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Magnus Nandrup-Pettersen

NTNU
Norwegian University of
Science and Technology
Faculty of Engineering
Department of Geoscience and Petroleum

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Norwegian University of
Science and Technology

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Resources of the deep ocean

The new frontiers waiting on the seafloor

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Magnus Nandrup-Pettersen

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Supervisor: Tor Berge Gjersvik

Norwegian University of Science and Technology
Department of Geoscience and Petroleum

Abstract

There is a current push both politically and from the industry to use the world's oceans, the seabed, and soil below as a new frontier for sustainable and renewable alternatives to current land-based industry. Motivated by the depletion of terrestrial mines, increasing power needs, an increasing world population, and an increasing need for material and options for transitioning from power sources using fossil fuel to carbon neutral ones. The last decades have seen a high degree of interest in mapping the resources of the ocean floor both in international waters and within the territorial waters of coastal states. Many large deposits of marine minerals have been identified, with many more expected to be identified. Some of these observed marine mineral deposits containing mineral estimates which far exceeds the know terrestrial mineral deposits. Metals like copper, nickel, molybdenum, cobalt, and zinc are expected to see a future increase in demand as the average ore grade quality and known mine reserves are decreasing. Precious metals like gold and silver are also found in these deposits. Marine minerals could also offer a new source for Rare Earth Elements which are currently only mined and distributed my one nation, giving concerns for the geopolitical stability for the availability of these important elements used in high-tech. No commercial exploitation efforts have so far taken place but there is an evident interest.

This Thesis presents some of the resources found on the seafloor with a special focus on the volcanically driven Mid-Ocean Ridge (MOR) system. The jurisdictional areas, national and international policies, national and commercial actors, and current commercial efforts are presented. Envisioning a new sector of subsea power generation, the results of some novel geothermal power options are presented and compared cost per kilowatt to current offshore power options being developed. These installations would utilize the hydrothermal water flowing from black smoker hydrothermal vents along the MOR. The results show that the cost per kilowatt of the proposed solutions are within the same order of magnitude as other emerging offshore power options like offshore wind and floating nuclear barges. However, the reliability issues and complexity of intervention for make it an unlikely candidate for future investment, at least at the proposed depth of 2100mbsl.

Sammendrag

De siste årene har sett mye interesse både innen verdenspolitikken og fra industrien for å utnytte verdenshavene, havbunnen, og jorden under for fremtidige kilder til bærekraftige og fornybare alternativer til nåværende landbasert industri. Motivert av minkende mineralreserver i landbaserte gruver, økt energibehov, en økende verdensbefolkning, og et økende material og alternativer for overgangen fra karbonproduserende kraft til klimanøytral. De siste tiårene har sett mye interesse i å kartlegge havbunnsressurser både i internasjonalt og nasjonalt farvann. Mange store mineralforekomster har blitt identifisert, og mange flere er forventet å bli identifisert i fremtiden. Noen av disse mineralforekomstene har mineralinnhold som langt overgår de kjente landbaserte forekomstene. Metaller som kobber, molybden, kobolt og zink er forventet å se økende etterspørsel i fremtiden, samtidig som de kjente landbaserte forekomstene av disse metallene minker. Edelmetaller som gull og sølv finnes også blant disse havbunnsforekomstene. Utvinning av havbunnsmineraler kan også tilby en ny kilde for sjeldne jordarter, som nåværende kun på stor skala blir utvunnet og distribuert av én nasjon, noe som har vært en kilde bekymring for den geopolitiske stabiliteten for tilgjengeligheten av disse grunnstoffene som er viktig i høyteknologisk elektronikk. Ingen kommersiell utvinning av havbunnsmineraler har hittil funnet sted, men interessen er tydelig.

Denne oppgaven presenterer noen av ressursene funnet på havbunnen med en spesiell fokus på den vulkansk formede Midthavsryggen. De juridiske områdene, nasjonale og internasjonale lovverk, nasjonale og industrielle aktører, og pågående kommersiell aktivitet blir presentert. En visjon for en ny type havbunnsinstallasjon der man utnytter det hydrotermiske vannet fra disse områdene blir presentert der man sammenlikner resultatene fra hvordan slike havbunns geotermiske kraftverk sammenlikner i kostnad per kilowatt til andre typer havroms-kraftverk som er under utvikling. Resultatene fra dette tyder på at om denne typen geotermisk kraftverk kan bygges så er det innen samme størrelsesorden som den nåværende kostnaden per kilowatt for havvind og atomkraftverk på lekter. Pålitelighets- og intervensjonshensyn gjør derimot denne typen kraftverk usannsynlig å være en løsning man diskutere i fremtiden, i hvert fall på den foreslåtte dybden av 2100meter under havet.

Achknowledgment

I would like to thank my Thesis advisor Professor Tor Berge Gjersvik for his patience and inspiration while I worked on this science-fiction fantasy of a subject matter. At times it has felt like the state of development of subsea mining was at the same technological maturity as mining efforts on the moon or on asteroids.

I would like to thank my family for their patience and support during my studies. This was a challenging year to write a Thesis, and no progress would have been possible without them.

I would also like to thank the thorough work of Baldur Kàrason. The power options presented and discussed in the later chapter are all but one based from his work and I apologize for butchering his calculations to fit my scenario. His work made the subject much less science-fiction.

Preface

This project focuses on the resources found on the seafloor around the globe with a special interest in the area surrounding the Mid-Ocean Ridge system. The resources include mineral deposits, industrially useful microorganisms, and the electrical power potential of hydrothermal systems.

The ambition to explore and utilize the bottom of the world's oceans is not new.
In 1870 Jules Verne wrote in his book *Twenty thousand leagues under the sea*:

> *"First off, I'll mention that at the bottom of the sea there are veins of zinc, iron, silver, and gold that I would quite certainly be capable of mining. But I haven't tapped any of these terrestrial metals and I've chosen to make demands only on the sea itself for the sources of my electricity."* [1]

My interest in of subsea production began while taking the fourth-year course in Subsea Production Systems during my MSc in Subsea Technology at NTNU in Trondheim, Norway. The course professor, Prof. Tor Berge Gjersvik, is now my thesis advisor and made the point one lecture that the concept of subsea production equipment was viewed as a science fiction dream not many years ago. The development of this field of technology has made the Norwegian petroleum industry highly advanced. Old reservoirs that would have been long since abandoned has now been reconditioned and in some cases recommissioned for extended production. This new technology was both economically and environmentally beneficial and caused me to question what other novel industries on the ocean floor are latently awaiting advances in subsea production equipment.

This Master's Thesis is building on a specialization project of mine, which looked at the possibility for power generation by utilizing the super-heated water exiting from volcanic regions near the tectonic boundaries and evolved into a deep-dive into identifying the resource potential surrounding seafloor hydrothermal vents. As depletion of land-based resources and the search for new carbon-neutral power sources continue, the need to identify new frontiers to prospect become apparent. Captain Nemo made *"demands only on the sea itself"* to advance his voyage; to reach the U.N. goals for sustainability and mitigating climate change we may need to make reality of some of the old Vernian fantasy.

Steinkjer, 31. December. 2020

Magnus Nandrup-Pettersen

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Abbreviations and definitions

Quotes taken directly from their sources are marked in quotations and cursive: *"as such"*

Bathometry – Topology of the seafloor

EEZ – Economically Exclusive Zone

ISA – United Nations: International Seabed Authority

MOR – Mid-Ocean Ridge system

Mt – Million metric tonne – 10^9kg

PNG – Papua New Guinea

PSV – Production Support Vessel

SPE – Seafloor Production Equipment

SPT – Seafloor Production Tools

Tpd – Tonnes per day

UNCLOS – United Nations Convention on the Law Of the Sea

1 Introduction

This Thesis aims to identify the resource potential of the hydrothermal vents scattered along the Mid-Ocean Ridge system. The United Nations and the European Union have both goals towards sustainable development of the world's oceans. The United Nations considering the international waters, the seabed, and earth below "the common heritage of mankind", and the European Union outlining its future goals of a Blue Economy based on sustainable marine activity.

The marine environment is an important part of the area of the European Union with about 50% of its territorial claims offshore. 25 member states are coastal nations with nearly 50% of EU citizens living within 50km of the coast, 3.5 million of its inhabitants being employed directly in maritime activities [2]. Worldwide about 40% of the global population lives within 150km of the ocean, with an estimated contribution of US$1.5 trillion directly to the global economy from ocean industries [3].

1.1 Scope of the work and limitations

The Thesis will present the three most common types of marine minerals and briefly discuss how the microorganisms of the ocean floor may be beneficial in advancing biotechnology as well as presenting some novel alternatives to the emerging field of offshore power generation.

