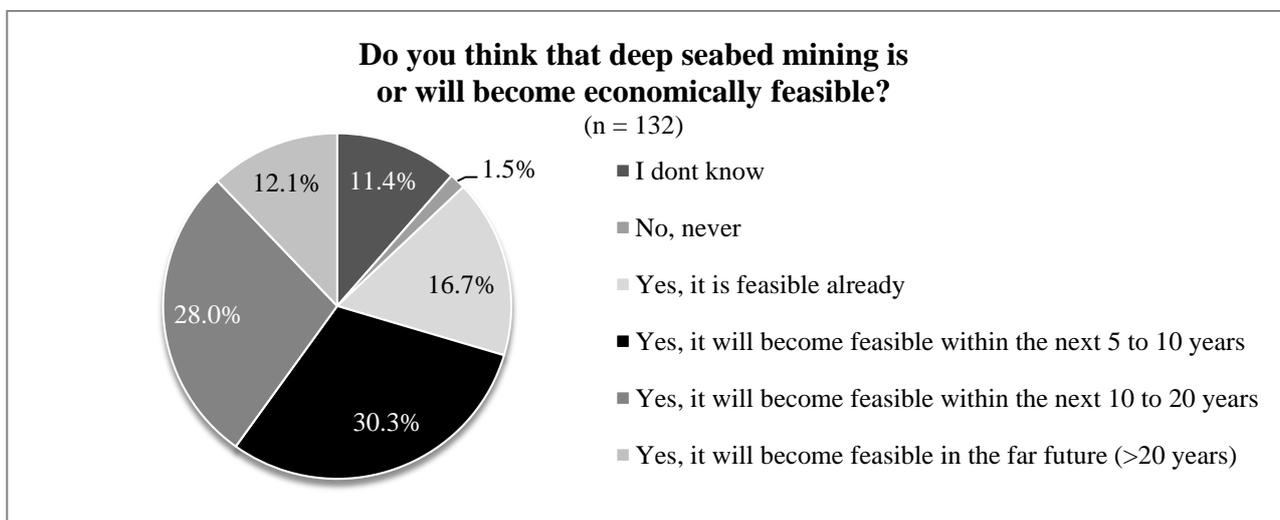


Figure 38: Economic Feasibility of Seabed Mining

Figure 38 presents the results on the perceptions on the economic feasibility. 30.3% of the participants believe that seabed mining will become economically feasible in the next five to 10 years, whereas only 1.5% believe that seabed mining will not become feasible at all. The majority of industry participants from the finance industries selected the feasibility within the five to ten years.

6.4 Societal Benefits

The questions on the societal benefits of minerals from the seabed aimed at identifying the understanding of the relevance of minerals in society and everyday life. It was assumed that a lack of knowledge on the use of minerals might be a hindering factor for the implementation of seabed mining for certain minerals.

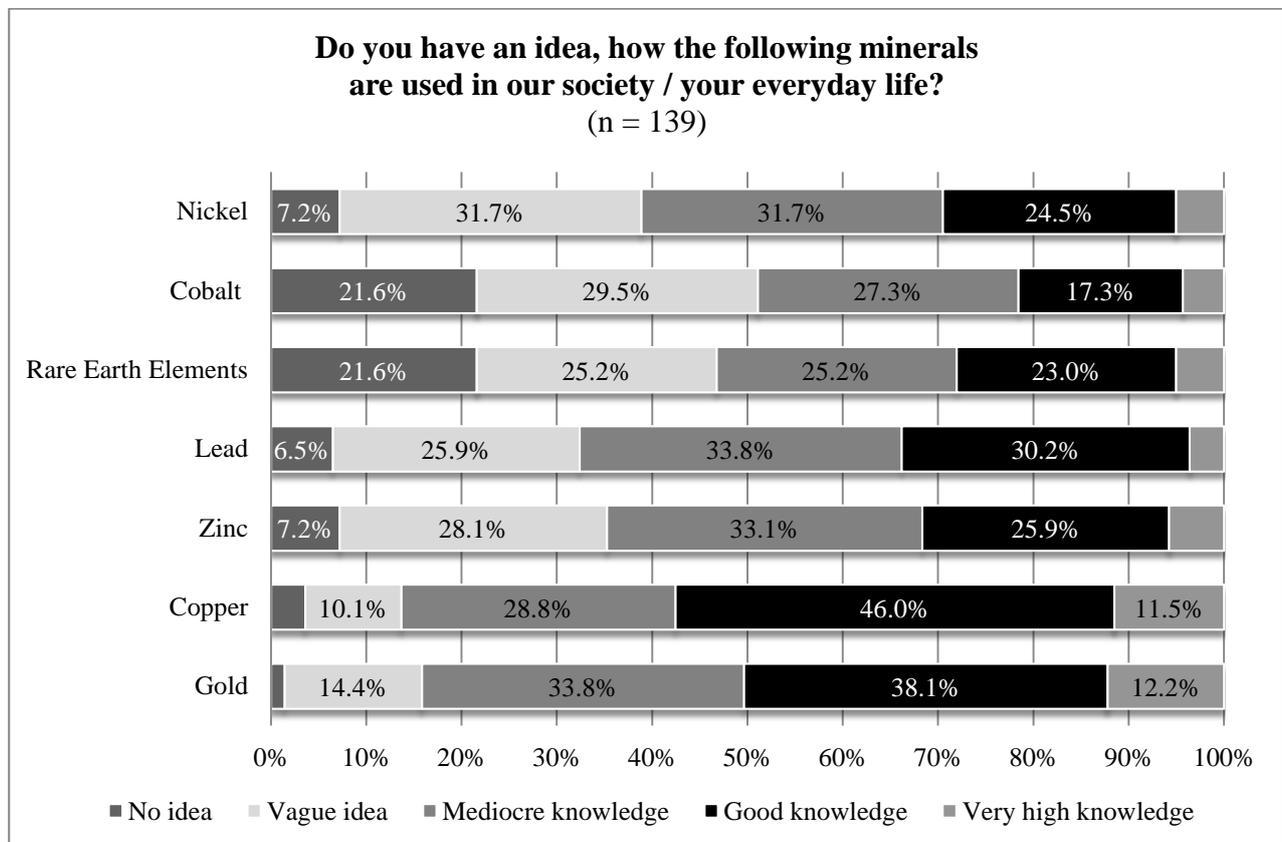


Figure 39: Knowledge on Applications of Seabed Minerals

In Figure 39, it can be seen that the participants have rather good knowledge on application of Gold and Copper, whereas Nickel, Cobalt, Rare Earth Elements, Lead and Zinc hold rather mediocre or vague knowledge in public. This aspects needs to be considered for public awareness and involvement for potential mining sites of the latter elements.

In a second question the participants were asked for societal and industrial benefits of seabed mining. Figure 35 underlines that especially electronics and telecommunication as well as scientific advancement are seen as major societal benefits that drive seabed mining.

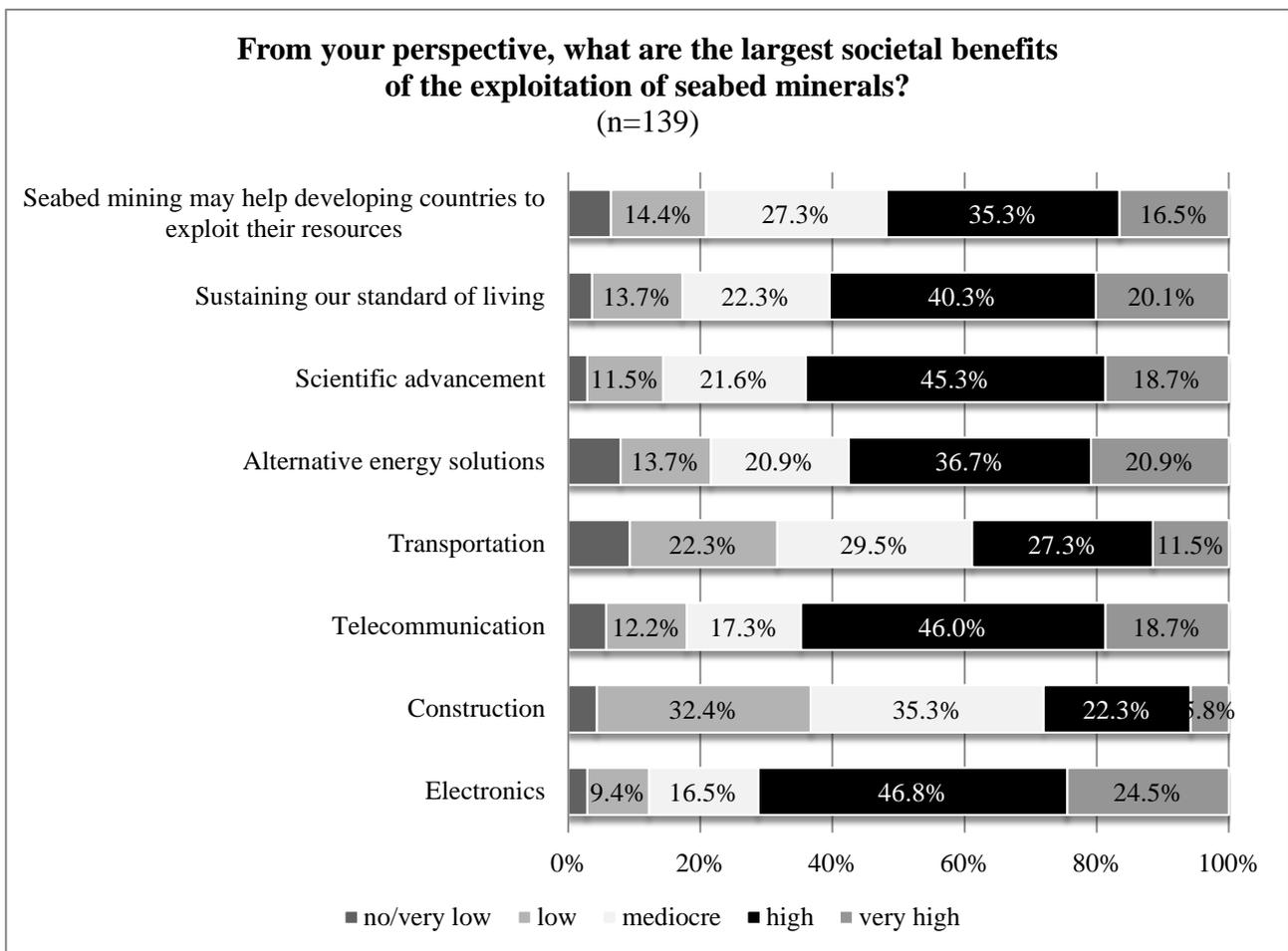


Figure 40: Societal Benefits of Seabed Minerals

6.5 Environmental Impacts

The participants were asked for their perceptions on environmental effects of seabed mining in different water depths. Figure 41 summarises the views and shows that mining is perceived less environmentally harmful in increasing water depths. This highlights that the public opinion on seabed mining in greater depths might be less contentious.

In addition, the participants were asked for their personal opinion on seabed mining from an environmental point of view. Figure 42 shows that 79.4% (strongly) disagreed with the statement that seabed mining should not be considered at all. On the other hand, only 24.4% stated that seabed mining should be considered right away. A large proportion answered that both piloting (53.4%) as well as thorough research and understanding (63.3%) is needed to assess the environmental impacts fully. Comparing the environmental impacts and safety of land mining and seabed mining, participants did rather not agreed (55%) or were indifferent (31.3%) with seabed mining being less harmful.

Finally, an open question was asked regarding what actions need to be taken to make seabed mining as less environmentally harmful as possible. From the 62 responses collected, exemplary statements are given in Table 6.

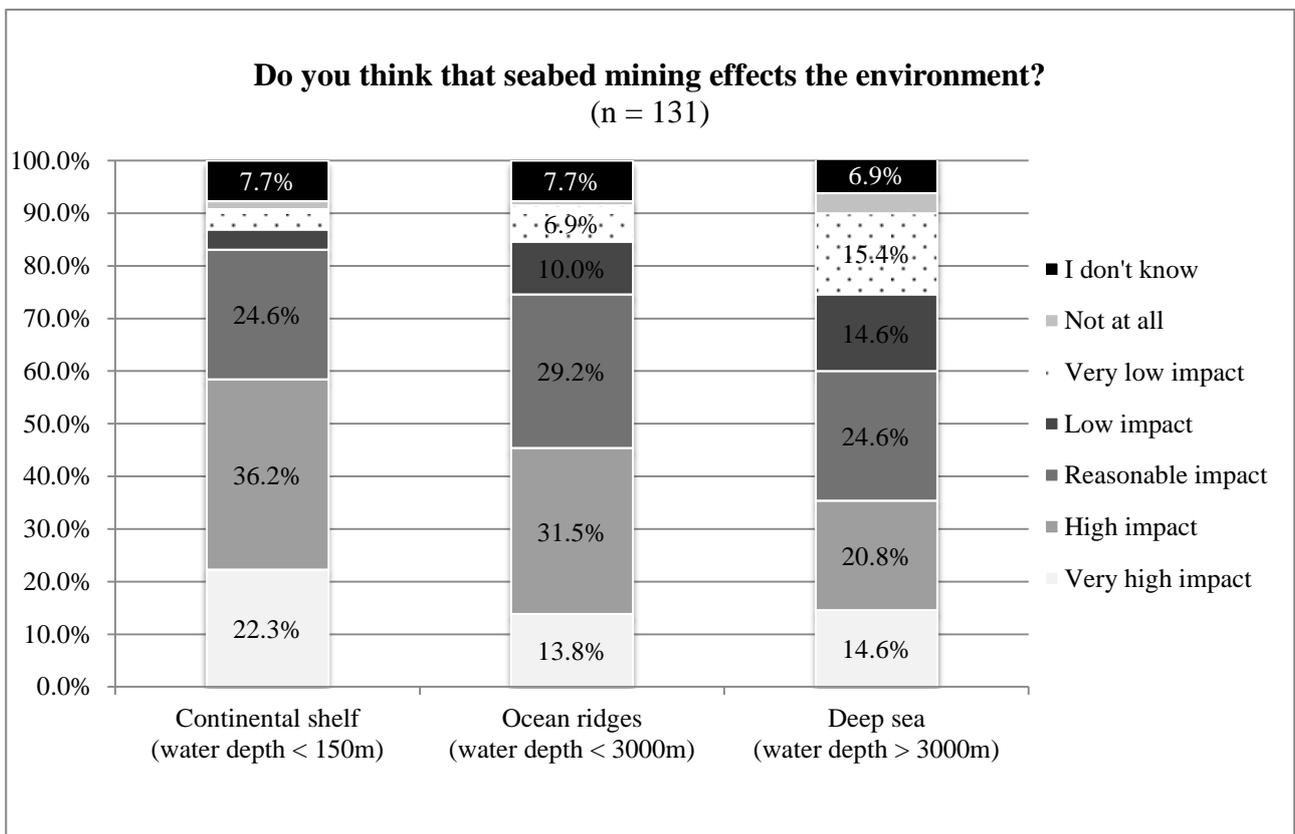


Figure 41: Environmental Effects in different Water Depths

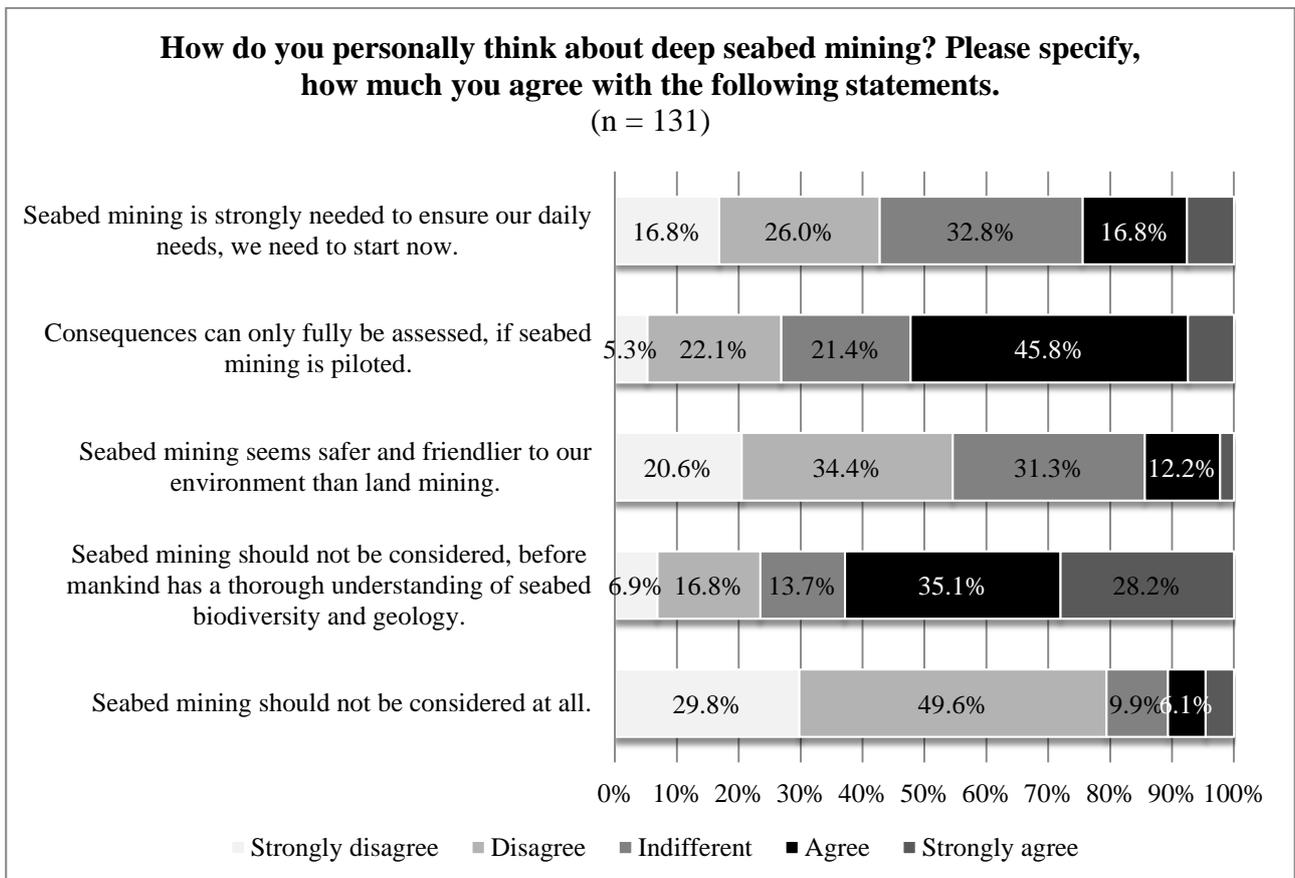


Figure 42: Statements on Seabed Mining from an Environmental Perspective

Table 6: Example Participant Statements on Environmental Actions

Research / Environmental impact assessment	<p><i>“It is almost impossible not to harm the environment while conducting the seabed mining. But it is acceptable to perform a detailed assessment to the potential value of the studied area. After having the assessment, one can start to consider about the trade-off between the economics value and environment protection.”</i></p> <p><i>“Thorough site evaluations of local biodiversity, understanding how released pollutants will affect local and broad scale biodiversity, minimal disruptions to local landscape”</i></p>
Piloting	<p><i>“Long term pilot trials with surveys as to how it is affecting the environment- counts of animal/plant life and water quality samples?”</i></p> <p><i>“Small areas mined at any one time and allowed to return to a normal condition before a neighbouring section of seabed is mined.”</i></p>
Mitigation strategies	<p><i>“Identify and avoid areas with large amounts of living organisms on/near the seabed, minimization of noise which might disrupt aquatic animal communication (eg. whale song), ensure proper containment of any/all chemicals used in the mining process, Minimization of dust/sediment disturbance near sensitive areas taking ocean currents into consideration (eg. reefs/kept forests)”</i></p> <p><i>“Proper technology, i.e. a hood over the operation / vacuum tube to the surface or vehicle that retains the resuspended and perturbed material. Keep the disturbance local unless it is deemed that this turbation stimulates the benthic community on a system scale.”</i></p>
Regulation	<p><i>“We need underwater marine national parks which are protected from anthropogenic influence”</i></p> <p><i>“Regulations based on scientific research.”</i></p> <p><i>“Proper regulation to avoid a situation of seabed mining similar to the large scale industrial pollution caused by oil drilling in the Niger Delta.”</i></p> <p><i>“Better rules than on land.”</i></p>
Further	<p><i>“Then there is of course the issue of minimizing damage to the surroundings when/if an accident happens. Previous experiences such as the BP oil rig, suggests that there is a lot of work needed here.”</i></p>

These statements were structured according to the major issues addressed: thorough research and environmental impact assessments, mitigation strategies, piloting and trial seabed mining as well as regulations. The respondents suggested for instance long term

trials, reserve areas or the covering of mining sites. Furthermore, the issues of accidents and risk assessments were underlined.

6.6 Engineering Systems and Technology

In the engineering section (see Figure 43), the participants were asked for perceptions on the readiness of seabed mining technology. In general the highest states of readiness were selected for the vessels and platforms in harsh environments and the navigation and positioning systems, whereas explorations technologies for environmental impact assessments, seabed mining machinery or seafloor tools, riser systems and the energy supply of the machinery were ranked least ready nowadays. These results underline our findings from the expert interviews in the following section.

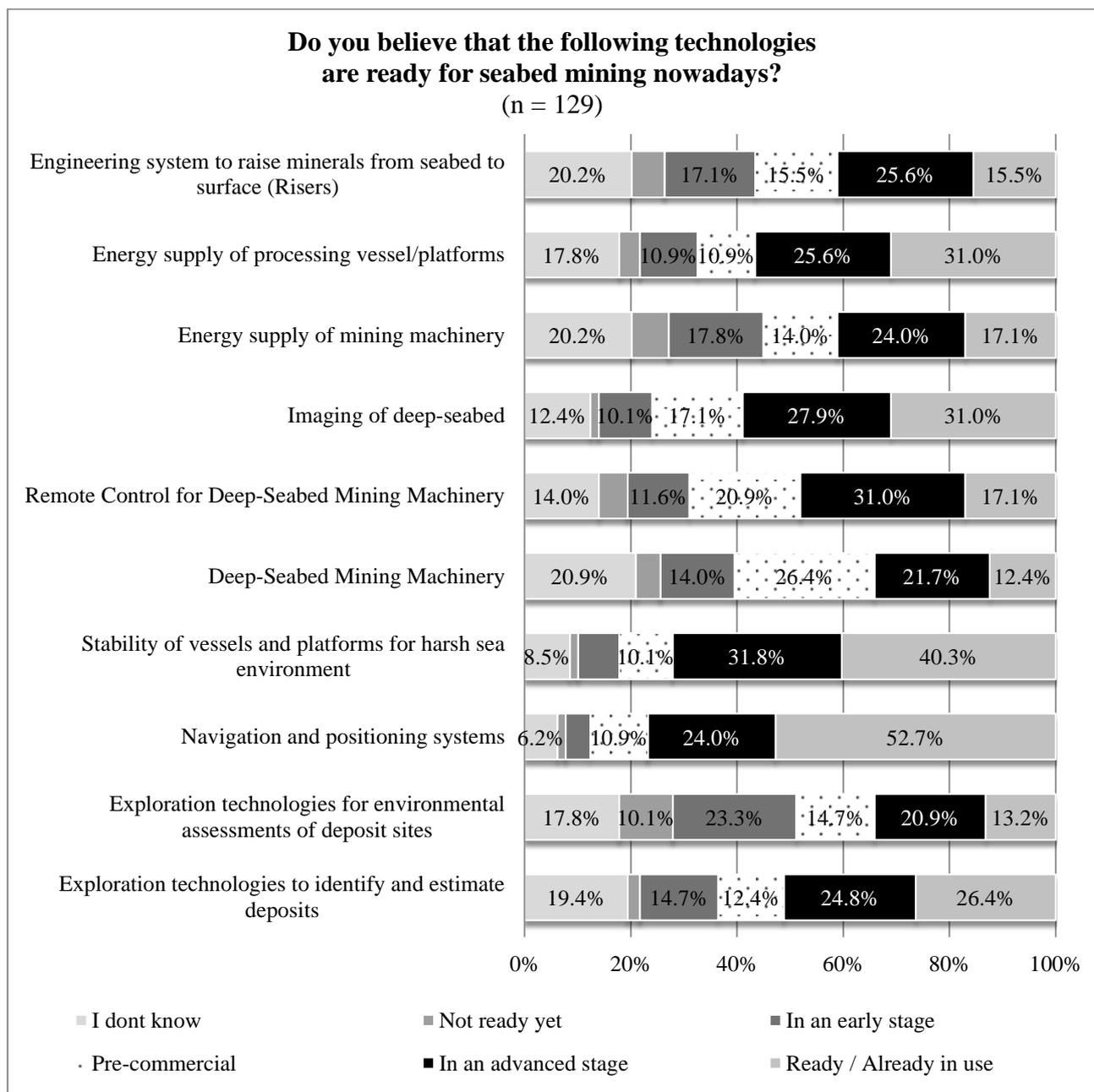


Figure 43: Readiness of Seabed Mining Technology

6.7 General Drivers and Barriers for Seabed Mining

Concluding to the general part of questions in the survey, the participants were asked for their view on major drivers and barriers for seabed mining. Figure 44 summarises the viewpoints on drivers and indicates that economic profit (80.5% high and very high driver) and scarcity of land resources (69.5% high and very high driver) are seen as the predominant drivers. The following strongest drivers are mineral demands for technological progress (64%) and the resource independency of countries (54.7%).

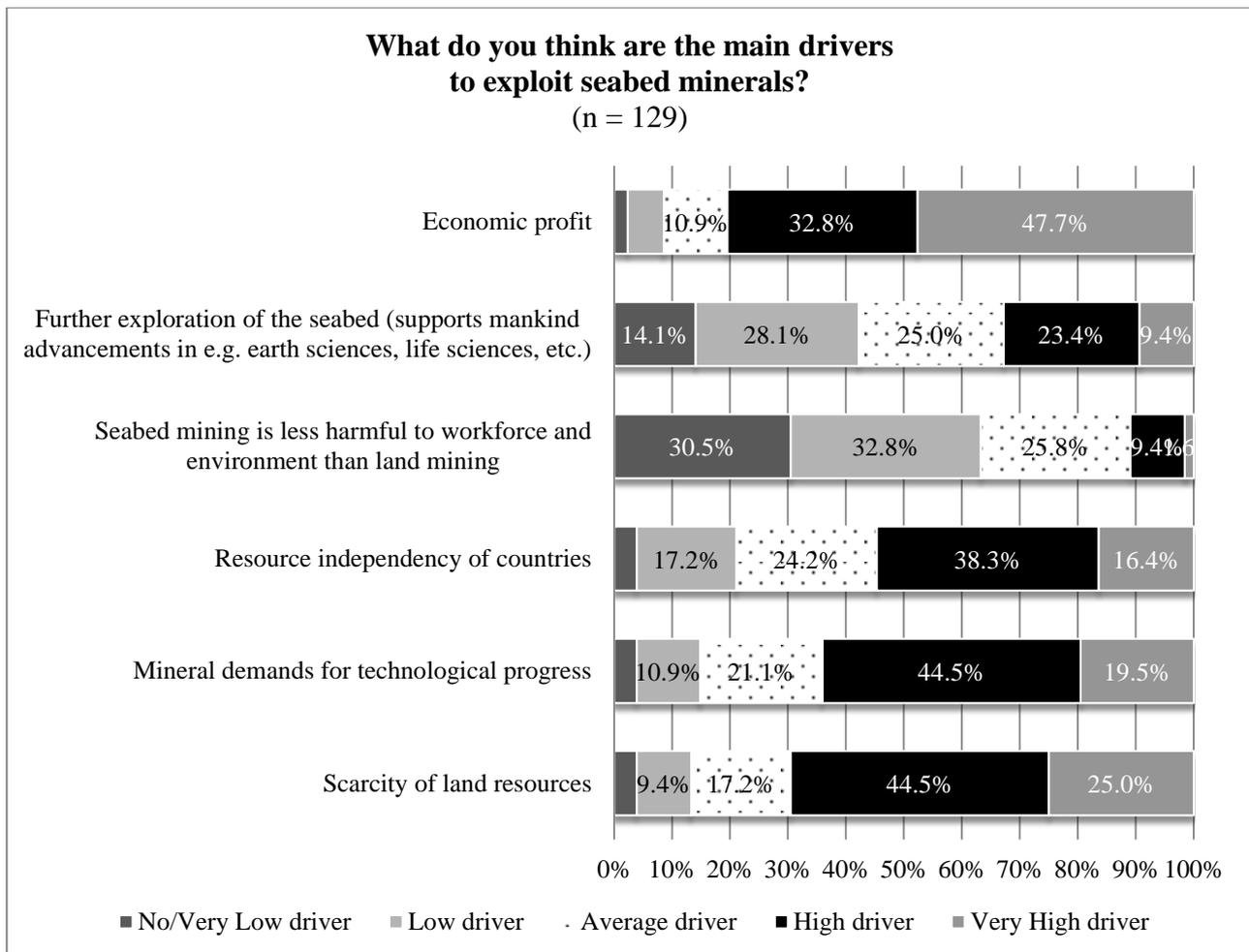


Figure 44: Main Drivers for Seabed Mining

Figure 45 presents the results on the major barriers from the view of 129 respondents. 62.5% of the participants see environmental impacts as a high or very high barrier, followed by 57.8% for the economic challenge implying volatile mineral prices and high cost sea operations.

Legal boundaries were seen as high or very barrier by 46.1% of the respondents, whereas a lack of societal needs, engineering systems and logistics were stated as low or average barriers by 59.4%, 61% and 68.8% respectively. These results imply the multiple layers and determinants of seabed mining research and development.

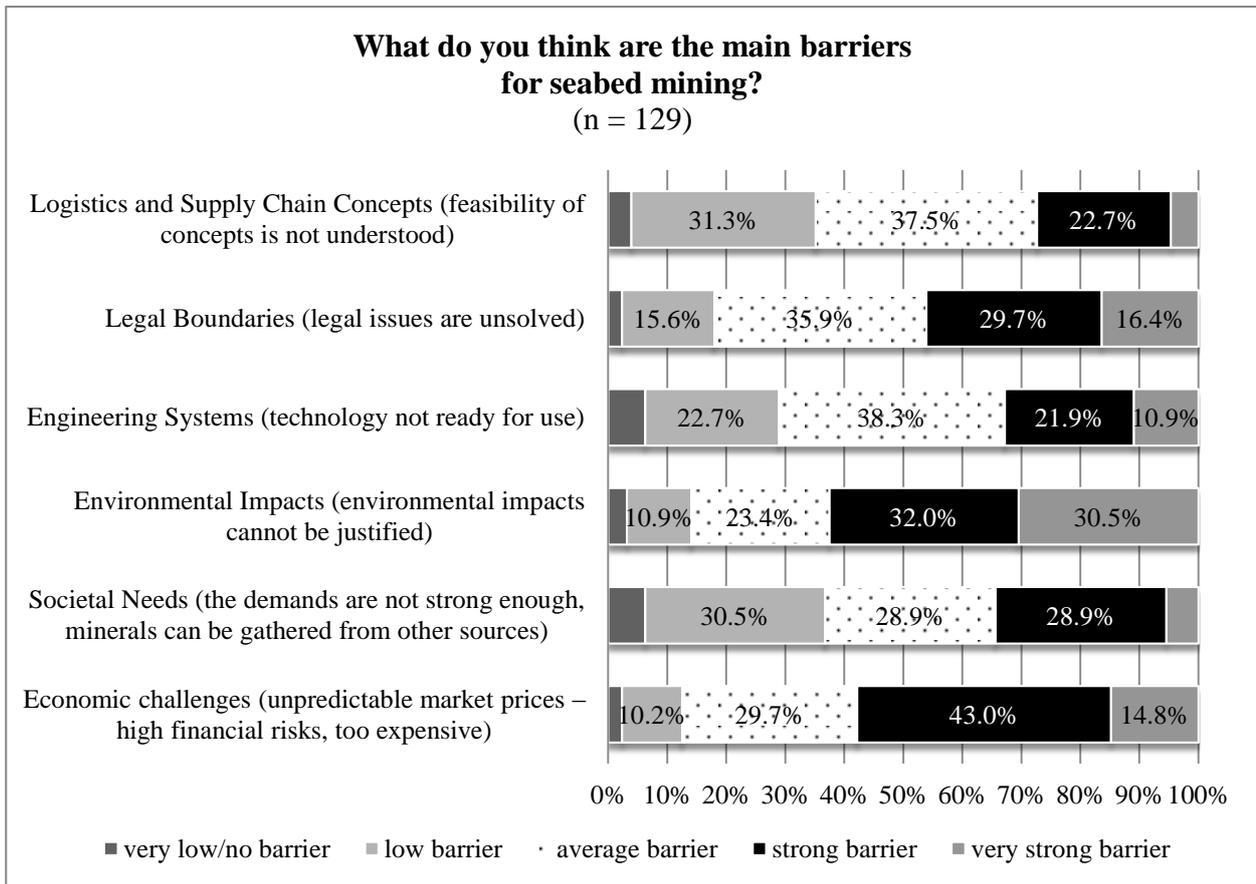


Figure 45: Main Barriers for Seabed Mining

6.8 Expert Opinions on Seabed Mining

In a final optional section, expert views on seabed mining were requested. These expert questions addressed the feasibility of mining of various seabed resources as well as of Atlantis II Deep. Furthermore, environmental specifics of Atlantis II Deep were addressed by an open question.

Figure 46 presents the views of 30 respondents, who considered themselves as experts in the field. According to the majority views, diamond and phosphorite mining is considered as feasible already with 53.1% and 34.4% respectively. Massive sulphide mining is seen as feasible in the next five to ten years by 37.5% of the respondents for sediments and active vents and 46.9% for inactive vents. However, manganese nodules are seen as feasible resources by 46.9%.

For Atlantis II Deep (see Figure 47) seabed mining is indicated to become feasible in the next five to ten years by 45% of the experts, whereas 13% believe not in feasibility at all. For the site, the experts were also asked what actions need to be taken to mitigate the environmental impacts. Within the given statements, the semi-enclosed area of the Red Sea was outlined. Furthermore, valuable insights for environmental impact assessments were gained, e.g. on the brine environment, the effects of operational and discharge plumes, the

loss of endemic microbial and faunal communities and the assessment of natural capital values in comparison to total economic values.

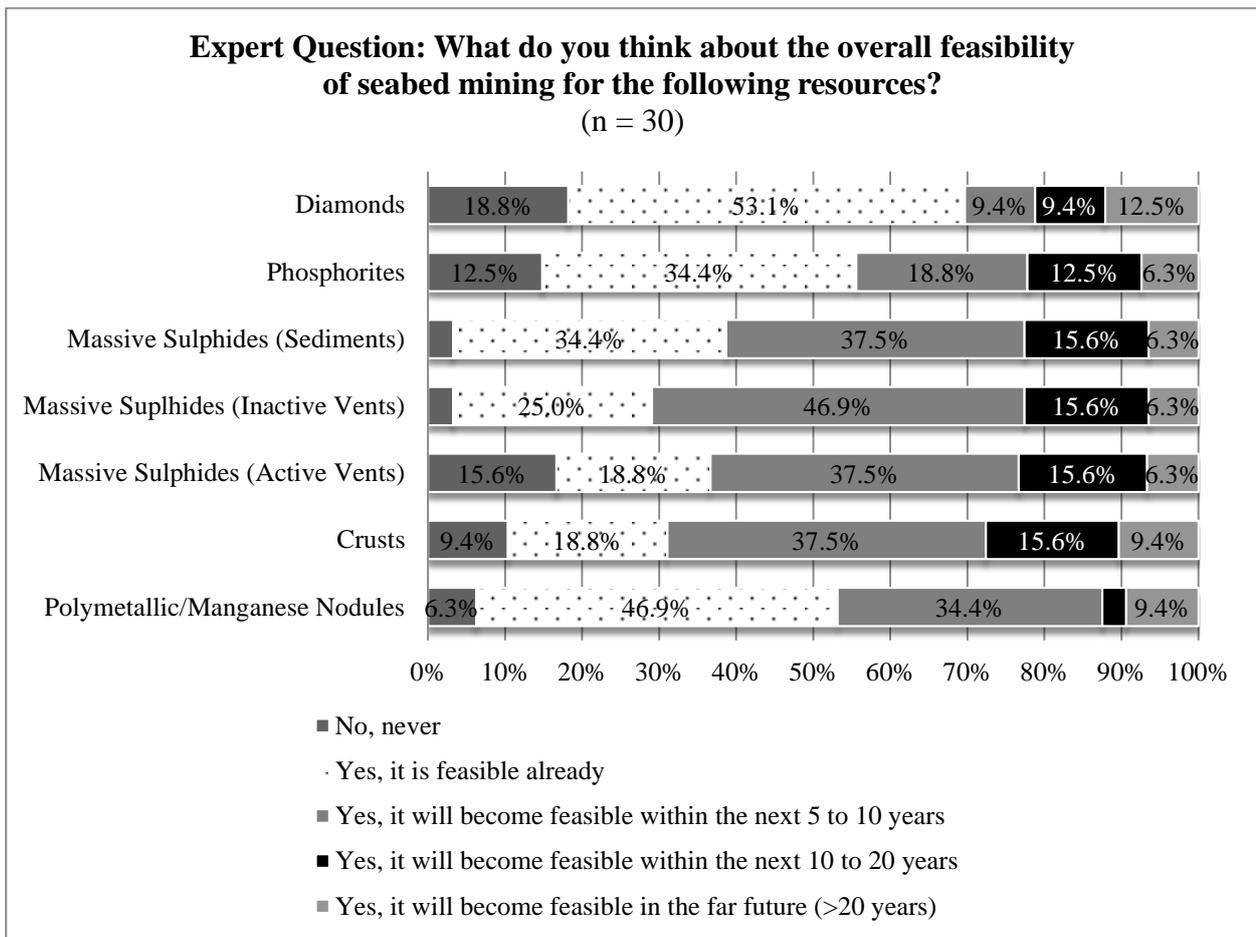


Figure 46: Experts View on the Feasibility of Mining of Seabed Resources

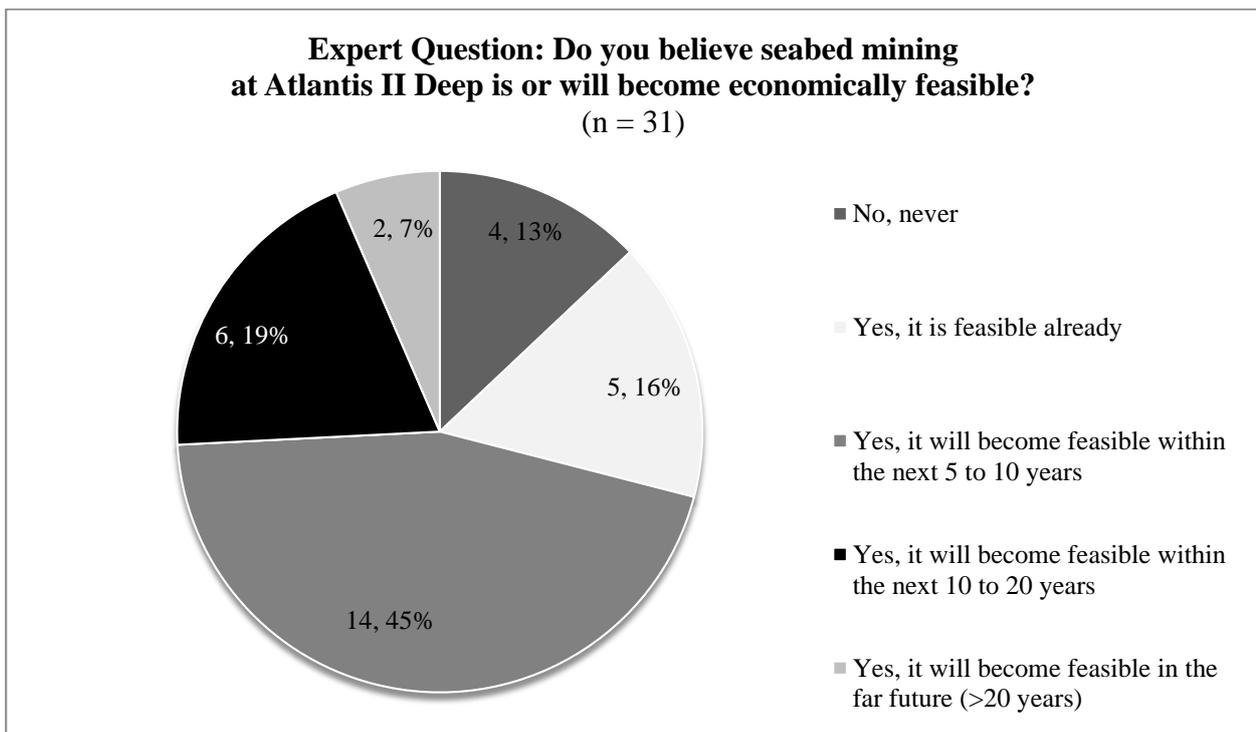


Figure 47: Experts View on the Feasibility of Atlantis II Deep Mining

6.9 Concluding Remarks

The survey on seabed mining was attended by 147 participants. 129 respondents completed the mandatory parts of the questionnaire and 30 filled in the expert section. The respondents represent academic (80%) and industrial views (20%) from various fields related to seabed mining such as economics, earth sciences and engineering.

Overall economic profit, scarcity of land resources, mineral demands and resource independency of countries are seen as the strongest drivers for seabed mining. On the other hand, environmental impacts and economic challenges are assumed to be largest barriers, whereas engineering systems, legal boundaries and logistics issues are seen as mediocre barriers.

From an economics point of view major barriers are the high research and development costs as well as operations costs on sea. The majority of participants proposes an economic feasibility of seabed mining in the next five to ten years.

From an environmental point of view, the participants outline the necessity of thorough biological and geological research in the field to fully assess impacts and define mitigation strategies. However, pilots of seabed mining are proposed to understand issues in a comprehensive manner and to derive regulations for seabed mining.

Engineering systems are seen as generally ready for seabed mining. The largest developments needed are seen in exploration technologies, particularly for environmental impact assessments, seafloor tool and lifting system development and energy supply of seafloor machinery.

Finally, the expert section of the survey outlines that manganese nodules and massive sulphides in inactive hydrothermal vents and sediments are assumed to be the feasible for mining in the next five to ten years.

The results of the survey underline several findings of the expert interviews in the next section. Furthermore, it presented a first analysis of academic and industry perceptions on seabed mining from different discipline viewpoints.

7 Expert Interview Results

7.1 Introductory Remarks

In order to develop a feasible concept for Atlantis II Deep and guidelines for sustainable seabed mining of massive sulphides in inactive hydrothermal vents, the research group conducted interviews with subject matter experts in seabed mining. As stated in Section 5, the interview partners were selected according to their expertise in either one or more of the fields of the holistic approach, namely engineering systems, economic, environmental impact assessments and mitigation strategies, legal aspects and supply chain. The interviews were conducted in person or as telephone interviews and took between 60 and 120min depending on the number of dimensions covered. An overview of the questions and interview guidelines is given in the Appendix. The following subchapters give an overview of the interview partners and summarise the lessons learned for the development of the concept for Atlantis II Deep.

7.2 Interview Partners

Within our study, nine expert interviews were conducted. Table 7 gives an overview of the interview partners, their organisations and positions as well as related research framework dimensions and questions. The following subchapters give an overview of the issues stated by the interview partners and the general conclusions.¹

Table 7: Overview Interview Partners and Research Framework Dimensions

Interview Partner	Organisation	Position	Research Framework Dimensions / Questions
Dr David Heydon	Deepgreen Resources	Chairman	<ul style="list-style-type: none">▪ Economics▪ Engineering System▪ Supply Chain / Logistics
Martijn Schouten	IHC Merwede	Managing Director Mining	<ul style="list-style-type: none">▪ Economics▪ Supply Chain / Logistics
Rick Lotman	IHC Merwede	Deep Sea Dredging and Mining Project Engineer	<ul style="list-style-type: none">▪ Economics▪ Engineering System
Dr Rachel Mills	National Oceanography Centre Southampton	Professor in Marine Biogeochemistry	<ul style="list-style-type: none">▪ Environment
Sunil Shastri	Hull University	Lecturer Marine Policy	<ul style="list-style-type: none">▪ Legal Environment

¹ The views expressed here are summarised “lessons learned” for the concept and guideline design based on personal communications with the interview partners. They are not intended to represent organisations’ viewpoints or the individual viewpoints.

Interview Partner	Organisation	Position	Research Framework Dimensions / Questions
Robin Plumley	National Oceanography Centre Southampton	Research Ship Manager	<ul style="list-style-type: none"> ▪ Logistics
Roland Rogers	National Oceanography Centre Southampton	Advisor Marine Law and Policy	<ul style="list-style-type: none"> ▪ Legal Environment
Prof Damon Teagle	National Oceanography Centre Southampton	Professor in Geochemistry and Mineralisation	<ul style="list-style-type: none"> ▪ Economics ▪ Engineering System ▪ Environment
Prof David Billett	National Oceanography Centre Southampton	Ocean Biogeochemistry and Ecosystems	<ul style="list-style-type: none"> ▪ Environment ▪ Legal Environment ▪ Supply Chain

7.3 Economics

In the economics dimension, the interviewees were asked for their opinion on the potential and feasibility of mining of massive sulphides in inactive hydrothermal vents and sediments. Moreover, they were asked for potential next mining sites and whether Atlantis II Deep was seen as one of them.

In general mining of massive sulphides has been proven to be economically considerable by the Nautilus Minerals case in Papua New Guinea. However, the economic challenges are still among the strongest barriers for seabed mining nowadays. These economic challenges are inter alia the volatile market prices of minerals, the high financial risks and upfront capital expenditures. The economic feasibility of seabed mining is thus strongly dependent on the composition and concentrations of the deposit site and the related market prices.

The 1970s samples from Atlantis II Deep have shown that the deposit size is comparable to land mines. Since then Atlantis II Deep is been discussed as one of the largest seabed mineral deposits on earth. However, the composition and concentration of the deposit indicates a critical issue that needs to be taken into account for economic modelling: Atlantis II Deep's major mineral is zinc. Beyond this, the deposit holds significant amounts of Copper, Gold and Silver as well as silicates. According to Diamond Fields International, the exploitation license holder, the concentration is proposed to be between 2% and 4%. The research samples from the 1970s indicate an average concentration of around 2%. The economic model thus needs to take estimate uncertainties into account. Moreover, Zinc is not traded as highly as other minerals, which influences the economic model as well. Finally, the sediment structure influences the economic feasibility. At Atlantis II Deep the minerals occur in sizes of 2µm, which affects the processing and engineering system design. As a conclusion, Atlantis II Deep is seen controversially: the deposit size is seen as

prospective, whereas the composition, structure and uncertainties are critical issues for the actual feasibility.

7.4 Environmental Impact Assessments and Mitigation Strategies

Regarding the environmental impacts and mitigation strategies, the interviewees were asked for steps and international regulations for appropriate environmental impact assessments and strategy development in particular for the Red Sea / brine environment.

First, inactive hydrothermal vent sites such as the Atlantis II Deep are assumed to have a lower macrobenthos density than active vent sites due to lack of chemosynthesis processes. However, exploration of the biodiversity in the brines of the Red Sea is still in an early stage. Therefore, the environmental impact assessment needs to map the biology and geophysics of the environment in a first step. This mapping includes not only the benthos communities, fisheries and sediment structures at the actual mining site, but also sites that are in reach by currents (e.g. used by desalination plants or leisure). Second, all possible environmental effects need to be examined.

This implies a thorough analysis of light, noises, emissions, vibrations, plumes and discharges of the engineering systems and transportation vessels intended to use. The brine environment shows 7 to 8 time higher salinity than normal seawater, so that the waste water may cause severe impacts. Dewatering of the metalliferous sediments leaves behind highly acid fluids with metallic traces that need to be considered for neutralisation and safe return. Due to the size and weight of the metallic traces, the discharges and machinery can cause plumes easily in the Red Sea environment. Third, mitigation strategies need to be defined to reduce and/or compensate the environmental impacts as far as possible in order to reach the target for sustainable seabed mining. These strategies may include reserve areas as well as re-location and re-colonisation methods.

In terms of regulations worth considering for the development of guidelines, there is a wide variety of national and international frameworks. Since deep seabed mining is still a very new field, standards need to be adapted from the oil and gas, dredging and mining industries. Furthermore, the InterRidge community offers a code of conduct for research activities at hydrothermal vent sites that may be applied as an indicator. From the legal side, environmental assessments should consider the MARPOL 73/78 (International Convention for the Prevention of Pollution From Ships), Protection of the Sea (Prevention of Pollution from Ships) Act 1983, Prevention of Pollution at Sea Act 1979, the Dumping of Wastes at the Sea Act 1979, and the Convention on Biological Diversity, the International Union for Conservation of Nature (IUCN) and the agreements and workshops of the International Seabed Authority.

7.5 Engineering Systems

Regarding the engineering systems, the interviewees were asked for their perceptions on the state of readiness. Moreover, they were questioned for specifics that need to be considered for engineering system design for the Atlantis II Deep environment.

In general the state of the technology for seabed mining was perceived as sufficient to become operational to water depths of 2,000m. However, exploration technologies to estimate deposits more precisely, technologies for environmental impact assessments and the energy supply of seafloor tools have been outlined as critical. In addition differential GPS systems need to be applied for accurate vessel navigation and positioning on the sea surface.

For the Atlantis II Deep environment, two specific issues could be identified for the engineering system design: a high salinity / brine and the low strength of the sediments seafloor. These specifics have implications on the design of the seafloor tools, such as the movement and control system. The buoyancy configuration seems to be ideal for the specific requirements but demands for in-depth contemplation of the control device. The high saline and corrosive environment challenges the material selection and design of the maintenance cycles for the seafloor tools.

7.6 Logistics and Supply Chain Concepts

Logistics and supply chain concepts for seabed mining have been named as one of the most critical issues. In contrast to land mining, where the processing facilities are directly at the mining site, seabed mining demands for pre-processing offshore and processing of ores on land. Therefore, intermodal transportation and handling solutions for bulk cargo over far distances need to be created.

Against this background, the interviewees were asked for best practices in terms of supply chain design and aspects that need to be considered for transportation and handling, specifically in the Red Sea area. From a logistics point of view, Atlantis II Deep is advantageous due to its short distances to the Port of Jeddah and the Port of Sudan. Moreover, fuel prices in the region allow the transportation and processing efforts. However, onshore processing of Atlantis II Deep sulphides requires facilities that are able to process small size metalliferous sediments and are capable of multi-mineral processing of Zinc, Copper, Gold and Silver at the same time. Though the Red Sea / Middle East have numerous mining facilities, very few are able to fulfil the processing requirements. Therefore, multi-mineral mining facilities in Saudi Arabia, Oman and Cyprus will be considered in the concept development. For the actual implementation of the transportation and handling processes, the composition of the sediments needs to be taken into account. If

acid fluids and oxidations can occur during transport and handling, the sediments need to be treated according to dangerous goods regulations.

In a wider sense, the supply chain security has been addressed in the interviews. Piracy may affect the mining production and security of valuable machinery, so that the necessity of safeguarding vessels for the operations needs to be considered. Furthermore, Atlantis II Deep is located within the transit passage for maritime transport.

7.7 Legal Environment

Regarding the legal environment, the interviewees were asked for policies that apply for commercial mining at Atlantis II Deep as well as for opportunities and challenges at the particular site.

Since Atlantis II Deep is in the EEZ's and thus in the national jurisdiction of Sudan and Saudi Arabia, the revenues of commercial mining activities are shared according to the joint development agreement. The exploitation license was granted to a joint venture of Diamond Fields International and Manafa in 2010. Both countries support the technological advancement as well as research and exploitation activities around Atlantis II Deep. Therewith, the legal environment is seen as beneficial to a further development of the mining site. However, the joint venture needs to conduct comprehensive environmental impact assessment to the involved regions and proof sufficient mitigation strategies to the regulators.

7.8 Concluding Remarks

The expert interviews provided insights into seabed mining and site specifics of Atlantis II Deep from various different viewpoints. The qualitative statements are used for the concept and guideline development in the later parts. The knowledge is further extended by the single case study on Nautilus presented in Chapter 8.

8 Case Study “Nautilus Minerals – Solwara 1”

8.1 Introductory Remarks

Deepsea mining is considered to be the new offshore frontier. Nautilus Minerals, the world’s leader in exploration and development of deep ocean seabed resources, located seabed massive sulphides in the Bismarck Sea, Papua New Guinea (PNG). This chapter provides a case study review and analysis on the status of Nautilus Minerals exploration results and its production development plan up to delivery of seabed ore in PNG. The chapter starts by looking at the Nautilus Minerals mining engineering system. Thereafter, the focus moves briefly to summarise the Solwara 1 seafloor mining development project estimation of the capital and operation expenditure. The oceanic environmental background is also reviewed and the potential environmental impacts and mitigation strategies are discussed. Furthermore, the current state of the logistics of the mining site is evaluated. Finally, the legal and environmental regulations of Solwara 1 are reviewed.

8.2 Engineering System

8.2.1 Nautilus Mining System

The key components of offshore mining systems are the seafloor mining tools, the riser and lifting system and the production support vessel. The components, illustrated in Figure 48, will be elaborated in detail in this chapter.

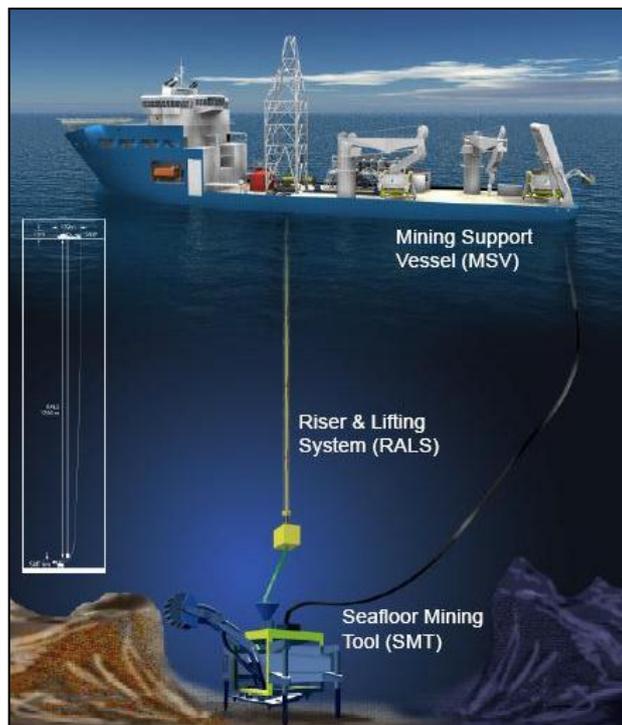


Figure 48: Nautilus Offshore Mining System
Source: Smith (2011)

8.2.2 Seafloor Tools

Nautilus Minerals has proposed a technology of mining mineral resources from the ocean floor using three distinct seabed mining tools. The current approach for the seabed mining system is analogue to many land mining systems, where it is common for a more flexible and mobile machine to prepare the mining site. Because of the topography of the mining site with its relatively steep slopes (up to 20°) and the numerous chimneys that cover the mine sites, three different subsea mining machines are used, namely the auxiliary miner, the bulk miner and the gathering machine.

During production operations, two seafloor mining tools will excavate ore from the seabed. The auxiliary miner (AUX) will initiate mining operations and prepare an adequate landing area for the bulk miner (BM) and the gathering machine (GM). The AUX will also remove edge sections of benches which cannot be accessed or efficiently mined by the BM. The BM is proposed to be a high production cutting machine to cut the majority of a bench, once an adequate working area has been prepared by the AUX. Cut and gathered ore will be pumped by a GM as slurry via a flexible riser transfer pipe to a Riser and Lift System.

8.2.3 Riser and Lift System

The main purpose of the riser and lift system is to lift the mineral ore particles mined from seabed massive sulphide deposits to the floating vessel using a subsea lift pump and a vertical riser system hung from the floating vessel. The ore deposits mined by the subsea mining tools are gathered using the collecting machine and the seawater/ore slurry pumped into the positive displacement subsea lift pump at the base of the riser, where it is pumped to the floating vessel. Once the slurry reaches the floating vessel it passes through a dewatering process. The solids are transferred to a transport barge for shipment to shore and the filtered return water is topped up with additional seawater as required to be pumped down to the subsea lift pump to being discharged into the sea close to the depth at which it was originally collected.

Riser and lift systems are critical components to the engineering technological mining system. Riser and lift systems and their components have been utilised directly from oil and gas industry where these items are field proven in similar applications. The Solwara project has presented that the key issues of the riser systems are the erosion rates and the subsea lift pump performance. As shown in Figure 49, the riser and lift system consists of:

- Vertical slurry riser complete with connectors, flex-joint and accessories
- Return water riser complete with connectors
- Subsea slurry lift pump
- Riser transfer pipe from the collecting machine to the slurry lift pump

- Surface pressure seawater supply system (mud pumps)

The riser and lift system will conduct the following functions:

- Receive the ore slurry from the gathering machine and pump it vertically up the riser system to the dewatering plant inlet on the deck of the floating support vessel.
- Send the return water to the seabed.

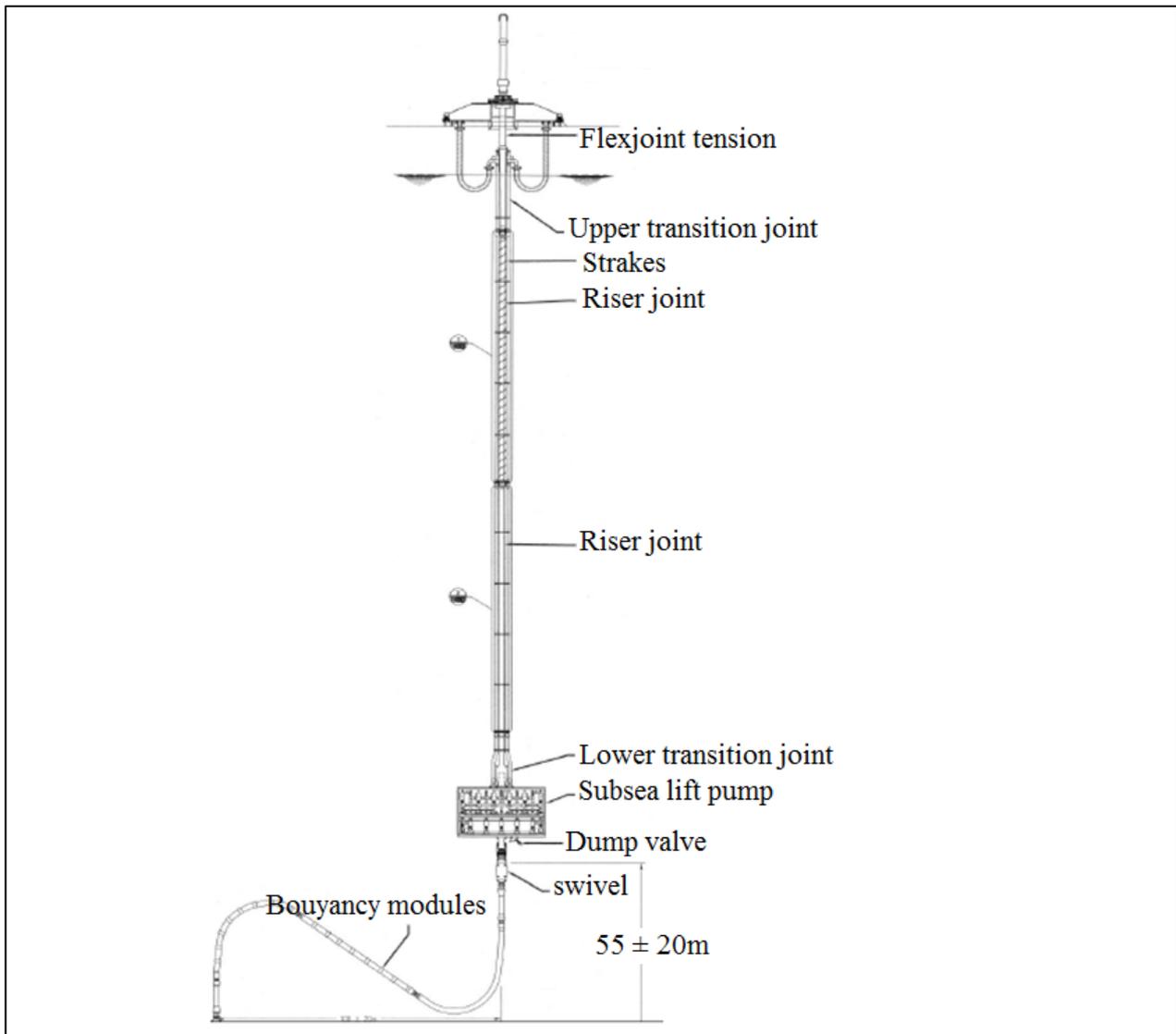


Figure 49: Nautilus: Riser and Lift System
Source: SRK Consulting (2010)

Riser Transfer Pipe

The nominal inner diameter of the riser transfer pipe is 280mm which is a flexible hose 150-200m long and used to connect the subsea slurry pump to the collecting machine. The mixed seawater/ore slurry is pumped through the riser transfer pipe from the seabed collecting machine to the subsea slurry lift pump. The riser transfer pipe configuration is

behaving like dynamic risers which are widely used in the offshore oil and gas industry to connect the wellheads to the floating production unit.

Subsea Lift Pump

The subsea lift pump is hanged at the bottom of the riser and receives slurry from the collecting machine tool through the riser transfer pipe. Subsequently, it pumps the slurry to the floating vessel. The pump assembly involves two pump modules, each module containing five positive displacement pump chambers driven by pressurised return water delivered from the floating vessel to the pump through the riser assembly. The use of multiple pump chambers provides a consistent pressure and also provides a high degree of redundancy. The subsea lift pump is expected to weigh approximately 129 tonnes in air and measure 5.2m x 6.4m x 3.7m high, see Figure 50.

The sub-components or sub-assemblies of the subsea lift pump are rated and have been tested to 2,500m water depth. The subsea pump was originally designed to operate using electrically-driven hydraulic pumps at the seabed. The pump assembly incorporates an automatic dump valve assembly that will open to discharge the contents of the riser to the seabed in the event of an emergency shutdown or unplanned loss of flow, to prevent the ore within the riser setting out and plugging the system (Smith, 2011).

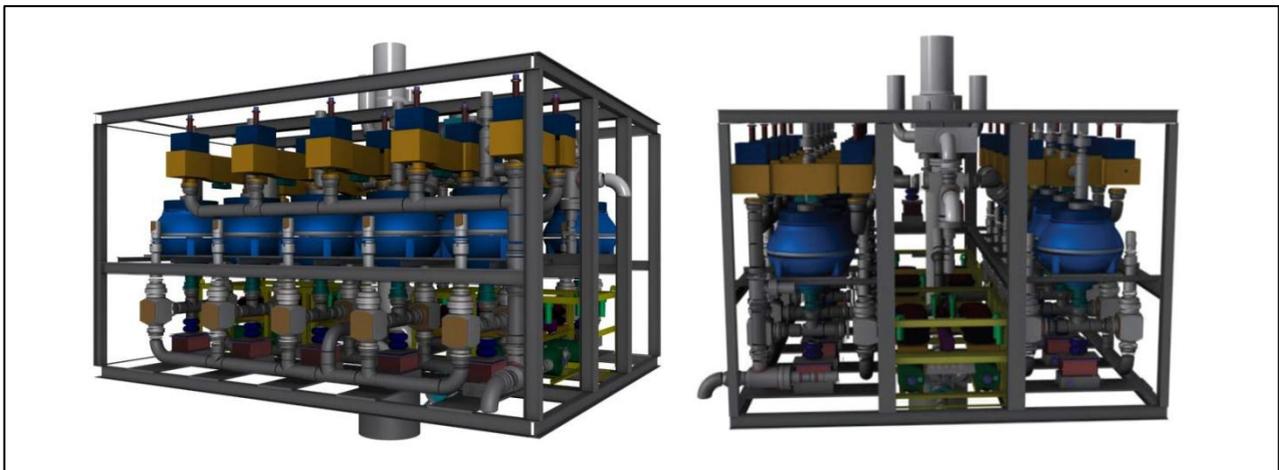


Figure 50: Dual-Module Multiple Chamber Subsea Pumps
Source : Smith (2011)

8.2.4 Floating Support Vessel

The floating support vessel is similar to the floating units that service the offshore drilling and production oil and gas industry. In the Solwara project the floating unit has not yet been selected (SRK Consulting, 2010). The main technical requirements for a suitable floating production vessel are adequate deck space, accommodation for up to 140 persons, dynamic positioning reliability and adequate electrical power.

The floating support vessel will maintain its position over the seabed mine site using a dynamic positioning system and support the surface as well as subsea operations to cut, collect, pump/lift, dewater, and discharge ore to shuttle barges. The primary basis for crew change-out will be crew boat and Helicopter facilities will also be provided for emergency evacuation purposes. Vessels under consideration by Nautilus are a barge, a heavy lift transportation vessel and a bulk carrier.

The vessel will be delivered with a large clear aft deck with adequate room to fit the mining spread. The vessel will also incorporate the following two production tanks:

A dewater ore storage bin to store onboard approximately 1 day's production capacity. A dewater ore out of specification bin for storage and re-feed of dewatered ore that does not meet transportation specifications.

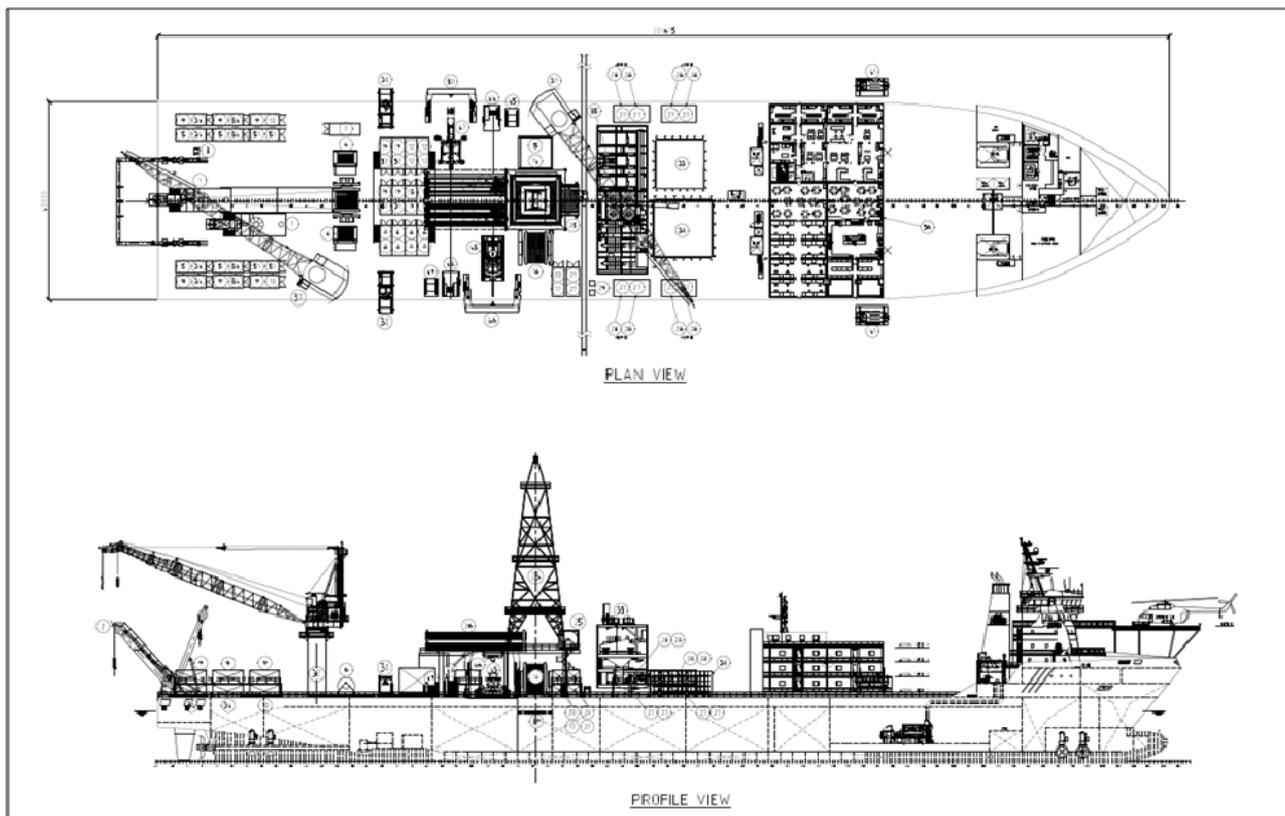


Figure 51: General Arrangement of the Production Support Vessel
Source: SRK Consulting (2010)

8.3 Economics

In the Solwara 1 Seafloor Mining Development Project (Larson, 1986), they estimated capital expenditures (CAPEX) and operating expenditures (OPEX) for the offshore components. However, a comprehensive economic analysis is not available publically. In this section, we present the brief summary of their estimation of CAPEX and OPEX.

8.3.1 CAPEX estimation

The total capital expenditure in the Solwara 1 Seafloor Mining Development Project including 17.5% contingency is US 383 million. The summary of this cost is shown in Table 8.

Table 8: Summary of Capital Expenditures in Solwara 1
Source: SRK Consulting (2010)

Nautilus Capital Expenditures in Solwara 1		Amount US\$ (millions)	%
Mining	Subsea Mining Equipment	84.1	25.8
	Riser and Lift System	101.1	31.0
	Dewatering Plant	24	7.4
	Production Support Vessel Mobilisation	6.5	2.0
	Integration and Testing	59.7	18.3
	Barges	10.8	3.3
Other	Project Services	32.2	9.9
	Owners Costs	7.4	2.3
	Capex Sub-Total	325.8	100.0
	Contingency (17.5%)	57	17.5

In order to estimate CAPEX, they considered the following elements (SRK Consulting, 2010):

- Seafloor Mining Tools (SMTs)
- Auxiliary Mining Machine (AUX)
- Bulk Mining Machine (BM)
- Gathering Machine (GM)
- Riser and Lift System (RALS)
- Production Support Vessel (PSV) with Dewatering Plant (DWP) and ore transfer facilities
- Shuttle barges for transfer of ore from vessel to onshore
- On-shore stock piling and load in/load out facility at Rabaul

The following items were excluded from the CAPEX and OPEX estimates:

- Ore unloading, stock piling and load-out onto transportation vessels at the Port of Rabaul
- Shipping from load out facility to concentrate processing plant
- Concentrator facility and/or charges
- Shipping from concentrator facility to smelter clients
- Expended (sunk) costs prior to 31 December 2009
- Escalation over project life
- PSV / transportation barge dry docking costs (for maintaining class obligations) during life of mine operations
- Site demobilisation costs

The major three parts, subsea mining equipment, the riser and lift system and integration and testing, were estimated based on the following considerations.

The subsea mining equipment estimate was based on the subsea mining device contract value plus an allowance to cover for the scope changes from two machines to three machine configuration. Spares and freight to South East Asia for integration in to the vessel were included in the costs. The riser and lift system estimate was based on a combination of actual purchase orders placed or vendor quotes including the major packages which include allowances spares and freight. The integration and mobilisation costs included the charter costs while the equipment was being integrated (SRK Consulting, 2010).

8.3.2 OPEX Estimation

Operating expenditure estimates of cost per tonne were based on an average production rate of 3,714 tonnes per day of produced dry ore based on their production schedule. The daily operating costs of the Solwara 1 project for delivery of ore to the port of Rabaul was estimated to be US\$237,000 (excluding contingency) or approximately US\$64 per tonne mined ore per day. The summary of operating cost is shown in Table 9.

Table 9: Summary of Operating Expenditures in Solwara 1
Source: SRK Consulting (2010)

Description	Total Daily Cost	Unit Mined Cost per tonne (US\$)	%
Production Support Vessel	144,796	39.2	61.1
Seafloor Mining Equipment	20,130	5.4	8.5
Workclass ROV's	20,910	5.7	8.8
Riser and Lift System	23,184	6.3	9.8
Support Services	15,235	4.1	6.4
Barging	12,694	3.4	5.4
Sub-Total	236,949	64.1	100.0
Contingency (10%)	23,695	6.4	10.0

Considering a 10% contingency, the operating costs become US \$261,000 per day or approximately \$70 per tonne. Operating the production support vessel is most expensive part and it takes around 60% of total OPEX. Among production support vessel cost, labour cost is 100,273 US\$/day (SRK Consulting, 2010).

8.4 Environmental Impact Assessment and Mitigation Strategies

The Nautilus Mineral project is in the permitting and engineering phase. Mining operation is scheduled in early 2013. Based on the current resource estimates, the project has a mine life of approximately 30 months with extracting ore at a maximum rate of 5,900 ton per day. The mining operation will have inevitable environmental impacts. In this section, first, the oceanic environmental background is reviewed. Second, the potential environmental impacts and mitigation strategies are discussed.

8.4.1 Oceanic Background of Bismarck Sea

Solwara 1 is located 1,600 m below the surface of the sea and 30 km from shore in the Bismarck Sea of PNG.

Tide and Current

The tide in the Bismarck Sea is relatively small. The diurnal tides (one high and one low per day) are the predominated component, with a maximum tidal range in the order of 1m.

Nautilus Mineral conducted a year-round current observation (Nautilus Minerals Inc, 2008) using moored Acoustic Doppler Current Profiler (ADCP) around Solwara 1 site. The results show that the average current velocities at Solwara 1 range between 10 and 20cm/s, with the greatest current speed exceeding 50cm/s in the upper water column (from the surface to around 250 m water depth) at various times throughout the year. The upper 400m of the water column has a constant northwest net flow. The mid-water column (from 400 to 800m) is characterised by current velocities of 10 to 20cm/s moving in a south-easterly direction during the northwest monsoon season. During the southeast monsoon season, currents in the mid-water column are predominantly northwest at similar speeds. Currents above the seafloor at Solwara 1 are relatively weak. The median current velocity recorded above the seabed is 6cm/s and the maximum speed is 35cm/s; however, only 5% of the current speeds exceeded 15 cm/s. Progressive vector plot results from 12 months of continuous monitoring show that over a period of weeks the net horizontal water direction above the seabed in Solwara 1 is from the southeast to the northwest. At shorter time scales (days), currents above the seabed in Solwara 1 are influenced by the tidal cycle and oscillate along an axis aligned northeast to southwest.

Biology

Marine life varies with the water depth. At the Solwara 1 site the ocean may be divided into three broad zones (Nautilus Minerals Inc, 2008). The ‘Surface Mixed Layer’ which is the upper water column between ~0-200m and contains mostly pelagic fish species including tuna, squid and sharks. Other animals known to exist in the area include dolphins, turtles and migrating whales. The ‘Mesopelagic Zone’ which is the mid water column between ~200-1,000m and where amongst others squid and occasional short visits by, for example, tuna in search of prey and migrating whales may occur. The ‘Bathypelagic Zone’ which is the bottom water column, deeper than ~1,000m where animals typical of active hydrothermal vent sites, such as gastropods, shrimp, crabs, barnacles occur.

Re-colonization: Natural Volcanic Disruption

The presence of natural plumes over the Solwara 1 area and periodic volcanic deposition originating from North Su (approximately 1 km southeast of Solwara 1) and other sources

indicates the dynamic natural processes at play. In 1994 the Rabaul volcano erupted. The ash and mud flows significantly disrupted the flourishing coral reefs ecosystem along the coastal region. However, by 1996 corals had extensively recolonized.

Re-colonization: Alternation between active and inactive vents

The environmental research surveys during a 3-year period (2006 to 2008) found that venting activity exhibited significant variability at Solwara 1, with an apparent switching on and off of vents (Nautilus Minerals Inc, 2008). Piles of dead snails were also observed at several of the areas where venting had ceased, suggesting that these areas could no longer support these vent-dependent species. Furthermore, resumed venting was observed after disturbance during exploration, with chimney lattice starting to reform in a matter of days. These observations at the Solwara 1 site indicate a hydrothermally dynamic system with natural variation in the active and inactive areas, where conditions are not conducive to establishment of long-term, stable, vent-dependent communities.

8.4.2 Environmental Impact and Mitigation of Seabed Mining at Solwara 1

The seabed mining operation at the Solwara 1 site will have inevitable environmental impacts on the seafloor and its biological communities, which will arise from a number of sources during exploration and extraction of massive sulphide deposit, as demonstrated in Figure 52. The impacts can be categorised as follows: direct material and habitat removal; sediment plumes; light, noise and vibration impacts; waste water disposal and potential machinery leaks and malfunctions. The potential environmental impacts of seabed mining at Solwara 1 site are mainly from the seabed mining tools operating on the hydrothermal vent fields, raiser and pump system lifting the ore to sea surface and the production support vessel at the sea surface.

The seabed mining tool will directly remove seafloor substrate, including active and inactive areas, causing loss of habitat and associated animals. Disturbance to the seafloor and sedimentation will generate plume above the seabed.

Seabed rock will be pumped to the surface as slurry mixed with seawater. The rock will be dewatered and collected in a barge for shipping. The slurry water will be filtered and pumped back to depth above the seabed. There will be no chemical treatment or processing of the collected materials involved in the process, simply separation of the seafloor rocks from water.