The Thesis is limited by all these sectors being either novel or in its technological infancy. The only commercial seabed mining activity currently undertaken is the mining operation of diamond-rich gravel off the coast of Africa. This operation is at depths an order of magnitude or more shallow than the ones proposed for metalliferous marine minerals. The Thesis will attempt to give a sense of scale of these marine mineral deposits, the current state of exploratory activity, and the efforts being put into future exploitation.

The Thesis presents the novel concept of utilizing the warm hydrothermal waters that emerge from hydrothermal vents and compares the cost per kilowatt to other offshore power options currently being constructed.

1.2 Method

The literature study includes of publications regarding the Mid-Ocean Ridge system, hydrothermal vents, geothermal power and global power potential, the Icelandic Deep Drilling Project, marine biodiscovery and bioprospecting, marine minerals, world energy and mining policy, the currently ongoing development of a legal framework for mining within international waters, and what commercial activity is being undertaken to exploit marine minerals. Very little public information is available for commercial activity in marine minerals and even proprietary reports are likely to few given the small number of commercial actors.

1.3 Structure of the thesis

- **Chapter 2** gives a general introduction to the motivating factors for developing new industries on the seabed as well as defining the jurisdictional areas of the seabed
- **Chapter 3** presents the Mid-Ocean Ridge system and hydrothermal vents. The different marine minerals are described along with how microorganisms might hold future industrial or pharmaceutical applications
- **Chapter 4** presents the current state of commercial actors which have made their plans for mining activity publicly available
- **Chapter 5** describes the reservoir conditions of hydrothermal vents along a portion of the Mid-Ocean Ridge system, as well as the power generation options most fitting to generate geothermal power offshore
- **Chapter 6** presents six power generation solutions and discuss the cost per kilowatt installed compared to other offshore power options currently being undertaken
- **Chapter 7** discusses the state of Deep-Sea Mining and offshore geothermal power
- **Chapter 8** presents the concluding remarks
- **Chapter 9** discusses future work that can be undertaken within the subjects

2 Background

The world's oceans cover about 70% of Earth's surface area, yet the ocean depths remain largely unexplored while holding the potential for future solutions to our current challenges. The world is consuming its resources at a high rate and old power generating technologies are being planned for obsolescence without its replacement being presently known [4]. Investment in new renewable power sources is a political high priority due to climate change policies but the new technology requires material to build it. Copper, lithium, nickel, and cobalt are required in great amounts if goals are to be met, with 1100-3000kg/MW of copper needed to manufacture wind turbines and 10-30kg of cobalt needed for electric vehicles [5].

The International Monetary Fund, in a 2019 report, estimates fossil fuel subsidies from 191 countries at $5.2 trillion (6.5% of global GDP) in 2017 with coal and petroleum together accounting for 85% of the subsidies. Concluding that *"Efficient fossil fuel pricing in 2015 would have lowered global carbon emissions by 28 percent and fossil fuel air pollution deaths by 46 percent, and increased government revenue by 3.8 percent of GDP"* [4]. The underpricing of fossil fuel sources is keeping carbon emitting power sources competitive. At present 583 new coal-fired power plants either announced or under construction across the globe [6].

2.1 Motivation for Deep-Sea Mining

Technological development in recent years have seen an increasing demand for extraction of land-based resources. At its current rate this seems unsustainable in the long term given how much efforts have been put into accounting for our land-based (terrestrial) resources. Between 2004 to 2013 an estimated 4% of the available molybdenum and zinc was mined from terrestrial resources. An estimate 2% of copper, 1% of silver and nickel, and 0.6% of manganese were also extracted in the same time period [7], and the average copper ore grade mined on land having decreased from 3% to 0.5% in less than a century [2]. A *"tremendous amount of raw materials needed"* for transitioning into a more sustainable society is notes as a paradox of the future [8].

These figures do not cover the potential resources on the ocean floor and below. At more than 360 million km^2, 99% of the ocean floor remains unexplored, and the world oceans could offer a new frontier in sustainable mineral extraction [9]. In its 2014 publication Henckens et al. defined sustainable extraction as *"The extraction rate of a mineral resource is sustainable if it can provide 9 billion people with that mineral for at least 1000years, assuming that the per capita use is equally divided over the countries of the world".* To adhere to this definition the rate of antimony extraction would have to be reduced by 96%, zinc by 82% and molybdenum by 81% [7]. The demand for materials like cobalt, nickel, lithium and copper are estimated to ten to hundredfold in the foreseeable future [8].

The 1987 Brundtland Commission defined sustainability in its report *Our Common Future: Sustainable* as *"Sustainable development is the kind of development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* (World Commission on Environment and Development, 1987) [7].

The current extraction rate on land is clearly not sustainable by any definition. The depletion does not just cover exotic materials like indium for touch screens or Rare Earth Elements (REE) for electronics, but zinc for corrosion protection and molybdenum for steel alloying. Both zinc and molybdenum are found in abundance in subsea deposits and are essential for our modern society.

In 2014 the European Union funded an international European consortium of 19 large industry and research organizations from 6 European countries called the "Blue Mining". The consortium ran for 48 months and focused on deep-sea mining of polymetallic sulfides and manganese nodules sampling the Peru Basin in the Pacific, The Mid Atlantic Ridge and the Arctic Mid Ocean Ridge. The depth of the survey varied from 500m to 4200m and surveyed the seafloor at an altitude of 1-2m using underwater vehicles such as ROVs (Remotely Operated Vehicles) and AUVs (Autonomous Underwater Vehicles) [8]. An offshoot of the Blue Mining consortium takes part in the EU Horizon 2020 research program Blue Nodules which continues the work with developing technology for mining polymetallic nodules [8].

Finding deposit on land is today often done with hyperspectral imaging from satellites using sunlight as a light source. Since sunlight does not penetrate beyond about 200m of water the underwater vehicles were equipped with Underwater Hyperspectral Imaging (UHI) sensors [9]. The true scale and value of marine minerals remain to be determined but the indicated resources so far are motivated by the of mining efforts being *"a lot easier to go down a couple of thousand meters of water than through a couple of thousand meters of rock"* [10].

2.2 Motivation for Deep-Sea energy generation

The focus for sustainability and renewable power has been driving forces for international energy policy in the last decade. With climate accords like the Paris Agreement working towards zero-carbon solutions being competitive in sectors representing 70% of global emissions by 2030 [11]. The European Union's Horizon 2020 has for the last 7 years (2014 to 2020) run the biggest EU research and innovation program ever with €80 billion in funding available for investment in the *"EU's blueprint for smart, sustainable and inclusive growth and jobs"* [12]. DEEPEGS (Deep Enhanced Geothermal Systems) has been one of the beneficiaries of the Horizon 2020 funding. Receiving about half (€19,999,741) of its total project cost (€44,057,259) from EU contributions [13]. The DEEPEGS project aim was to demonstrate the feasibility of Enhanced Geothermal Systems (EGS) in three types of geothermal reservoirs across Europe. The most relevant for this Thesis is the Icelandic location at the Reykjanes volcanic environment which is a feature along the Mid-Ocean Ridge. The Icelandic Deep Drilling Project is discussed further in a later chapter and has supplied a significant number of publications on geothermal systems like the ones driving black smoker hydrothermal vent systems on the seafloor. The IDDP-2 well drilling into the same root-zone magmatic origins which creates the marine deposits around hydrothermal vents. Offshore wind power is receiving a high degree of attention and investment lately with an expected compound annual growth rate of 16.2% between 2019 and 2030 [14]. Seven out of ten of the world's largest offshore wind farms are located in UK waters with Prime Minister Boris Johnson announcing £160million for upgrading ports and factories for building turbines for the UK to become *"the world leader in clean wind energy"* [15]. Offshore wind power and other offshore power solutions are discussed and compared to the proposed subsea power generation options in the later chapter.