Water containing elevated concentrations of metals and some retained sediments from the dewatering of ore will be discharged 25 to 50 m above the seafloor. This decision was made primarily for pumping efficiency, but effectively avoids any exposure or impacts on surface and mid-water ecosystems. Modelling has shown that plumes from this return seawater will

not rise above 1,300 m in the water column. As such the intention is to discharge such material horizontally along the seafloor rather than into the water column to minimise plume formation and enhance the rate at which material settles to the seafloor. The processes of mining and dewatering will therefore not affect the pelagic tunas, tuna fisheries or near shore coral reefs including traditional reef fishing activities such as shark calling.

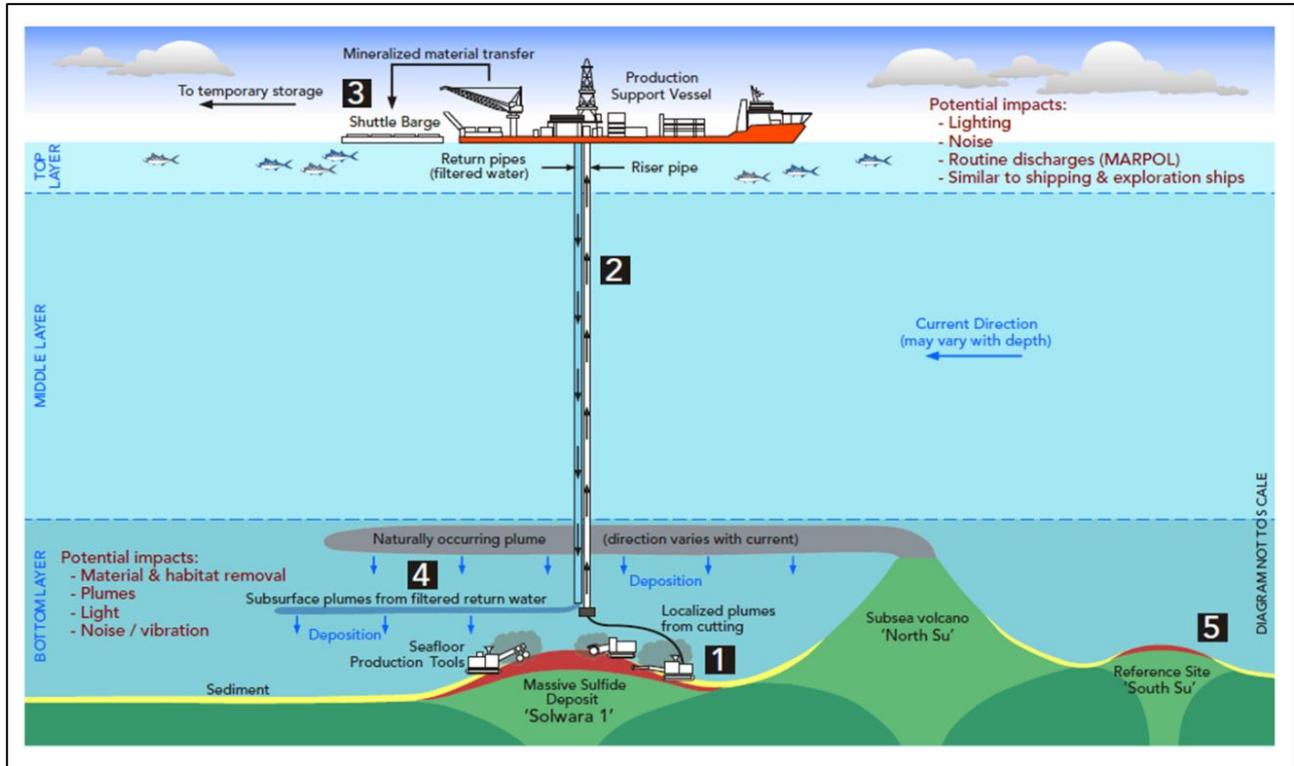


Figure 52: Potential Environmental Impacts of Mining Operations
Source: Nautilus Minerals Inc (2011)

Potential impacts to surface pelagic animals result only from the presence of the surface vessels and their normal operations, including lighting, underwater noise and routine discharges (in compliance with relevant maritime acts and regulations). These impacts are similar to shipping generally.

Transmission of noise from operating machinery through the water is an important consideration due to the presence of marine turtles and whales. Papua New Guinea's entire exclusive economic zone was declared as a sanctuary for whales, protecting them from being harmed in these areas. There is a chance that further deep sea exploration with its various seismic profiling methods and deep seabed mining operations with its ambient noise from the vessel power generation, dynamic positioning system thrusters or seafloor mining tool, might cause "harm" to marine animals.

Air emissions will consist of combustion emissions from the vessel power supply and the mining, transfer and processing power supply. Air emissions of most concern are carbon dioxide, carbon monoxide, nitrogen oxide and sulphur dioxide. The ecosystem can recover

from natural disruptions including volcanic eruption and alternation between active and inactive vents as discussed above. Within this setting, the ecosystem at Solwara 1 site is expected to be re-established after a transition period of a few years.

To ensure the reestablishment of the ecosystem and lower the risks of loss of biodiversity and endemism, the following mitigation strategies was proposed by (Nautilus Minerals Inc, 2008) to protect seafloor biodiversity and maintain nearby communities of animals to enhance the rate of recovery. First, provide an unmined reference area at South Su close to Solwara 1 to provide parent stock for repopulation and a control site for environmental monitoring, see Figure 52. Second, create a temporary refuge area within Solwara 1 to allow progressive rehabilitation. Third, to enhance re-colonization, some animals will be moved from non-excavated areas where excavation is complete. Last, if appropriate, artificial substrates will be established to provide re-population habitats.

The unmined area at nearby South Su contains very similar biological communities and will also provide source of recruitment to Solwara 1, which is about 2 km down current. The effectiveness of the methods proposed to protect biodiversity and enhance recovery at Solwara 1 will be monitored throughout and beyond the life of the Project to determine recovery rates, and will provide valuable scientific information to assess the potential for any cumulative effects of future seafloor mining prospects.

8.4.3 Indirect Environmental Impact

The direct in-situ impacts of seabed mining activities are demonstrated in Figure 52. The post-process from ore to pure copper and gold as part of the mining production chain could cause even severe and lasting environmental impact.

Transport, Storage, and Processing the Ore

Preliminary studies conducted by Nautilus Minerals determined that offshore processing and/or storage of the ore would be financially infeasible (Birney et al., 2006). The collected ore will be transported from production vessel to Port of Rabaul for temporary storage. Then the ore will be shipped to Tongling Nonferrous Metals Group in China for post-processing (Nautilus Minerals Inc, 2012).

The highly sulphidic nature of the ore may give rise to the potential for acid generation once exposed to air during the dewatering process, transport and while temporarily stored in stockpiles. Acid rock drainage (ARD) increases the ability for heavy metals to leach from the ore into the surrounding environment, resulting in contamination and potential toxicity to aquatic organisms and groundwater. The risk of pollution and product spillage is likely to be greater around areas such as refuelling stations and loading/unloading areas. A drainage

treatment facility will be added for the onshore storage and handling at the Port of Rabaul of produced ore to minimise acid generation and deal with acid rock drainage.

Ore processing technology has the most widespread, concentrated, and lasting environmental impacts in the mining industry. Acid leaching techniques for copper and gold in particular have been the source of some of the worst environmental mining catastrophes (e.g., Summitville Mine in Colorado, Marcopper Mine in the Philippines, or Omai Gold Mine in Guyana) (Birney et al., 2006).

Tailings Disposal

Tailings contain heavy metals which could not be recovered through acid leaching technique. A potential place for tailings disposal may be the ocean. This method relies upon anoxic conditions at the bottom to be sufficient to inhibit the formation of sulphuric acid and heavy metal dissolution and transport associated with terrestrial acid mine drainage problems. There are 26 such tailings disposal operations in the world and the majority are found in the Asia-Pacific region (Pearce, 2000).

8.5 Logistics and Supply Chain Concept

The review of the logistics and supply chain concept of the Nautilus Minerals Solwara case contemplates the transportation and handling processes from sea surface to markets for best practices and challenges. Furthermore, the current state of the mining site logistics shall be evaluated. Figure 53 indicates the operations in scope of the review.

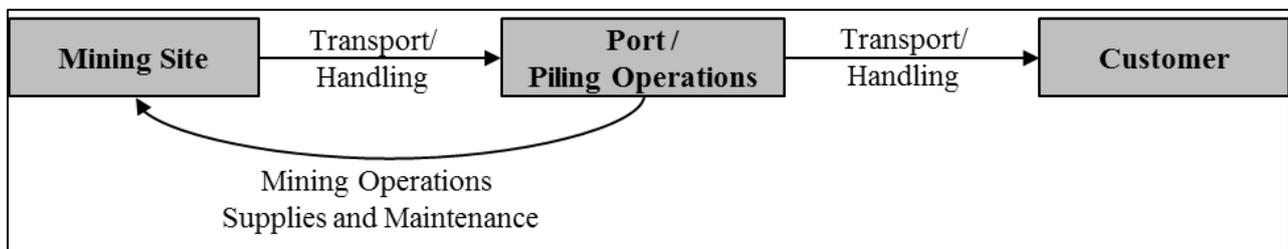


Figure 53: Logistics and Supply Chain Operations

The daily production rate for ores at Solwara 1 is planned to range between 2,200 and 4,320 tonnes with an average of 3,710 tonnes per day excluding downtimes. At the current stage, the transport of ores between the mining site Solwara 1 and the Deepwater Port Rabaul is planned to be conducted by chartered transport barges. The distance from the mining site to the Port of Rabaul is approximately 60km. The ores are planned to be transported by a 6,000 tonnes flat boat dumb barge with tugboats for manoeuvring. The ores will be loaded after the dewatering process by an ore conveyor to the transport barge (see Figure 54). The reactivity of the ore is identified as one of the risks for the transportation process. This risk shall be limited by monitoring and controlling the transportation moisture limit and coverage of the ores and stockpiles.

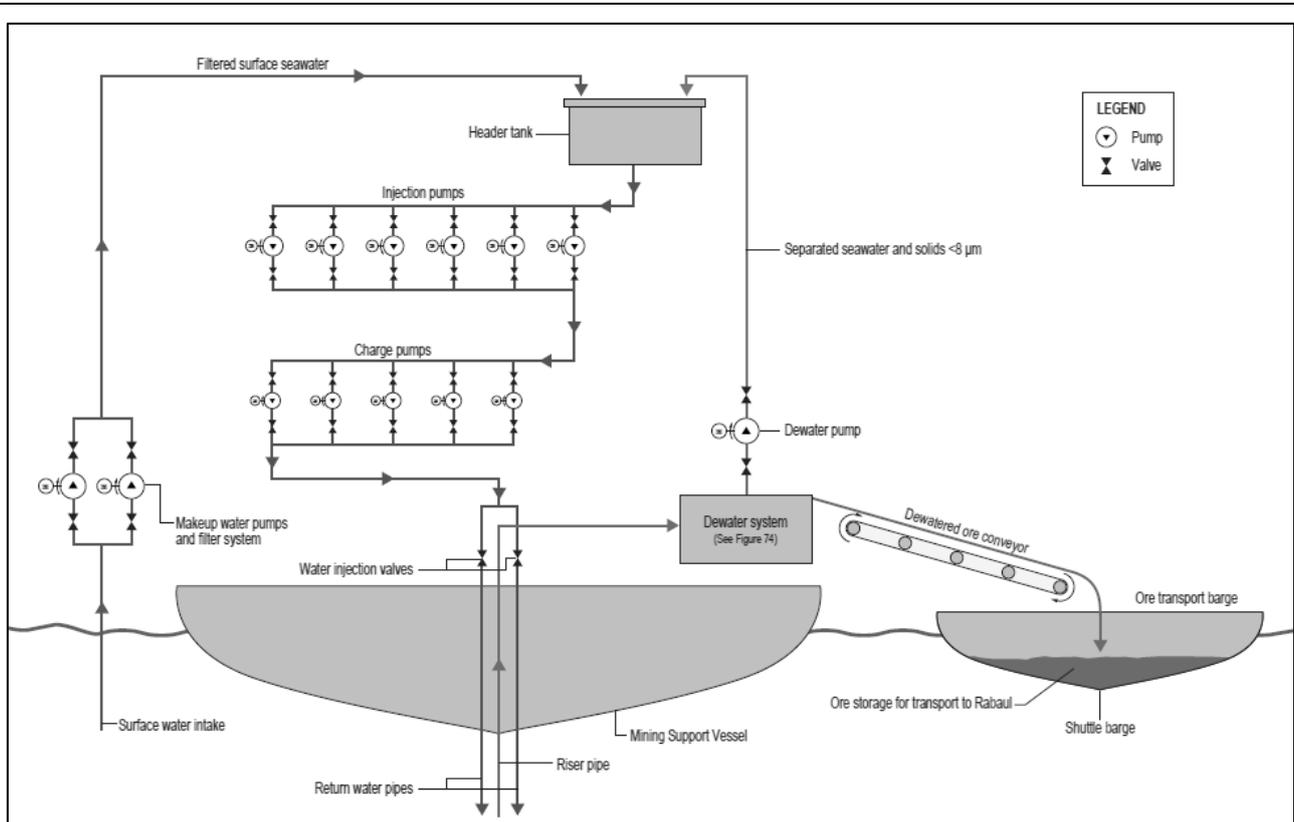


Figure 54: Handling Production Support Vessel to Transport Barge

Source: www.cares.nautilusminerals.com

At this stage, no information is provided on capacity optimisation and scheduling of the barge(s), detailed operating and fuel costs, safety and risk management or influences of weather conditions on the handling processes.

At the Port of Rabaul Nautilus Minerals agreed on a Port Upgrade and Operations Deed with PNG Ports Corporation Limited for a port handling capacity of 1.5 million tonnes of ore per year for three years. It includes the concepts for the hardstand areas for temporary ore stockpiling prior to shipment to processing facilities overseas. All port operations such as ore unloading, stevedoring services, stacking and ship loading will be conducted by PNG Ports Corporation.

According to the original supply chain concept indicated in Figure 55, Nautilus Minerals planned to produce concentrates onshore and stockpile them prior to shipping out. However, in April 2012 Nautilus signed a contract with the Tongling Nonferrous Metals Group a large importer of copper concentrates in the Yangtze River Delta in China. It has been agreed that 1.1 million tonnes of ore (+/- 20%) will be shipped to Tongling for production of copper concentrates annually. This refers to 80% of the planned total production rate in the first year. After the production of copper concentrates the material will be smelted and refined. The final purchasing price is dependent on the material quality and thus, the recovery of

copper, gold and silver reduced by logistics and processing costs as well as smelter treatment and refining charges.

Up to date, no information is provided on the vessel requirements for the 2,886nm journey from Port of Rabaul to Tongling. It is not stated, whether the stockpiling facilities are going to be used in the same extent and what transportation schedules are aimed at.

Table 10: Logistics Processes and Areas for Future Development
Source: Data adapted from www.nautilusminerals.com

Logistics Processes	Nautilus Minerals Case	Areas for Future Development
Transportation Mining Site – Port	<ul style="list-style-type: none"> ▪ 50km distance Solwara1 – Port Rabaul ▪ Chartered transport barges ▪ 6,000t dump barges with tugboats for manoeuvring ▪ Handling of ores from production support vessel to barge by conveyor belts 	<ul style="list-style-type: none"> ▪ Capacity optimisation and scheduling for barge specification ▪ Estimation of operating and fuel costs ▪ Safety and risk analysis (e.g. reactivity, moisture, weather conditions) ▪ Feasibility testing of handling processes in different weather conditions, estimates of downtime ▪ Cleaning specifications for ore discharges
Port Operations and Stockpiling	<ul style="list-style-type: none"> ▪ Port handling capacity of 1.5 million tonnes of ore ▪ Hardstand areas for temporary ore stockpiling ▪ Port operations by PNG Ports Corporation 	<ul style="list-style-type: none"> ▪ Stockpiling-transport optimisation ▪ Influences of weather conditions on stockpiles / environmental impact assessment for port operations ▪ Handling and stockpiling guidelines
Transportation Port – Customer	<ul style="list-style-type: none"> ▪ Contract with Tongling Nonferrous Metals Group (Yangtze River Delta) for 1.1 million t ▪ Distance: Rabaul - Tongling 2,886nm – 12 days 	<ul style="list-style-type: none"> ▪ Logistics optimisation with regards to customer requirements ▪ Specifications for safe high sea transportation (e.g. vessel, waterway and port requirements) ▪ Development of intermodal transportation concepts for various customers
Mining Site Logistics	<ul style="list-style-type: none"> ▪ n/a 	<ul style="list-style-type: none"> ▪ Process mapping of production vessel demands and supplies ▪ Maintenance logistics for seafloor tools, risers and production support vessel

Table 10 summarises the current specifications presented in the Nautilus case and derives futures issues and areas for development for the Atlantis II Deep concept and the guidelines for sustainable seabed mining. The key issues identified are the lack of specifications for handling and transportation as well as recommendation on stockpile management. Furthermore, the reactivity of the ores and moisture limits demand for clarifications and in-depth impact assessments. The currently presented concept indicates a bulk purchasing of

one customer. Future developments should take variations of customer-mining site relationships into account, e.g. varying number of customers, varying markets. These scenarios might have significant implications on the requirements for port operations, barges and vessels.

8.6 Legal Requirements and Issues

8.6.1 Existing Guidelines and Previous Examples

Seabed mining is a nascent industry and still in the exploration phase. Detailed guidelines associated with mining operation have not been in place or do not exist. Different marine legislations and a few broad guidelines have been developed in the past and can be applied to seabed mining, including international legislation, national legislation, environmental regulations, local and state government legislation and guidelines and code for environmental management of seabed mining.

The ISA has developed regulations for prospecting and exploration of seabed minerals including polymetallic nodules, polymetallic sulphides and cobalt-rich crusts. ISA also provides recommendations for the guidance for the assessment of the possible environmental impacts arising from exploration for polymetallic nodules in the international water (also known as “the Area”). Those guidelines can be found on the ISA website under the mining code section. In 2001, the International Marine Minerals Society (IMMS) drafted a code for environmental management of marine mining based on the Madang Guidelines (1999), the PNG Green Paper on offshore mining policy (1999), and consulting with international marine scientists and mining engineers. This Code establishes industry standards for deep sea mining and can be used by industry, regulatory agencies, and other stakeholders in creating, implementing, and evaluating a comprehensive environmental management plan for deep sea mining. InterRidge published a statement (Code of Conduct) for researchers at deep sea hydrothermal vents. There are also many international maritime legislations related to the worker’s safety, transportation, dumping wastes on the sea. Over different national jurisdiction, specific local maritime legislations may also in act.

Seabed mining is a high environmental impact activity. Environmental impact assessment has to be conducted and submitted for approval to the corresponding government or originations prior the mining operation. The Gorda Ridge environmental impact assessment is one of the earlier examples closely related to seabed mining.

Considering the environmental impact, tailings disposal needs particular attention in the mining operation. The Scottish Association of Marine Science was commissioned by the Papua New Guinea government to conduct a study on the deep sea mine tailings placement

(DSTP) in PNG. This was in response to community concerns about plans for the Ramu nickel mine to dump 100 million tons of waste into the seas off Madang.

8.6.2 Legal and Environmental Regulations for the Solwara 1 Project

The Solwara 1 deposit is located inside the exclusive economic zone of PNG. The Mining Act 1992 is presently the principal policy and regulatory document governing the mining industry in PNG. The Mining Act 1992 vests ownership of all minerals in or below the surface of land with the national government, and governs the exploration, development, processing and transport of minerals.

In the case of Solwara 1 project, waste from ships will be managed in accordance with the MARPOL 73/78 Convention and the Protection of the Sea (Prevention of Pollution from Ships) Act 1983 which states that no disposal of food wastes or untreated sanitary wastes shall take place within 12 nautical miles of land. The marine support vessel is more than 12 nautical miles from land and food scraps and sewage will be macerated and treated to MARPOL standards. In the case of no regulation is in place, the government/organization and mining contractor have to work together to create new regulation for the specific situations. Emergency response plans have to be developed to mitigate the effects of natural disasters and unplanned events.

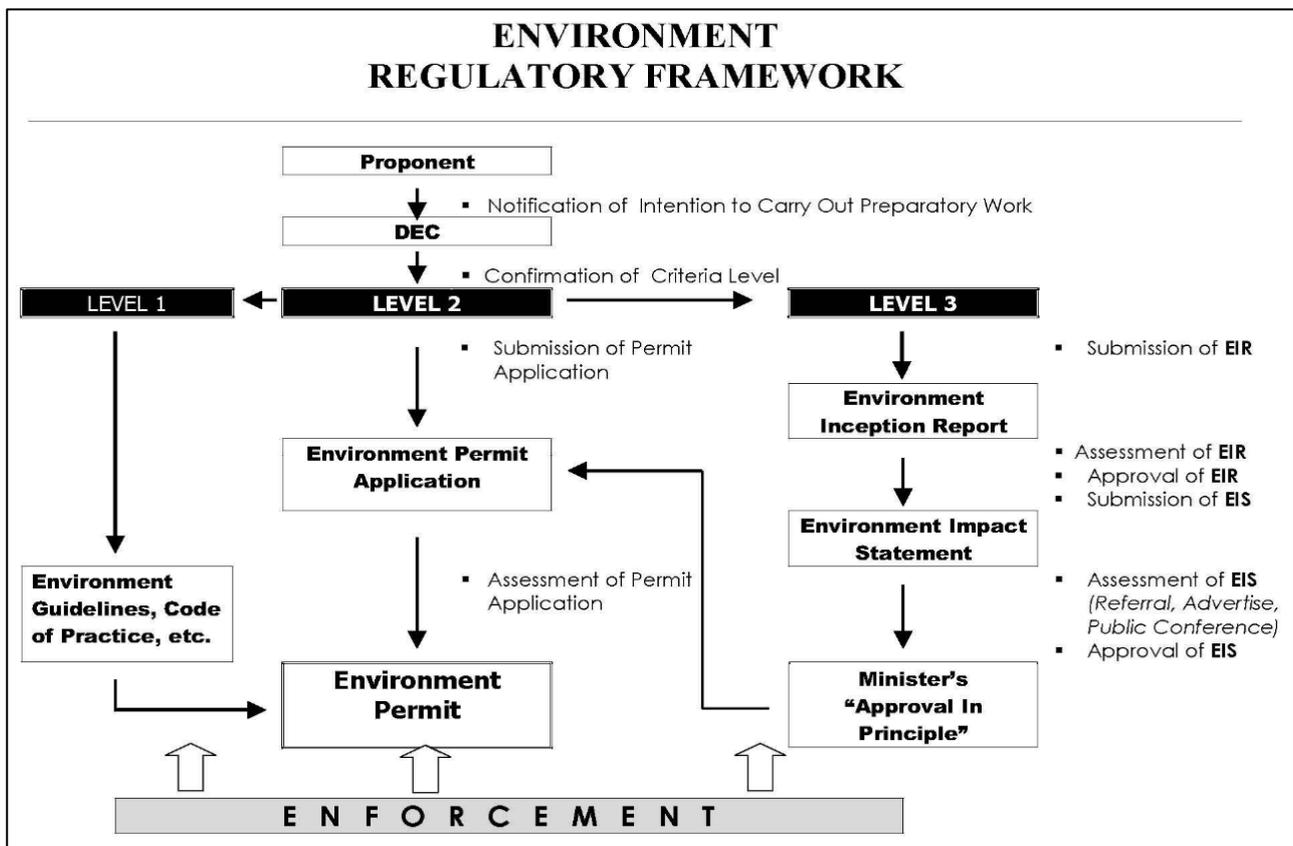


Figure 56: Environment Regulatory Framework
Source: Smith (2010)

Environment Act 2000 outlines environmental requirements. The Solwara-1 Project is a 'level 3' activity under the Environment Act 2000, which requires that an Environmental Impact Statement be submitted to the Department of Environment and Conservation (DEC) of Papua New Guinea. Smith (2010) outlined the leading edge approach Nautilus had taken in completing the Environmental Impact Statement (EIS) for the world's first deep seafloor copper and gold mine. In addition, Smith (2010) reviewed the permitting process and the government and stakeholder engagement undertaken as part of Nautilus' desire to "do it right" in this new industry. The first step in the permitting process is the preparation of the Environmental Inception Report (EIR), which describes the project, its envisaged impacts and the proposed studies for the Environmental Impact Assessment (EIA).

The Environmental Impact Statement (Nautilus Minerals Inc, 2008) was submitted to the PNG government in September 2008. The main objectives of the EIS were to understand the existing environment, potential impacts due to mining and how to mitigate significant impacts. The EIS discusses the issues and impacts associated with the project in a range of spatial contexts such as the mining areas at Solwara 1, barge corridor and crew transfer routes and the project facilities to be used during operations at the Port of Rabaul and emergency response plans for accidental events and natural hazards.

To ensure transparency, collaborating researchers are free to publish their findings. Following its submission, the EIS was made available for public review and public hearings were held at several locations. The EIS has also undergone a rigorous independent review by PNG government-engaged consultants. Outside the permitting process, Nautilus worked alongside government officials to carry out ongoing community consultations. Information dissemination and feedback acquisition had also occurred through the Nautilus website and attendance at a number of international conferences, workshops, and meetings.

The Environmental Permit for the Solwara 1 Project was granted on 29 December 2009 from the Department of Environment and Conservation (DEC) of PNG for a term of 25 years, expiring in 2035. The next steps for Nautilus are to prepare the draft project Environmental Management Plan (EMP) for submission and approval by the DEC 3 months prior to project commissioning in the early 2013. The Environmental Management Plan for the Solwara 1 Project will address the management, monitoring and reporting requirements for the various phases of the Project, e.g. baseline, operations and decommissioning, accounting for the commitments made in this EIS and the conditions of approval stipulated by the state. The latter includes validation of predicted impacts and identification of unforeseen effects and needs for additional management measures.

8.7 Concluding Remarks

This chapter provided a review on the status of the Solwara 1 project of Nautilus Minerals. It presented the publically available specifications on the engineering system, implying the seafloor tools, riser and lift system as well as the production vessel. Furthermore, a brief summary of the estimation of the CAPEX and OPEX is indicated, which shall serve as a starting point for economic modelling in seabed mining. Since the case study provides in-depth information on the environmental impact assessment and mitigation strategies for a seabed mining system, the environmental regulatory framework is discussed in detail. The supply chain concept of the Nautilus Minerals Solwara case contemplates the transportation and handling processes from sea surface to markets and concludes with critical issues for logistics network design.

The next chapter will introduce a new concept and solutions for sustainable seabed mining for Atlantis II Deep based on the comprehensive datasets collected. A site specific assessment of Atlantis II Deep will be conducted and a new engineering system will be introduced. Moreover, an economic model and supply chain concept will be proposed and potential environmental impacts will be evaluated.

9 A New Concept for Atlantis II Deep

9.1 Introductory Remarks

The most promising seabed mining locations are along the oceanic spreading ridge. As outlined in Chapter 5 Atlantis II Deep is a potential site for future seabed mining operations. The mining potential and reserve have been studied in the past. A mining engineering system was built and tested successfully in a pre-pilot mining project in 1979. With the increase of metal prices and advances in technology, seabed mining in Atlantis II Deep becomes tangible in the near future.

The mining engineering systems in the pre-pilot test and in the Solwara 1 project provide valuable experiences for the development of a new concept. Moreover, the expert knowledge gained in Chapter 7 provides valuable aspects for the design stage. The objective is to design an engineering system and supply chain that addresses the developed sustainability framework in Chapter 5 by means of efficiency, energy consumption, economic and environmental feasibility.

9.2 Characterisation of Mining Site “Atlantis II Deep”

9.2.1 Mining Site: Atlantis II Deep

Atlantis II Deep is located at latitude 21°23' N and longitude 38°04' E, 70km from the nearest shore as shown in Figure 57. The deposit has a mining depth of 1,900-2,200m metres. Noteworthy is that the area contains hot brines of 200m thickness with water temperatures ranging up to 56°C and salinities up to 270 parts per thousand, which are 7 times that of normal seawater (Hartmann, 1985). Metallic trace elements such as zinc, copper, and cobalt, are present in concentrations exceeding those of normal seawater by about 1,000 times.

Metallic sulphide deposits are associated with hydrothermal systems along ocean-floor spreading centres. The most promising deposits found thus far lie in a series of deep basins along the central rift valley beneath the Red Sea. The largest, the Atlantis II Deep, has an area of about 62 km². The upper 10m of sediments are estimated to contain about 2.9 million tons of zinc (Zn), 1 million tons of copper (Cu), 0.8 million tons of lead (Pb), 45,000t of silver (Ag) and 45 t of gold (Au), worth a few billion dollars (see Chapter 9.4).

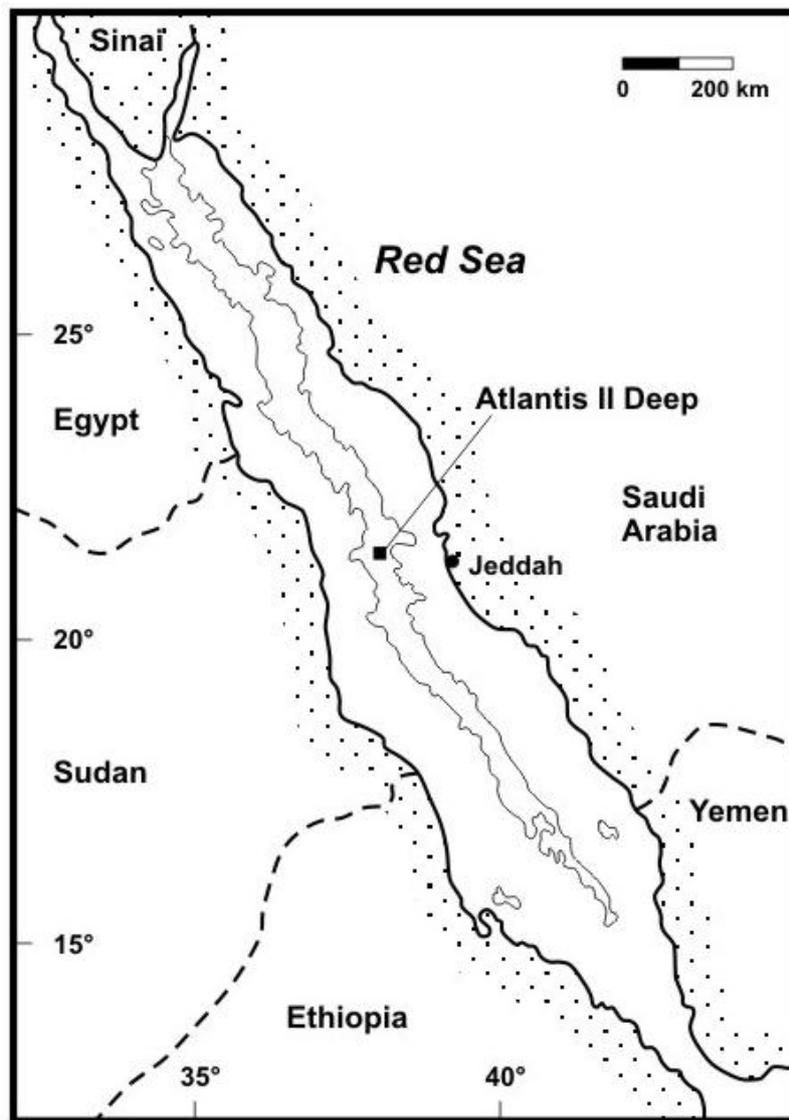


Figure 57: Location of Atlantis II Deep
Source: Winckler et al. (2001)

Atlantis II Deep has two layers of hot brine. The lower layer has temperatures of 56°C and 60°C and a salinity of 257 PSU. The upper layer has a temperature of 44°C to 60°C in the and a salinity of 135 PSU (McKelvey, 1986). The average density of the brine is 1,190 kg/m³ (Winckler et al., 2001).

Table 11: Comparison of Metal Grades in Atlantis II Deep with Land-based Deposits
Source: Bertram et al. (2011)

Average grads	Atlantis II Deep	Mt. Isa, Australia	Meggen, Germany
Zinc (%)	2.06	7.00	7.00
Copper (%)	0.45	0.10	0.10
Silver (g/t)	38.40	150.00	14.00
Size (Mt)	89.50	150.00	55.00

Beneath the brines, up to 40 m of fine-grained metalliferous sediments have been accumulating for the past 25,000 years. These sediments are characterized by a high horizontal and vertical variability in metal concentrations, with generally high average grades of metals such as zinc, copper and silver ($Zn > 2\%$, $Cu > 0.5\%$, $Ag > 39 \text{ g/t}$). As indicated in Table 11 the deposit contains 89.5 million tons of in-situ resources (dry salt free). Therewith, Atlantis II Deep is of a considerable size, even compared to land-based deposits (Bertram et al., 2011).

9.3 Engineering System

The engineering system developed comprises the system from the seafloor sediment collection to the production support vessel at the sea surface. Figure 58 indicates the overview of the system. In the following paragraph, the components of the system, namely the seabed mining machine, the riser, the deepsea mining pump, the floating platform, the vessel positioning and the energy supply system.



Figure 58: Overview of Engineering System

9.3.1 Seabed Mining Machine

The seafloor mining machine is designed to collect the material from the seafloor and transfers the slurry to the riser. The design of the seafloor tool faces various challenges in the Red Sea environment. First, the equipment must be resistant to high ambient pressures. Every ten meters the pressure in the water column increases by one bar. For Atlantis II Deep with a depth of more than 2,000m this results in an ambient pressure of more than 200 bars. Second, the equipment must function in a brine environment with extreme high salinity. Therefore, an optimal corrosion protection is necessary. For the wide range of seawater protected components that will be used, corrosion resistant materials and/or special coatings need to be applied. Third, the equipment must be reliable because the machines that work at such a depth cannot easily be hoisted up in the case of malfunctioning. Therefore, the maintenance accessibility for the machine components needs to be taken into account.

The seabed mining machine of interest in this concept is a collection machine which consists of several major subsystems that will be discussed in the following: the collecting system, the electro-hydraulic system, the movement system, the power supply system and the control system.

Collecting System

For ore gathering of sediments on the seafloor, the collection vehicle is fitted with an auger device that channels the ore to the inlet of a large centrifugal dredge pump as the vehicle traverses the mine site. The machine will also be equipped with a cutter head, which excavates the soil before it is sucked up by the subsea pump. The ability of the auger to convey the mined ore to the pump inlet is seen as a key element to the success of the vehicle. The total system head for the gathering machine to the centrifugal pump is estimated with 18 bar (SRK Consulting, 2010). This discharge pressure will require centrifugal pumps in series.

Centrifugal pumps are connected in series if the discharge of one pump is connected to the suction side of a second pump (Wilson, 2006). Three similar pumps, in series operate in the same manner as a three-stage centrifugal pump. The head will be three times that of a single pump at the same flow rate. Centrifugal pumps in series are used to overcome larger system head losses than one pump can handle alone. Each of the pumps is putting energy into the pumping fluid so that the resultant head is the sum of the individual heads. This configuration allows a more compact way to place equipment and a more efficient use of machine compartments as shown in Figure 59.

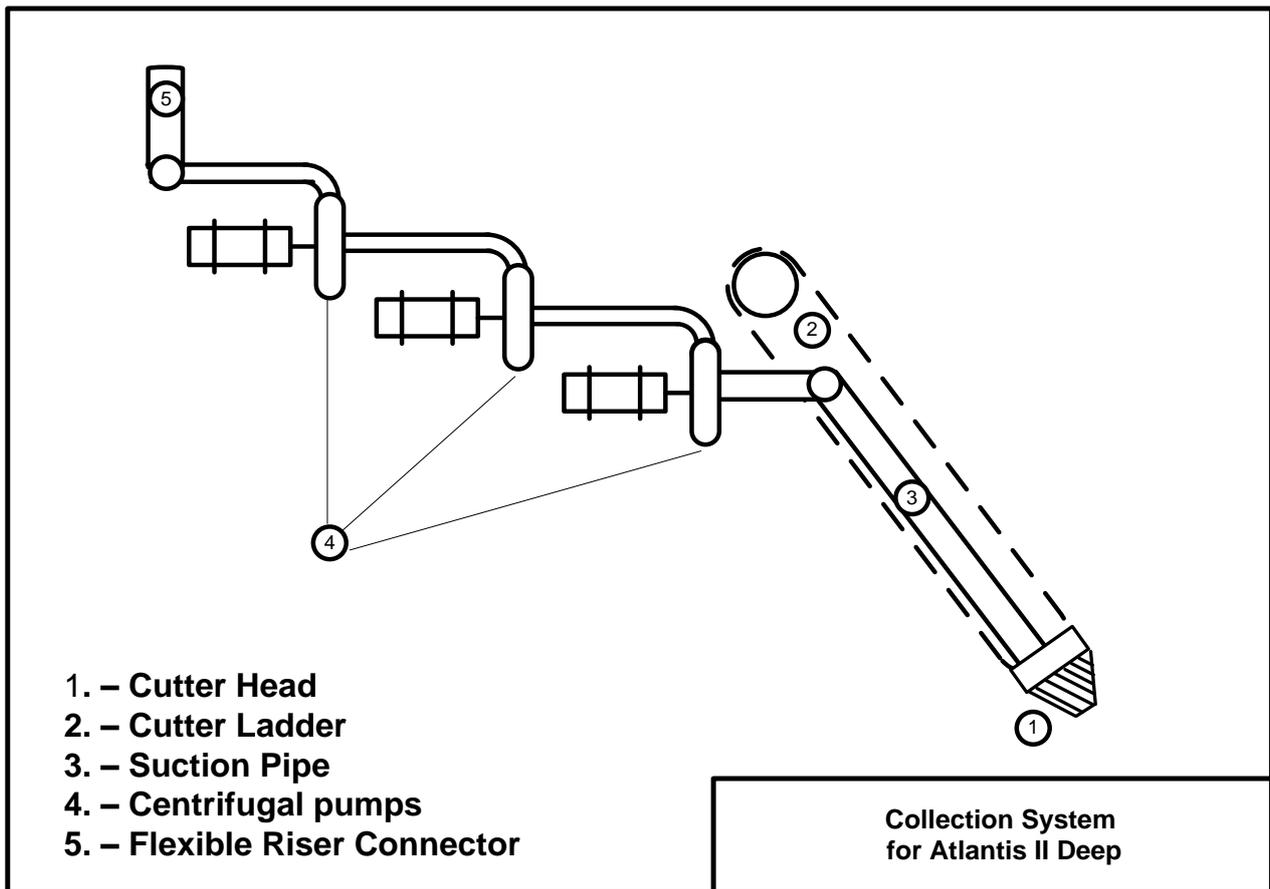


Figure 59: Schematic of the new Collection System

The cutter head type and size depend not only on the technical specifications of the collecting system, but also on the type of soil to be dredged (Eisma, 2006). High cutting forces can be generated with relatively high side winch forces and a small cutter diameter. Thus, harder soil can be cut as well. In soft ground it is necessary to use a bigger cutter diameter for the same cutter power and exchange the high side winch forces for a higher speed. This can be achieved by changing the gears of the side winch drive. When cohesive soil is being cut different boundary conditions are relevant. For instance, blockage of the cutter head needs to be avoided. As a conclusion, the general guidelines for the design of cutter heads for various types of soil are:

- For hard soil: The cutter head should be suitable, thus heavy and robust, to withstand impact forces on one or more teeth. The design should be small in contour with replaceable teeth in order to withstand extreme wear on both the cutter head itself, the teeth and the adapters. The size of the fragments may not exceed the minimum passage of the pump.
- For non-cohesive soil: The cutter head should be suitable for very high production rates. Many replaceable chisels (wide or narrow) or cutting edges and wide though flattened contour (little pumping action). Well able to withstand wear, especially of the cutting elements. Here also good, accurate tooth positions are needed.