2.3 Jurisdictional areas

The clear distinction for the jurisdictional areas of a territory is important when assessing resources and claims. An area of the seabed may be within the territorial confines of a coastal state or governed by international law. The Law Of the Sea is an international agreement established in 1982 by the United Nations Convention on the Law Of the Sea (UNCLOS) in which it defines the area of ocean and territories of the sea as either sovereign territorial waters or as part of an Area governed the convention. Exploration and eventual exploitation contracts within the sovereign waters of coastal states are subject to the laws governing that state. To be granted contracts within the ISA Area the applicant need to be a member state of UNCLOS, or private companies sponsored by a member state which is *"effectively controlled by them or their nationals, when sponsored by such States"* [16], [17]

2.3.1 **Coastal state sovereignty**

Coastal states have sovereign authority within these maritime zones [18], [19]:

Coastal waters and Territorial Sea: with a breadth not exceeding 12 nautical miles measured from the baseline. These rights include the marine resources both living and non-living

A Contiguous Zone (CZ): which cannot extend more than 24 nautical miles from the Territorial Sea Baseline (TSB). In the CZ the coastal states may exercise sovereignty regarding customs, fiscal, immigration or sanitary laws

An Exclusive Economic Zone (EEZ): which cannot extend more than 200 nautical miles from the baseline. The EEZ defines a specific legal regime where the coastal State has sovereign rights to explore, exploit, conserve and map the natural resources in the water, seabed and subsoil

Continental Shelf (CS): extends to a maximum of 350 nautical miles from the baseline. Otherwise, the CS shall not exceed 100 nautical miles from the 2500meter isobath, which is a line connecting the depth of 2500 meters. The CS is limited to the outer edge of the continental margin. When the continental margin does not extend beyond 200 nautical miles from the baseline, then the EEZ and the CS cover the same territory

2.3.2 <u>International Seabed Authority Area</u>

The United Nations Convention on the Law Of the Sea (UNCLOS) outlines the areas of national jurisdiction as a twelve-nautical-mile territorial sea and an exclusive economic zone of up to 200 nautical miles and a continental shelf. The international Seabed Authority Area - the area under ISA jurisdiction - is defined as *"the seabed and ocean floor and the subsoil thereof, beyond the limits of national jurisdiction"* [20].
The U.N. considers the sea bottom beyond the EEZ that are confirmed extended continental shelf claims as *"the common heritage of mankind"* [21]. Any commercial exploitation within this Area will be subject to ISA jurisdiction. Exploitation of this Areas is proposed to be for the benefit of all and have a clause for wealth redistribution or *"a sovereign wealth fund, that could be used to support global sustainable development goals"* [22], as a part of Goal 14 adopted by the United Nations Member states to *"Conserve and sustainably use oceans, seas and marine resources for sustainable development"* [23].

The Convention has been ratified by 168 countries as of July 2017, with members of every major maritime nation except The United States [24]. The ISA Area is defined indirectly as the part of the oceans not governed by national Exclusive Economic Zones and covers 53% of the world's oceans [20]. The Authority has so far enacted regulations governing the exploration of resources, but regulations for exploitation is still to be completed. Talks are ongoing and in a 2019 interview the secretary-general of the ISA said that the exploitation regulations (Mining Code) for seabed mining *"could be adopted by the end of 2020"* [25], with the draft code being transferred to the council of the ISA in July 2020 [26]. By December 2020, the work is pending the Council being able to *"meet again physically and resume its work on the matter",* as well as work on the financial and economic model for seabed mining and a study for the proposed environmental compensation fund [27].

While the work on the Mining Code framework for exploitation is yet to be finalized, the ISA has over the years issued several exploration licenses within the area which are given for 15-year periods at a time. Several of the 15-year licenses have expired with the data collected being added to a central data repository as part of the international cooperation within the Authority. With the 14th December 2020, announced inclusion of Blue Minerals Jamaica Limited there will be 31 active mineral exploration projects in the deep seabed Area, involving 23 different countries [28]–[30]. Before the inclusion of Blue Minerals Jamaica Ltd. *"This represents 0.7 percent of the international deep seabed area and 0.3 percent of the world's oceans. Twelve of these contracts are sponsored by developing countries. Thirteen countries and one intergovernmental consortium currently have contracts for the exploration of polymetallic nodules, seven countries for the exploration of polymetallic sulphides, and five for the exploration of cobalt-rich ferromanganese crusts"* [30].

3 The Mid-Ocean Ridge system

"The mid ocean ridge systems are the largest geological features on the planet" [31]. The ridge system is around 60.000km and form the boundary between tectonic plates where material is ejected from the upper mantle to form the ridge and trench structures [32]. Water penetrate cracks deep into these volcanic regions heating up and form hydrothermal vents on the ocean floor. This process can occur along the length of the ridge system regardless of spreading rates [33]. The hydrothermal vents and their root-zone magmatic origins form the area of interest for this Thesis. The minerals that emerge are interesting for new avenues of mineral exploitation and the superheated fluid that circulate these systems may have potential for novel offshore electrical power generation.

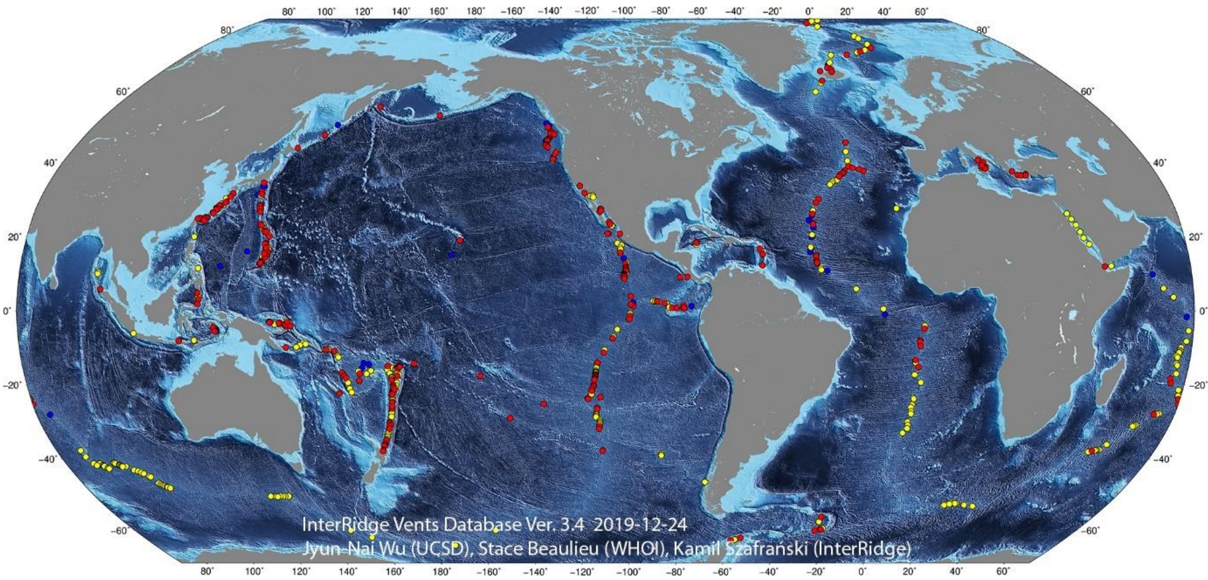

Figure 1 hydrothermal vents along the Mid-Ocean Ridge system
Source: Beaulieu, Stace E; Szafrański, Kamil M (2020): InterRidge Global Database [48]

3.1 Hydrothermal vents

Hydrothermal vents are a relatively new discovery and were first observed in 1979 after hot springs were found near the Galapagos islands two years prior [18]. Hydrothermal vents are underwater geysers that form on the seabed around the mid ocean ridge system and at volcanic hotspots such as Hawaii. They form when cracks in the sea floor allow water to penetrate volcanic regions causing the water to heat and rise due to convection. The hot water flowing in these cracks dissolves minerals from the surrounding basaltic rock which flows to the surface. Hydrothermal vents are formed where this mineral rich fluid exits into the cold sea water causing precipitation of the minerals.

Hydrothermal vents are found at an average depth of 2100mbsl, and are categorized in two main types; white smokers and black smokers depending on the temperature and mineral content of the fluid [10]. The figure below shows a volcanic hotspot with temperature gradients of the system [34].