- For cohesive soil: The cutter head may not become blocked so is ample and round in contour. Open near the hub, often with one less blade (thus 5 blades). Good cutting properties in clay, small fragments, plain or serrated edges or many small teeth (Eisma, 2006). This type of cutter head is the most useful for Atlantis II Deep sediments.

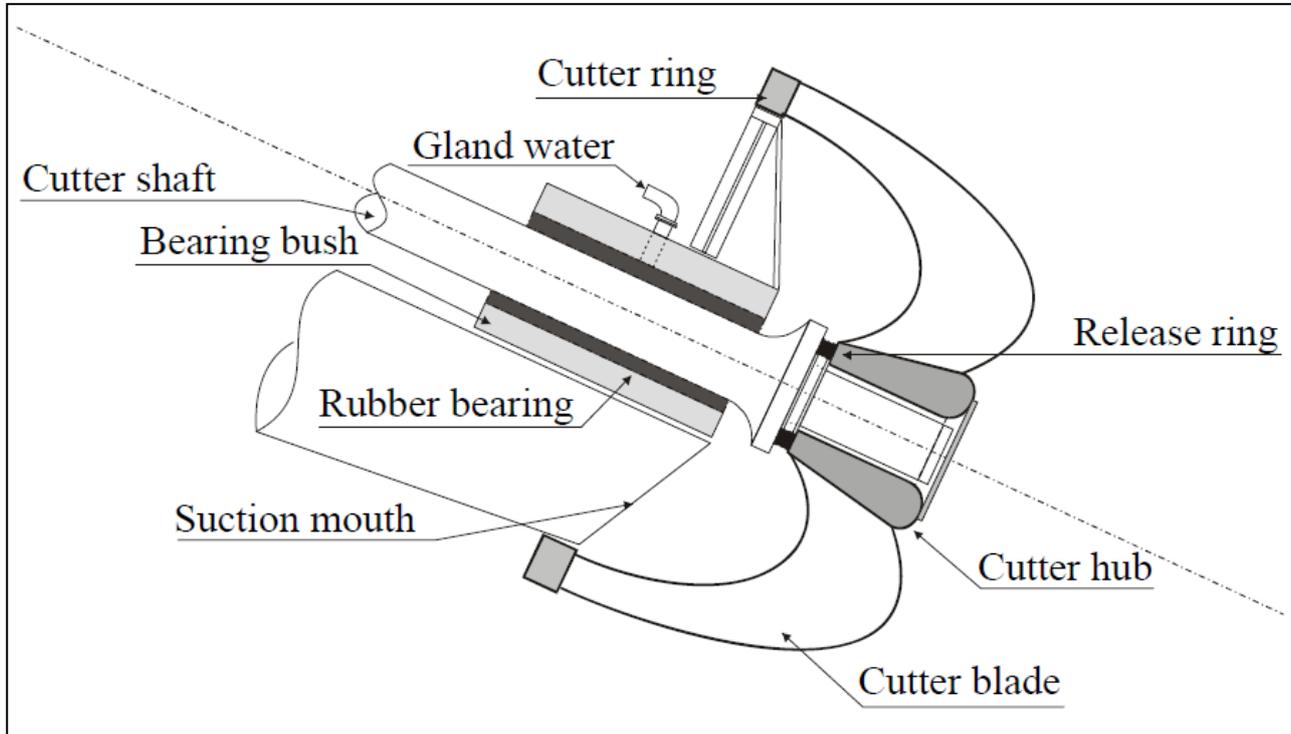


Figure 60: Schematic of the developed cutter head
Source: Eisma (2006)

The cutter head comprises a back ring on the bottom side. The inside diameter of this ring fits the suction mouth and cutter shield. The second part is the hub by which the cutter head is mounted via an 'Acme' or three threaded screws onto the cutter shaft. The cutter arms or blades are usually five or six. The number is related to the required strength and/or space between the arms. The cutter arms form a screw shape and link the ring to the hub. The cutter head is termed a normal helical cutter head, if the chosen screw shape allows that the dredged material is transported to the ring. If the thread of the screw runs in the other direction, the cutter head is termed a reverse helical cutter. Edges (knives) or replaceable teeth or chisels are mounted on the cutter arms. There are various tooth and cutting edge systems on the market, each with its own advantages and disadvantages. They are all based on the principle to quickly replace the parts that are subject to a heavy wear if needed. In addition to the property mentioned above, a tooth must satisfy a good transfer of the cutting force to the cutter arm. The teeth and adapters must be positioned in a way that there is little or no wear to the cutter arms and thus, the blades run freely (Eisma, 2006).

Electro-hydraulic Equipment

In the hydraulic machine, hydraulic fluid is transmitted throughout the machine to various hydraulic motors and hydraulic cylinders (Merkle et al., 1994). The fluid is controlled automatically by control valves and distributed through hoses and tubes. The popularity of hydraulic machinery is due to the very large amount of power that can be transferred through small tubes and flexible hoses, and the high power density and wide array of actuators that can make use of this power. Electro-hydraulic equipment has many advantages such as a high accuracy and manoeuvrability of the equipment, high static forces or torques of rotation, easy control of a wide range of speed and forces, effective overload protection, low vibration and considerable flexibility of location. Furthermore, the weight and maintenance accessibility of the hydraulic components needs to be considered.

Movement System

The collection machine can move on one pair of tracks and be electrically powered from the surface. Within this concept, this machine is developed with a buoyant configuration as shown in Figure 61 and Figure 62. It can be fitted with buoyancy and thrusters to improve the manoeuvrability and provide bouncy characteristics for the machine (SRK Consulting, 2010).

An azimuth thruster is a configuration of propellers placed in pods that can be rotated in any horizontal direction. These give the gathering machine a better manoeuvrability. An L-drive thruster has a vertical input shaft and a horizontal output shaft with one right-angle gear. Retractable thrusters can provide thrust in any direction, which is very important for dynamically positioned (DP) vehicles. The main advantages are the electrical efficiency, better use of machine space and lower maintenance costs. Tracks are often considered as the most versatile locomotion system and can handle relatively large obstacles and loose soils (Liu, 2005). Therefore they have been used predominantly in vehicles like tanks and excavators. The advantages and disadvantages tracks system are shown in Table 12.

Table 12: Advantages and Disadvantages of Tracks Systems

Advantages of Tracks Systems	Disadvantages Tracks Systems
<ul style="list-style-type: none"> ▪ Smooth locomotion on relatively smooth surface ▪ The technology is well understood and simple ▪ Superb traction on cohesive soil ▪ Can handle large hinders and small holes and ditches ▪ Good payload capacity 	<ul style="list-style-type: none"> ▪ High-energy consumption ▪ Inefficiency due to friction in the tracks ▪ Slip friction when the vehicle must turn ▪ Not especially gentle with the ground they travel over, e.g. when turning in place ▪ Vehicles with one pair of belts suffer from impacts when e.g. climbing over large boulders or when they start going down steep slopes

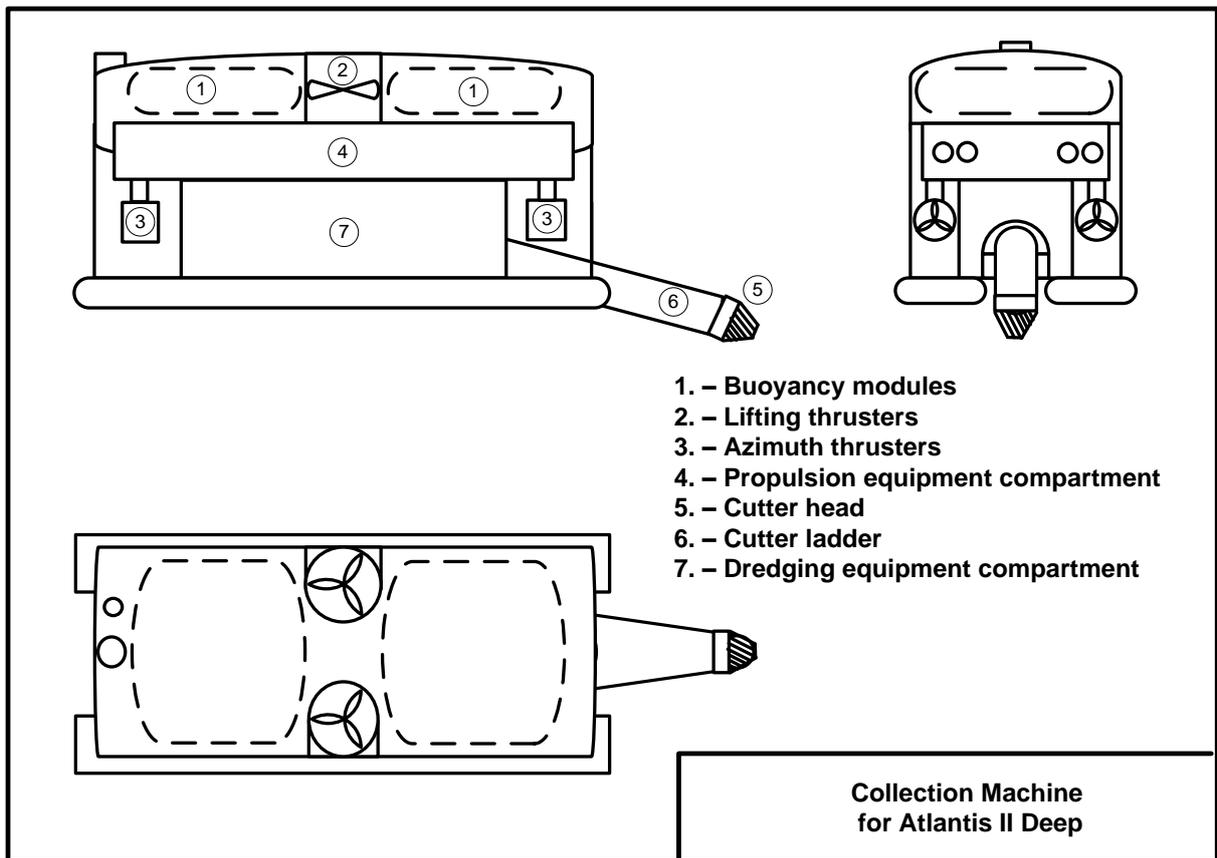


Figure 61: Schematic of the developed Buoyancy Configuration of the Collection Machine

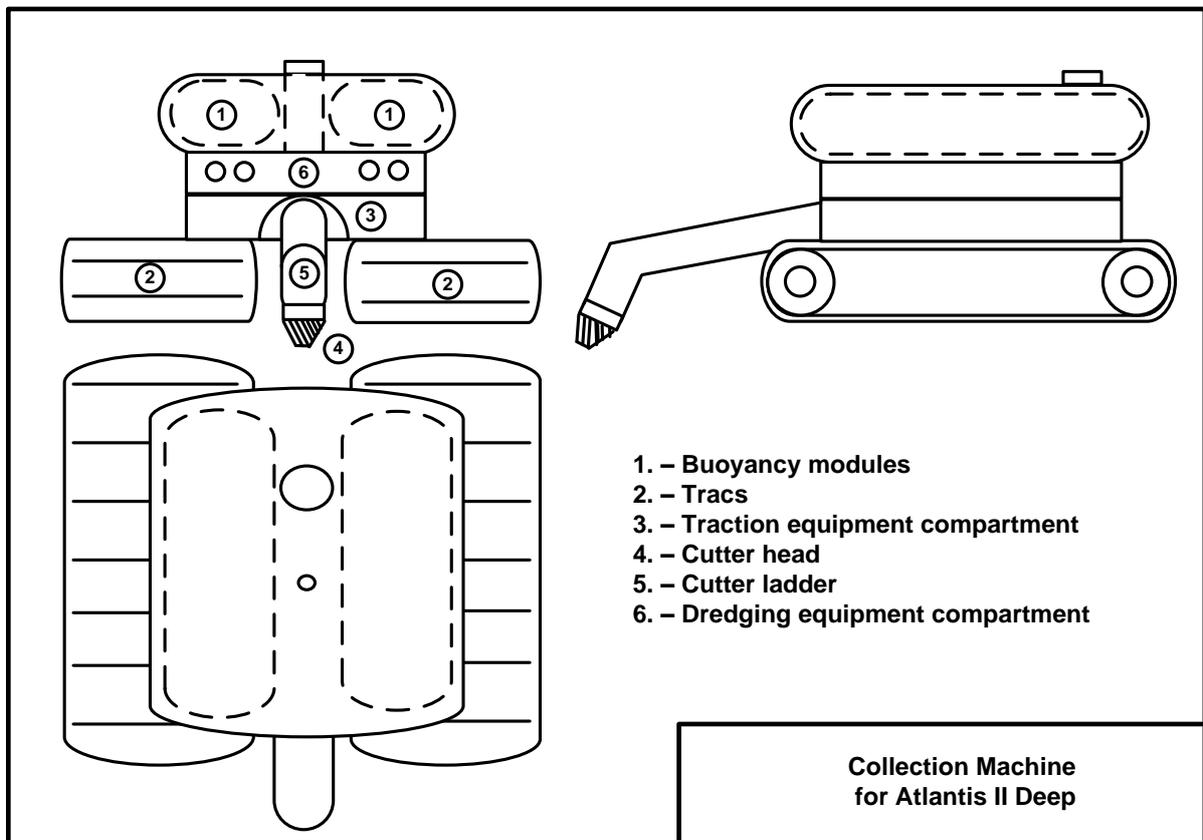


Figure 62: Developed Configuration Concept of the Collection Machine

The main types of movement drive systems are the electro-hydraulic drive and variable-frequency electric drive. An electro-hydraulic drive system is a drive or transmission system that uses pressurized hydraulic fluid. A hydraulic drive system consists of three parts: The hydraulic pump, driven by an electric motor; valves, filters, piping etc. (Merkle et al., 1994). A variable-frequency drive (VFD) is a type of adjustable-speed drive used in electro-mechanical drive systems to control AC motor speed and torque by varying motor input frequency and voltage.

Power Supply System

The collection machine will be supplied by electrical energy from the shipboard. The machine total power will be about 2 MW and the cable length will exceed 2,000 meters. Thus, it is necessary to consider the complexity of the transmission. A power supply system with high voltage 6,600 volts is selected to satisfy the long distance transmission.

The basic calculations are as follows. For the 2 MW load and a 0.8 power factor, the full-load current will depend on the voltage according to the following equation:

$$\text{Equation 1: } I = \frac{2 * 10^6}{\sqrt{3} * U * 0.8}$$

By a substitution of different values corresponding values for the current can be obtained. The calculation results are given in the relevant diagrams to determine the high voltage benefits. Figure 63 demonstrates the advantages of high voltage, which can decrease the full-load current, reduce power losses in the cable and load, decrease cable cross sections and decrease the size of the equipment.

The power loss can be calculated as follows:

$$\text{Equation 2 } \quad \text{PowerLoss} = I^2 * R$$

I is the current carried by the conductor; R is the resistance of the conductor. Thus, power loss varies square of the current carried by the conductor. The use of a higher voltage will reduce the size of a supply cable and other electrical equipment.

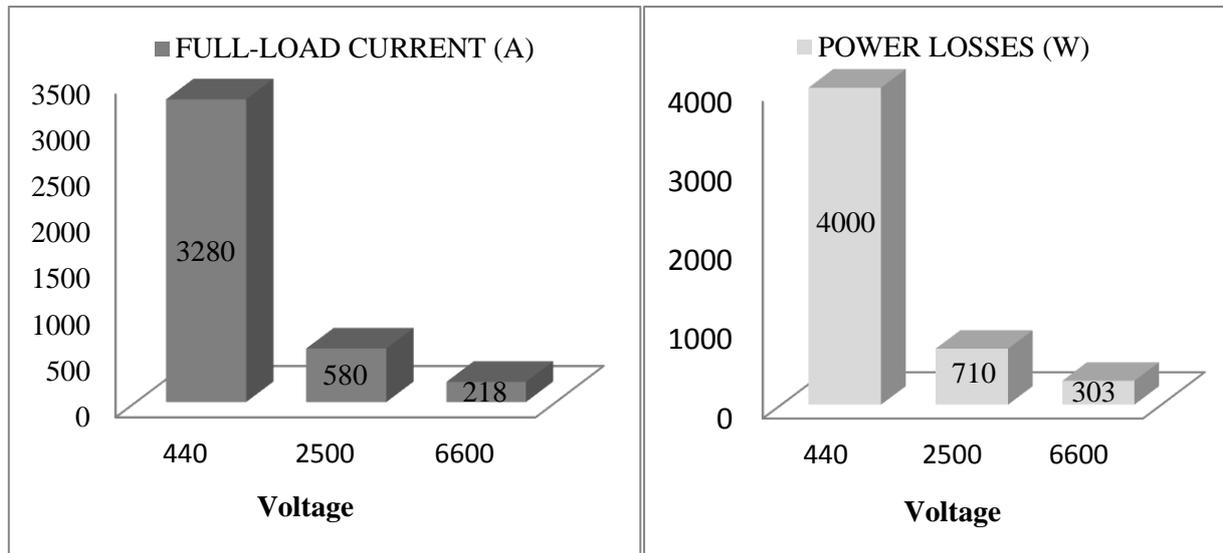


Figure 63: Illustration of Full-Load Current and Power Losses from Voltage

Control System

The collecting machine must be equipped with a camera, various sensors and detectors for effective control by the vessel operator. It is necessary to provide reliable means of transmitting control signals from the vessel to the machine and feedback signals from the machine to the vessel. Optical fibre cables are used and routed in one sheath with the power supply cable. An optical fibre cable contains one or more optical fibres. The optical fibre elements are coated with plastic layers individually and contain a protective tube which must be suitable for the high-salinity environment in Atlantis II Deep. An optical fibre is made from glass (silicium) or plastic, a bit thicker than a human hair. It works as a light pipe, or waveguide, for transmitting light between the two ends of the fibre fibre (Crisp and Elliott, 2005). Optical fibres are widely used in the communication industry and permit to do transmission over longer distances by give higher bandwidths (data rates) than other forms of transmission. Fibres are used instead of metal wires since signal travelling induces less loss and is also immune to electromagnetic interference.

Usually the optical fibres include a crystalline core surrounded by a transparent cladding material with a lower index of refraction. Light is kept in the core by total internal reflection. This causes the fibre to act as a waveguide. There are two modes fibres; Multi-Mode Fibres (MMF) that support many transverse modes and Single-Mode Fibres (SMF) that only support a single mode. Single-mode fibres are used for most communication links longer than 1,000 meters (Chesnoy, 2002). These fibres are more useful for transmission control signal to Seafloor Machine from surface.

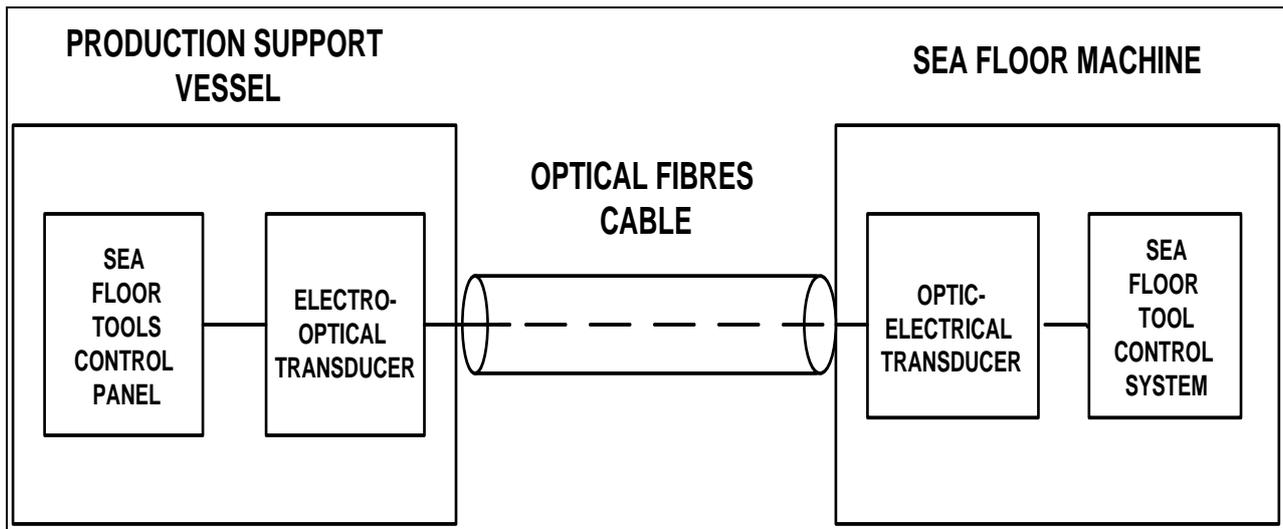


Figure 64: Illustration of Transmitting Control Signals for Collecting Machine

9.3.2 Marine Riser System

Marine risers are structure systems that connect the subsea fields to the production floating unit. The main purpose of the riser system is to transfer the mineral ore particles mined from seabed massive sulphide deposits to the floating vessel. The massive sulphide deposits collected by the seabed mining tool are then pumped as a seawater/ore slurry into the positive displacement subsea lift pump at the base of the riser, where it is pumped to the floating vessel. A failure in the riser will result in stoppage of mineral ore production and can also lead to pollution and spillage as well as very high economic and political consequences. Therefore, the riser is considered as a vital element for seabed mining platforms.

The selection of a riser system type for the Atlantis II Deep depends on the metocean data and the water depth. Several types of risers are available extending from the flexible risers, SCR, and free-standing hybrid risers to the top-tensioned rigid risers. There are primarily two main types of risers: rigid risers and flexible risers. A hybrid riser is a combination of these two (Bai, 2001; Bai, Y. and Bai, Q., 2005). Chapter 3 presented a detailed description for the available riser systems in the offshore industry. The most popular marine riser used in deepwater is the Steel Catenary Riser which presents major merits over conventional flexible or freestanding hybrid risers.

Riser Engineering Systems for Deepwater Mining

The choice of the riser system depends on the environmental conditions, water depth and economic feasibility. The compliant floating platforms for deepwater offshore hydrocarbon have advised the development of new systems of riser pipes to meet the demands of harsh operating conditions and economics, which makes the compliant risers or hybrid risers the

system of choice due to lower cost and simplicity in arrangement. The use of a riser system has increased with the progressive expansion of ore production into deeper water.

Compliant Riser

Compliant risers have been accompanied floating platforms since the mid-1990s by utilising steel catenary risers and were first used as export risers for Auger TLP. The compliant risers are divided broadly into steel catenary and flexible risers and provide a simple and cost-effective riser system solution for deepwater and harsh environment. The nominal top tension is determined by hanging weight due to the effect of the sagbend and hang-off angle.

Compliant riser configurations can be categorised as shown in Figure 65. The elected riser configuration is influenced by many parameters including water depth, host hang-off location, field layout, vessel motions characteristics and metocean data.

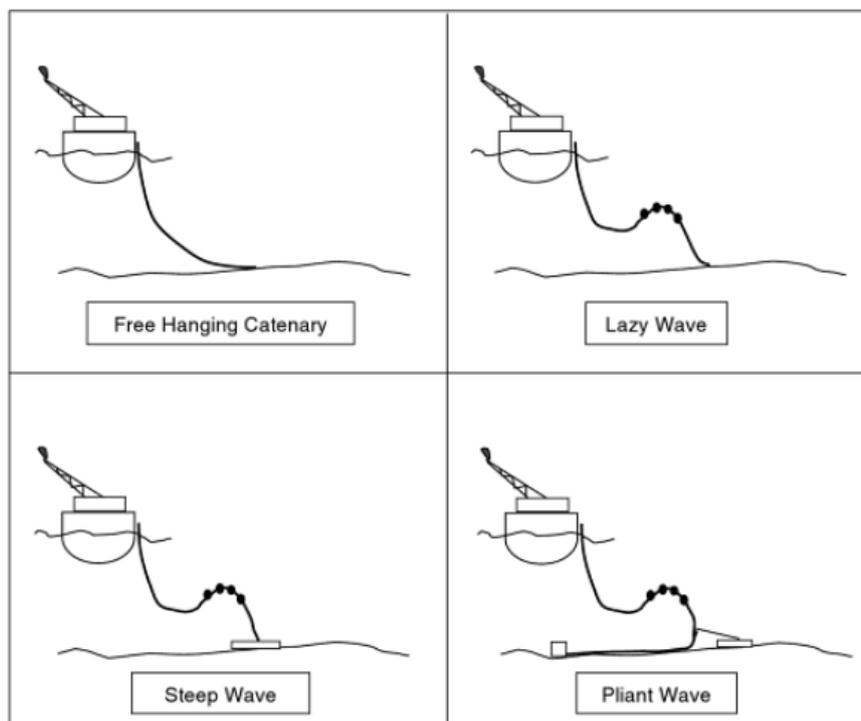


Figure 65: Compliant Riser Configurations
Source : Guo (2005)

Steel Catenary Risers (SCRs): Recently, SCR systems have been exhibited to utilise hydrocarbon resources in deepwater around the world. SCR systems introduce an economic alternative to rigid and flexible risers, which are used with all major floaters. Additionally, an SCR can be installed using the same lay vessel as the pipeline. This configuration does not need heave compensation equipment when the riser is moved up and down together with the floater; the riser is simply lifted off or lowered down on the seabed (Bai, 2001; Bai, Y. and Bai, Q., 2005). At the seabed, the riser base and base connector are eliminated.

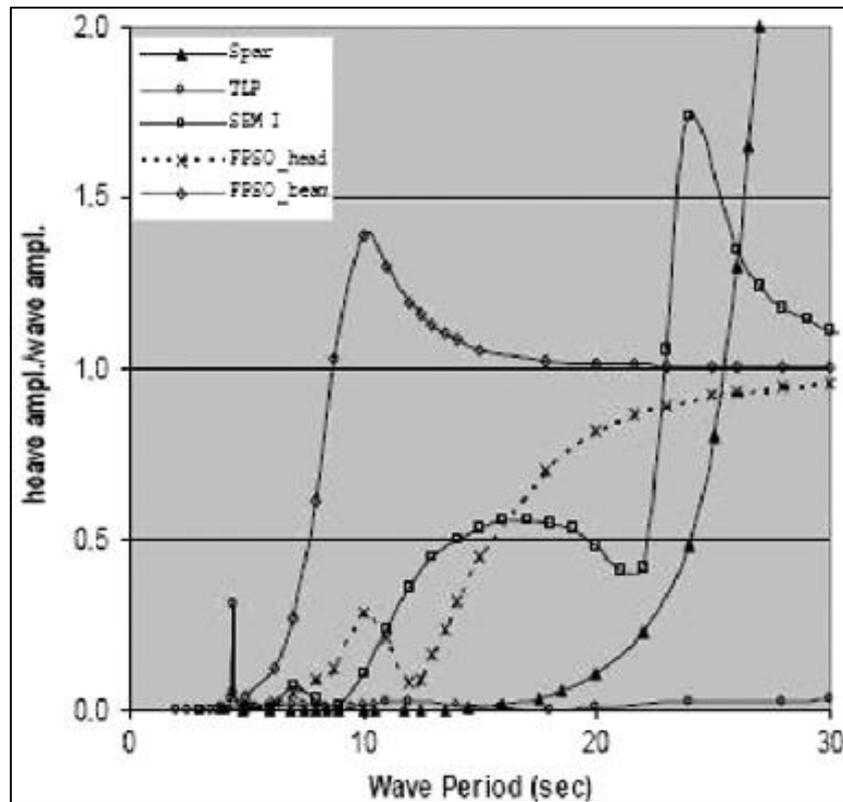


Figure 66: Typical heave RAOs for different Floaters
 Source: Hansen et al. (2004)

At the platform, the SCRs are connected to the pontoon by way of a flex joint, stress joint or pull tubes. The benefits of the SCR compared to the TTR arrangements include the surface valve stack being statically accommodated, eliminating the need for a hydro-pneumatic tensioner system and surface jumper hoses, and substantially simplifying access. As an alternative to rigid pipe solutions on fixed platforms, jumper spool tie-ins and caisson risers can be eliminated with an associated reduction in the offshore operations required for installation. Cost savings are made as a result of the simplified arrangement.

The main concerns for the design of SCRs hanged on floaters are the dynamic behaviour and fatigue performance of an SCR due to cyclic dynamic motion. SCR designs are very sensitive to motion response of a host vessel as well as environmental loadings. Figure 66 shows typical heave natural period ranges and heave Response Amplitude Operators (RAOs) of Spar, TLP, Semisubmersible and FPSO. As offshore hydrocarbon exploration is pushed into deeper and deeper water with the heavier payload, many innovative floating offshore structures are being proposed for economic savings (Bell et al., 2005).

Flexible Risers: Flexible pipes were initially used in calm weather conditions in pioneering works conducted in the late 1970s. However, since then flexible pipe technology has developed rapidly and today flexible risers are employed in various projects with large significant vessel motions in harsh weather conditions.

As presented in Figure 67 the flexibility is achieved through the use of multiple concentric layers of different materials in the fabrication of pipe wall. This flexibility gives many advantages such as prefabrication and storage of long lengths on reel, which reduces the transport and installation costs.

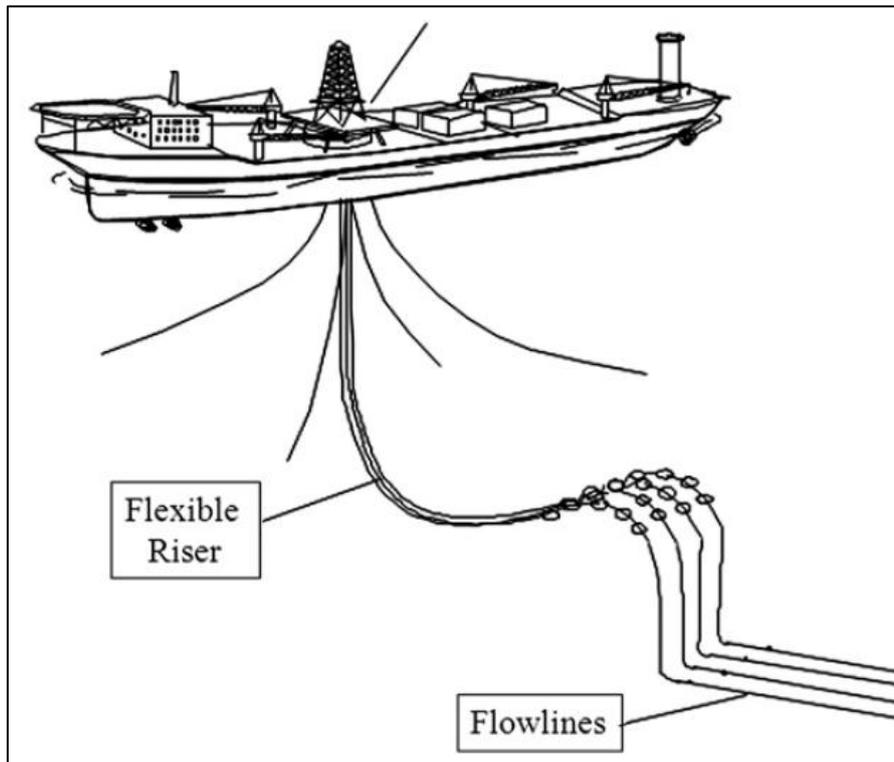


Figure 67: Schematic of Flexible Risers
Source: Bai, Y. and Bai, Q. (2010)

The structure of the flexible riser is made up of several different layers: an inner metallic carcass for collapse resistance; a plastic pressure sheath fluid containment that is leak-proof; a zeta and flat steel spiral for resisting internal pressure, external crushing loads and hoop stress resistance; steel armours to resist axial tensile loads; anti-wear layer to avoid friction; and a plastic outer sheath to prevent seawater penetration (Sparks, 2007).

Hybrid Risers

The new concept of Floating Production, Storage and Offloading (FPSO) accompanied by hybrid risers were introduced as the oil and gas industry moves towards deeper water. The main consequence of utilising FPSO was the significance excursion of the floating unit. Therefore, a new riser system was introduced to overcome FPSO dynamic motions. The single or multiple line hybrid risers aimed to decouple the floating unit motions from the vertical steel riser through the use of flexible jumpers.

Why a Compliant Riser for Deepwater Mining?

Compliant risers offer an alternative to conventional flexible risers: they can be suspended in longer lengths, removing the need for mid-depth arches or buoys. They can be used in

high pressures, temperatures and diameters that cannot be achieved by a flexible pipe. This allows the use of a smaller number of larger diameter lines and they are less costly. Furthermore, steel catenaries are more congenial for design purposes and steel pipes have better availability than a flexible riser (Howells, 1995). Compliant risers have been enjoying a widespread acceptability for many types of different deepwater floaters.

Riser Model Description

The riser descends from the FPSO's moon pool in a steep wave configuration. The steep wave riser is similar to the buoyant wave riser in that it also has arch formed using buoyancy. The steep wave riser is not orientated horizontally on the seabed as the simple catenary risers are but terminates vertically into a system mining tool on the seabed, see Figure 68. This riser type requires a stress joint or flex joint at the base where bending loads can be high.

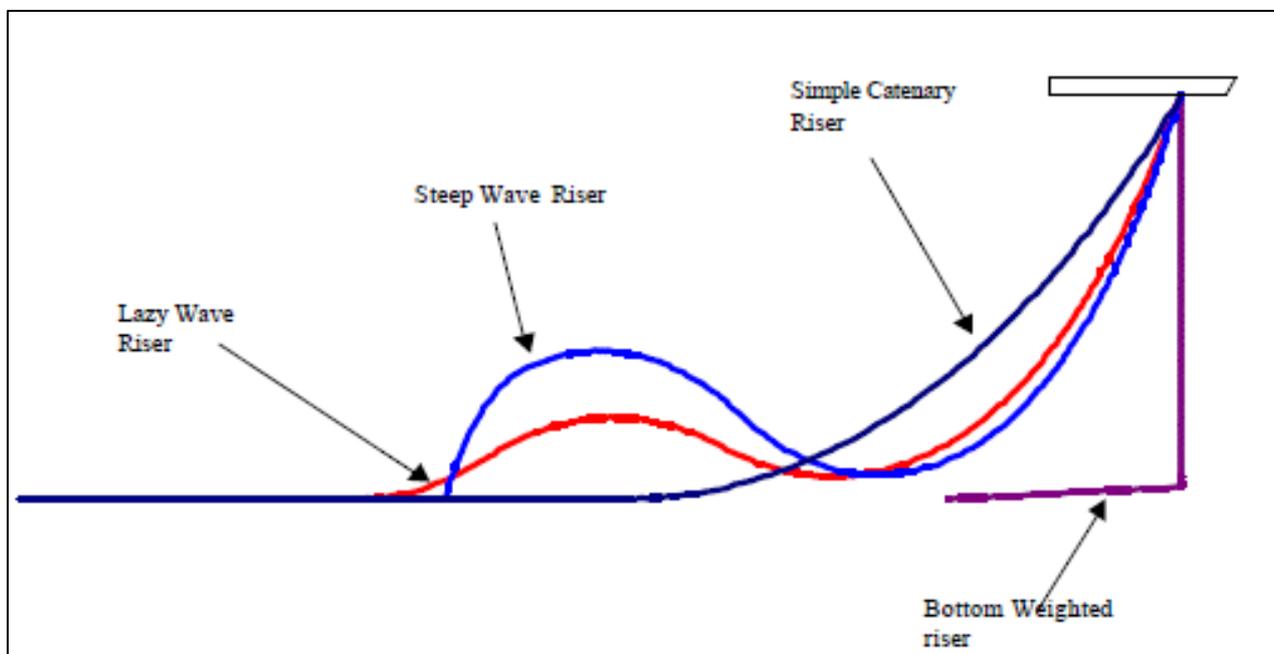


Figure 68: Simple Catenary, Lazy wave and Steep Wave Risers Configurations
Source: Alderton and Thethi (1998)

The riser is connected to the seabed collection tool after 3,000m arc length, since the Atlantis II deep location has a water depth of 2,000m. The riser is to be constructed of line pipe in accordance with the API Spec 5L, grade X70 steel, with 551.58 MPa of yield stress. The outside diameter is 340 mm with a wall thickness of 20.6 mm and riser total length of 3,310m.

Material Selection

The common material for SCR includes carbon steel pipe, clad steel pipe, steel forgings and titanium. Carbon steel line pipe is less expensive and most common used material for SCR where corrosion resistance is not required although their properties could vary. Normally,

API X52 through X70 and X80 line pipes are widely used for SCR pipe. Figure 69 gives an overview of the standard grades yield strength (API, 2004). Alternatively, other high strength steels such as 13% chrome or super-duplex may be applied. Titanium alloys are also very attractive to deepwater applications (Bai, 2001). The flowline risers will internally be exhibited to the well fluids, which will be corrosive due to CO₂. The corrosive resistant alloy (Bruton et al., 2005) is discussed in detail by Karunakaran et al. (2005).

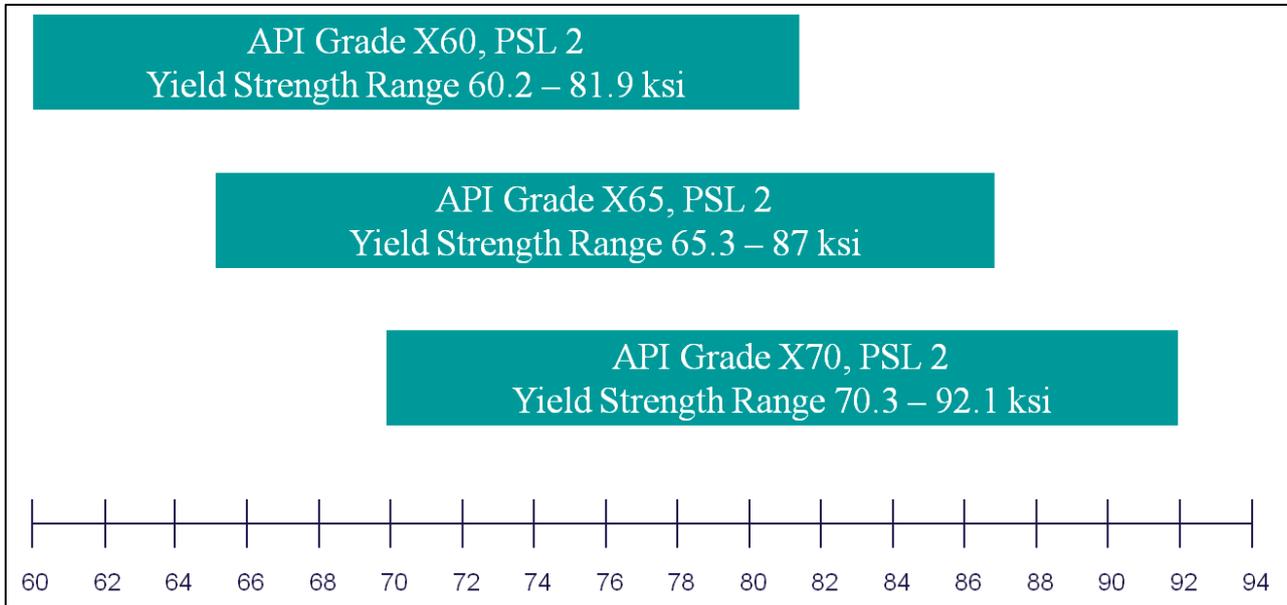


Figure 69: API Standard Grades Yield Strength in KSI

Steel Riser Coating

Polymeric external coatings are generally used on flowlines and risers for corrosion protection, mechanical protection and thermal insulation. The most common coating systems used in the offshore oil and gas industry are:

- Multilayer polypropylene (PP) or polyethylene (PE)
- Polyurethane / syntactic polyurethane (PU)
- Rubber coating

The different coating systems have various density limits which are qualified for deepwater. Rubber coating is classified as a high density coating system while PP and PU are classified as low density coating systems.

A multilayer technology is applied to achieve the various functional requirements for SCR systems. Five-layer syntactic PP coatings have been used in deepwater projects with coating thicknesses ranging from 34 to 102mm (Deka et al., 2010; Karunakaran et al., 2005) as shown in Figure 70. The normal coating density ranges from 750-950 kg/m³.

The five-layer syntactic PP coating consists of:

- 1st Layer - Fusion bond epoxy
- 2nd Layer - PP adhesive
- 3rd Layer - Solid PP
- 4th Layer - Syntactic PP
- 5th Layer - Solid PP

The functions of the five-layers are:

- 1st to 3rd Layer – for corrosion protection
- 4th Layer – for buoyancy and thermal insulation
- 5th Layer – provide protective top coating

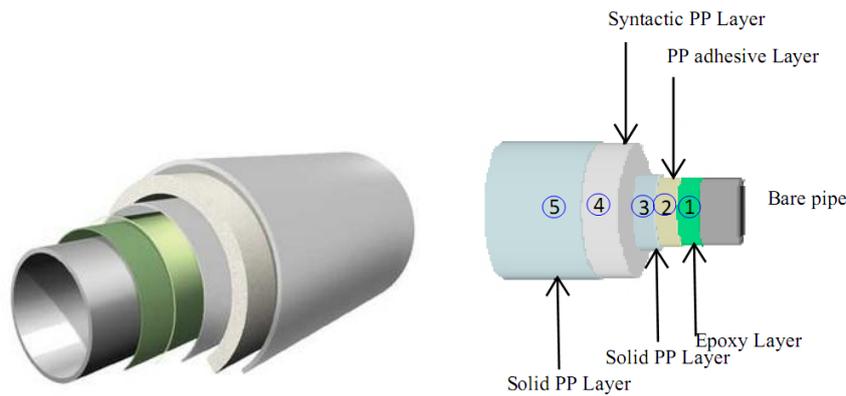


Figure 70: Five-Layer Syntactic Polypropylene

Design Criteria for Marine Riser

The following design codes are commonly employed for the design and analysis of deepwater marine riser:

- API RP 2RD (API, 1998)
- DNV-RP-F201 (DNV, 2002)
- DNV-OS-F201 (DNV, 2009)

Marine riser design is to comply with design criteria such as the Serviceability Limit State (SLS), Ultimate Limit State (ULS), Accidental Limit State (ALS) and Fatigue Limit State (FLS).

Marine riser strength should be checked in terms of maximum stress according to the following relationship:

Equation 3: $(\sigma_p)_e < C_f \sigma_a$

$(\sigma_p)_e$ is the extreme von Mises stress; $\sigma_a = C_a \sigma_y$ is the basic allowable combined stress; C_a is the allowable stress factor which equals to 2/3; σ_y is the material minimum yield strength, defined for steel or titanium as the tensile stress required to produce a total

elongation of 0.5% of the test specimen gauge length; C_f is the design case factor, 1.2 for extreme condition (100 year), 1.5 for survival condition (1,000 year).

For plain round pipe, where transverse shear and torsion are negligible, the three principal stress components of primary membrane stress (average stress across pipe wall) are σ_{pr} , $\sigma_{p\theta}$, and σ_{pz} , where r , θ , z refer to radial, hoop, and axial stresses respectively (API, 1998). Thus,

Equation 4:
$$(\sigma_p)_e = \max \left[\frac{(\sigma_{pr} - \sigma_{p\theta})^2 + (\sigma_{p\theta} - \sigma_{pz})^2 + (\sigma_{pz} - \sigma_{pr})^2}{2} \right]^{1/2} \leq C_f \sigma_a$$

Riser Hang-off System

Compliant risers are very sensitive to dynamic environmental loading. Vessel motions and wave actions near the water surface produce bending and tension stress at the top end of the SCR. High bending moments can be generated in a riser's top end due to severe vessel motion response. Therefore, the riser is using hang-off system termination at the vessel in order to accommodate bending moments of the riser due to excessive vessel motions. A better understanding of the hang-off system is essential for evaluating maximum stresses and fatigue life of the riser near the water surface.

Compliant risers can be attached to the floating vessel by way of a hang-off system. Generally, three hang-off systems have been used: flex joint, taper stress joint (TSJ) and pull tube as shown in Figure 71, Figure 72 and Figure 73 respectively. SCR hang-off systems typically include a porch structure on the hull or pull tubes and a connection of the top of the SCR to the porch structure. A porch utilises a receptacle-type structure consisting of a basket that accommodates the flexing mechanism and a welded-plate structure that connects the basket to the hull near the water (Mark Chang et al., 2010). In addition, a porch can hold both flexible joints and stress joints. As an SCR is attached to the lower end of a flex joint or a stress joint, a spool piece attaches the upper end of the flexing mechanism to the piping system of the floating vessel.

The functional requirement of an SCR governs the selection of the hang-off system in terms of the required angular deflection, SCR size and the expected riser's top tension. Porch termination, which is used to accommodate a flex joint or TSJ, is preferred as a designer's perspective, as it can accommodate both flexing mechanisms, hold multiple SCR dimensions and can afford the potential riser hang-off angle change.

Schematics of the flex joint configuration are given in Figure 71. The flex joint incorporates elastometer/alternating laminations of spherically shaped rubber and steel components within a steel bellow support structure, which involves an extension of welding to the main riser. Therefore, a flex joint simulates a hinge and allows the SCR to rotate with a minimum

bending moment imposed onto the vessel hull structure under severe environmental conditions. A better understanding of flex joint stiffness is necessary in determining strength behaviour and fatigue performance at the SCR top end.



Figure 71: SCR Hang-Off Systems: Flex Joint and Stress Joint
Source: Bai, Y. and Bai, Q. (2010); Song and Stanton (2007)

A TSJ is typically a tapered tubular system as shown in Figure 72. A TSJ simulates a rigid attachment and may be used in place of flex joints but reveals larger bending loads to the floating vessel. In addition, it is a simple, solid metal structure and is able to cope with high pressure. It can be made from steel or titanium. Flanges are required at both ends of titanium TSJ due to the transition from titanium to steel riser on the lower end and the transition to steel hull piping on the upper end.

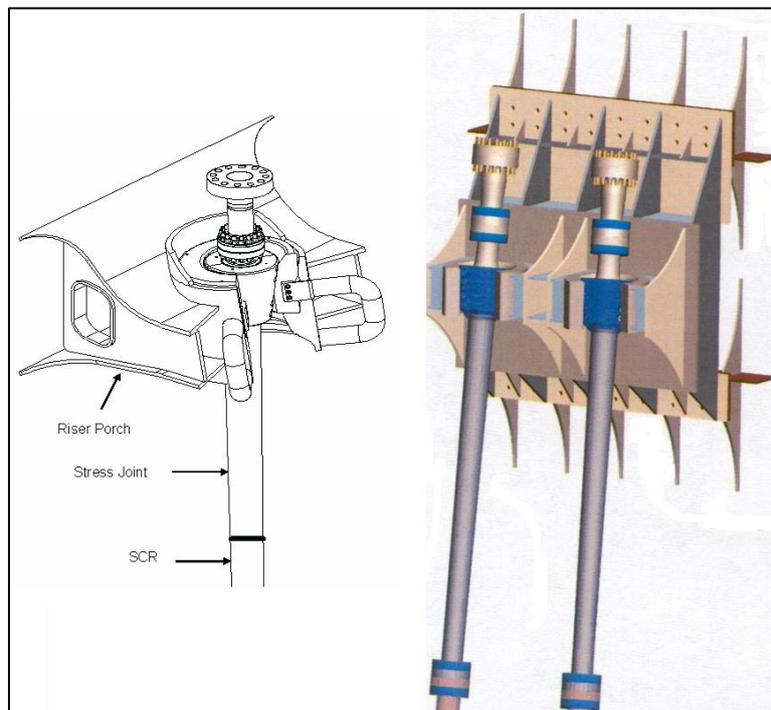


Figure 72: Tapered Stress Joints at Porch Hang-Off
Source: Chang et al. (2010); Kenny (2007)

Alternatively, pull tubes have been used with spars to guide SCRs through the spar truss while the SCR is hanged from the top of the spar. The pull tubes serve as a continuous curved guide for the SCR passing through the hull of the spar and hanging on the top spar deck. Pull tubes can extend from either inside or outside the hull of a spar. Figure 73 shows a pull tube attached to a spar and extending outside the truss of the hull. Generally, a stress joint is required at the lower end of the pull tube to accommodate bending moments under environmental conditions.

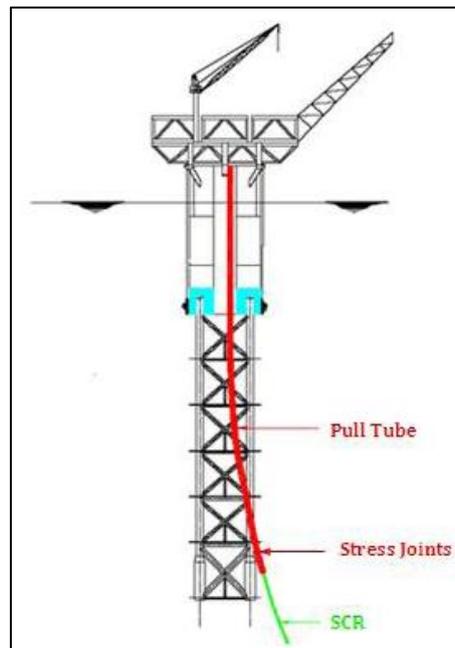


Figure 73: Spar with Pull Tube Hang-Off

Source: Chang et al. (2010); Luk and Chang (2011); Shi et al. (2011)

9.3.3 Deepsea Mining Pump Selection

Generally, mud pumps are used on the vessel to move the mud from the vessel through a pipe to the drill bit and also back up the wellbore annulus and the return riser. Consequently, the surface pumps provide all the pumping horsepower to move the mud from the vessel to the wellbore and back again. On the other hand, in the dual gradient drilling pump the mud in the return riser is replaced with seawater, and a pump is placed on the seabed to provide transport for the cutting-laden fluid back to surface. Therefore, the main difference between the subsea pump and the surface mud pumps is that the subsea pump must be handle the transferring of large solids of varying concentration up to the floating unit.

The dual gradient pump is designed to be powered by seawater supply from the drilling floating unit, so that the main movers are on the surface available for servicing. The subsea parts are mainly a pumping chamber and actuated isolation valves, driven by a subsea hydraulic system. The pump chamber is fitted with a elastomeric diaphragm, which acts as a separating barrier between the process fluid being pumped, and the power fluid generating

the diaphragm movement to push the process fluid up the return line (Judge and Yu, 2010). As shown in Figure 74, three chambers are used to describe the pump cycle. Each pump is fitted with four actuated valves to control the flow into and out of the chamber. The actuated valves allow the opening and closing times for each chamber. The fill and compression cycles are described in Figure 74 and Figure 75.

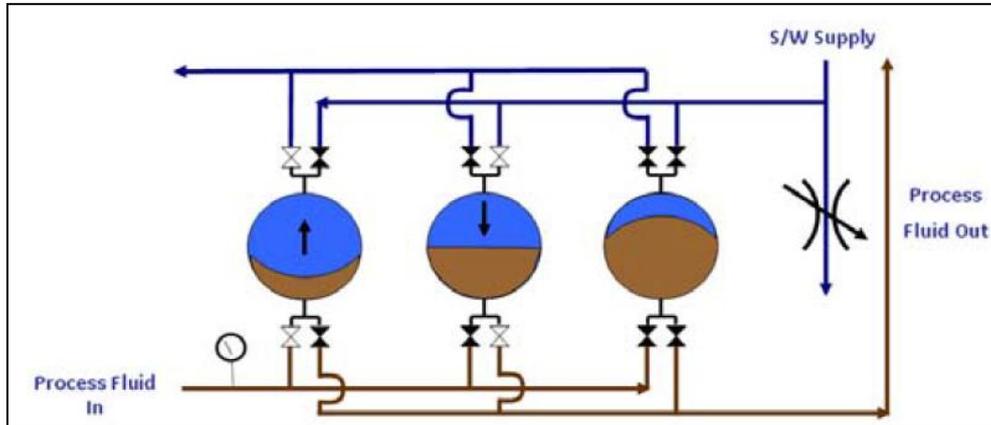


Figure 74: Mud Lift Pump during the Fill Cycle
Source: Judge and Yu (2010)

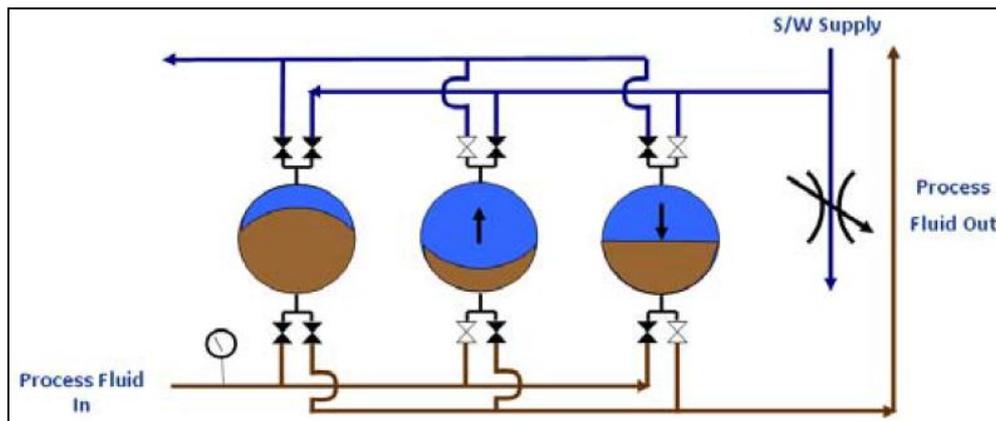


Figure 75: Mud Lift Pump during the Compression Cycle
Source: Judge and Yu (2010)

Centrifugal pumps are extensively used in marine applications, particularly dredging, where handling solids is one of the primary selection criteria. Therefore, these centrifugal pumps can put in series to provide the required head for the ore/seawater mix up to the floating unit. The pressure head of a centrifugal pump is limited to about 12 bars (160 psi). For pumping the massive sulphide cuttings, the total pressure required can be as high as 65 bars for a 1,700m system or 90 bars for a 2,500m system. These values of discharge pressure will require the use of multistage pumps when using centrifugal pumps. A centrifugal pump has potential issues such as power cable management, complicated flow path through the pump and the pumping efficiency is lower than the SSLP system.

The dual gradient pump was modified to accommodate the production rate requirement of the massive sulphide mining system. The conventional triplex pumps can easily achieve the pressure and flow rate requirement of a 1,000 m³/hr slurry flow. A total of approximately 10 chambers needs to be used in the subsea slurry lift pump. Therefore, the pump technology designed primarily for a dual gradient drilling operation can be utilised in the subsea slurry lift pump to accommodate the fluctuation flow process conditions.

9.3.4 Floating Platform

The floating support vessel as shown in Figure 76 should provide adequate deck space, accommodation, electrical power supply and dynamic positioning system. The floating unit utilised for mining Atlantis II Deep will be similar to the floating units that service the drilling and production of offshore oil fields. The floating unit will also include dewater ore storage and tailings dewater tanks.

FPSO is a floating vessel for the processing and storage and is used in oil and gas market. It is also designed to offload its production onto barges or through pipelines. FPSO is very responsive because of the large water plane area and consists of large monohull structures, generally in the ship-shaped, equipped with processing facilities. FPSOs are generally preferred in deepwater offshore regions as they are easy to install, and do not require a local pipeline infrastructure to export their storage. Furthermore, once the field is depleted, the FPSO can be moved to a new location.

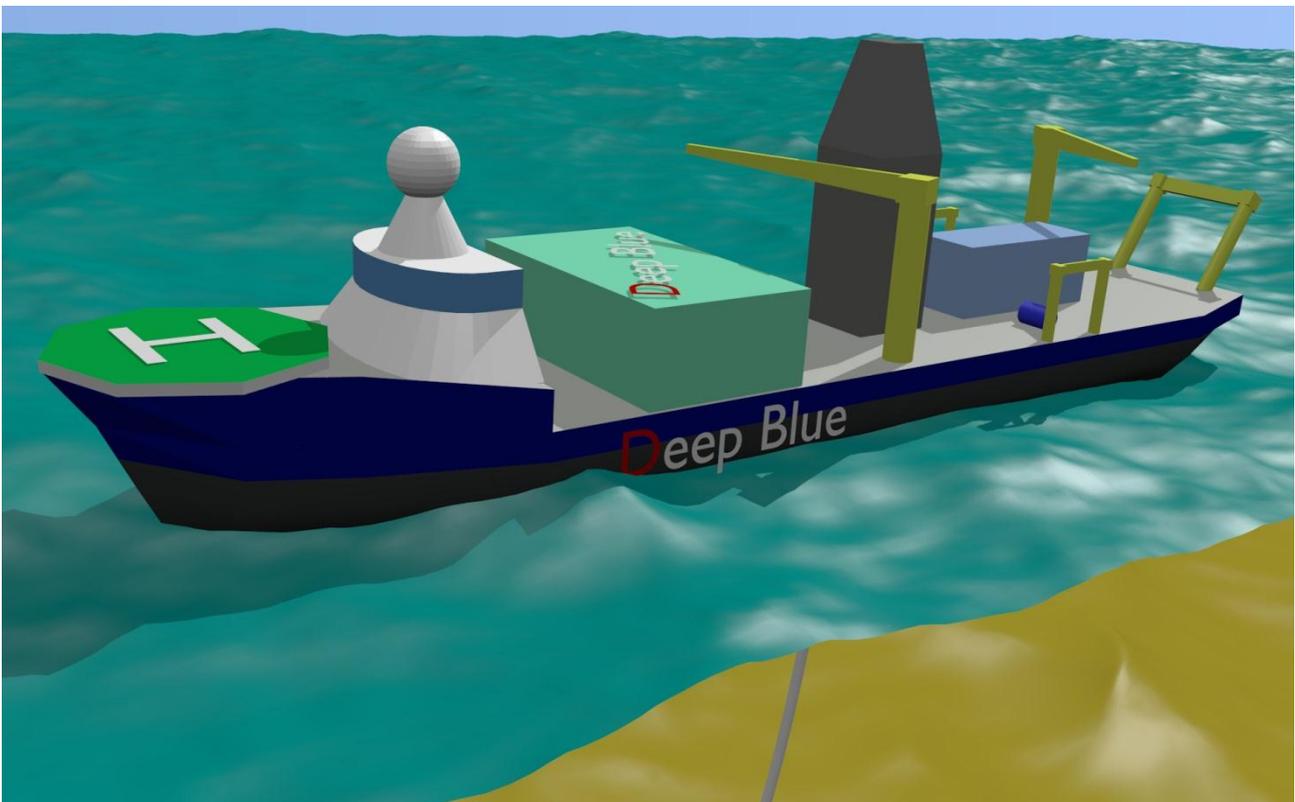


Figure 76: Floating Production Vessel Model

Risers are being considered for these production units in deepwater environment such as Atlantis II Deep. Risers used in conjunction with a FPSO in deepwater harsh environments exhibit substantial design challenges. The large vertical motions of the FPSO induce severe riser response, which results in adversity achieving strength criteria at the hang-off. The RAOs of FPSO should be carefully considered in the design stage. The static vessel offset regarding the extreme response analysis is 15% of water depth.

9.3.5 Vessel Positioning System

To provide effective and safe mining operations at large water depths the floating vessel must hold position over the mine site during a long time. This is difficult to achieve into the deepest parts of the ocean and sea, where winds and waves tend to be perpetually altering. The vessel must also be able to change its position to reposition the mining machine from one mining place to another and to be able to weathervane to optimise the motions of shuttle barges when moored alongside for materials offloading.

Using the anchors in this case will be ineffective because it could prove very tedious for a vessel's crew to lay the anchors. For this purpose it is most suitable to use a dynamic positioning (DP) system which does not require the usage of anchors. Vessel under control of DP are independent of anchors and other support systems because a DP vessel enables the use of thrusters and propellers to make the vessel stay on course and steady rather than get carried away by the fluctuating winds and waves. Perhaps this is the most advantageous quality of the DP system.

The concept of the DP vessel includes a control panel which estimates the fluctuation of wind and the waves and sends appropriate signals to the thrusters to maintain the position of the vessel. IMO MSC/Circ. 645 (IMO, 1994) addresses the redundancy and establishes three classes for DP systems:

- Class 1: loss of position may occur in the event of a single fault.
- Class 2: loss of position is not to occur in the event of a single fault in any active component or system.
- Class 3: loss of position is not to occur in the event of a single failure of any active or static component or system, and does not occur if all components in one compartment are lost due to fire or flooding.

On production support vessels used for deep water mining the DP system should not be lower than Class 2. Accidents on the vessel could cause huge expenses and inflict substantial harm to the environment. The DP system is an integration of several vessel subsystems to maintain accurate manoeuvrability. The DP system automatically controls the vessel's position and heading only with help of an active thrust. Figure 77, indicates the six

different elements of the proposed DP: (1) Environment Reference System, (2) Position Reference System, (3) Heading Reference System, (4) Control System, (5) Thrusters and Propulsion System and (6) the Power Supply System.

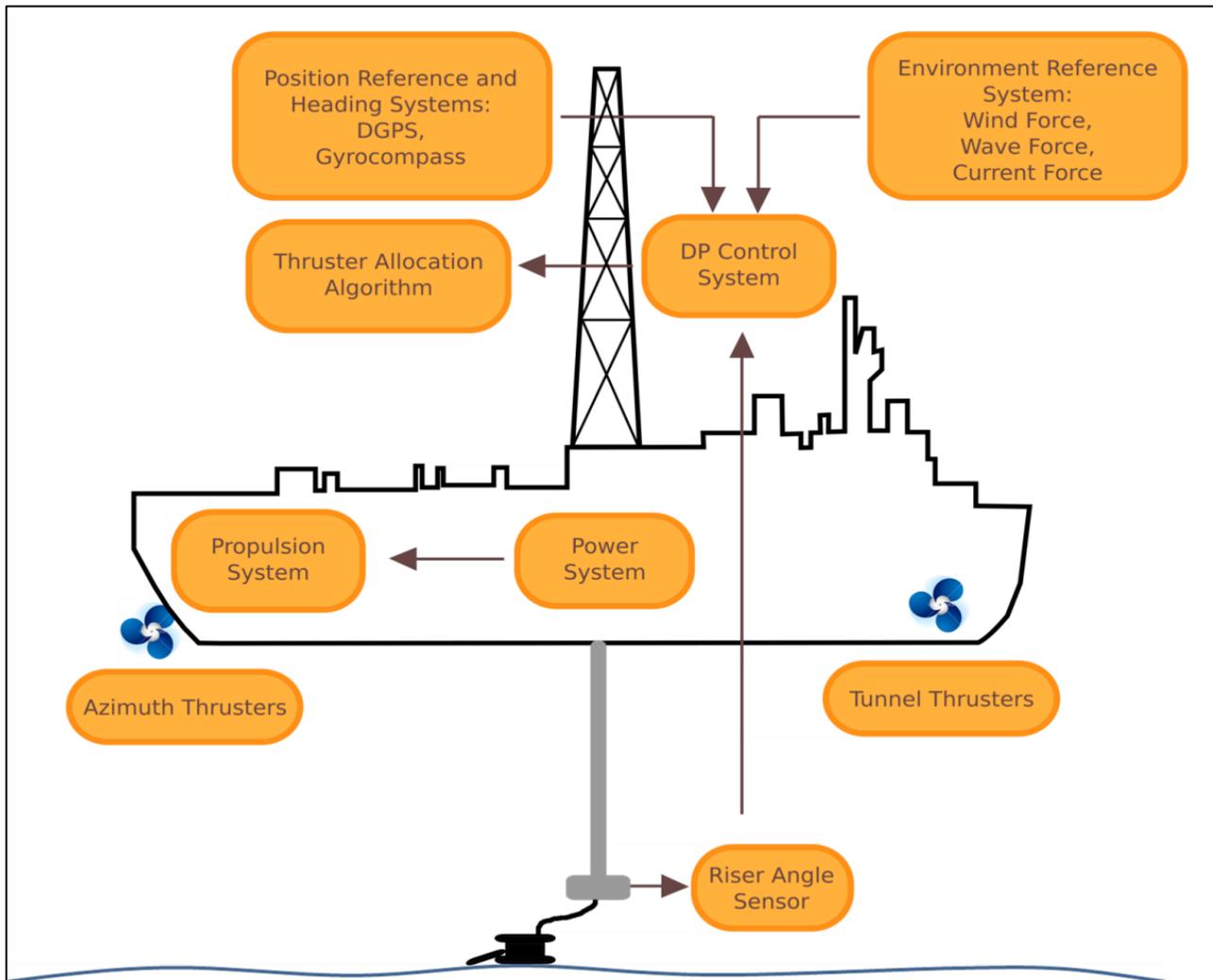


Figure 77: Dynamic Positioning System for Mining Vessel

Environment Reference System

The environmental forces which act on the vessel are winds, currents and waves (Faÿ, 1990). These environmental forces are very variable and need accurate measuring of changes. The wind speed and direction are normally defined in knots or metres/sec. Large changes in wind speed or direction can cause major disturbances in the positioning of the vessel. The wind forces can be defined by three components, surge, sway and yaw. This data is used to calculate wind-induced forces acting upon the vessel's hull and structure, allowing these forces to be compensated before they cause a position or heading change. All DP systems have wind sensors. Typically, a wind sensor consists of a simple transmitting anemometer, usually of the rotating-cup type. The forces acting on the vessel are very dependent on the superstructure shape (the part of the vessel above the water line), and the wind direction relative to the vessel.

The sea current can be caused by several factors, such as the windflow, the slope of the seabed, tidal or storm surges along coastline, outflows from rivers. Also it can be caused by the effect of heating and cooling as well as salinity. The effect of currents on the vessel determines the requirement regarding the vessel shape.

Waves are also described as sea states. The spectrum of wave energy is defined by Jonswap for the North Sea, and Pierson-Moskowitz for the North Atlantic. The direction of propagation of the waves also matters, but predicting wave drift forces is complex (DNV, 2011).

However, environment conditions for Atlantis II Deep project are not severe. As a semi-enclosed ocean, the Red Sea has low wind, wave and current loading in comparison to other offshore locations. Maintaining the vessel position is thus, relatively easy.

Position and Heading Reference System

The main function of DP system is to enable a vessel to maintain at a fixed position and heading. Other sub-function are track-follow or weathervane modes (IMCA, 2007).

Any vessel (or other floating body) has six freedoms of movement; three rotations and three translations. In a vessel they can be illustrated as roll, pitch, yaw, surge, sway and heave. Dynamic positioning is connected with the automatic control of surge, sway and yaw. Surge and sway comprise the position of the vessel, while yaw is defined by the vessel heading. Both of these are controlled about desired position set-point and heading set-point. Position and heading must be measured in order to get the error from the required value. Position is measured by one or more of a range of position references, while heading information is provided from one or more gyrocompasses. The difference between the set-point and the feedback is the error or offset, and the DP system operates to minimise these errors.

Several factors determine the number of allowed position references. It can be such factors as: the specific risk level for deep water operation, the required redundancy level, the availability of references of a suitable type, and the consequences of loss of any position reference. Position information for the DPS from position-reference systems may be received in several forms. Different types of co-ordinate systems may be used also such as a Cartesian or geodetic co-ordinate system. The control system of DPS must be able to handle information based on each co-ordinate system. A Cartesian, or local, co-ordinate system is based on a flat-surface two-dimensional measurement of the North/South (X) and East/West (Y) distances from a locally defined reference origin. This type of co-ordinate reference system is purely local, or relative, not absolute or earth-fixed.

DGPS (Differential Global Positioning System) is most suitable and reliable form of position reference for ships of the leading mining a depth of about two kilometres (Shaughnessy, 1999). Two separate and distinct DGPS systems must ensure required

redundancy, in case different differential correction links are used. Further position-reference is achieved by deep water Long Baseline acoustic systems. Which are widely used in deep water areas more than 1,000m. The long baseline system based on array of several transponders laid on the seabed in the vicinity of the worksite with the mining vessel at the centre above.

DGPS is the most commonly-used position reference for DP operations because without special corrections GPS accuracy is not adequate for DP purposes (Gallego, 2005). For improving accuracy of GPS to levels which useful for DP, differential corrections must be used to GPS data. This is achieved by using special reference stations, which are located in known points of the area of the GPS system works. The pseudo ranges obtained by the receiver are compared with data from the known places of the satellites and reference station. A Pseudo-Range Correction (PRC) is obtained for each satellite. These corrections are sent to the ship's receiver in special messages by data link. After that the receiver uses the PRCs to calculate position corrections in the above mentioned pseudo ranges.

The DGPS can receive multiple differential inputs from several of reference stations which can be widely separated from each other. Usually, network DGPS systems provide greater stability and accuracy and remove more of the ionospheric error than obtainable from a single reference station. The DGPS network is more fully monitored at the Hub, or control stations, where different information and warning data will be generate and send out. The accuracy obtainable from DGPS systems is in the area of 1-3m dependent upon the distances to the reference stations, ionospheric conditions, and the constellation of satellites available (Kechine, 2003).

For cargo operations at sea involving transshipment of extracted material from the Production Support Vessel to the barge, the DP system must provide the position of a vessel relative to a moving structure. But DGPS tends to be less reliable in close proximity to large floating bodies due to interference to satellite and differential signals (Chen et al., 2009).

DARPS system (Differential, Absolute and Relative Positioning System, www.km.kongsberg.com/seatex) are configured to handle this problem. For the measurement of a relative position by GPS, differential corrections are not needed, as the errors induced are the same for the barge as they are for the PSV. A DARPS transmitter on the PSV sends the received GPS data to the UHF receiver aboard the barge. A computer aboard the barge then calculates a range/bearing from the PSV's, which is put in to the DP control system as position reference.

Riser Angle Sensor

For mining operations, is important for the vessel to keep over the mine site, because the riser connecting the vessel to the well is practically vertical. The profile of the riser is,

however, determined by current forces and tension, as well as by vessel position. The parameter which must be continuously monitored is the lower main riser angle. If this exceeds 3° , action needs to be taken so that it does not get worse and force an unwanted disconnection (IMCA, 2007). For each case, the vessel must have well-specific operational guidelines, which determine when alerts are to be given and what action is appropriate. Watch circles might be used and set which are distances that represent angles at the lower end of the riser.

It is also possible to use a function known as 'riser angle mode' (Imakita et al., 2000). When selected, the DP continues with a geographical position reference, but moves to reduce the riser angle. The reference for positioning is the angle of the riser at the stack, using sensors attached to the riser and the lower marine riser package (LMRP). These sensors may be electrical inclinometers, hard-wired to the PSV up the riser and sending angular and positional information interfaced to the DP.

A standard electrical riser angle sensor consists of two inclinometers that measure the riser angles in two orthogonal directions, and a combination of the two signals enables calculation of the true angle and heading. A basic inclinometer is however not able to distinguish between gravity and acceleration induced forces. The top termination of a drilling riser follows the horizontal movement of the drilling vessel. In a situation with horizontal accelerations of 0.5 m/s^2 , the error in the estimated top angle will be more than 2.5° . This error adds to the true dynamic angle variations. The DP system aboard the PSV will have special display pages showing Riser angle offsets as part of a Position Plot display page.

Control System

DP is a multi-loop feedback control system. The primary function of the control system is designed to keep the vessel at a fixed position, or on a specified track, and with a set heading, each within tolerable limits. The system must be able to handle transient conditions such as changes in external forces, failure of a signal from sensors and position measurement equipment, and system hardware failures. Secondary functions are to control the vessel so as to minimise fuel consumption and to keep the thrusters wear to a minimum. It is possible to divide DP control into two separate functions:

- Measure the environmental forces acting on the vessel and estimate/calculate the forces needed to counteract their effect
- Measure the deviation of the vessel from its target position and estimate/calculate the forces needed to restore the vessel to the required position

The control system software consists of the following components (Balchen et al., 1980):

-
- **Model Ship.** This is as accurate a description as possible of the vessel's response to any external forces. The model should be subjected to the same forces that effect on the real vessel: thrusters, wind, waves, currents, anchors, other external forces such as cable/riser tensions.
 - **State Gains.** These are the factors that determine the tonnes thrust from the speed and position errors.
 - **Thruster Allocation.** This is a set of equations which take the total thrust demand, expressed in X, Y, N coordinates, to be applied by the vessel's thrusters and converts it into individual thrusts matched to the available thrusters and their characteristics.
 - **Actual Thrusters.** These are the available working thrusters.
 - **Thruster Model.** This model takes the individual thruster demands and calculates the total thrust exerted on the vessel.
 - **Pool.** This combines the various estimates of the vessel position, and creates a best estimate of position.
 - **Kalman Gains.** The factors, which can vary between 0 and 1, determine if the model or estimated position is to be given preference. A value of 0.5 would provide equal weight.
 - **Wind Speed and Direction.** The wind speed and direction are converted into the estimated wind forces on the vessel.

The processors operating the DP control software are generally known as the DP computers. The main distinction of concern to the DPO is the number of computers, their methods of operation, and the level of redundancy they provide. The computers must be installed in dual configuration, providing the required level of redundancy. Modern systems communicate via an Ethernet, or local area network (LAN), which may incorporate many other vessel control functions in addition to the DP. The DP control computers are dedicated specifically for the DP function, with no other tasks. A dual or two-computer system provides redundancy and auto-changeover if the online system fails (IMCA, 2007).

Propulsion Systems

For reliable vessel position control all propellers and thrusters must be well-positioned on board. Typically, a conventional monohull-type DP vessel has six thrusters; three at the bow and three aft (IMCA, 2010). Forward thrusters tend to be tunnel thrusters, operating athwart ships. Usually three tunnel thrusters are fitted in the bow and one tunnel thruster on stern. Stern tunnel thruster common operating together but controlled individually, as are azimuth thrusters aft. Azimuth thrusters project beneath the bottom of the vessel and can be rotated to provide thrust in any direction. Propeller drive is usually by bevel gearing from above.

Azimuth thrusters have the advantage that they can provide thrust in any direction and can be used as main propulsion in lieu of conventional propellers.

For all thrusters more useful the fixed-pitch propellers with variable speed of rotation, which can regulate it from zero to full value in both direction of rotation (Sørdalen, 1997). Drive for all thrusters will be AC electric motors with adjustable speed of rotation in combination with PWM frequency converters. Multilevel pulse width modulation (PWM) drives are now the industry standard for most electric propulsion applications. The basic power components of a PWM drive are: three-windings step down transformer, 12-th pulse diode rectifier; DC-link, multilevel PWM-inverter, optional output filter and AC electric motor (see Figure 78). For tunnel thrusters it will be asynchronous motors with power 2MW for forward thrusters and 1MW for stern thruster. For stern azimuth thrusters will be use permanent magnet synchronous motors 3 MW each. All drives will be supplied from main switchboard 6.6kV. Also important part of DP system is a Power Supply System, which described in next chapter and at the Figure 79 shows the structure of DP2 System for mining vessel Atlantis II Deep.