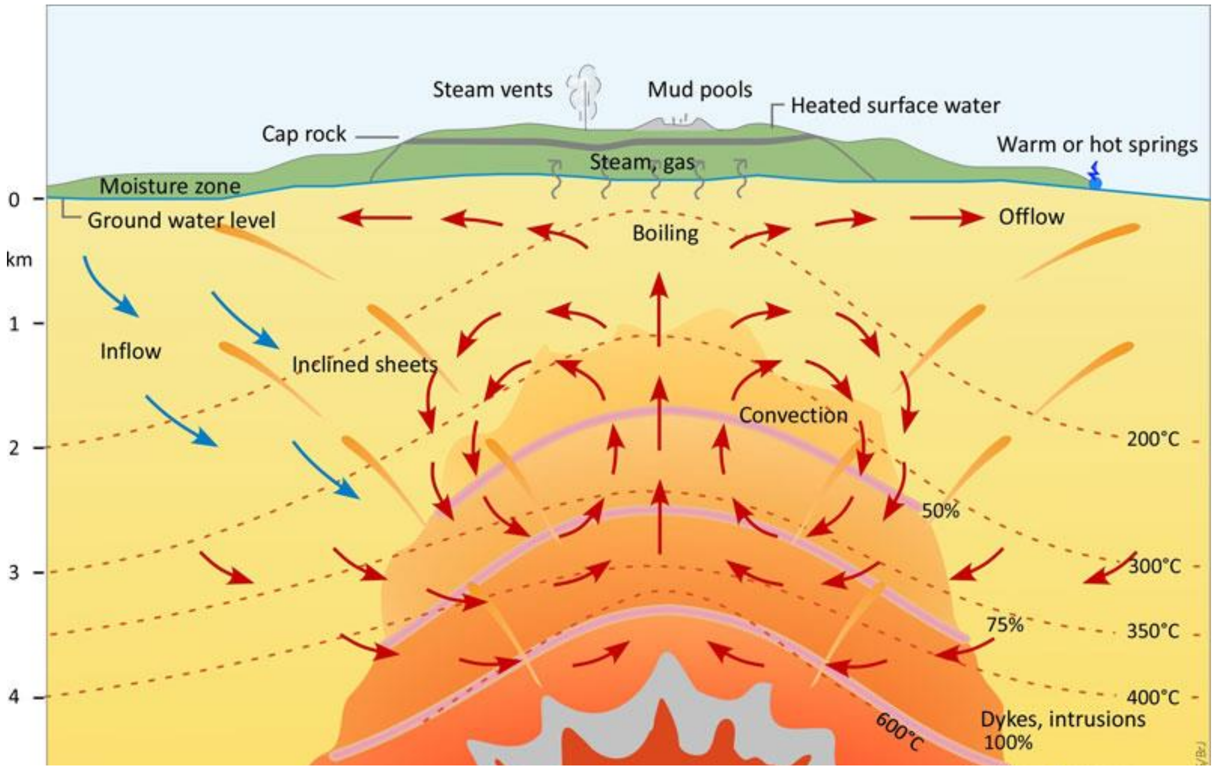

Figure 2 Hydrothermal system around a volcanic hotspot [37]

3.1.1 <u>Black smokers</u>

Black smokers are formed above magmatic hotspots where water can penetrate deep cracks and become super-heated and buoyant, bringing hot mineral-rich brine rushing upwards. The fluid rises through the crust and exits into the cold ambient seawater where precipitates of metal sulfides can grow to form valuable deposits of polymetallic sulfides [35].
The water temperature of the hydrothermal fluid can reach 400°C and the containing metal sulfides and hydrogen sulfide makes the surrounding environment very acidic. Hydrothermal vents like black smokers are not permanent features on the seabed, since they are a product of new seabed being formed and moved by tectonic activity. Old vent systems are moved away from the new volcanic hotspots by the conveyor belt motion of the newly formed seabed. Old deposits are left scattered around the ridge system as a result and these old deposits are known as Seafloor Massive Sulfides (SMS) [19].

Black smokers usually contain lead, zinc, barium, copper, cobalt, gold and silver. The compositions of these deposits are the same as the ones in the inland Norwegian copper mines at Løkken, Røros, Sulitjelma and Visnes. These, now terrestrial deposits, were raised up by tectonic drift under the formation of the Caledonian mountain range about 430 million years ago [18].

3.1.2 <u>White smokers</u>

White smokers are hydrothermal vents that form off-axis at a distance from the most active regions of the mid-ocean ridge hotspots as seen in the figure below [36]. The hydrothermal fluid is rich in carbonate and sulphate forming an alkaline environment with precipitates of manganese, iron, barium, calcium and silicone. The vents tend to have a lower temperature (250°C to 300°C) compared to black smokers [19]. The mineral deposits grow slower and are of less value and interest than black smoker systems.

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3.1.3 <u>Ecosystem</u>

Hydrothermal vents are home to a specially adapted ecosystem starting with chemosynthetic microorganisms feeding of the anerobic oxidation of methane and sulfides from the hydrothermal fluid [2]. These regions are theorized to be the origins of life on earth since hydrothermal vents *"existed as soon as liquid water accumulated on earth 4.2 billion years ago"* [37]. It is possible that the microorganisms found around hydrothermal vents today can give a glimpse back at how the earliest microorganisms looked on Earth.

The food chain begins with chemosynthetic bacteria and microorganisms which are eaten by tube worms, shrimp and mussels, which in turn are food for fish and crabs [18], [38]. The area containing of these ecosystems is very small and entirely contained around the vents which supply the heat and nourishment. The largest known (2016) active sulfide occurrence be being $<0.03km^2$, which would fit 14 times in the area occupied by Vatican City [23], [33].

Hydrothermal vent systems are a product of tectonic activity where the seafloor and chimney structures move away from the geothermal hotspots over time. Inactive vent structures may be defined as places of hydrothermal sulfide deposits >50m from active venting and contain a smaller and less studied ecosystem of microorganisms [23]. The terms active and inactive are fitting both for the temperature and flow of the hydrothermal vent as well as the diversity of the surrounding ecosystem. With the hydrothermal activity, temperature and flow of the vents dissipate with the movement of the seafloor the composition of the microorganisms also changes from thermophilic (>45°C) and mesophilic (20°C-45°C) to psychrophilic (<10°C). As a result, the invertebrate and macrofauna found at active vents are absent at inactive regions [23]. Sampling from hard and soft sediments from inactive areas has found comparably very low number of macrofauna (organisms larger than 1mm) and meiofauna (microorganisms in the sediments). However, pyrite (FeS_2) associated chemolithoautotrophic microbes can reportedly feed on polymetallic sulfides long after hydrothermal activity has ended. These inactive regions are not well studied with *"the paucity of ecological studies and environmental baselines for inactive sulfide ecosystems makes environmental management of mining challenging"* [39].

The microorganisms of the hydrothermal vents could prove a valuable resource through the emerging industry of marine bioprospecting. The unique organisms could offer new bioactive materials to pharmaceutical or chemical processes, making new detergents or enzymes for biochemical processes [18], [40].

3.2 Marine minerals

The ocean floor is host to several mineral deposits of interest. Formed slowly by precipitation or rapidly by volcanic activity, the deposits may grow over the course of millions of years and may eventually become pushed by tectonic activity into mountains where they become the mines we know today. The three distinct resource occurrences of interest for deep-sea mining are polymetallic nodules (also called manganese nodules), polymetallic crust (also called cobalt-rich ferromanganese crust), and polymetallic sulfides (also called Seafloor Massive Sulfides) [41]. Polymetallic crust and nodule mining have a high commercial potential with more than 120 million tonnes of cobalt resources identified from these kinds of deposits on the floor of the Atlantic, Indian, and Pacific Oceans [42].

Polymetallic sulfides are the most relevant for this Thesis, as they are formed from precipitation from black smokers along the Mid-Ocean Ridge systems and at volcanic hotspots along the ocean floors. Polymetallic nodules and -crust hold great interest for future mineral exploitation but these deposits are usually found scattered over a greater area on the abyssal plains in international water.

Commercial interest for exploiting polymetallic sulfides, polymetallic nodules and -crust has existed for decades. In 1981 the first systematic investigation of polymetallic crusts was carried out by groups from Germany, the US, the USSR, Japan, France, the UK, China and the Republic of Korea. The most detailed studies were performed in the equatorial waters of the Pacific, mostly within the EEZ of island nations like Papa New Guinea which has since 1992 issued exploration permits within its waters [18], [43]. Between 1981 and 2001, 42 research cruises has studied the cobalt-rich crusts in Pacific waters totaling expenditures of between $70-100 million for fieldwork and research [43].

Since the early 2000s several companies have explored the possibility of subsea mining, with notable examples of Nautilus Minerals and Neptune Minerals which operate in the territorial waters of Papa New Guinea and New Zealand respectively [18]. The Government of Norway has also shown interest in mapping the scope of its marine minerals by budgeting 139 million NOK (US$16 million) for exploration [44]. Having recently found Seafloor Massive Sulfide and manganese crust deposits along the Mohn's Ridge of the Mid-Ocean Arctic Ridge between Jan Mayen Island and Svalbard [45], [46]. Among them is the SMS deposit Loki's Castle which covers a very large area at 35.000m^2 which is the largest SMS deposits identified along the Mid-Atlantic Ridge [33].

3.2.1 Polymetallic sulfides

Polymetallic sulfides are fast depositing minerals precipitating out of the superheated brine exiting black smokers. The composition of the precipitant structures vary but metallic sulfides of lead, zinc, barium, copper and cobalt with silver and gold are often found in the depositions in the form of pyrrhotite, pyrite/marcasite, sphalerite/wurtzite, chalcopyrite, bornite, isocubanite, barite, anhydrite, and amorphous silica [18], [23]. The deposits found around black smokers can grow up to 60 meters before collapsing and reforming [19]. The debris of these vents reform into new hydrothermal vents and precipitation continues as long as the volcanic hotspot driving the hydrothermal system is present.

Since black smoker systems are found around the mid-ocean ridge system and this area of tectonic movement, the hydrothermal hotspots are not permanent features on the seafloor. When the hotspot moves, or the seabed is moved by the emergence of new seafloor the hydrothermal system becomes inactive and the mineral resources are known as Seafloor Massive Sulfide (SMS) deposits. These deposits are considered to be geologically modern analogues to the ancient terrestrial Volcanic Hosted Massive Sulfide (VHMS) deposits that are host to the majority of the world's reserves of copper, lead, and zinc with gold and silver also produced. More than 800 terrestrial VHMS deposits are known and are found in clusters of dozens of individual deposits ranging 1 – 10Mt [47].

The size of the SMS deposits depends on the amount of mass ejected from the hydrothermal vents and the rate at with the seafloor is moving away from the ridge axis. The largest sulfide deposits of commercial interest on the Mid-Ocean Ridge system are found on slow (2-4cm/year), and ultra-slow (<2cm/year) spreading centers [23]. About 25% of the Mid-Ocean Ridge crest is slow-spreading zones (2-4cm/year). Hydrothermal fields found overlying tectonic areas (rather than neo-volcanic hotspots) are expected to be typically larger than 10.000m^2 and exhibit high Cu (>10wt%) and Au (>3ppm) surficial samples [33].

The size of inactive sulfides along fast-spreading ridge axes like the East Pacific Rise have been shown to be in the order of 10m in height, 5m in diameter, spaced 4-5m apart, for 50m along the strike of the ridge axis. For slow-spreading ridge axes like that of the Trans-Atlantic Geotraverse hydrothermal system of the Mid-Atlantic Ridge the footprint are shown to be much larger in the order of 200m in diameter and up to a 50-60m elevation above the surrounding seafloor [23]. Inactive hydrothermal regions are harder to detect since hydrothermal vents are often found by following the "smoke trail" from the expelled mineral rich fluid. About 75% of the vent sites listed in the InterRidge database are categorized as active with an estimated 80% of the yet to be discovered SMS deposits expected to be found on slow to ultra-slow spreading ridges [23], [45],

[48]. With a predicted 86% of the cumulative tonnage of SMS deposited at sites with spreading <40mm/year which make up ~50% of the Mid-Ocean Ridge system [33].

New seismic and electromagnetic tools are being developed to identify deposits buried beneath several meters of sediments without relying on the "smoke trail" from active vents. This technology may be used to estimate the area but a shortage of this method of detection is that they lack a depth of penetration to assess the volume and composition of a SMS deposit [47]. *"Current studies, using bulk geochemical data from 95 sites published in the literature suggest a global resource potential for modern SMS deposits along the neovolcanic zones of the seafloor of 600 million tons, with a median grade of 3 wt% Cu, 9 wt% Zn, 2 g/t Au, and 100 g/t Ag"* [49]. Geochemical data for SMS deposits are mostly gathered from surface-grabs of high temperature active chimney structures and are not representative of the whole deposits [33], [49]. The chimney structures reportedly contain a higher mineral concentration than the precipitated deposits surrounding the vents [47], but few SMS deposits have been had drill sample assay to date [49].

3.2.2 Polymetallic nodules

Polymetallic nodules are found at depths of about 4000m – 6000m on the abyssal plains of the ocean floor around the world [50]. They grow from slow precipitation of metallic minerals which attach to a core of rock or shell fragment and grow in layers as metals precipitate from the seawater. The layers grow very slowly at a rate of a few millimeter per million years with nodules usually found at about "potato size" of 5-10cm diameter. Some estimates place the total mass of polymetallic nodule deposits at 500 billion tonnes [19], making this type of deposit very interesting and likely to affect the global metal market if exploited [45]. The area of highest concentration to be commercially viable which has been identified is in the central parts of the Pacific Ocean in the Clarion Clipperton-zone. Only in the Pacific and the Indian Ocean have there been found commercially viable concentrations of the nodules [18]. Polymetallic nodules has seen the most exploration licenses granted within the ISA Area and mining efforts are awaiting the completion of the Mining Code.

The composition of the nodules varies, with the main components iron and manganese and inclusions of nickel, copper and cobalt. The nodules can contain up to 40 different metals [19]. With land-based manganese resources being depleted at a growing rate, the prospect of mining polymetallic nodules is becoming more economically interesting [18].

Identifying the mineralized nodules from rocks scattered on the seafloor can be difficult with the nodules visually looking indistinguishable from common rocks. One method of identification is through Underwater Hyperspectral Imaging (UHI) where the electromagnetic absorption and reflection of the minerals differentiate it from rocky minerals. Since the nodules grow from precipitation, they are commonly found in areas of low sedimentation.

3.2.3 Cobalt-rich ferromanganese crust

Cobalt-rich ferromanganese (polymetallic) crust are formed in the same way as polymetallic nodules. The difference being that the precipitation layers attach to exposed rocks where it can grow to a thickness of 25cm over the course of millions of years. The crusts grow at a rate of one molecular layer every one to three months, or 1-6 millimeters per million year. At this rate it makes the forming of the crust one of the slowest natural processes on earth [18].

The minerals in the crust are found at usually depths of 400m to 4000m in contrast to the 4000m to 5500m of the polymetallic nodules. According to one estimate about 6.35 million km^2, or 1.7% of the ocean floor is covered by cobalt-rich crust, totaling 1 billion tonnes cobalt [43]. Comparatively, the known global terrestrial cobalt mine reserves of 7 million tonnes, and total estimated terrestrial reserves of 25 million tonnes, shows the potential impact seafloor crust-mining could have on the global market [42].

The layers of the crust contain a more varied composition of minerals than the polymetallic nodules and are of notable interest for its high cobalt content. Crusts may have a cobalt containt up to 1.7% and large areas of individual seamounts may contain crusts with average cobalt content of up to 1%. These cobalt proportions are much higher than in land-based ores where the content range from 0.1% to 0.2% cobalt. Other valuable metals in the crust are titanium, cerium, nickel and zirconium. The composition of polymetallic crust can vary greatly, but an estimated composition with its 2007 value is presented in the figure below [43].

Value of metals in one metric tonne of cobalt-rich crust

	Mean price of metal (2007 $US/kg)	Mean Content in Crusts (ppm)	Value per Metric Ton of Ore ($US)
Cobalt	54.56	6,899.00	376.41
Titanium	14.66	120,350.00	176.36
Cerium	88.00	1,605.00	141.20
Zirconium	150.00	618.00	92.70
Nickel	26.72	4,125 .00	110.22
Platinum	54,481.00	0.50	27.24
Molybdenum	56.76	445.00	25.26
Tellurium	242.00	60.00	14.52
Copper	6.90	896.00	6.18
Total	--	--	**$970.09**

Kg is kilogramme; ppm is parts per million, which equals grams per tonne.

Figure 3 Table gathered from the International Seabed Authority showing the composition of a crust sample with content and price in 2007 value [43]

3.3 Marine bioprospecting

The local biosystem around the hydrothermal fields are home to a community of species that thrive in one of the planets most inhospitable environments. To survive in these conditions, they have adapted by developing biological processes which may be of great value for the pharmaceutical and chemical industry. Heat-active and thermostable enzymes are used in paper and pulp industry, to make textiles, food, pharmaceutical and medicine [51]. New enzymes and biotechnological discoveries are vital for pharmaceutical research and development. Exploitation or farming of these bioprocesses can be an important part of exploring seabed resources.

"Due to the intrinsic characteristics of enzymes, they have influenced almost every industrial market and their demand has constantly increased over the years. These natural catalysts are fast, efficient, and selective, in addition to producing low amounts of by-products. They are also fully biodegradable molecules, resulting in a low environmental impact and a greener solution to many industrial challenges.

Through actively bioprospecting extreme environments and/or using genetic engineering, it is possible now to discover and develop extremozymes that can accommodate existing industrial processes or products. Extreme biocatalysts offers exciting opportunities to improve current enzyme technologies and represents a highly attractive, sustainable, cost-effective, and environmentally friendly option compared to chemical catalysis" [52].

Hyperthermophile enzymes were first identified in 1967 from microorganisms found growing in the hot springs of Yellowstone National Park. These organisms are stable at temperatures over 80°C and have gained importance in biorefineries for bioethanol production, paper and pulp industry, production of amino-acids and in petroleum and chemical processes where the elevated temperatures make for difficult conditions for most other enzymes [53].

In 2009 Canada reported about 6.4% of their GDP came from biobased production [38]. The role of finding new processes from new sources can prove valuable in developing new technology and can offer a lucrative side venture when exploring the ecology of the deep oceans. One example of useful bioprospecting that could potentially come from hydrothermal vents are enzymes that break down hydrogen sulfide, or the production of methane from carbon dioxide and hydrogen. Since high-temperature enzymes have proven difficult to obtain from laboratory cultivation, there exists the possibility of collecting them through cultivation near the source of hydrothermal vents [52].