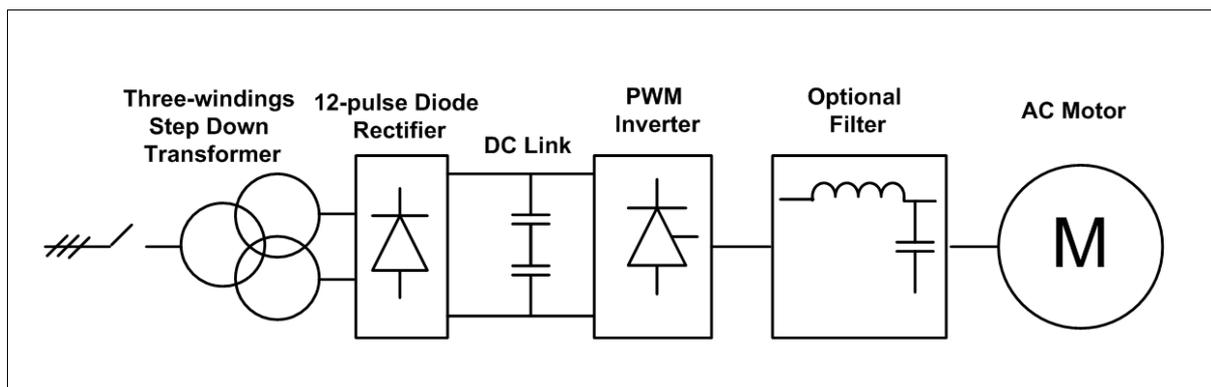


Figure 78: PWM Drive Structure

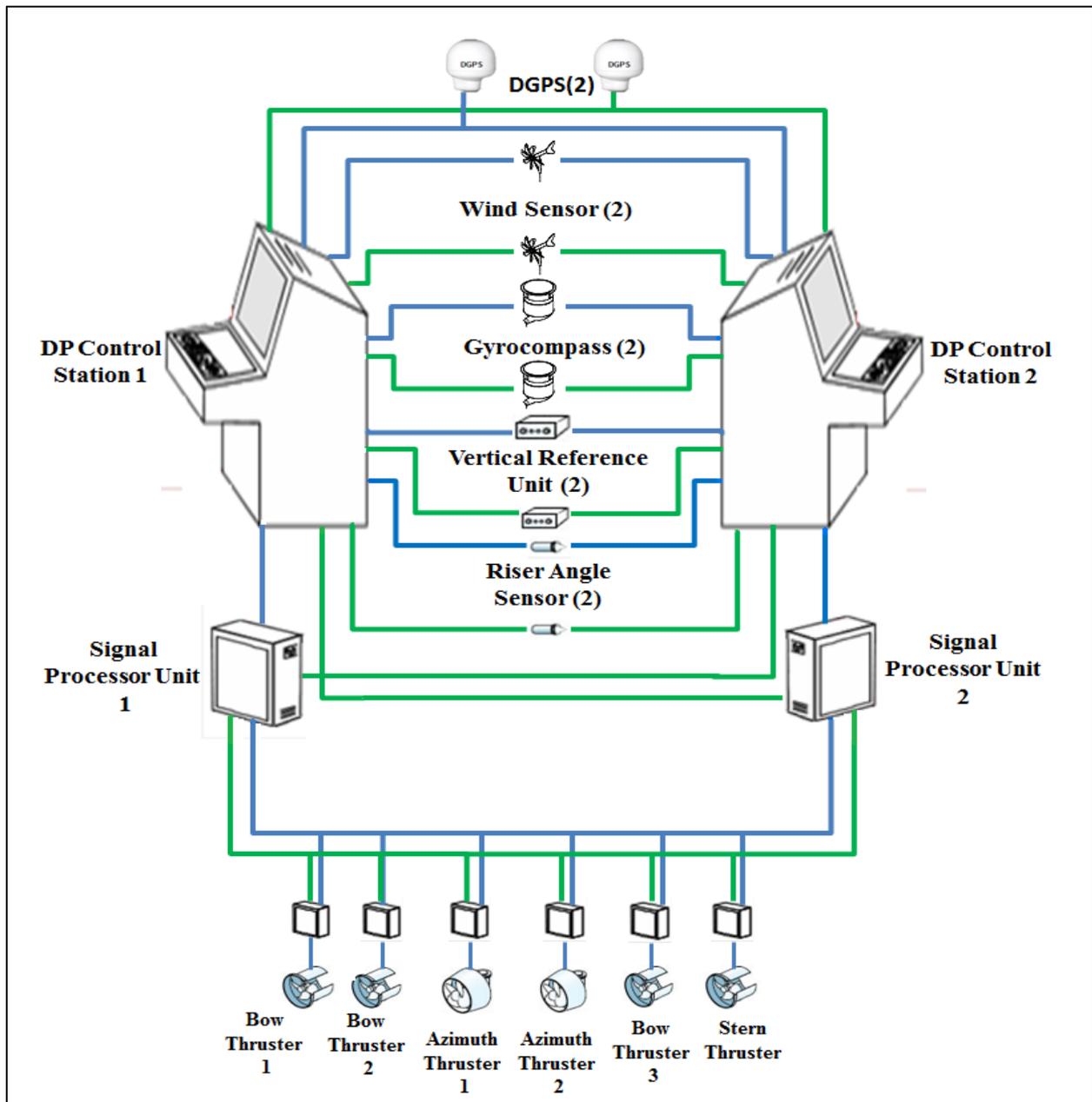


Figure 79: Structure of DP2 System for Production Support Vessel Atlantis II Deep

9.3.6 Energy Supply System

The Energy Supply System for DP2 Vessel must have the required level of redundancy consistent for deep water mining operations. Also fuel consumption associated with dynamic positioning is a primary cost for the mining vessel. Therefore central to the operation of mining vessel are the power generation, supply and distribution systems. Power needs to be supplied to the thrusters, mining equipment and all auxiliary ships systems, as well as to the DP control elements and reference systems.

The thrusters on a production support vessel are high power consumers on board. The DP control system may demand large changes of power due to rapid changes in the weather conditions. The power generation system must be flexible in order provide power rapidly on demand while avoiding unnecessary fuel consumption.

More useful for mining vessel is a diesel-electric power plant with all thrusters and consumers electrically powered from diesel engines driving alternators (Ådnanes, 2003). A diesel engine and alternator is known as a diesel generator set. The diesel electric principle gives a more efficient use of the installed power. All consumers onboard will benefit from the centralized power-plant and separate power generation units are not required. The diesel electric solution gives greater freedom to distribute the equipment in order to achieve optimum layout and performance of the vessel.

A multiple diesel-generator installation allows the selection of the appropriate number of generators working at their optimum fuel efficiency point with respect to the power demand. With the diesel electric solution the appropriate number of diesels may be selected and the fuel consumption will be optimal. PSV with Dynamic Positioning will have a varying power demand depending on the weather conditions and the activities onboard. The diesel electric solution is ideal for this type of application. Advantages of centralized diesel-electric energy supply system:

- Using centralized power-plant are not required additional power generation units
- Better load sharing between the diesels due to multiple use of the power plant
- Lower fuel consumption
- Better manoeuvrability (Dynamic Positioning)
- Improved redundancy
- Space saving, the power plant and propulsion equipment connect through cables – long and inconvenient shaft lines are eliminated
- Simple lay-out of machinery spaces
- Improved smooth running, less vibration and low noise levels

Requirements

The power-generation system must be quality designed and be able to keep the vessel in her position and keep the operation running in the certified conditions, is reliable, is easy to maintain, and can operate with minimal losses. Low atmospheric emissions are also a big issue. The floating support vessel with DP2 requires a special design of power-generation system. That system must be resist to damage of any it element. Electrical system must contain components adapting to marine requirements and focus on minimizing the risk that a single failure can shut down an entire Production Support Vessel. A power distribution system for a PSV must be split into three separate systems made up of two engines and generators with two thrusters in each system.

Creating a centralized Power Generation System for deep water mining vessel need provide proper quality of electrical energy and keep the total harmonic distortion (THD) level below

the required 5%. PSV must have least distortion to the electrical system, caused THD generated by the thruster and mining frequency drives. For this purpose frequency drives need connected in a 12 pulse configuration and install optional filters, this eliminates the need for space, circuit breakers and cables required for previous filters (Ådnanes , 2003).

For improve control, maintain and protect the power supply system, protection relays and controls must be using microprocessors and communicate on high-speed busses (Baranov, 2005). The DP control system must be protected against a mains power failure by the inclusion of an uninterruptible power supply (UPS). This system must provide a stabilised power supply that is not affected by short-term interruptions or fluctuations of the ship's AC power supply. It supplies the computers, control consoles, displays, alarms and reference systems. In the event of an interruption to the ship's main AC supply, batteries must supply power to all of these systems for a minimum of 30 minutes.

To prevent blackout situations on PSV in DP system must be develop function automatic power control. This function limits the thrusters to avoid overloading the electrical power system. A total load in DP regime must not exceed 80% available power capacity. The function of power load control produces a dynamic reduction pitch of thrusters to avoid loss power supply due to the application too much power by the thrusters. This is achieved by controlling the load on the main buses and reducing thruster's power lower available set-point, if the design load exceeds the rated limit. Reduction divided between connected thrusters so that minimizes impact on the control of the vessel position. The fast recovery the electrical system after blackout situation require special attention. Additional requirements to recover, such as "Fast Recovery after Blackout", must develop to achieve short recovery time for thrusters and mining systems within 30 to 60 seconds.

Also must be develop solutions to improve protection against the loss of diesel engines and generators; when one generator set has a control error, the diesel generator monitoring system must detect and disconnect the faulty generator. Need to develop a distance control system, when using a remote diagnostic system, when all system parameters can be monitored from shore. Communication on a high-speed communication bus will reduce the number of cable interfaces but increase information capacity this is must be available for protection relays and control unit.

Configuration

The Power Supply System for Production Support Vessel with DP2 must be Stable to failure any it's element. The worst case is the shut down all generators and as a result the total blackout of the vessel. It can happen due two variants of damages: failure of any auxiliary system of diesels and short circuit on buses the main switchboard. The auxiliary

systems of diesel include fuel oil system, lubrication oil system, water cooling system and air starting system.

Table 13: Approximate Electrical-Load Analysis

Item	Max Load (KW)
Mining Equipment	10,000
Bow Tunnel Thruster 1	2,000
Bow Tunnel Thruster 2	2,000
Bow Tunnel Thruster 3	2,000
Stern Tunnel Thruster	1,000
Azimuth Thruster 1	3,000
Azimuth Thruster 2	3,000
Auxiliary Vessel Systems	2,000
Total Electrical Load	25,000

The damage each of these systems will stop all diesel engines and shutdown the generators, so the system must be designed so that it be stable to any such failure. Also electrical power distribution system must be stable for one short circuit on its main switchboard buses.

For this purpose Energy Supply System must be split into three separate systems containing two diesel engines and generators. Each system must have independent diesel auxiliary systems and three separate main switchboards must be also. The Power distribution system must be designed so that any electrical consumer can feed from each of them. Also from each system will supply two thrusters, this will enable in the worst case single failure to reduce power generating capacity to 33% and to lose only two thrusters (IMCA, 2010). Thus the Production Support Vessel not loses their position and the seriously consequences of failure can be avoided.

The fuel consumption which needed for dynamic positioning is one of the main costs for PSV. But the Atlantis 2 Deep project has the benefit because located in Red Sea where there is low wind, wave and current loading and hence lower fuel consumption by comparison to other offshore locations.

The approximate electrical load analysis for PSV Atlantis 2 Deep presented in Table 13. For Mining equipment Atlantis 2 Deep Project required less Power than for Solvara 1 because Auxiliary and Bulk Cutters not uses. These machines consume about 4 MW of energy (SRK Consulting, 2010). As can be seen from the table the Total Power Load is 25MW. The total electrical power of Energy Supply System for this load must be 27MW assuming design generator loading is limited to around 90%. In this case it is advisable to use six generators by 4,5MW each. The configuration of energy supply system is present on Figure 80.

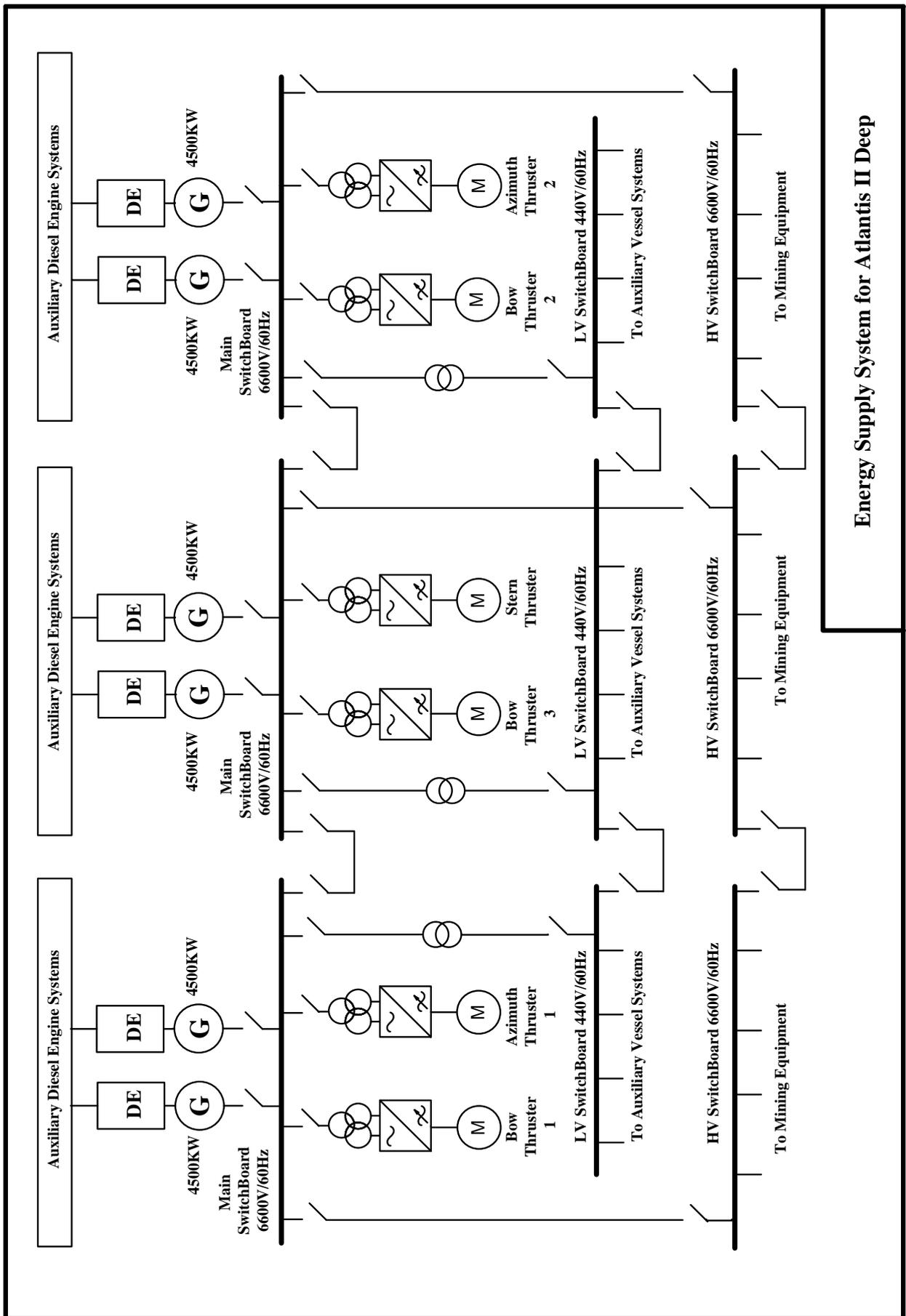


Figure 80: Energy Supply System for Production Support Vessel

9.4 Economics

9.4.1 Estimate of Production Rate

Metal production rate is a critical parameter to estimate economic feasibility. In the Atlantis II Deep, metal resource exists in very fine grain and low concentration status. Thus, pre-processing on-board should be conducted to increase the concentration and consequently get high production rate. To calculate the production rate some information about gathering material, pre-processing and processing are identified.

Starting point of production is pumping slurry from the deep sea bed to the ship. It depends on pumping rate and nominal pumping capacity is assumed 1,000 m³/h as in the Nautilus case (SRK Consulting, 2010). Specific gravity of the slurry is 3.3 and volumetric ratio of solid is 12%. Gathered slurry will experience pre-processing to increase the concentrate of resources in the muds. Flotation technique is usually used for that purpose because it is effective and simple way. Air bubble is injected into the bottom of the flotation tank and hydrophobic (unfriendly to the water) material - in our case it is metal resource - will be attached to the air bubble. The air bubble will float on the free-surface of the tank and the material then will be collected (Karbe et al., 1981). 5% of material is useful and other 95% of material will be disposed. After pre-processing the slurry contains about 32% zinc, 5.3% copper, 0.06% silver and 0.0007% gold (Nawab, 1984). Concentrated slurry will be transported to the processing plant on land. In this calculation 80% recovery rate is assumed.

Schematic diagram of production procedure is given in Figure 81 and expected production rate of each metal based on the previous literature study and assumption is given in Table 14.

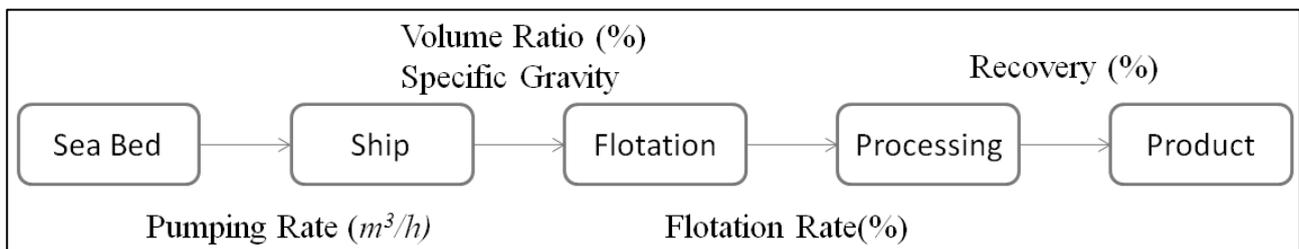


Figure 81: Schematic Diagram of Metal Production Procedure

Table 14: Production Rate of each Metal Resource

Metal Resource	Production Rate (t/year)
Zinc (Zn)	30,108
Copper (Cu)	4,014
Silver (Ag)	60.2
Gold (Au)	0.3985

9.4.2 Economic Model

The developed economic model for Atlantis II Deep sea bed mining is shown in Figure 82. Useful metal resources will be produced in a certain rate of production from the deposit. Applying metal prices to the produced metals per year, the total income will be calculated. Since the metal prices are unknown in the future, some price scenarios should be considered and the metal prices will be anticipated according to those price scenarios. The total expenditure can be calculated from the total investments and operating costs which are obtained from the case study of similar sea bed mining project. Subtracting the total expenditure from the total income, the future value is obtained. The future value is different from the present value which is used as a criteria value to assess the economic feasibility. In economic assessment those values should be distinguished because of the interest rate of bank. Applying a certain discount rate the future value can be transformed into the present value. In Atlantis II Deep sea bed mining, one another factor should be taken into account. That is the influence of government. Saudi-Arabia government takes a positive stance to sea bed mining, so that the operation cost can be reduced by government support. On the other hand, the mining company should pay royalty. In this study, we discard the government portion because it has many uncertainties.

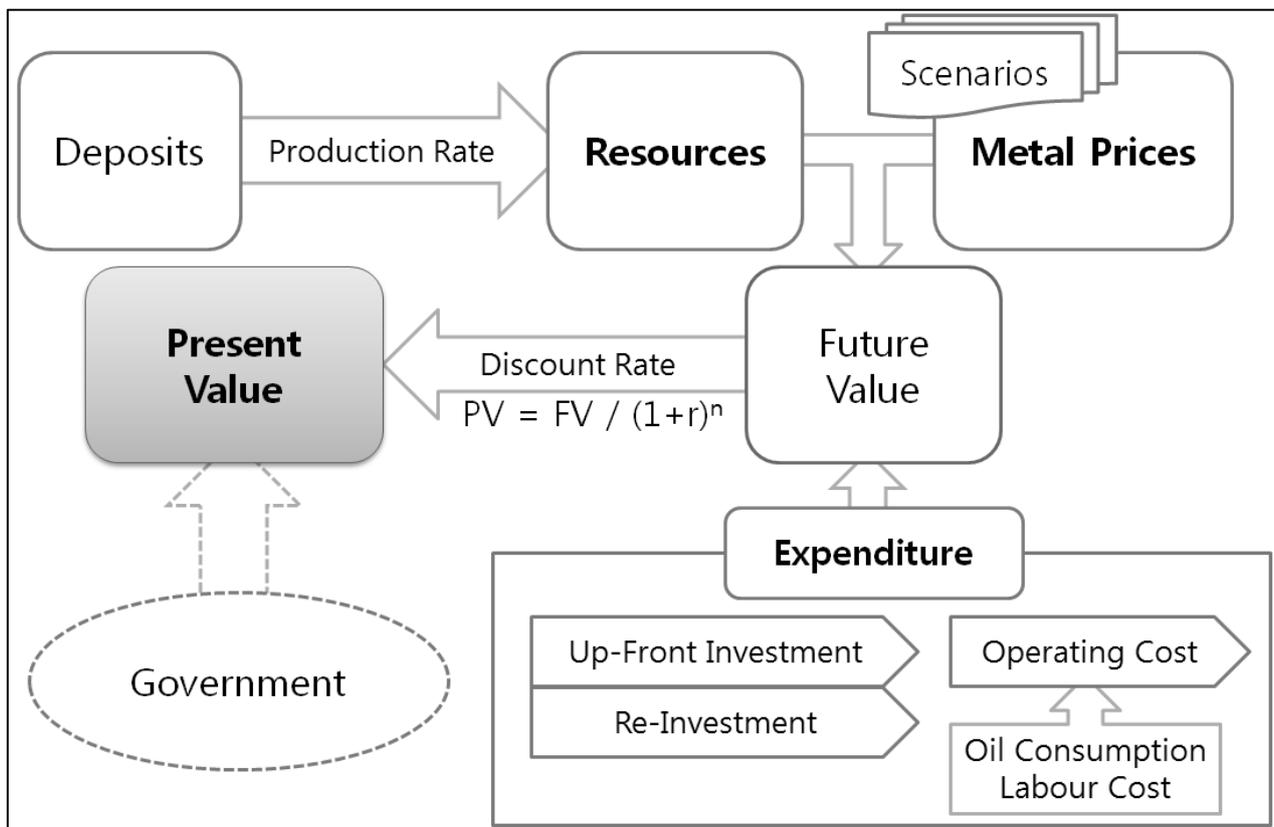


Figure 82: Economic Model developed for Atlantis II Deep Mining

9.4.3 Economic Estimation

Based on the previous economic model, we calculated the present values (PVs) of Atlantis II Deep resource. To do this, we assume that exploitation will be conducted over 20 years (2011-2030) with constant production rate which is calculated in the previous section. Since the amount of produced metal per year is less than about 0.1% of annual global mine production, the influence of the extraction of metal resources from the Atlantis II Deep to world mineral prices is negligible.

In Figure 83, time history of metal price indices is shown from 1960 to 2020. The metals and minerals price indices compiled by the World Bank (2010) includes prices of aluminium, copper, gold, iron ore, lead, nickel, silver, tin, and zinc. The German company Preussag conducted the research program, “Atlantis II Deep Metalliferous Sediments Development Program” (MESEDA) lasted until the end of 1981. The main purpose of this program is the environmental survey of deep water. It included the assessment of the technical issue of deep sea bed mining and the processing of metalliferous mud on-board vessels by a pre-pilot mining test (PPMT), as well as an economic assessment. During the PPMT, the mining system and the on-board processing of the mud proved to be feasible. However, because of low price of metal (see Figure 83) the economic interest in the Atlantis II Deep mining halted in the early 1980s (Bertram et al., 2011).

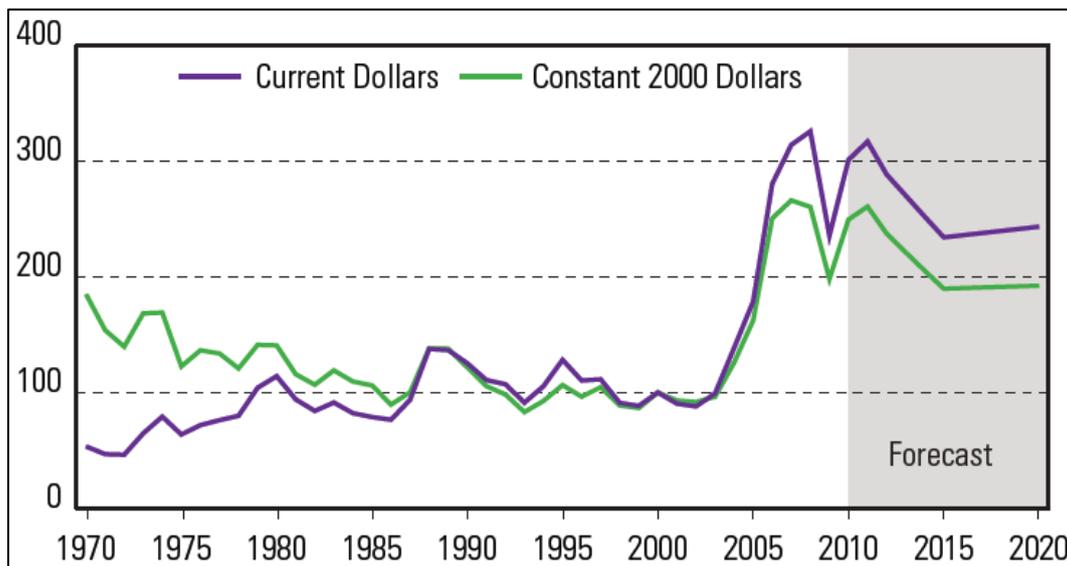


Figure 83: Metal and Mineral Price Indices
Source: World Bank (2010)

In 2005, metal price dramatically increased and metal markets have been extremely volatile during the last years because of imbalances of supply and demand. There was unexpectedly strong demand from China and India, which is caused by increased industrial production. Metal prices were reduced significantly between 2008 and 2009 to reflect the economic downturn caused by the financial crisis. Due to a demand from China and recovering

industrial production, metal prices rose again in March 2009. However, European debt crisis and uncertainty of future economic growth resulted decreasing of metal prices in late 2010 (Bertram et al., 2011). The World Bank (2010) expects metal prices to increase moderately during 2011 as the global economy recovers and demand expands.

Table 15: World Metal Prices in 2009 and Forecasts until 2020
Source: Bertram et al. (2011)

Metal prices	2009	2010f	2011f	2012f	2015f	2020f
Zinc (US\$/t)	1,660	2,250	2,500	2,300	1,700	1,800
Copper (US\$/t)	5,165	7,000	7,500	6,500	5,000	5,100
Silver (US\$/oz)	14.68	15.5	15.25	15	13.5	14
Gold (US\$/oz)	972	1,000	975	950	850	900

To calculate total income of the resource extraction, metal prices should be determined beforehand. Metal prices which are forecasted by the World Bank (2010) from 2010 to 2020 are presented in Table 15. Metal prices in 2013, 2014, and from 2016 to 2019 are linearly interpolated and three different price scenarios are assumed after 2020. The first scenario is optimistic prediction of metal prices, which means that the peak price in 2011 will be occurred in 2030 again. The second one is neutral scenario that metal price will remain constant same as 2020 price. The last case is pessimistic scenario. The metal price will gradually decrease as 2.5% per year until 2030.

Table 16 shows the summation of PVs for all produced resource according to the different scenarios and different discount rates (5–10%). The expected total PV of the resources in the Atlantis II Deep is minimum 1.02 billion US\$ to maximum 1.53 billion US\$. All calculation is based on the assumption that the production in the Atlantis II Deep does not affect to the world metal prices.

Our assessment provides smaller present values than other calculation (Bertram et al., 2011). They assumed that half of the total deposit will be exploited over 20 years, which gives much higher production rate, about 100,000 tons per year for zinc. Due to the limitation of pre-processing technique, increasing production rate of metals is very difficult and their assumption of high production rate is slightly unrealistic.

Table 16: Present Values of Produced Resources over 20 years (unit: million US\$)

Discount Rate	Optimistic	Neutral	Pessimistic
5%	1,527.43	1,448.02	1,385.08
7%	1,320.99	1,261.87	1,214.94
10%	1,090.63	1,052.10	1,021.46

To calculate the total expenditure, we assumed that total CAPEX and OPEX are the same as Nautilus estimation. Since the seabed mining tools are different for the mining, only one

gathering machine is needed in our case while three different types of machines including cutter, gathering, and auxiliary are needed in the Nautilus cases. It may reduce the CAPEX of our case, but this cost will be compensated with the pre-processing facility cost.

Subtracting the total expenditure from total income, we have the total surplus of this project. The total surplus is expected to be around 0.7 billion US\$ and corresponding internal return of rate (IRR) which is a parameter that makes the net present value equal to zero is about 26%. Based on the metal market price and IRR, the sea bed mining of the Atlantis II Deep is economically feasible. Furthermore, our production rate calculation is based on relatively old (1980s) technology and current technology could provide more efficient gathering and processing rate of metals.

9.5 Environmental Impact of Seabed Mining in Atlantis II Deep

9.5.1 Oceanic Background of Red Sea

Physical oceanography plays an important role in the study of environmental impact of seabed mining. A number of large scale oceanic surveys were conducted in the past in order to improve the oceanography knowledge in the Red Sea. The Saudi-Sudanese Red Sea Commission carried out a number of comprehensive physical oceanographic surveys from 1977 to 1981 focusing on the environment and metalliferous sediments around the Atlantis II Deep. The environmental study included reef ecology surveys along the Saudi-Sudanese coasts, biological baselines studies along a transect from Atlantis II Deep to the coasts, in situ and laboratory toxicity tests, long-range monitoring of environmental parameters including the behaviour of tailing discharge. Recently, an on-going joint program was conducted by King Abdullah University of Science and Technology (KAUST) in Saudi Arabia and Woods Hole Oceanographic Institution (WHOI) in United States focusing on the hydrography, circulation and ecosystem of the Red Sea.

The Red Sea is a semi-closed elongated basin with unique oceanic environment. Large-scale circulation in the Red Sea is influenced by high rate of evaporation, the Bab el Mandab and the monsoon cycle. The intense basin wide evaporation in the Red Sea leads to high surface salinities at the northern end. The evaporation creates a two-layer anti-estuarine circulation with an inflow of Indian ocean surface waters from the Gulf of Aden and a bottom outflow of salty Red Sea waters above the shallow sill of Bab el Mandeb. The anti-estuarine circulation is modulated by the seasonal reversal of the monsoon winds. During winter, southerly winds enhance the surface inflow. During summer, northerly winds create a three-layer system in the strait, with a shallow surface outflow, intermediate inflow of water from the Gulf of Aden and bottom outflow of Red Sea water (Murray and Johns, 1997). The annual wave statistics in Red Sea (Area 37) have presented a maximum annual wave height

up to 6m and zero crossing period up to 10 seconds (British Maritime Technology Ltd., 1986)

The Atlantis II Deep is located within the transition zone between the northern northwesterly wind regime and the monsoon regime featuring North-northwest (NNW) winds during summer and South-southeast (SSE) winds during winter.

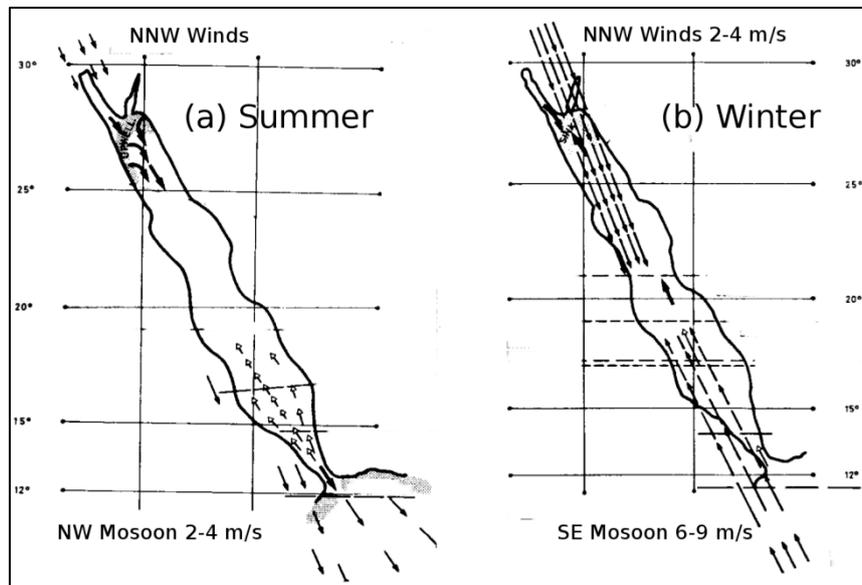


Figure 84: Surface Wind-driven Circulation of upper 250m in the Red Sea
(a) Summer, (b) Winter
Source: Karbe et al. (1981)

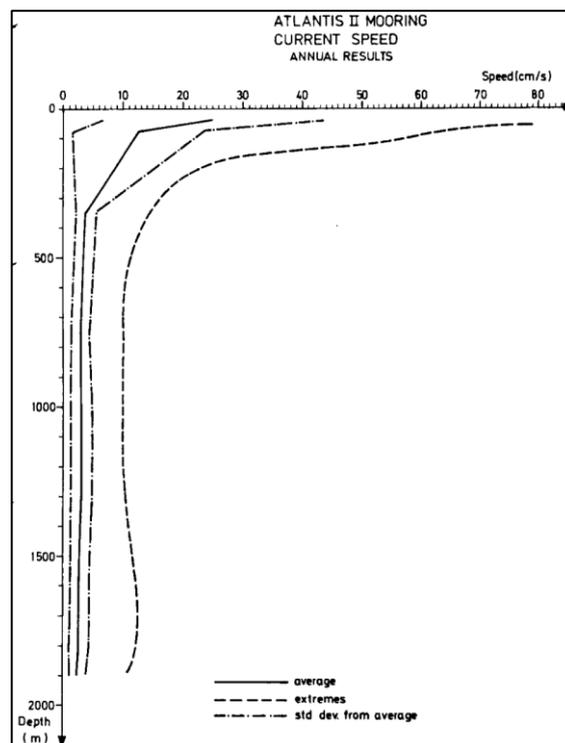


Figure 85: Atlantis II Deep Current Vertical Profile
Source: Karbe et al. (1981)

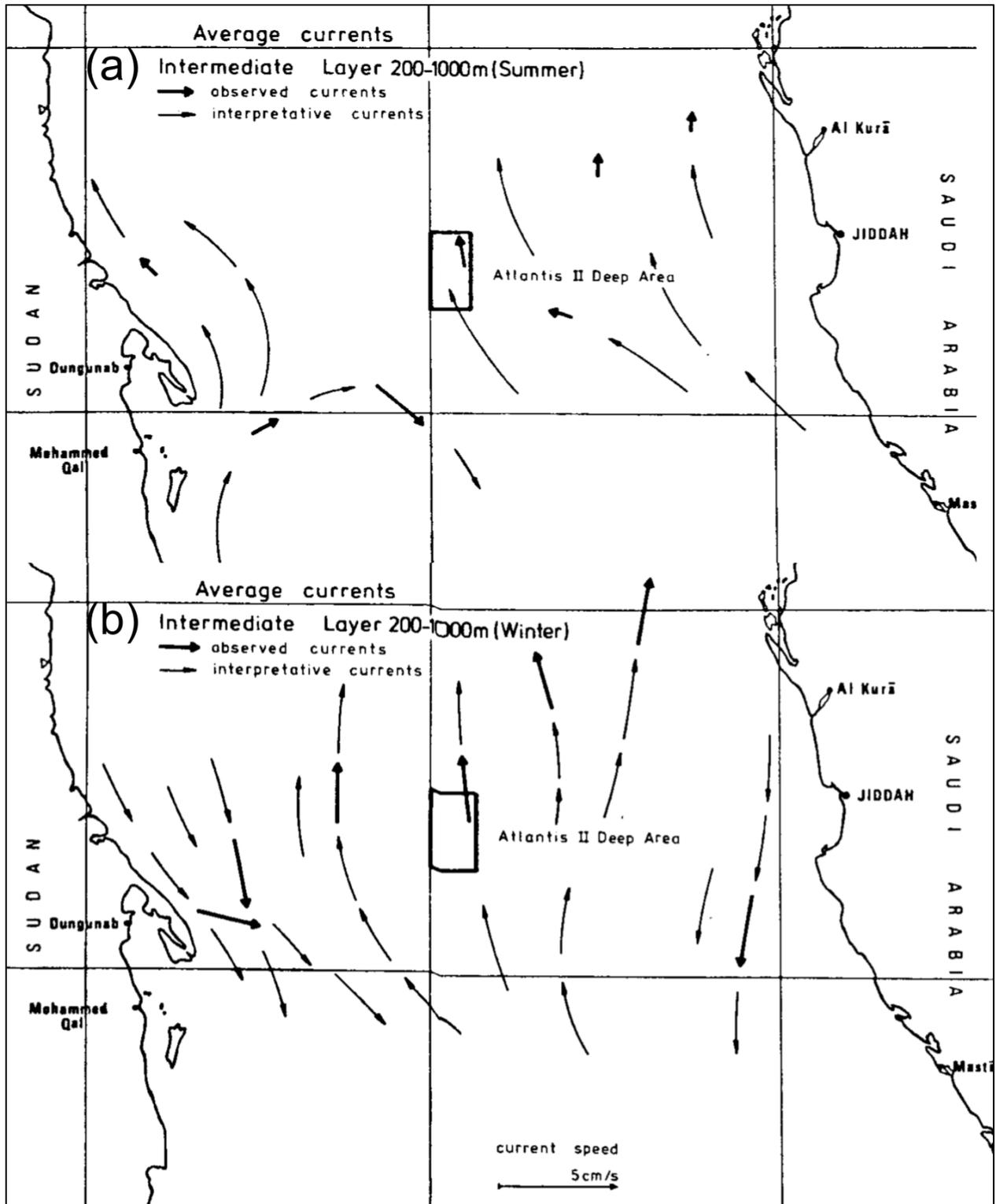


Figure 86: Observed and Interpreted Circulation Pattern at Layers 200-1000m
(a) Summer, (b) Winter

Source: Karbe et al. (1981)

The one year mooring observations in the whole water column above the Atlantis II Deep (Karbe et al., 1981) shows the speed and direction of currents. The averaged current speed is between 45cm/s near the surface and nearly constant 4cm/s from 350m water depth down to

the bottom. The direction of the averaged currents is predominantly to northwest. The general transport is to northwest direction as seen from the average currents (Figure 85). On top of the mean currents, the tidal currents are oscillating with a semi-diurnal M_2 frequency in the axial direction. The maximum current speed in the lower deep layer can read up to 15cm/s due mainly to topographic effect during tidal peaks.

Figure 86 shows the circulation pattern at deep layer during summer and winter seasons at Atlantis II Deep. The winter patterns are more reliable because most of the surveys were conducted during winter time.

9.5.2 Fishery and Benthic Communities

Karbe et al. (1981) concluded that the Atlantis II Deep area is not a nursery ground for fish larvae and does not have large standing stocks of fish. Benthic samplings (Karbe et al., 1981) show low standing stocks in the deep benthos for all the sampling sites and the results do not show any variation between regions or in the course of a year. Samples collected north of the Atlantis II Deep did not show any deviation from this trend in respiratory activity, suggesting a similar functioning of the ecosystem, at least for a large part of the Red Sea (Karbe et al., 1981). The benthic system of the Red Sea is governed by low energy production and transport in the water column and by low energy availability; bottom organisms use much of the energy in metabolism, while only a small part is used in production to build up the consequently low standing stocks.

Densities of benthic fauna are lower in the Central Red Sea in comparison with benthic communities in other ocean basins. Sampling along the Red Sea axial region suggested that most of the Red Sea bottom is poorly populated. The uniqueness of Red Sea ecosystem is due mainly to the high salinity, high water temperature and its related high metabolic rates. Low primary production and high metabolic rates explain the low standing stocks of all organisms in the Red Sea ecosystem. Community structure is characterised by many endemic species. The Red Sea ecosystem demands great care.

9.5.3 MPA in the Red Sea

The Red Sea and Gulf of Aden are globally renowned for their unique and beautiful marine and coastal environments, the diversity of species inhabiting them, the high degree of endemism, and the value of these resources for human development and as part of the region's cultural heritage.