4 Current commercial seafloor mining efforts:

No commercial deep-sea mining operations have taken place yet. Commercial interest for mining operations have been so far been focused within the territorial waters of coastal states in cooperation with the local governments. Nautilus Minerals and Neptune Minerals have been the two pioneering companies most often mentioned when discussing deep-sea mining. These companies have focused on SMS deposits off the coast of Papua New Guinea (PNG) and New Zealand, respectively.

Nautilus Minerals' efforts are discussed in some detail in the coming subchapter and is used as an example for how efforts in deep sea mining of SMS deposits could look.

Neptune Minerals' efforts appear much more conservative with them adopting a "baby steps" approach to mitigate economic and environmental concerns. Their mining plan does not involve the same seafloor production scheme which Nautilus Minerals propose. Instead opting for topside operated clamshell excavators mining mineral rich chimney structures depositing the material in collectors which is then retrieved up to the mining vessel [54]. Neptune Minerals has contracted the French engineering company Technip to investigate the profitability of the company's operations in the north coast of the New Zealand's North Island. Here they estimated the SMS deposit value of $500 to $2000 per tonne with Neptune's operating costs estimated to $145 to $162 per tonne [10], [55], [56].

The concept of seafloor mining has been proven off the coast of Namibia at shallower depths. Seafloor diamondiferous gravel have been mined since 1961 [47], with the most recent efforts by Debmarine Namibia since 2002 [57]. The mining venture of Debmarine Namibia is jointly owned 50/50 by the Namibian Government and De Beers Centenary AG. The mining effort is the only one in the world and operates a fleet of five mining vessels that mine diamonds at depths of 120m to 140m below the ocean surface. The inclusion of marine diamonds has proven to be lucrative, with Namibia's marine diamond production now outperforming land-based mining. In 2016, Namibia produced 1,17 million carats of marine diamonds compared to 403.000 carats produced on land [58]. To mine the diamondiferous gravels a 280 tonne track-mounted crawler is used, equipped with a cutting head with multiple steel picks at the end of a sloughing arm. Similar to the "collection machine" designed by Nautilus Minerals for use at depths an order of magnitude deeper [47].

4.1 Nautilus Minerals

Nautilus Minerals has attempted to become the world's first commercial mining company for seafloor SMS deposits. The company has supplied most detailed plans for subsea mining operation this Thesis could find publicly available. Most of the information gathered for this chapter was collected from their comprehensive January 2018 Preliminary Economic Assessment (PEA) [47]; a 274-page report commissioned from the independent AMC Consultants Pty Ltd. The PEA details the efforts made to assess the occurrence of submarine sulfides in the Bismarck Sea stretching back to its discovery in 1985. Subsequent research studies of the area have been performed by research groups from several countries, "*including France, Germany, Canada, USA, Japan, Korea, UK, and Australia*" indicating the interest for future exploitation of these types of deposits around the world. The Solwara mineral field was first discovered in 1985 when the US research vessel RV Moana Wave photographed submarine hydrothermal sulfides deposited around black smokers in the Manus Basin of the Bismarck Sea, Papua New Guinea. This area was to become the Solwara-2 deposit. As of writing the PEA, Nautilus has identified 17 separate SMS prospects in the Manus basin with their initial focus on the deposits at Solwara-1 and Solwara-12. This chapter will focus on the efforts being put into assessing and exploiting the Solwara-1 deposits. The Papua New Guinean Government has had a 15% interest in the Solwara-1 Project as an unincorporated joint venture, with the financial modelling for the project indicating a profit of over US$100million in taxes and royalties to the PNG Government.

As of writing this Thesis, the future of mining efforts off the coast of Papua New Guinea is uncertain. The company was delisted from the Toronto Stock Exchange in early April of 2020 following the efforts of restructuring after their bankruptcy and refinancing over the last year. The assets and contracts have been acquired by Deep Sea Mining Finances ltd. In late 2019, the Government of Papua New Guinea indicated support for a moratorium on deep-sea mining. Recently the PNG Prime Minister's office announced plans to unveil a new national ocean policy to manage the country's marine resources. With the Deputy Prime Minister Davis Steven expressing: *"The Solwara 1 project continues to remind us, as a nation, to be careful in how we deal with our maritime resources, the blue economy that we have."* Adding: *"Our Government's priority right now is to reform the law, take back PNG using lawful means, building investor confidence, building industry, building capacity but what belongs to the people of Papua New Guinea must be given to the people and not by stealing but by the right way."* [26], [59], [60].

The thesis will however present the mining plans developed by Nautilus Minerals as they offer an insight into how seafloor mining might be undertaken in future ventures.

4.1.1 **Solwara mineral field**

The hydrothermal field at Solwara-1 was first discovered in 1996 when the RV Franklin detected intense particulate plumes emanating from volcanic edifices in the Eastern Manus Basin of the Bismarck Sea. The volcanic ridge is an active subduction zone of the New Britain Trench, approximately 5km long and is mainly comprised of basaltic rock. The Solwara-1 mineral deposits are comprised of six closely-spaced massive sulfide bodies covered by a thin layer of unconsolidated sediments stretching approximately 1.4km at a depth of 1.500-1.650mbsl, about 30km off the shore of New Ireland Province. [47], [61]

The main area of the deposit contains numerous active hydrothermal vents with chimney height generally ranging from 2-10m with the tallest measured to 15m in height. Drilling at Solwara-1 has been investigated by shallow diamond drilling to a maximum depth of 51.62m. The results of the drilling program found massive sulfides extending deeper into the feeder zones under the chimney areas and localized breccia zones. *"These deeper zones can contain significant copper and gold mineralization with low levels of zinc. It is likely that these zones are narrower than the footprint of the deposit".* These deeper feeder-zone deposits, shown in the figure below, are harder to measure since the Ocean Floor ElectroMagnetic system (OFEM), which responds very well to the chalcopyrite, is limited to a surface penetration of 3-6m, making the mineral estimates very conservative and dependent on drill core assay.

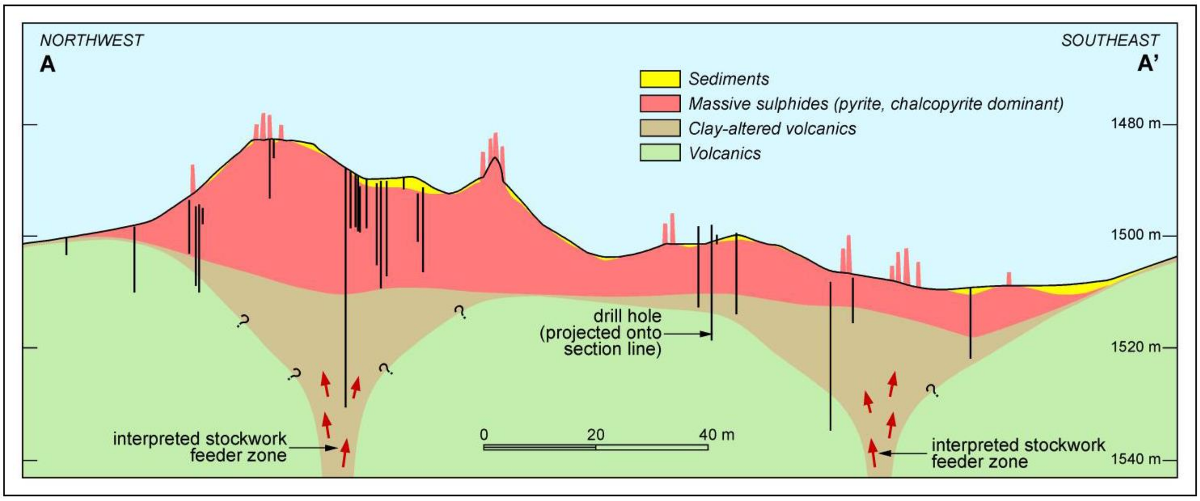


Figure 4 Showing schematic geological cross section of the Solwara-1 field. Depicting the interpreted feeder zones which may hold additional resources [47]

Adjacent to the west of Solwara-1 is the smaller Solwara-12 field which was discovered in 2009. Unlike the hydrothermally active chimneys of Solwara-1, the Solwara-12 deposit are comprised of inactive sulfide chimneys and covered by a thicker layer of sediments.

This project will only focus on the Solwara-1 deposit since it has been studied more intensely, but it will be helpful for future development within this subject to see how mining efforts in a hydrothermally inactive region will compare to that of an active.