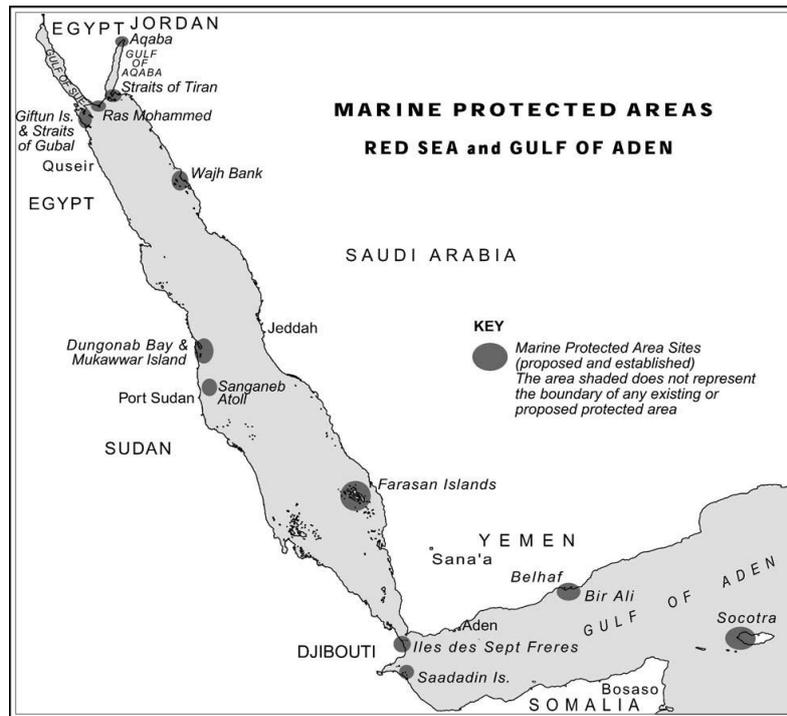


Figure 87: Red Sea and Gulf of Aden Regional Network of MPAs
Source: Gladstone et al. (2003)

Coral reefs of the Red Sea are diverse and important biologically. The principal reef type is the fringing reef, but extensive regions of patch reefs are found behind protective barrier systems. This ecosystem is threatened by the increasing activities in petroleum-based industry, international dive tourism, international fisheries operations, coastal developments and the general population growth in the coastal zone. An integrated regional network of Marine Protected Areas (MPAs) was established in the Red Sea and the Gulf of Aden including 12 sites (Figure 87).

9.5.4 Pre-Pilot Mining Test in 1979

It is known today that all industrial activity changes the environment and that many marine habitats and communities are affected. Preussag, which was a German mining and metalliferous processing company with knowledge and experience of the Atlantis II Deep, was entrusted with the feasibility study 1979. A pre-pilot mining test (PPMT) was carried out successfully during the spring months of 1979. The main target was to mine the metalliferous muds in depths exceeding 2,000 m and pump the diluted mud up to the surface for flotation onboard the mining vessel. The PPMT established the technical feasibility and environmental acceptability of Red Sea metalliferous muds mining from depth below 2000m. According to the original plan, a pilot mining operation (PMO) was scheduled, which would be ten times larger than the PPMT, and about one tenth of the future commercial mining (CM). Due to the collapse of the metal market, the PMO project was aborted.

9.5.5 Tailings Disposal

The research program conducted in the 1970s and 1980s (Karbe et al., 1981) suggested that possible effects of a mining operation in the Atlantic II Deep on the surrounding environment are mainly expected from the disposal of flotation tailings, which primarily affect the water column. Effects at the sea floor are expected to be of minor importance. Tailings represent a mixture of warm, nutrient- and CO₂- rich seawater, brines and metalliferous sediments depleted in sulphides and containing small amounts of flotation reagents. During mining, tailings are to be discharged into the environment which contains significant amounts of metals and metalloids. Zinc, copper, cadmium, lead and mercury, which are found in the tailings, are known to be potentially toxic and to accumulate in the marine food web. Gideiri (1984) summarized the potential influences of tailings discharged into the marine environment of the Red Sea:

- (a) Heavy metals in solution (Zn, Cu, Mn, Fe, Ag, Cd, Ni, Hg, Au, Co) which may have lethal effects on marine life at certain levels of concentration.
- (b) Suspended matter that accumulates to clog the filtering structure of zooplankton, corals and even gills of fishes.
- (c) Particles that adhere to the outer parts of the plankton and impair their floating ability.
- (d) Coverage and destruction of benthic fauna by sediments.
- (e) Increase of suspended matter decreasing light penetration and biotransport of particles, thus resulting in reduced food production in the euphotic layer.
- (f) Influences from enhanced salinity, temperature and decreased pH.
- (g) Decrease of oxygen content through consumption by incompletely oxidized metallic material of tailings.
- (h) Disturbance in content of nutrients like phosphates and silicates.

The idea of depositing the tailings in topographic deeps near the mining area (e.g. Discovery Deep) was considered but discarded in the PPMT because of the high costs and the technical risks of a disposal unit, which would have to be firmly anchored and in permanent connection with the slowly moving mining vessel (Karbe et al., 1981). Therefore only surface or subsurface disposal in water depths to be determined can be employed in the PPMT.

Predicting the evolution of the tailings plume is challenging. A tailing jet discharge model was used to describe the flow of waste from the tailings pipe in three stages: jet convection, jet decay and long term diffusion and deposition. Figure 88 shows theoretical profiles of jet decay and plume formation released at different depth.

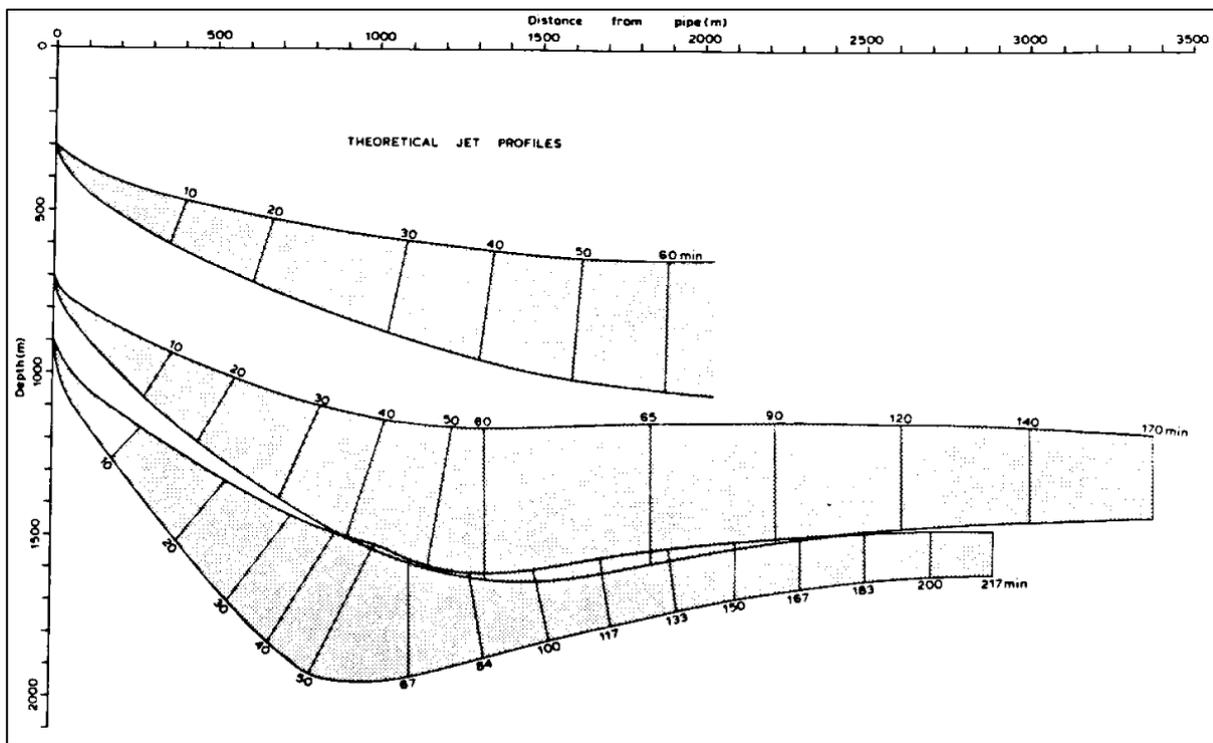


Figure 88: Theoretical Profiles of Jet Decay and Plume Formation
 Source: Karbe et al. (1981)

During the pre-pilot mining test (PPMT) in 1979, 480 m³ of tailings mixed up with 50 kg of iridium-enriched sediments were discharged at 400 m. The following sediment sampling about 1.7 years later confirms the net transport is axial in a northerly direction, see Figure 89.

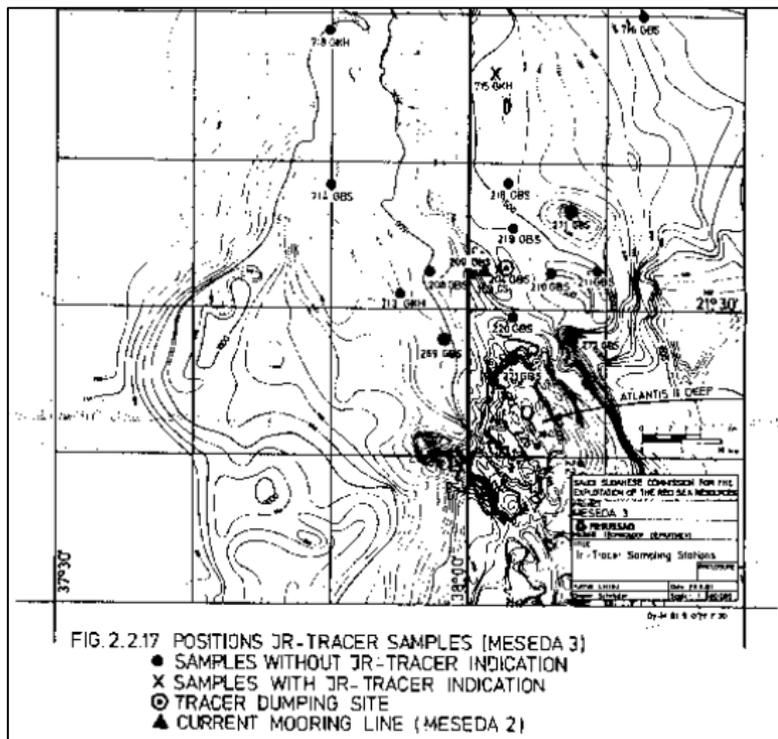


Figure 89: Positions of Sediment Samples
 Source: Karbe et al. (1981)

A tailing released at depth may have relatively less environmental impact. Based on the observed circulation pattern (Karbe et al., 1981), tailings released at 1,000 m depth above Atlantis II Deep would float for several days on semi-circulate tracks in the mining area and then slowly float along main axis of the trough to the north. Some benthic life is present in the deep sea bottom around Atlantis II Deep, which is covered by hot brine water. There is no substantial difference between the benthic population around the Atlantics II Deep and the seabed further north (Karbe et al., 1981). It is very likely that any damaged area in the range of the tailing sink could probably be repopulated. Gideiri (1984) concluded that a well-controlled tailings disposal below 1,000 m water depth could keep the environmental impact of seabed mining operation in Atlantis II Deep in acceptable dimensions.

A fully enclosed mud delivery system using riser and pump as proposed in the previous engineering system section could significantly reduce the environmental impact of the discharging of tailings. The previous tailing discharge at the depth of 400 m during PPMT was limited by old technologies. After 30 years development in the offshore oil and gas industries, a fully enclosed riser and pump system could be used to discharge the wastewater back to the brine layer above the seabed in order to reduce the environmental impact from the plume development.

9.5.6 Recommended Further Studies for Environmental Impact Assessment

An ocean circulation model for the Atlantis II Deep should be developed for assessment of the physical ocean condition, spreading of sediment plume and water quality, especially for heavy metal and nutrient concentration in the water column. The model will be based on realistic bathymetry and atmospheric forcing. The hydrodynamic component could be used in the risk assessment, and prediction of the sea condition. The statistics of extreme weather and sea condition around the Atlantis II Deep site from the model will help scheduling the operation and maintenances of the engineering system. The sediment component could be used to predict the development of plume and settlement of mud particles. The water quality component could be used to understand the advection and diffusion of heavy metal in tailing and its impacts on the ecosystem.

Baseline study of the heavy metal concentration in the red sea is essential for the environmental impact monitoring and assessment. The first baseline study in the Red Sea was conducted during the PPMT. This baseline study provides a valuable dataset and sets the background reference of heavy metal concentration in the Red Sea. A new water quality survey should be carried out as part of the environmental impact assessment with specific focus on the heavy metal concentration. The new observed dataset will be compared with the dataset from PPMT to understand the trend and variation of heavy metal concentration

in the Red Sea. A new background reference will be set for the further mining. A long term monitoring program of heavy metal concentration should also be set up during, before and after the mining.

9.6 Logistics and Supply Chain Concept

The supply chain for the seabed mining operation in Atlantis II Deep covers the processes from sea surface to the market. In the following, four generic value chain concepts will be discussed regarding their strengths, weaknesses, opportunities and threats (SWOT analysis). Table 17 provides an overview of this discussion. One scenario will then be detailed for Atlantis II Deep and further aspects for development will be outlined.

Table 17: SWOT Analysis of Supply Chain Scenarios

Scenario	Strengths	Weaknesses	Opportunities	Threats
Processing of Ores Offshore	<ul style="list-style-type: none"> ▪ Direct processing or pre-processing ▪ Reduced transportation costs / lean supply chain 	<ul style="list-style-type: none"> ▪ Technology development ▪ Environmental impacts ▪ Harsh conditions ▪ Increased operation costs 	<ul style="list-style-type: none"> ▪ Technological advantage ▪ Reduced production times ▪ Higher feasibility of seabed mining 	<ul style="list-style-type: none"> ▪ Economic and environmental challenge ▪ Technology not ready yet ▪ First mover – high risks
Processing of Ores Onshore Newly Built	<ul style="list-style-type: none"> ▪ Processing of multi minerals according to needs ▪ Site selection close to port 	<ul style="list-style-type: none"> ▪ Facility is only needed for one particular mining site (feasibility testing) ▪ High costs 	<ul style="list-style-type: none"> ▪ Support by governing state (e.g. employment, technology) 	<ul style="list-style-type: none"> ▪ High financial and environmental risk
Processing of Ores Onshore Existing	<ul style="list-style-type: none"> ▪ Using existing knowledge and infrastructure ▪ Offering complete solution to customers 	<ul style="list-style-type: none"> ▪ Optimal facility needs to be found and contracted ▪ High transportation / handling costs ▪ Intermodal transport solution needed 	<ul style="list-style-type: none"> ▪ Joint venture with land mining company 	<ul style="list-style-type: none"> ▪ No feasible facility for all target minerals ▪ Dependency on processing facility and developed infrastructure
Processing of Ores Onshore Centralised	<ul style="list-style-type: none"> ▪ Standardised and optimised comprehensive solution for seabed mining supply chains 	<ul style="list-style-type: none"> ▪ Legal limitations ▪ Early state of seabed mining ▪ Differences of ore compositions 	<ul style="list-style-type: none"> ▪ Competitive advantage ▪ Technology pool and exchange ▪ Customer pool 	<ul style="list-style-type: none"> ▪ High risks, not a first mover solution ▪ No exploitation licenses for further sites
Direct Distribution of Ores	<ul style="list-style-type: none"> ▪ Simple and feasible solution ▪ Transport, handling and storage need to be solved only 	<ul style="list-style-type: none"> ▪ May deter potential solution customers 	<ul style="list-style-type: none"> ▪ Competitiveness to land mining 	<ul style="list-style-type: none"> ▪ Customer dependency (single)

9.6.1 Supply Chain Scenarios

Different possible scenarios for supply chain concepts are presented in Figure 90. The *first scenario* assumes processing of the sediments offshore on the production vessel or platform. Within this scenario only the processed concentrates of zinc, copper, gold and silver are shipped onshore to the port and then to the customers. Processing offshore reduces the transportation times to processing facilities and allows the seabed mining operator comparability to land mining and a competitive advantage to other seabed mining operators. Customers of minerals can be addressed directly. On the other hand, engineering systems for offshore processing are not available yet. Environmental impacts by the processing are not sufficiently researched and can be assumed to be higher than in pre-processing or onshore processing scenarios.

The *second scenario* is also a comprehensive service solution adapted from the first approach of Nautilus Minerals. The sediments are shipped to a port close to the mining site. The ores are then handled at the port and transported by road or rail to either an existing processing factory or to a newly built factory in close proximity to the port. In the case of Atlantis II Deep for instance the port of Jeddah is in close reach (~120km). A newly built processing facility has the advantage of site selection close to the port. Moreover, it can be designed to be capable of multi-mineral processing. However, it extends the high financial risks of seabed mining and may not be feasible for the seabed mining site solely. The other alternative (2b) uses an existing mineral processing facility that is capable of smelting and treating small grain sediments. These facilities may not necessarily be in close distance to the off-shore mining site and thus, increase transportation and handling costs. This implies that intermodal transport solutions for bulk cargo need to be developed. The scenario offers a feasible approach with low additional financial and technological risks.

The *third scenario* extends the approach 2a and offers a processing solution for various seabed mining sites in world's regions. A newly built facility would provide smelting and treating solutions for seabed massive sulphides from various mining sites. Therewith, this scenario presents a long-term solution to standardise and optimise the seabed mining supply chain.

The *fourth scenario* addresses the current approach of Nautilus Minerals, which sell and distribute the ores directly to their customer(s). Since the processing is in the hands of the customer, this scenario reduces the financial and technological risks. However, the number and location of customers determine whether bespoke or consolidated logistics solutions can be offered. In the case of Nautilus a single customer contracts has been closed, which induces a high dependence, whereas multiple customers decrease risks but increase transportation and handling costs.

As conclusion from the assessment of different supply chain concepts for Atlantis II Deep, the second scenario with an existing processing facility onshore is chosen. A full processing

of multi-minerals offshore is not yet feasible from an economic, technological and environmental point of view. The second and third scenarios that involve newly built processing facilities are not considered at the moment, due to the increase of investment risks. Both the scenario 4 and 2b seem to be most feasible for an early stage of operation. Since a potential customer analysis and development of supporting logistics networks demands for comprehensive datasets, the most adequate solution is proposed to identify a multi-mineral processing facility in close proximity and outline critical issues for the logistics network.

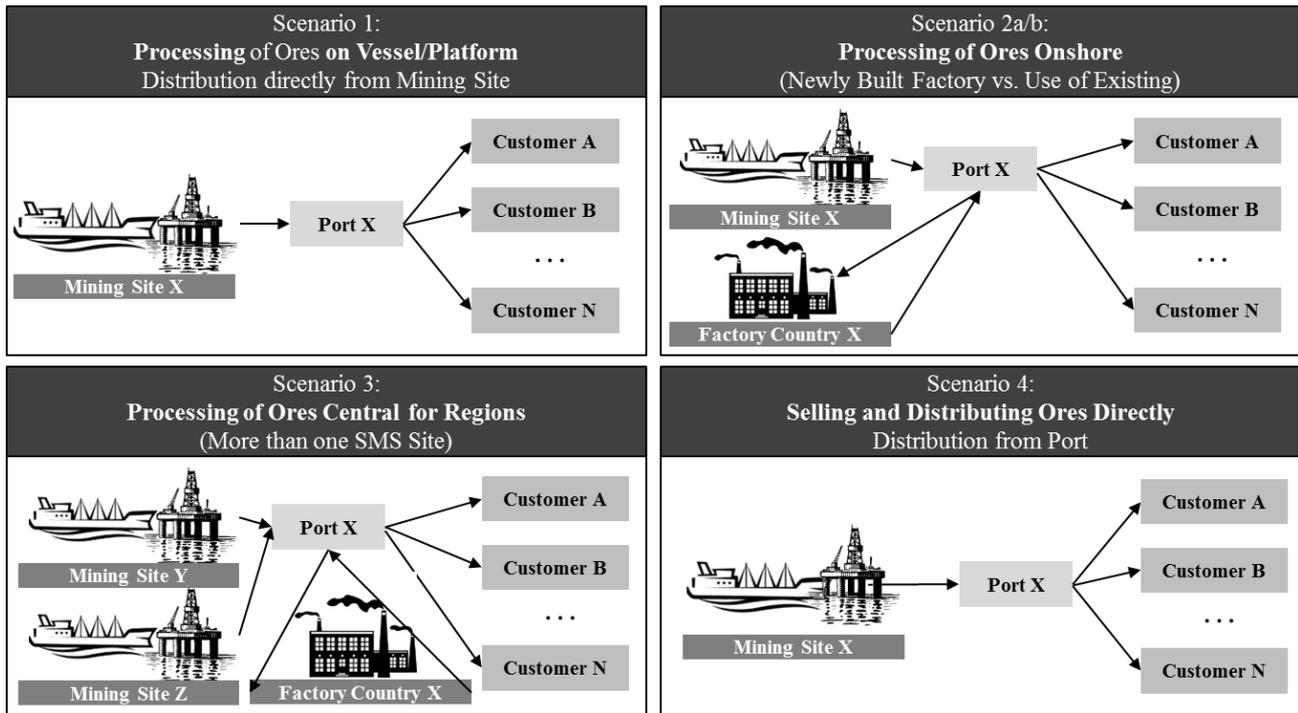


Figure 90: Supply Chain Scenarios

9.6.2 Proposed Supply Chain Concept and Logistics Network Design

As defined in the previous chapter, the proposed concept for Atlantis II Deep is to ship pre-processed sediments to a multi-mineral processing facility. The pre-processing step offshore is hereby essential to reduce the transport volumes to the onshore mining site. Thereby, the economic benefits of the fine grain polymetallic sediments can be utilised fully. The first step is to identify a potential facility in close proximity. Due to the composition of the deposits, the processing facility needs to have capabilities in zinc, copper, gold and silver concentration. Figure 91 maps the mining facilities in the Red Sea region. Two facilities in Saudi Arabia have been identified for processing the outlined minerals: the Al Masane mine near the Yemen border and the Jabal Sayid project 350km northeast of Jeddah (still in the development stage).

The Jabal Sayid mining project is located 120 km south-east of Medina. The facility is accessed by a multi-lane, sealed expressway from Jeddah, followed by a sealed two-lane

highway to within two kilometers of the project site. Although the site holds a copper-gold-silver-zinc deposit, it announces to produce copper concentrates only at the current development stage. If in the future processing capabilities for Zinc and Silver are developed, this mining site should be considered for Atlantis II Deep processing due to its beneficial location. However at the current early stage, the logistics concept is developed exemplary for the Al Masane mine.

The Al Masane mine is located 640 km south east of Jeddah and 414 km east from the Port of Gizan. It is linked by a newly paved road from the port of Gizan on the Red Sea. It produces copper and zinc concentrates as well as gold and silver bullion since 2011. Within this concept, we assume a contract with the Al Masane processing facilities for the polymetallic sediments of Atlantis II Deep².

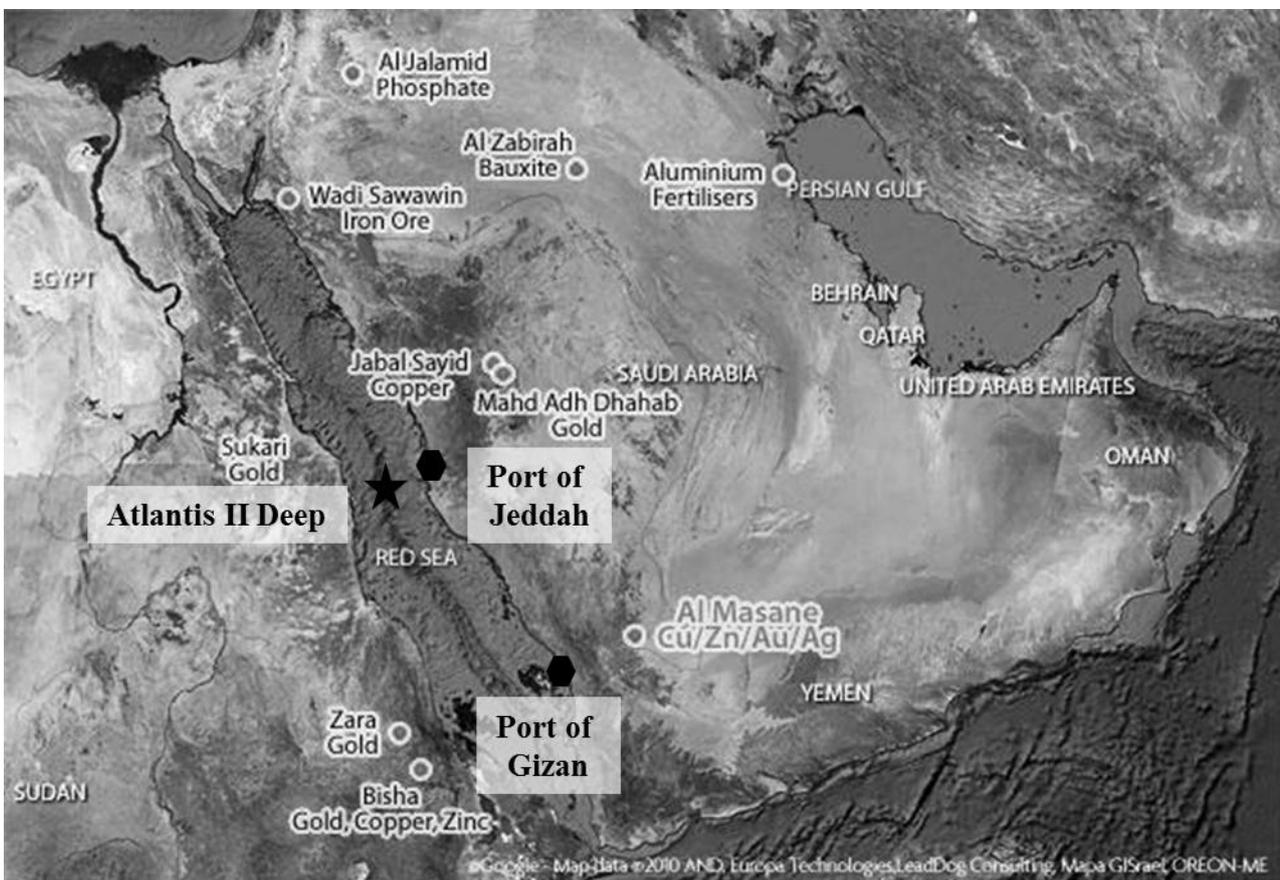


Figure 91: Mining Environment Red Sea

Source: www.arabianamericandev.net/AMAK/images/Saudi-Map1-HR.jpg

Based on this assumption, the logistics network for Atlantis II Deep includes the transport to the mining site Al Masane. All subsequent logistics processes (after the processing stage) are excluded here, since further customer data is needed. In Table 16, the logistics processes

² The processing site proposed here is selected based on the multi-mineral processing capability and proximity to Atlantis II Deep only. In order to provide a sustainable seabed mining concept for the future, the site selection needs to consider a thorough risk assessment and analysis of potential mining sites, especially regarding the environmental impacts and processing standards.

in scope are outlined and its specification and requirements are presented. These cover offshore logistics and maintenance as well as handling and transportation processes.

The maintenance cycles should be planned according to the safety and risk assessments of the engineering systems, implying the production support vessel, the seafloor tools and the riser/lifting system. The planning needs to consider spare part stocks, labour and transportation for regular maintenance as well as emergency situations.

The second aspect of consideration is the handling of the dewatered sulphides offshore. Within the Nautilus case, the technical drawing includes a conveyor belt for ores. For Atlantis II Deep, knowledge of the dredging industry may be conferred. Figure 92 indicates an exemplary pipe loading of sands and gravel to a flatboat dump barge with a tugboat for maneuvering.

Table 18: Proposed Logistics Processes, Specifications and Requirements

Logistics Processes	Specification	Requirements / Critical Issues
A2D Logistics and Maintenance	<ul style="list-style-type: none"> ▪ Maintenance of machinery ▪ Food and fresh water supply 	<ul style="list-style-type: none"> ▪ Definition of optimal maintenance cycles, planning of regular and emergency maintenance operations (transportation, inventory, etc.) ▪ Planning of food and fresh water supply logistics
Handling Offshore	<ul style="list-style-type: none"> ▪ Handling capacity: Approx. ~380 t/d ▪ Storage containers ▪ Conveyors/Pipes ▪ Loading of barge ▪ Cover for sediments 	<ul style="list-style-type: none"> ▪ Identify requirements for storage containers for ores onboard (e.g. transport moisture limitations, oxidation discharges) ▪ Design of pipes/conveyors for safe loading of vessels in harsh weather conditions ▪ Estimate downtimes ▪ Planning of safe and efficient loading processes ▪ Coverage for sediments to prevent oxidations
Transport A2D – Port (Barge)	<ul style="list-style-type: none"> ▪ Barge transport distance: ~620km 	<ul style="list-style-type: none"> ▪ Capacity optimisation and transport planning: barge specifics, storage, transport ▪ Barge “buy or charter”
Handling Port	<ul style="list-style-type: none"> ▪ Barge unloading equipment ▪ Hardstand area ▪ Discharges and waste guidelines ▪ Cleaning barge ▪ Loading Trucks 	<ul style="list-style-type: none"> ▪ Development of guidelines for all port operations, e.g. environmental hazards, wastes and discharge ▪ Contracting port operator and needed areas ▪ Design barge unloading and truck loading equipment with respect to capacity needs ▪ Define hardstand areas for stockpiles and covers
Transport Port – Mine (Road)	<ul style="list-style-type: none"> ▪ Distance: ~420km 	<ul style="list-style-type: none"> ▪ Capacity optimisation and transport planning ▪ Dump truck specification and “buy or charter” decision ▪ Assessment of guidelines for transporting polymetallic sulphides ▪ Analysis of safety and environment risk
Storage	<ul style="list-style-type: none"> ▪ Stockpiling of concentrates in Al Masane 	<ul style="list-style-type: none"> ▪ Estimation of production rates and design of logistics networks towards customers

The barge and handling equipment needs to be chosen or designed according to the outcomes of a logistics optimisation that analyses the transport and storage processes and costs. Within our concept an average production rate of approximately 380 tons per day is assumed. Based on this production rate, transportation costs from Atlantis II Deep to the Port of Gizan (~620km) and to Al Masane (~420km) can be estimated for different transport vehicles, e.g. barge sizes. In addition to this economic viewpoint, environmental aspects may be considered for the transport mode selection and capacity determination. Finally, the storage costs and stockpile carrying costs need to be taken into account. Therewith, buy or charter decisions for the sea and road transport means can be made.



Figure 92: Example of Loading of Sediments to Barge
Source: www.damendredging.com

Further critical issues that need to be assessed and detailed for seabed mining operations at Atlantis II Deep are concrete transport schedules, safety and risk assessments, environmental assessments and subsequent guidelines for discharge, cleaning and waste treatment. Since the logistics operations will include (numerous) subcontractors, the specifications and requirements can be used for identifying adequate partners.

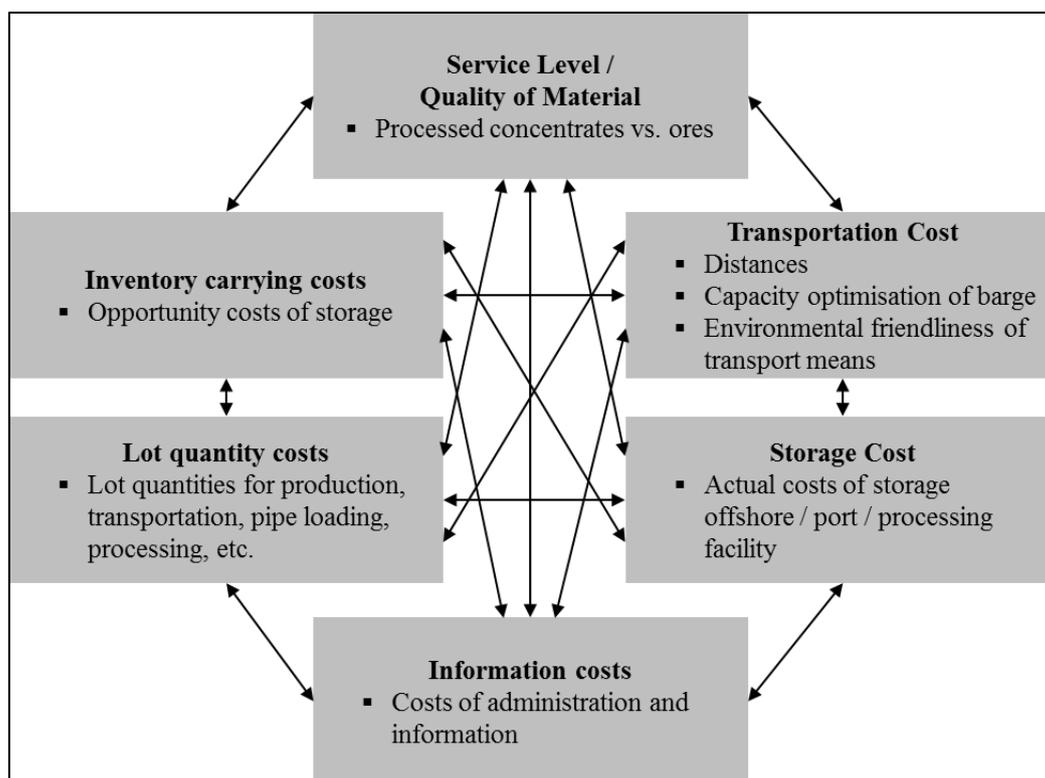


Figure 93: Logistics Optimisation and Network Design Model
 Source: Adapted from Stock & Lambert (2001)

9.7 Legal Requirements and Issues

The first deep seabed mining project developed by Nautilus Minerals Inc. at the Solwara 1 site has set up a good example in terms of following rules and regulations and obtaining environmental and mining permits from the government of Papua New Guinea. Based on the Nautilus experience and the recommendation from Birney et al. (2006), the development of Atlantis II Deep can use the Madang Guidelines as a framework and The Code for Environmental Management of Marine Mining by International Marine Minerals Society to formulate a deep sea mining industry standard in the Red Sea. In general, the development of mining at Atlantis II Deep could follow the footprints of Nautilus Minerals Inc. to fulfil the legal requirements and obtain an environmental permit.

There are similarities and differences between the Solwara 1 project and the Atlantis II Deep. Three special aspects are worth an in-depth discussion. First, the Atlantis II Deep deposits are shared by two countries: Saudi Arabia and Sudan. Second, there are a few Marine Protected Areas (MPAs) around. Third, the Atlantis II Deep is situated on the major transportation route. In this section, the above issues will be discussed with associated legal and environmental regulations.

9.7.1 Exclusive Economic Zones in the Red Sea

Saudi Arabia and Sudan signed an agreement in 1974 (United Nations, 1974) indicating the beginning of the Saudi-Sudanese Red Sea Commission. Both countries agreed to divide the Red Sea area between 18° N and 24° N into three zones (see Figure 94).

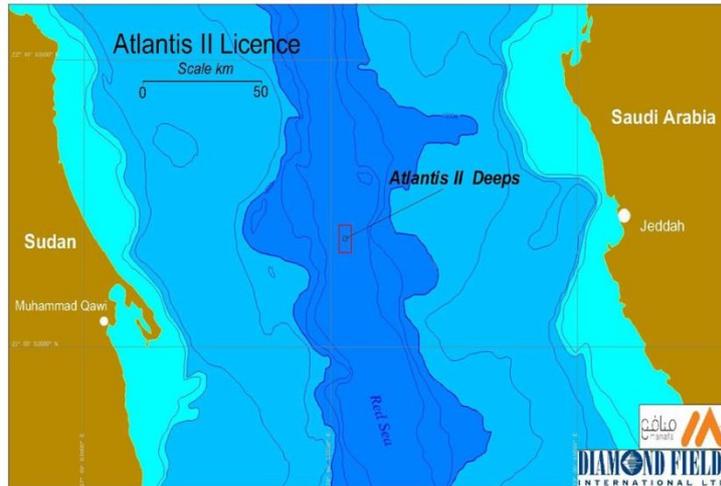


Figure 94: Exclusive Economic Zones (EEZ) in the Red Sea
Source: www.diamondfields.com/i/photos/atlantis/Atlantis-Map1.jpg

Each country has exclusive sovereign rights to the area nearest to its coastline, both have common but equal rights to the common zone where the depth exceeds 1,000 m. All 18 mud deposits including the Atlantis II Deep lie in this common zone. Saudi Arabia Government is a diver position in the Red Sea Commission. In the 1970s and 1980s, the Sudan had limited financial resources and funding of the Joint Commission activities was provided by Saudi Arabia.

9.7.2 Marine Protected Areas

An integrated regional network of Marine Protected Areas (MPAs) was established in the Red Sea and the Gulf of Aden including 12 sites. Most countries of the region have enacted site-specific legislation related to the establishment of specific MPAs. Saudi Arabia in 1995 enacted the Protected Areas Act, which sets out the requirement for a network of protected areas to be established and managed, and the range of activities prohibited within all protected areas.

9.7.3 The Jeddah Convention

The International Ocean Dumping Convention (London Convention on the “Prevention of Marine Pollution by Dumping of Wastes and other Matter”) came into force in 1975 to protect the marine environment against uncontrolled waste disposal. However, the London Convention excludes any regulations concerning environmental pollution and waste

disposal originating from ocean mining. The potential environmental impacts of ocean mining were taken into account in the draft of the Convention on the Protection of the Red Sea and Gulf of Aden (1976). A regional framework for cooperative environmental management of the marine and coastal environments of the Red Sea and Gulf of Aden came into effect in 1982 with the signing in Jeddah of the Regional Convention for the Conservation of the Red Sea and Gulf of Aden Environment, the so called Jeddah Convention.

The Jeddah Convention explicitly includes environmental risks from ocean mining, based on the awareness of environmental alternations through the disturbance of particulate sedimentary matter, chemical changes within the sediments and water, chemical additions from processing and increases in particulate matter and sedimentation after disposal (Karbe et al., 1981).

9.7.4 Transportation

The Atlantis II Deep is situated on the major commercial shipping route as shown in Figure 95. The mining operation requires continuously occupying an area on the shipping route for about 20 years based on the estimated production rate and mineral deposits. There is a chance the seabed mining operation may potentially warrant permits from the transportation departments of Saudi Arabia and Sudan.