4.1.2 Mineral estimates

The true scale and composition of seafloor deposits take an extensive effort and various techniques to compile. Since its discovery, the subsequent intensive efforts to map the true size and value of the Solwara-1 field has given the inferred and indicated mineral resources presented below. The mineralization varies between the different domains, as seen in the table below, showing the 2007 drill sample assay from the main sulfide-dominant mineralization domain, and the 2005 chimney sample grab. The 2007 metallurgical test work estimated 96% of the Solwara-1 Inferred and Indicated Resources are types of mineralization of chalcopyrite and chalcopyrite-pyrite, an estimated 3% zinc mineralization, and remaining 1% unclassified [47].

Mineralogical examination and metallurgical test work have been carried out on material from 61 drill-holes and 37 chimney grab samples. Showing: *"The uniformity of the mineralization types, the excellent correlation between mineralogy and metallurgical response and the shallowness of the drill-holes into Solwara-1 (less than 20 m) give very high confidence in the prediction of metallurgical performance for the mineral resource"* [47].

The inclusion of zinc, lead and other metals are not regarded as substantial due to their relatively low concentration and value.

Drill assay of sulfide-dominant domain: *"The 2007 Wave Mercury program to sample the Solwara-1 field about recovered 100kg of pulverized homogenized composite of sulfide material from coarse and pulp rejects from drill cores into the sulfide-dominant domain. The material was blended and split into 60g samples. The results were deemed satisfactory for resource estimation"* [47]. This research cruise saw the world's first use of underwater mineralization delineation EM-surveying with *"The survey results correlated "extremely well" with the drill-hole data and was used to aid the interpretation of the geology"* [47].

Test assay of chimney mineralization: 2005 test work a composite sample of chimney mineralization from Solwara-1 deposit was tested. Bulk flotation recovered 97% of the Cu, 75% of the Au, 93% of the silver, 90% of the lead and 96% of the Zn. [47]

	Cu [wt%]	Zn [wt%]	Au [g/t]	Ag [ppm]
2007. Sulfide-dominant domain sample assay	5,11	1,71	5,91	44
2005. Chimney sample assay	26,64	4,92	15,51	440

Table 1 showing the drill sample assays from the Solwara-1 field [47]

The mineralization of the deposit varies greatly between the main sulfide-dominant mineralization domain and the chimney structures. The potential for additional high-grade mineralization extending into the hydrothermal feeder sones is possible. However, the complexity of drilling into these narrow regions have yielded no conclusive data at present. The PEA concludes that data and methods used in accordance with Canadian National Instrument 43-101, are adequate to support estimates of:
1.0 Mt of Indicated Mineral Resource at: 7.2% Cu, 5.0 g/t Au, 23 g/t Ag.
1.5 Mt of Inferred Mineral Resources at: 8.1% Cu, 6.4 g/t Au, 34 g/t Ag.

The resulting inferred/indicated gold and copper grades are significantly higher than most terrestrial mines. To increase the confidence of the Inferred mineral resources to Indicated, a trial mining and drilling program in excess of US$50 million would be required.

The 2007 drill assay from Solwara-1 contain mineralization comparably higher than one of the only examples of previously assayed samples from the interior of an SMS deposit. About a decade prior, the slow spreading SMS deposit at the Trans-Atlantic Geotraverse hydrothermal field was assayed at 2.3wt% Cu, 0.2ppm Au [33].

4.1.3 <u>Seafloor Production Equipment</u>

The proposed mining operation is based on a common surface mining method, open pit benching: *"the process of mining is the same as terrestrial mines: to expose mineralized material, achieve fragmentation, load and haul".* [47] To achieve this, the three main mining tasks of sediment removal, rock cutting, and transfer of fragmented cuttings to the surface are performed by three seafloor production tools and a positive displacement pump. The four machines, detailed below, are collectively known as the Seafloor Production Equipment (SPE), are powered via umbilical cables from a Production Support Vessel (PSV). The equipment is designed to be reusable for future mining projects and is currently in storage after having successfully undergone submerged production trials in 2012 [61].

The Auxiliary cutter:

The Auxiliary Cutter, seen below, is a track-mounted primary rock cutting tool designed to prepare a suitably flat production area for the Bulk Cutter to operate by: flattening chimneys, removing sediments overlying the mineralized area, cut ramps and stockpile areas, and preparing production benches. The Auxiliary Cutter is similar in design to a "roadheader" found in the tunneling industry and the RT1 subsea pipeline trencher of found in the petroleum industry. It utilizes two counter-rotating cutting heads with tungsten carbide bits attached to a 6.4m sweeping boom with a dredge system designed to pump a 4.6% slurry at 3.206 m^3/h, delivering approximately 472 tonnes of mineralized material per hour [47], [61].

Figure 5 Auxiliary cutter. The primary "benching" cutter for leveling chimneys and flattening the production area [65]

The Bulk cutter:

The Bulk Cutter, seen below, is the main production unit and has a single transversely orientated 4.2m-wide cylindrical cutting drum. The drum houses 119 helically laced picks on a spacing of 50mm powered by two 600kW variable speed drive electrical motors. The electrical motors can deliver up to 900kW of cutting power via two gear boxes housed inside the cutter drum.

Figure 6 The Bulk Cutter during onshore function test [59].

The drum is designed to cut rock up to 100MPa in strength, with test work indicating that expected hardness of sulfide-dominant rocks will be approximately 52MPa, which is expected to be the hardest rock encountered. The dredge system is designed to pump a 4.6% slurry with a flow of 3.206m3/h, delivering 472 tonnes per hour, same as the Auxiliary Cutter [47].

The mineralized cuttings produced by the Auxiliary and Bulk Cutters are pumped to a nearby seafloor stockpile where the Collection Machine begins preprocessing and transfer to the Subsea Slurry Lift Pump.

The bulk cutter is designed to operate in two modes of cutting as shown below: continuous cutting and cyclic cutting, dependent on the height of the cut area.

Continuous cutting, as seen below, is expected to offer higher productivity, and is expected to advance in the order of 0.5-0.9m/min cutting at a 1m height.

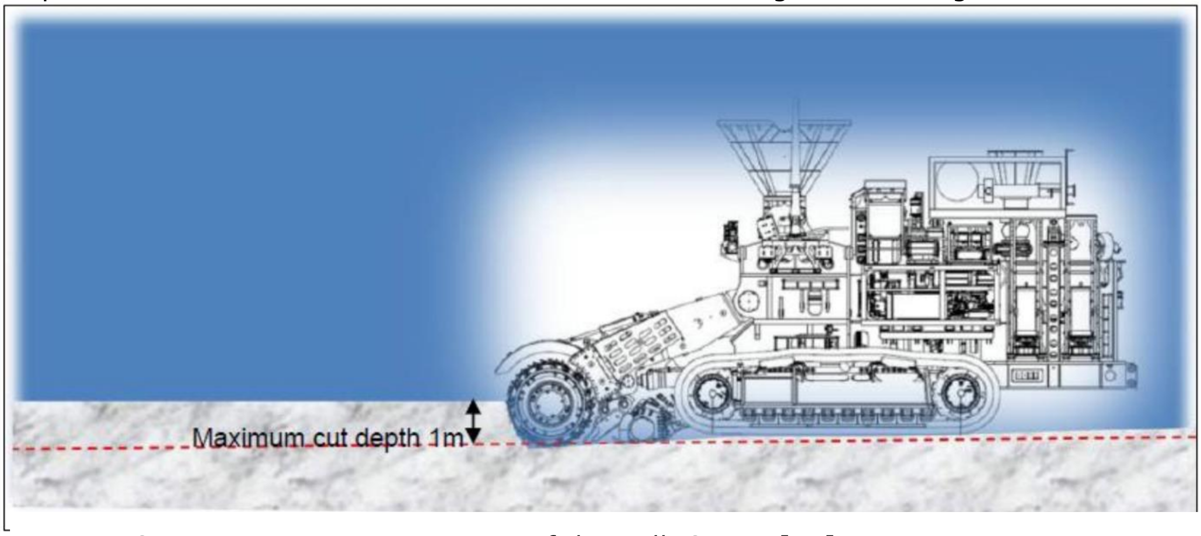


Figure 7 Continuous cutting operation of the Bulk Cutter [47]

Cyclic cutting, as seen below, is stationary during the cutting operation, and is expected to offer lower productivity and higher risk of oversized material than continuous cutting. This cutting mode will only be nessisaity with cutting heights over 1.0m, with it's maximum being 4m.