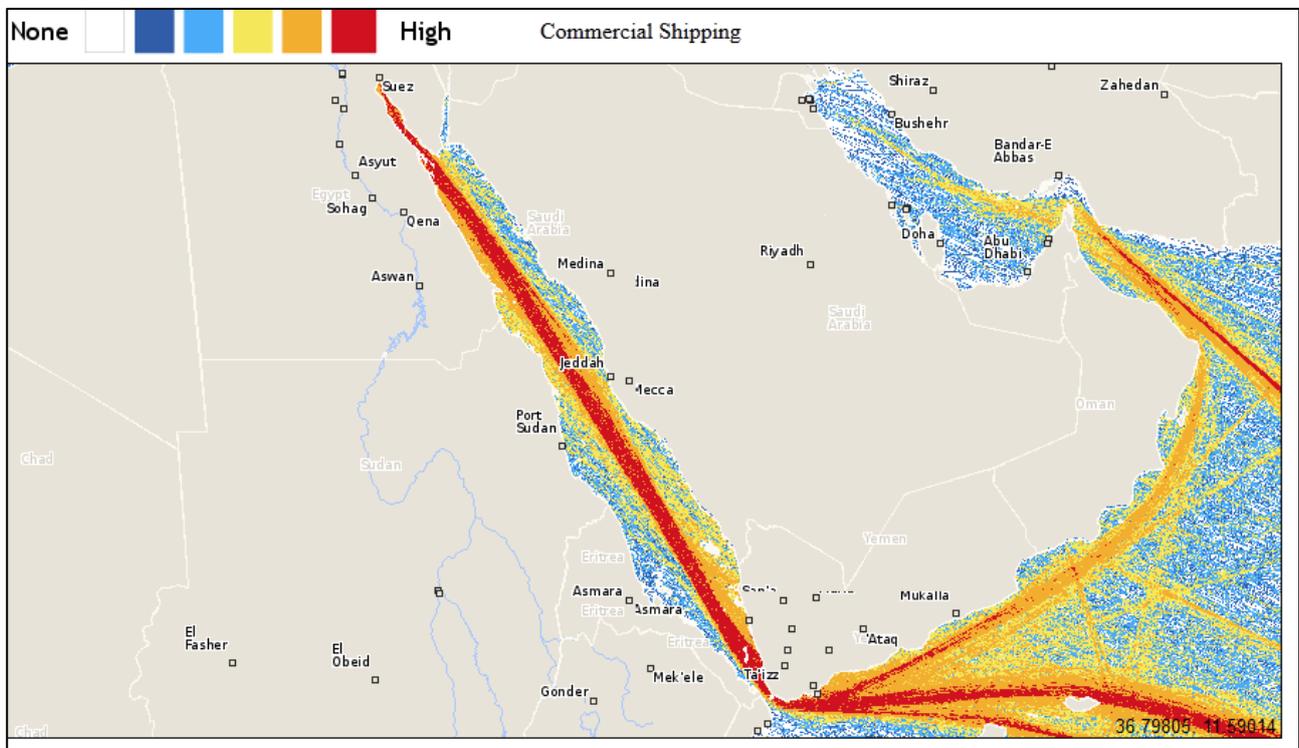


Figure 95: Commercial Shipping Activities in the Red Sea

Source: <http://globalmarine.nceas.ucsb.edu/>

9.8 Experiences Learned from Solwara 1 Project

The Solwara 1 project is the first commercial deep seabed mining project to be commenced in early 2013. The experiences learned from this project can shed light on the future development of the Atlantis II Deep and in some cases the same issues may apply. The Nautilus Mineral Inc. is doing business with the PNG government while the Diamond Fields International Ltd. is working closely with the Saudi-Sudanese Red Sea Commission. Experience transfer will immensely benefit the Atlantis II Deep project. The mining company and governments will be able to bypass costly and time consuming mistakes, and implement proven policy applications.

Contribution to Scientific Community

Scientific community and mining company are trying to answer the same questions (e.g. distribution of hydrothermal vent) from different motivations. In an effort to enhance scientific knowledge while meeting the needs of the EIA process, Nautilus Mineral Inc. collaborated with international scientific experts to design and conduct many environmental studies over the hydrothermal vents. These collaborations provided funding and opportunities to scientists and researches and added significant knowledge on deep sea marine environments. During the seabed mining operation, monitoring of the deep seafloor is anticipated to extend into more non-classified and general scientific research, for which Nautilus will encourage publication through the normal scientific peer review process.

Transparency

Deep sea mining companies are interested in making a profit, while at the same time they understand that as a cutting edge industry with many uncertainties, with many eyes watching them, they have a responsibility for protecting the environment (Birney et al., 2006). Nautilus Minerals Inc. is working with marine science researchers, and the government of PNG to ensure environmental protection at each stage of their operation. It is the responsibility of society to encourage these actions, whereas it is industry's responsibility to make these actions as transparent and accessible as possible. The Nautilus Minerals Inc. had a clear guidelines and timelines. The whole development of Solwara 1 project is very transparent. News releases and associated documents can be found on the company's website (www.nautilusminerals.com)

Public Awareness

Nautilus Mineral Inc. created the Nautilus CARES program to present company's principles and efforts on the Community, the environment, and workplace health and safety initiatives associated with company's activities. Nautilus used a number of media including radio, posters, brochures, newspaper articles, face-to-face meetings and workshops in both Tok

Pisin and English (the official languages of PNG). The future development of the Atlantis II Deep should also consist of public awareness campaigns employing all kinds of media in both Arabic and English.

Safety Operation

In the design of the Solwara 1 project, an exclusion zone of 500 m will apply around the surface production vessel at all times to avoid risks of collisions (Nautilus Minerals Inc, 2008). Atlantis II Deep is located on the busy transport lane in the Red Sea. A similar buffer zone should be created. In order to enforce the buffer zone, guarding vessels could be employed.

9.9 Concluding Remarks

Within this chapter a new concept for Atlantis II Deep was developed which considered the dimensions outlined in the sustainability based research framework.

The engineering solution for Atlantis II was detailed for the seafloor tools, the riser and lift system and the floating platform. In terms of the seafloor machinery a collection machine was developed applying gathering technologies from the dredging industry. It uses a tracks system for movement, which is customised to the environmental conditions of the Atlantis II Deep seabed. For the power supply of the machine a high voltage concept is suggested. For the transmission of control signals fibre optical cables are proposed.

The riser and lift systems are critical to the mining system at Atlantis II Deep especially with respect to the environmental risks. For the deepwater operation a steep wave steel catenary riser was proposed as most reliable and cost effective. Moreover, its advantages are the simple arrangement and congenial design.

The production support vessel is proposed to be transferred from the oil and gas industry. The concept identified specifications for the dewatering system, pre-processing of sediments, and offloading barges.

Economic feasibility strongly depends on the metal production rate, operating costs, and metal prices. The increase of the metal production rate is identified as a key issue to establish the economic feasibility. Especially, flotation techniques are critical for Atlantis II Deep deposits due to the very fine-grain states of metals.

The Red Sea is a semi-enclosed environment and contains various marine protected areas that need to be taken into account for the environmental impact assessment and subsequent mitigation strategies. A fully enclosed mining system is essential to mitigate the environmental risks. Thereto, an ocean circulation model for Atlantis II Deep should be

developed contemplating physical ocean conditions, spreading of sediment plumes and water quality.

The supply chain concept for seabed mining at Atlantis II Deep suggested the contracting of a multi-mineral processing facility in close proximity to the mining site. Based on these specifications a logistics network can be designed, which optimises the storage, handling and transportation capacities.

The legal environment for Atlantis II Deep is seen as supportive for seabed mining operations in particular when the mining contractor works in close collaboration with the Red Sea Joint Commission. A further development of Atlantis II Deep may use the Madang Guidelines as a framework and The Code for Environmental Management of Marine Mining by the International Marine Minerals Society to formulate a deepsea mining industry standard for the Red Sea.

10 Guidelines for “Sustainable Seabed Mining”

The following guidelines summarise the knowledge of the survey on sustainable seabed mining, the expert interviews, the case study on Nautilus Minerals and the concept development for Atlantis II Deep. These guidelines are structured according to the research framework developed within this study.

They aim to provide decision makers in the seabed mining industry with key aspects or critical issues for systems design. This implies a sustainable outline of the engineering system and supply chain network regarding to economic feasibility and environmental impact assessments and mitigation strategies. Furthermore, the guidelines summarise our findings on the mining site selection and critical issues regarding the legal environment.

For all dimensions discussed in the tables below, we suggest the following steps to derive informed decisions:

- (a) **General Assessment and Review:** Identification of alternatives and specification of their feasibility.
- (b) **Concept Selection:** Development of a selection matrix based on site specifics and e.g. cost and environmental requirements.
- (c) **Concept Specifications:** Definition and specification of the chosen concept.
- (d) **Execution, Design and Operation:** Consideration of the specified engineering system towards construction and installation

In the subsequent paragraphs each dimension in the table is described in detail.

Table 19: Guidelines for Sustainable Deepsea Mining

Dimension	Subtopic	Guidelines for Key Issues of Consideration
Massive Sulphides Deposits Selected as Mining Site	Mineral Reserves	<ul style="list-style-type: none"> ▪ Exploration of mineral deposit concentrations and compositions ▪ Analysis of market demands and mineral prices / Cross-check with economic analysis
	Locations	<ul style="list-style-type: none"> ▪ Proximity to ports and processing facilities ▪ Water depths around 2,000m
	Environment/ Ecosystem	<ul style="list-style-type: none"> ▪ Active hydrothermal vents are inhabited by chemosynthesis ecosystems. ▪ Inactive hydrothermal vents are preferred potential mining sites.
	Legal	<ul style="list-style-type: none"> ▪ Most promising mining sites are located within EEZ. Contracting with specific states is relatively easy in comparison with the unpredictable international legal and political environment.
Engineering System Design	Seafloor Tools	<ul style="list-style-type: none"> ▪ Seabed Mining Tools (SMT) must be resistant to high ambient pressures, corrosive environments and have maintenance-free life span ▪ For power supply a high power machine needs to use high voltage electrical energy 6,600 V and higher ▪ For reliable transmitting control signals to SMT from surface, fibre-optical cable is needed
	Riser Engineering System	<ul style="list-style-type: none"> ▪ Top-tensioned risers (TTRs) require a platform with good motion response characteristics. Therefore, they are accompanied by tension leg platforms (negligible heave motion, 0 to 0.3 m) or spar platforms (moderate heave, 0.15 to 4 m). A heave compensation system can be fitted in the top-tensioning system which keeps constant tension on the riser. TTRs have encountered a significant buckling and bending stress issues due to platform motions and vortex-induced vibration. ▪ Flexible risers are designed to have a small bending stiffness and are characterised by their wall structure. Generally, they considered to be economically expensive due to their fabrication process. ▪ Steel catenary riser offers major advantages over the ‘conventional’ flexible or ‘hybrid’ freestanding risers. The number of SCRs is increasing quickly due to simplicity, economic effectiveness, and well-known material properties and is strongly recommended for transferring ore from seabed to surface. ▪ Steel catenary riser is attached to the floating vessel using a flex joint to simulate a hinge and allows the SCR to rotate with a minimum bending moment under severe environmental conditions. A better understanding of flex joint stiffness is necessary in determining strength behaviour and fatigue performance at the SCR top end.
	Subsea Lift Pump	<ul style="list-style-type: none"> ▪ To meet the challenge of lifting large quantities of mined ore from subsea massive sulphide deposits from deep water, an existing positive displacement design needs to be selected over other lift equipment. Building on the pump technology used on the offshore drilling operations, the subsea slurry lift pump can accommodate the fluctuating process flow conditions while maintain a commercially viable flow-rate based on the operational mining operations.

Dimension	Subtopic	Guidelines for Key Issues of Consideration
	Floating Platform/ Production Vessel	<ul style="list-style-type: none"> ▪ Testing of the subsea lift pump to validate design for erosion, slurry pumping operability and the design life. ▪ The slurry pumping induced vibration on the vertical riser pipe should be assessed and evaluated. ▪ The selection of floater type depends on the combinations of water depth, metocean conditions and topsides, field layout and future expandability, riser options and platform motions and deck requirements which will influence the selection between a Tensioned-Leg Platform (TLP), Semisubmersible, Spar and FPSO. ▪ FPSO normally have the heave period above 20 seconds that there is seldom any wave energy to excite resonance heave oscillations. ▪ FPSO is less sensitive to water depth than other floaters. It has a spread catenary or turret moored mooring system and has large mooring footprint approximately twice the water depth and allow mining operation flexibility. It has also a large storage capability. ▪ TTRs, suggested by Nautilus, are not suitable for FPSO due to large heave motions compared with TLP and spar. ▪ The main technical requirements for FPSO are accommodations for up to 140 persons, dynamic positioning reliability and adequate electrical power supply. ▪ The vessel will also incorporate a dewater ore storage tank to store onboard approximately 1 day's production capacity and a dewater ore out of specification tank for storage and re-feed of dewatered ore that does not meet transportation specifications.
	Vessel positioning	<ul style="list-style-type: none"> ▪ For deep water mining vessel, dynamic positioning system not lower than DP 2 Class is recommended. ▪ Differential global positioning system is most suitable and reliable for vessels position reference. Differential, absolute and relative positioning system is more suitable for the offloading process. ▪ For control the riser angle, electrical riser angle sensor is needed.
	Energy supply System	<ul style="list-style-type: none"> ▪ For energy supply system of mining vessel, the most suitable system is centralized Diesel-Electric System. ▪ The DES must be split into three separate systems containing two diesel engines and generators. ▪ The power electric system must be well protected.
Economics	Production Rate	<ul style="list-style-type: none"> ▪ Increasing metal production rate ▪ Developing a new technology of flotation for fine-grained material ($\leq 2 \mu\text{m}$)
	Feasibility Assessment	<ul style="list-style-type: none"> ▪ Reducing operating cost, especially labour cost ▪ Reasonable scenarios of metal prices (optimistic, neutral, and pessimistic) ▪ Suitable assumption of discount rate (5-10%)
Environment	Impact Assessment	<ul style="list-style-type: none"> ▪ Baseline observations to set references for the future comparison ▪ Pilot mining project to test the feasibility of the engineering system, quantify the environmental impact and assess the efficiency of mitigation strategies ▪ Long term monitoring before and after the project ▪ Emergency plans for unexpected events and natural hazards

Dimension	Subtopic	Guidelines for Key Issues of Consideration
		<ul style="list-style-type: none"> ▪ Comprehensive environmental impact assessment to be reviewed by expertise and approved by the corresponding authorities
	Mitigation Strategies	<ul style="list-style-type: none"> ▪ Design fully enclosed mining system ▪ Pump wastewater back to the bottom layer above the seabed ▪ Designate an unmined reference area to provide parent stock for repopulation and a control site for environmental monitoring ▪ Create a temporary refuge area within the mining site to allow progressive rehabilitation ▪ Move marine organisms from non-excavated site to mining site ▪ Add artificial substrates to provide re-population habitats
Legal	Requirements and Issues	<ul style="list-style-type: none"> ▪ Identify the jurisdiction of the mining site according to UNCLOS ▪ In international waters, follow the guidelines and recommendations provided by ISA, apply exploration and exploitation licenses from ISA ▪ In national waters, shared by multiple states, a possible solution is to form a Joint Development Commission (JDC) among those states, follow the guidelines and recommendations provided by the JDC, apply exploration and exploitation licenses from the JDC ▪ In national waters, solely owned by a state, follow the guidelines and recommendations provided by the state, apply exploration and exploitation licenses from the state ▪ Seabed mining industry standard in a state can be based on the Madang Guidelines and The Code for Environmental Management of Marine Mining by International Marine ▪ Corresponding authorities and mining contractor have to work together to create new regulation for the specific situations ▪ Following environment regulatory framework, according Environmental Inception Report, Environmental Impact Statement and Environmental Permit Application to issue Environment Permit
Logistics / Supply Chain	Logistics and Maintenance	<ul style="list-style-type: none"> ▪ Definition of optimal maintenance cycles, planning of regular and emergency maintenance operations (transportation, inventory, etc.) ▪ Planning of food and fresh water supply logistics
	Handling (Offshore)	<ul style="list-style-type: none"> ▪ Identify requirements for storage containers for ores onboard (e.g. transport moisture limitations, oxidation discharges) ▪ Design of pipes/conveyors for safe loading of vessels in harsh weather conditions ▪ Estimate downtimes ▪ Planning of safe and efficient loading processes ▪ Coverage for sediments to prevent oxidations
	Transport	<ul style="list-style-type: none"> ▪ Capacity optimisation and transport planning: barge specifics, storage, transport

Dimension	Subtopic	Guidelines for Key Issues of Consideration
	(Deposit – Port)	<ul style="list-style-type: none"> ▪ Barge “buy or charter”
	Handling (Port)	<ul style="list-style-type: none"> ▪ Development of guidelines for all port operations, e.g. environmental hazards, wastes and discharge ▪ Contracting port operator and needed areas ▪ Design barge unloading and truck loading equipment with respect to capacity needs ▪ Define hardstand areas for stockpiles and covers
	Transport (Port – Mine)	<ul style="list-style-type: none"> ▪ Capacity optimisation and transport planning ▪ Dump truck specification and “buy or charter” decision ▪ Assessment of guidelines for transporting polymetallic sulphides ▪ Analysis of safety and environment risk
	Storage	<ul style="list-style-type: none"> ▪ Estimation of production rates and design of logistics networks towards customers

10.1 Mining Site Selection

Massive sulphides deposits are commonly found along the oceanic ridges at water depth about 2,000m. The deposits are rich in copper, zinc, gold and silver. In comparison with manganese nodules (below 4,000m), water depth for massive sulphides deposits is relatively shallow, which imposes less the challenges to the mining engineering system. Hydrothermal vents can be divided into active and inactive. Active hydrothermal vents are the habits of chemosynthesis ecosystem. Therefore, inactive hydrothermal vents are preferred potential mining sites. Inactive vents are hard to detect due to the lack of venting plume. Scientific knowledge in inactive vents is limited. For detailed information of hydrothermal vents, InterRidge database is recommended. The InterRidge organization is actively conducting scientific research on hydrothermal vent. Most well-studied hydrothermal vents are located within EEZ. Contracting with specific states is relatively easier in comparison with the unpredictable international legal and political environment.

10.2 Engineering System Design

10.2.1 Seabed Mining Tools

For reliable and effective mining, seabed mining tools (SMT) need to overcome various challenges. First, the components and equipment of SMT must be resistant to high ambient pressure. Second, because the equipment operates in a salt water environment, an optimal corrosion protection is necessary and therefore corrosion resistant materials and/or special coatings must be applied. Third, all components of machine must have maintenance-free life span as long as possible. Forth, it is necessary to provide reliable communication between SMT and production support vessel. Using a fiber-optical cable is favourable for this purpose.

10.2.2 Riser Engineering System

The riser system should be independent of movement of the floating structure. To do this, motion compensator included in case of the top-tensioning system or buoyancy cans deployed around the riser can be applied. Several types of risers are available for seabed mining. Among them, the steel catenary riser (SCR) is suitable for deep water mining because of its simple arrangement, cost saving, easy implementation, and wide availability. The benefits of the SCR compared to the TTR arrangements include the surface valve stack being statically accommodated, eliminating the need for a hydropneumatic tensioner system and surface jumper hoses, and substantially simplifying access. SCRs also offer benefits as an alternative to conventional flexible risers: they can be suspended in longer lengths and

can be used at pressures, temperatures and diameters that cannot be achieved by a flexible pipe, allowing use of a smaller number of larger diameter lines, and they are less costly.

10.2.3 Subsea Lift Pump

The challenge is to establish a system pump that can deliver enough of the ore to achieve the financial goals while maintaining a level of reliability and performance. To provide the certain pumping rate and discharge pressure, the utilisation of multistage pumps is required. Building on the success of the dual gradient pump development in offshore hydrocarbon drilling fields, the subsea lift pump is well proven and positioned for seabed mining development.

10.2.4 Floating Production Vessel

FPSO has been applied in environments from harsh to the benign. During the last decades, FPSO with compliant risers have proven their excellence in use for deepwater development of oil/gas fields. Floating platform selection issues and comparison of primary characteristics are shown in Table 20. FPSO or ship-shaped structures are favourable for the seabed mining because of mobility and storage capacity.

Table 20: Primary Characteristics for Floating Platform Selection

Characteristics	TLP	Spar	Semi	FPSO
Water depth	More sensitive (up to 1,500m)		Less sensitive (no practical limit)	
Platform motions	Very low vertical motions (i.e. heave, roll and pitch)	Low vertical motions and sensitive to long period waves	Motions limit applications	Motions limit applications
Motions controlled by	Tendons mooring system and hull configuration	Hull configuration draft and taut mooring system	Hull configuration and mooring system	Hull configuration and mooring system orientation
Storage	No	No	No	Yes
Top-tensioned risers	No constraints	No constraints	No	No
Steel catenary risers	No constraints	No constraints	No	In mild environment

10.2.5 Vessel Positioning

To provide effective and safe positioning during the deep water mining process, dynamic positioning system, especially DP2-Class is suitable and differential global positioning system (DGPS) is most reliable form of position reference. For providing the relative positioning during transporting the material from the vessel to barge, differential, absolute

and relative positioning system (DARPS) should be needed. For safe mining operations, control the riser angle is important and electrical riser angle sensor is needed.

10.2.6 Energy Supply System

The most suitable energy supply system for mining vessel is centralized diesel-electric system which can supply all equipment. To supply high power to the machines from the floating vessel, high voltage electrical energy ($\geq 6,600\text{V}$) is needed. This system has to satisfy requirements of the dynamic positioning system and also has to be stable to failure of any elements. For this purpose, energy supply system should be split into three separate systems containing two diesel engines and generators. The protection relays and controls should use microprocessors and communicate on high-speed busses.

10.3 Economics

Economic feasibility strongly depends on metal production rate, operating costs, and metal prices. Reducing operating costs would lead to great difficulties in practice and prediction of world metal prices has many uncertainties. Sensitivity of discount rates becomes critical for the small income situation. Thus, increasing metal production rate is a key issue to establish economic feasibility. Especially, flotation technique is critical for Atlantis II Deep deposits because the metal exists in very fine-grain state. A new effective technology for extracting small scale material ($\leq 2 \mu\text{m}$) from the mixture of muds and salinity water should be developed and commercialised to increase metal production rate of Atlantis II Deep.

10.4 Environment Impact and Mitigation Strategies

Extensive environmental impact assessments have to be performed for a mining site. Baseline observations have to be conducted during the exploration stage to set references for the future comparison. A pilot mining project has to be designed to test the feasibility of the engineering system, quantify the environmental impact and assess the efficiency of mitigation strategies. A long term monitoring program has to be implemented before and after the mining operation. A comprehensive environmental impact assessment has to be reviewed by expertise and approved by the corresponding authorities.

Mitigation Strategies have to be proposed and tested in the pilot project to minimize the environmental impact and ensure the reestablishment of the ecosystem and lower the risks of loss of biodiversity and endemism. Emergency response plans have to be developed to mitigate the effects of natural disasters and unplanned events.

10.5 Legal Requirements and Issues

According to UNCLOS, the jurisdiction of the mining site shall be identified. In international waters, the mining contractor should follow the guidelines and recommendations provided by ISA, and apply exploration and exploitation licenses from ISA. In national waters, if the mining site is shared by multiple states, a possible solution is to form a Joint Development Commission (JDC) among those states. The mining contractor should follow the guidelines and recommendations provided by the JDC, and apply exploration and exploitation licenses from the JDC. In national waters, if the mining site is solely owned by a state, the mining contractor should follow the guidelines and recommendations provided by the state, and apply exploration and exploitation licenses from the state.

For the absence of seabed mining regulations in a state, the development of a seabed mining industry standard can use the Madang Guidelines as a framework and The Code for Environmental Management of Marine Mining by International Marine Minerals Society. In the case of no regulation is in place, the corresponding authorities and mining contractor have to work together to create new regulation for the specific situations. Following environment regulatory framework, the mining contractor should go through the Environmental Impact Assessment (EIA) processor to obtain an environment permit from the corresponding authorities.

10.6 Logistics and Supply Chain Concepts

The supply chain for seabed mining operation covers all processes from sea surface to market. Within the study at hand four distinct supply chain scenarios were developed and evaluated based on a SWOT analysis. The four developed scenarios differ regarding their subsequent transportation, handling and processing steps. Specifically to the mining site and deposit composition an adequate processing facility or direct customer needs to be identified. In particular massive sulphides hold multi-mineral compositions that challenge the selection of processing facilities. Based on this decision, the logistics network needs to be designed and optimised regarding to production rates as well as stocks onshore and offshore. This capacity optimisation thus influences the requirements for the transport barge offloading processes and vessel specifics.

11 Conclusion

The research project presented developed guidelines for sustainable seabed mining and a new concept for Atlantis II Deep. Within this chapter the main findings and contributions are presented. Finally the limitations and an outlook for future research is given.

11.1 Main Contributions

The research undertaken in this research provided a new perspective regarding sustainable seabed mining. The three-fold approach contributes to research and commercial implementation of seabed mining as follows:

Comprehensive online survey on drivers and barriers for sustainable seabed mining

An online survey for sustainable seabed mining on the perceptions of industry and academia was conducted. The survey was distributed to numerous universities, research institutions and industry partners.

The survey was attended by 147 participants. 129 respondents completed the mandatory parts of the questionnaire and 30 filled in the expert section. The respondents represent academic (80%) and industrial views (20%) from various fields related to seabed mining such as economics, earth sciences and engineering.

Overall economic profit, scarcity of land resources, mineral demands and resource independency of countries are seen as the strongest drivers for seabed mining. On the other hand, environmental impacts and economic challenges are assumed to be the largest barriers, whereas engineering systems, legal boundaries and logistics issues are seen as mediocre barriers.

From an economics point of view major barriers are the high research and development costs as well as operations costs on sea. The majority of participants proposes an economic feasibility of seabed mining in the next five to ten years.

From an environmental point of view, the participants outline the necessity of thorough biological and geological research in the field to fully assess impacts and define mitigation strategies. However, pilots of seabed mining are proposed to understand issues in a comprehensive manner and to derive regulations for seabed mining.

Engineering systems are seen as generally ready for seabed mining. The largest developments needed are seen in exploration technologies, particularly for environmental impact assessments, seafloor tool and lifting system development and energy supply of seafloor machinery.

Finally, the expert section of the survey outlines that manganese nodules and massive sulphides in inactive hydrothermal vents and sediments are assumed to be the feasible for mining in the next five to ten years.

The results of the survey underline several findings of the expert interviews in the next section. Furthermore, it presented a first analysis of academic and industry perceptions on seabed mining from different discipline viewpoints.

Expert interviews on different aspects of seabed mining and Atlantis II Deep

The research group conducted expert interviews as a part of developing the guidelines and the new concept. The interview partners were selected according to their expertise in either one or more of the fields of the holistic approach, namely engineering systems, economic, environmental impact assessments and mitigations strategies, legal aspects and supply chain. The interviews provide insights into critical issues.

Case Study “Nautilus”

The case study provided a review on the status of the Solwara 1 project of Nautilus Minerals. It presented the publically available specifications on the engineering system, implying the seafloor tools, riser and lift system as well as the production vessel. Furthermore, a brief summary of the estimation of the CAPEX and OPEX is indicated, which served as a starting point for economic modelling in seabed mining. The oceanic environmental background was reviewed and the potential environmental impacts and mitigation strategies were investigated.

Development of a new concept and a site specific assessment for Atlantis II Deep

The Red Sea has the largest sulphide deposit in the world. The next possible site for mining might be the Atlantis II Deep in the Red Sea. It was found that the economic feasibility strongly depends on the metal production rate, operating costs, and metal prices. The engineering solution for Atlantis II was detailed for the seafloor tools, the riser and lift system and the floating platform and a collection machine was developed that applied gathering technologies from the dredging industry. Since the Red Sea is a semi-enclosed environment and contains various marine protected areas, a fully enclosed mining system is identified as most beneficial to mitigate the environmental risks. Finally, a supply chain concept for seabed mining at Atlantis II Deep was developed that suggested the contracting of a multi-mineral processing facility in close proximity to the mining site.

Development of sustainable seabed mining guidelines for decision-makers in the seabed mining industry

The guidelines for deepsea mining based upon the case studies, online survey and expert interviews to provide a benchmark for the new frontier of offshore seabed mining. The

guidelines are proposed to help decision-makers in the industry to identify the critical issues that need to be taken into account if polymetallic sulphides in inactive hydrothermal vent sites shall be mined sustainably. The guidelines were thus structured broadly based on the general assessment and review of all dimensions outlined in the research framework, a detailed concept selection, the design specification and the execution for design and operations.

11.2 Main Findings and Research Objectives Achieved

In overall terms, the main concluding statements drawn from the research work undertaken in this study are summarised and introduced as follows:

- The potential resources of seabed regarding their characterisation, occurrence, economic, environmental impact and societal relevance are identified and classified. Both non-living and living seabed resources were reviewed.
- The state-of-the-art evaluation and review of the different relevant technologies for exploration and exploitation of seabed mining as well as cultivation and harvesting is conducted. The existing engineering technology challenges are identified.
- The guidelines, rights, regulations and responsibilities of nations regarding the seabed resources are assessed and defined. The seabed resources and their associated exploitation technologies and legal regulations were extensively reviewed.
- The online survey underlined drivers and barriers for engineering technologies, environmental impact, legal issues and economic benefits which need to be taken into consideration for the future seabed mining. It presented a first analysis of academic and industry perceptions on seabed mining from different discipline viewpoints.
- Expert interviews gained insights into seabed mining and site specifics of Atlantis II Deep from different perspectives.
- An economic analysis and estimation for the Solwara 1 project was developed and the potential environmental impact and the mitigation strategies were evaluated.
- A new concept and solutions for seabed mining of Atlantis II Deep is developed. The concept includes a detailed engineering system, economic feasibility study, environmental impact assessment, logistics and supply chain concept and legal requirements and issues.
- Extensive guidelines for sustainable seabed mining key issues were developed and presented. These give an information base for the industry and a benchmark for seabed mining.

11.3 Limitations

The developed concept and guidelines were based on qualitative and quantitative datasets of the survey, the interviews and the archival data for the Nautilus case study. Furthermore, a comprehensive review of literature in the field of was conducted.

The data collected in the survey and the interviews is of subjective nature and thus limits the generalizability to a certain extent. Furthermore, certain groups such as maritime engineers had a larger proportion in the sample, so that this might have influenced the results.

The research has been conducted by a group of researchers from various disciplines which transferred their specialty knowledge towards seabed mining within this novel project. Since the study has been conducted and written as a part of the LRET research collegium 2012, the results presented are limited by the given timeline of six weeks.

Moreover, the developed concept and guidelines need further validation and testing based upon real-world data in the future.

11.4 Outlook for Future Research

The seabed is a promising place for the future development of human society. Exploiting mineral resources on the seabed has gained significant attention from industry, government, scientific community and the general public. As an emerging industry, many aspects have not been fully understood and require further studies, including metal market demand analysis and prediction, long term marine environmental impact monitoring programmes or the reliability of seabed mining engineering systems. Obtaining not just metal resources but also sustainable energy from the seabed could be a future field of interest in order to find alternatives to fossil fuel energy usage. Harvesting biofuel energy and generating hydrothermal energy from the seabed are worth further investigation. Future research in those fields could thus apply the developed research framework to various resources of the seabed.

Appendix

Sustainable Deep Seabed Mining

About the survey

The following survey is part of a research project on "Sustainable Deep Seabed Mining", which is conducted within the LRET Research Collegium 2012. The aim of the project is to identify drivers and barriers for the future exploitation of the seabed from various perspectives in industry and research.

Therefore, it is essential to contemplate the issue of "sustainable deep seabed mining" from different viewpoints: Societal Benefits, Economic Feasibility, Engineering/Technology and Environmental Impacts.

The survey takes about 15 to 20 minutes.

The survey does not require expert knowledge for the questions 1 to 15. If you are an expert in the field, you may wish to answer the question 16 to 20 additionally.

Background Information on "Deep Seabed Mining"

The world's demands for mineral resources, such as Cobalt, Nickel, Copper, Gold, Zinc, Lead and Rare Earth Elements, will increase significantly in the next 30 years due to technological developments.

On land, mineral resources become shorter in supply and their exploitation consumes wide landscapes. On the other hand, the world's oceans cover 71% of the world and its seabed provides large amounts of scarce minerals.

A sustainable exploitation of these minerals has been controversially discussed over the past 50 years and demands for expertise and knowledge on key questions in various different fields.

Participant Information

1. What is your country of residence?

Country:

*2. What is your nationality?

*3. What is your gender?

Female

Male

*4. What is your affiliation?

Other (please specify)

*5. What is your current position?

Other (please specify)

Societal Benefits of Deep Seabed Mining

***6. Do you have an idea, how the following minerals are used in our society / your everyday life?**

	No Idea	Vague Idea	Mediocre knowledge	Good knowledge	Very high knowledge
Gold	<input type="radio"/>				
Copper	<input type="radio"/>				
Zinc	<input type="radio"/>				
Lead	<input type="radio"/>				
Rare Earth Elements	<input type="radio"/>				
Cobalt	<input type="radio"/>				
Nickel	<input type="radio"/>				

Comments

***7. From your perspective, what are the largest societal benefits of the exploitation of seabed minerals?**

	no/very low	low	mediocre	high	very high
Electronics	<input type="radio"/>				
Construction	<input type="radio"/>				
Telecommunication	<input type="radio"/>				
Transportation	<input type="radio"/>				
Alternative energy solutions	<input type="radio"/>				
Scientific advancement	<input type="radio"/>				
Sustaining our standard of living	<input type="radio"/>				
Seabed mining may help developing countries to exploit their resources	<input type="radio"/>				

Other (please specify)

Economics

* 8. From an economic point of view, what are the largest barriers for deep seabed mining?

	no/very low barrier	low barrier	mediocre barrier	high barrier	very high barrier
Volatility of mineral prices	<input type="radio"/>				
Research and development costs for engineering systems	<input type="radio"/>				
Licensing costs for seabed exploration and mining	<input type="radio"/>				
Lack of investors	<input type="radio"/>				
Lack of customers	<input type="radio"/>				
Costs of operations on sea/seabed	<input type="radio"/>				

Other (please specify)

* 9. Do you think that deep seabed mining is or will become economically feasible?

- I dont know No, never Yes, it is feasible already Yes, it will become feasible within the next 5 to 10 years Yes, it will become feasible within the next 10 to 20 years Yes, it will become feasible in the far future (->20 years)

Other (please specify)

Environmental Effects of Deep Seabed Mining

* 10. Do you think that seabed mining effects the environment?

	I don't know	Not at all	Very low Impact	Low Impact	Reasonable Impact	High Impact	Very high Impact
Continental shelf (water depth < 150m)	<input type="radio"/>						
Ocean ridges (water depth < 3000m)	<input type="radio"/>						
Deep sea (water depth > 3000m)	<input type="radio"/>						

Other (please specify)

* 11. How do you personally think about deep seabed mining? Please specify, how much you agree with the following statements.

	Strongly disagree	Disagree	Indifferent	Agree	Strongly agree
Seabed mining should not be considered at all.	<input type="checkbox"/>				
Seabed mining should not be considered, before mankind has a thorough understanding of seabed biodiversity and geology.	<input type="checkbox"/>				
Seabed mining seems safer and friendlier to our environment than land mining.	<input type="checkbox"/>				
Consequences can only fully be assessed, if seabed mining is piloted.	<input type="checkbox"/>				
Seabed mining is strongly needed to ensure our daily needs, we need to start now.	<input type="checkbox"/>				

12. From your point of view, what needs to be done to make seabed mining as unharmed to the environment as possible?

Engineering Systems / Technology for Seabed Mining

*** 13. Do you believe that the following technologies are ready for seabed mining nowadays?**

	I dont know	Not ready yet	In an early stage	Pre-commercial	In an advanced stage	Ready / Already in use
Exploration technologies to identify and estimate deposits	<input type="radio"/>					
Exploration technologies for environmental assessments of deposit sites	<input type="radio"/>					
Navigation and positioning systems	<input type="radio"/>					
Stability of vessels and platforms for harsh sea environment	<input type="radio"/>					
Deep-Seabed Mining Machinery	<input type="radio"/>					
Remote Control for Deep-Seabed Mining Machinery	<input type="radio"/>					
Imaging of deep-seabed	<input type="radio"/>					
Energy supply of mining machinery	<input type="radio"/>					
Energy supply of processing vessel/platforms	<input type="radio"/>					
Engineering system to raise minerals from seabed to surface (Risers)	<input type="radio"/>					
Other (please specify)	_____					

Drivers and Barriers for Deep Seabed Mining

* 14. What do you think are the main drivers to exploit seabed minerals?

	No/Very Low driver	Low driver	Average driver	High driver	Very High driver
Scarcity of land resources	<input type="radio"/>				
Mineral demands for technological progress	<input type="radio"/>				
Resource independency of countries	<input type="radio"/>				
Seabed mining is less harmful to workforce and environment than land mining	<input type="radio"/>				
Further exploration of the seabed (supports mankind advancements in e.g. earth sciences, life sciences, etc.)	<input type="radio"/>				
Economic profit	<input type="radio"/>				

Other (please specify)

* 15. What do you think are the main barriers for seabed mining?

	very low/no barrier	low barrier	average barrier	strong barrier	very strong barrier
Economic challenges (unpredictable market prices – high financial risks, too expensive)	<input type="radio"/>				
Societal Needs (the demands are not strong enough, minerals can be gathered from other sources)	<input type="radio"/>				
Environmental Impacts (environmental impacts cannot be justified)	<input type="radio"/>				
Engineering Systems (technology not ready for use)	<input type="radio"/>				
Legal Boundaries (legal issues are unsolved)	<input type="radio"/>				
Logistics and Supply Chain Concepts (feasibility of concepts is not understood)	<input type="radio"/>				

Other (please specify)

Expert Questions: Deep Seabed Mining

This page and its question is designed for experts in the field of seabed mining. It regards the feasibility of seabed mining and specific questions regarding the deposit site Atlantis II Deep in the Red Sea.

If you feel, that you are not an expert in this field, please go on to next page to finalise the study.

16. What do you think about the overall feasibility of seabed mining for the following resources?

	I dont know	No, never	Yes, it is feasible already	Yes, it will become feasible within the next 5 to 10 years	Yes, it will become feasible within the next 10 to 20 years	Yes, it will become feasible in the far future (>20 years)
Polymetallic/Manganese Nodules	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Crusts	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Massive Sulphides (Active Vents)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Massive Sulphides (Inactive Vents)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Massive Sulphides (Sediments)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Phosphorites	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Diamond	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Other (please specify)

17. Do you believe seabed mining at Atlantis II Deep is or will become economically feasible?

- I dont know
- No, never
- Yes, it is feasible already
- Yes, it will become feasible within the next 5 to 10 years
- Yes, it will become feasible within the next 10 to 20 years
- Yes, it will become feasible in the far future (>20 years)

Other (please specify)

18. Please rate the state of exploration of Atlantis II Deep deposits and its environment from your perspective.

- Very low state of exploration
- Low
- Medium
- High
- Very high state of exploration

19. Do you think that the environmental impacts of the seabed mining at Atlantis II Deep can be mitigated? What needs to be considered?

20. Do you think the technology is ready for operational mining in the brine environment of Atlantis II Deep (~270 PSU, highly corrosive)?

- Yes
- No

If no, what needs to be done?

Thank you!

Many thanks for your support.

If you have any further questions or are interested in the final publication of the this study, please use the fields below.

21. If you are interested in the publication of this study, please type in your email adress.

Email Address:

22. Further Comments:

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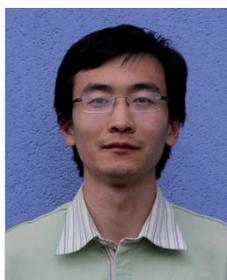
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