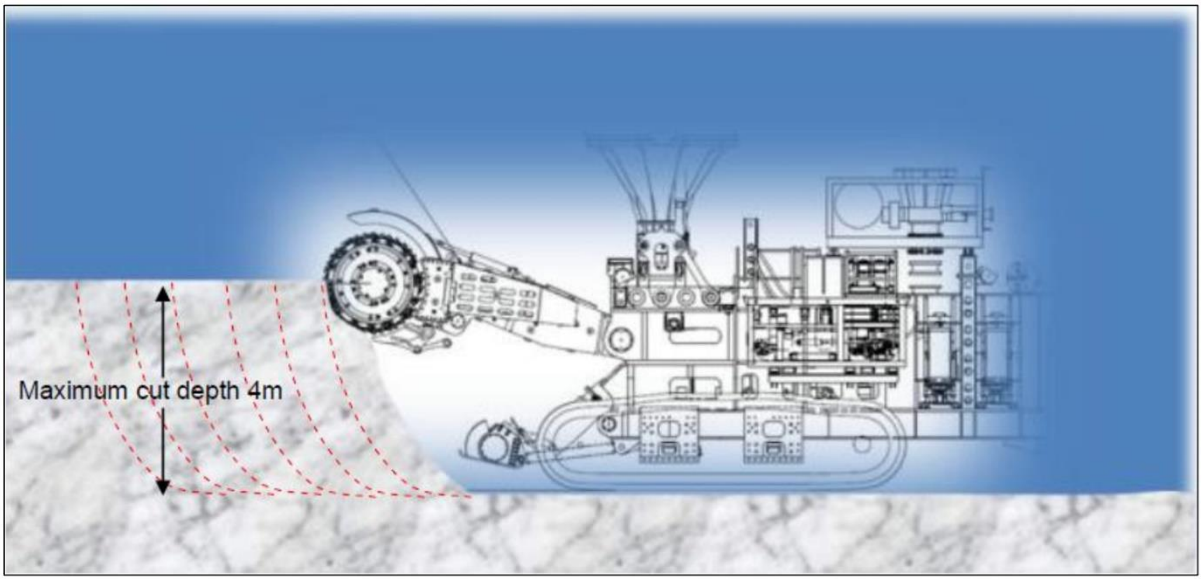


Figure 8 Cyclic cutting operation of the Bulk Cutter [47]

Collection Machine:

The Collection Machine is designed to reclaim the fragmented material produced by the Auxiliary and Bulk Cutters. The material is reclaimed from the seafloor stockpile and pumped as a slurry to the Subsea Slurry Lift Pump which in turn pumps it to the PSV. The Collection Machine is equipped with a three-stage slurry pumping system to deliver the slurry to the Subsea Slurry Lift Pump at a concentration of 12% at a minimum discharge pressure of 5 bar. The boom arm is fitted with a 1,05m-diameter dredge crown cutter driven by a 150kW hydraulic motor rotating at a maximum of 20 rpm. The 25-tooth chisel-pick laced cutting head is capable of cutting rocks, but this is a secondary function to avoid overloading the long boom arm. The primary function is to agitate the stockpile material to increase retrieval efficiency.

Figure 9 The Collection Machine [65]

The Seafloor Stockpiles which temporarily stores the material from the cutting operations is projected to be approximately 25m in diameter at a height of 12m. The Collection Machine is designed to gather material from the base of the stockpile moving circumferentially around it to avoid hang-ups. In the event of hang-ups, the Collection Machine has a vertical reach of approximately 5m to accommodate overhangs. During the retrieval operation the Collection Machine performs a crude preprocessing of unconsolidated, unmineralized sediments which is discarded before entering the slurry feed system.

4.1.4 Mining method

Open pit benching has been selected as the preferred mining method since the depth and complex bathometry of the resource field makes it unsuited for extraction by dredge technology. The benching process is based on common land-based mining methods with some alterations to fit the marine environment. The method and equipment selected for this type of mining operation considers the complex layout of the mineral field and could prove a useful template for future seabed mining efforts around the world.

The mine design for Solwara-1 divides the open pit benching into many mining blocks and panels. The mining sequence is top-down and will progress in two phases: Pioneering mine development by the Auxiliary Cutter for the ramp and bench set-up, and primary production by the Bulk Cutter.

Before the mining operation can start, the unconsolidated sediments which covers the deposit needs to be removed. This layer ranges in thickness from zero to 2,7m, and up to 6m in some throughs, with a density of about 1,2t/m^3. It is estimated that about 130.000m^3 of sediments needs to be removed during the mining operation. The hydrothermal chimneys are leveled by using clamshell excavators lowered from a surface vessel to break up the high-grade mineralized chimney structures and depositing the material near the mounds for the Auxiliary or Bulk Cutter to collect. The chimney structures can be more than 20m in height, with individual chimneys at a normal height of 15m.

Once the chimney structures have been leveled and the sediments are removed the Auxiliary Cutter will forms the area into terraces for the Bulk Cutter to perform the main cutting operation and transferring the mineralized slurry to the stockpile. The Collection Machine then works circumferentially around the base of the stockpile transferring the material to the Subsea Slurry Lift Pump, a 10-chamber positive displacement pump delivering a 12% slurry at nominal rates of 863m^3/h or 331t/h up to the PSV. Process samples tested have shown a Bond Ball Mill Work Index value in the range of 10-12kWh/tonnes, indicating a low to moderate ore hardness for mineral processing [47].

The only processing of the minerals performed on location prior to storage and transfer, is a dewatering process onboard the PSV. The proposed dewatering plant is similar to a well-established coal washing process and produces its own potable water through reverse osmosis at a capacity 70.000 liter per day. Up to four offloading vessels will be required a full production rate. Expressions of interest and budgetary pricing have previously been sought and it is estimated that the charter costs for these vessels would be equivalent to approximately US$25 per tonne of product produced and transferred.

4.1.5 Economic viability

The true scale of the mineral deposit is difficult to determine due to the limitations of mapping the depth and composition without an extensive drill sampling regime. The estimates of Indicated Mineral Resources and Inferred Mineral resources are conservative

The production plan schedule is set up for 29 months with a production ramp-up period of 15 months, with peak production of mineralized material estimated at 110kt per month. The average cost of production is expected to be approximately US$274 per tonne of mineralized material over the project lifetime. The total losses of mineralized material associated with the bench cutting has been estimated to be 10%, with another 3% expected to be lost during processing and transport.

In total a yield of 0.9 Mt material at a grading 6.4% Cu and 4.6 g/t Au and 1.3 Mt at grading 7.0% Cu and 5.5 g/t Au is expected for a recovery of approximately 130kt of copper and 180koz (~5.6tonnes) of gold. The economic modelling indicates that copper will contributes 80% of the project value, gold 19% and silver 1% [47].

The spot prices used to determine the economic viability of the project were based on 1. January 2018 compared to the present effective price collected at 1. December 2020 is presented in the table below. The values gathered are supplied by the consultancy GRU International Limited and The London Metal Exchange [47], [62].

	01.01.2018	01.12.2020	Change
Copper [per tonne]	US$7,250	US$7,644	+5.4%
Gold [per oz]	US$1,304	US$1815.1	+39.2%
Silver [per oz]	US$17.01	US$23.95	+40.8%

Table 2 Change in spot metal prices for the metals contributing to the economic viability of the Solwara-1 project [47], [62].

At the expected 2018 values, the project modelling indicates a positive economic outcome of a net value after sales, taxes, and royalties of US$56million. The project sensitivity analysis shows that the project profitability is heavily dependent on changes in the metal prices. A price drop of 10% in the price of copper and gold would result in the project being unprofitable. The current 2020 metal prices show an increase in the three relevant metal prices.

One important aspect when discussing the viability of subsea mining is how it economically compares to terrestrial mining operations. The C1 cash cost per pound is a financial performance measure factoring the cost of sales, treatment, and refinement, excluding the impact of depreciation and royalties. The C1 measure is not a standardized measure but may be used to give an indication of how the cost of different mining operations compare.
The average C1 cash cost of the Solwara-1 over its 29-month duration is estimated at US$1.36 per pound of copper which would place the mining operation in the second quartile of global terrestrial copper mining operations.

The C1 cash cost after the 15-month project ramp up is expected at US$0.80 for months 16-24. During this period where the production rate is expected to be stable at 3,200tpd with the maximum capacity 6,000tpd. If the mining operation can maintain a steady-state production rate of 4,500tpd then the C1 cash cost for the period is expected at US$0.63 which would put the mining operation within the upper first quartile of the world's copper mines [47], [63]. This shows the potential for further profitability of subsequent deep-sea mining operations like the Solwara-1 field.

4.1.6 Project risk

The project status is currently unknown following the bankruptcy of Nautilus Minerals in August 2019 [64]. The assets, patents, deep-sea mining IP, and ownership of interests and rights for Nautilus Minerals have been acquired by Deep Sea Mining Finance Limited (DSMF), a joint venture between the international holding group USM Holding Ltd. and the Sultanate of Oman group MB Holding Company LLC [65].
DSMF has indicated interest in continuing mining efforts at Solwara-1 and if the moratorium on deep-sea mining imposed by the Government of Papua New Guinea is lifted the project may progress as proposed in the PEA.

The pioneering nature of the mining operation leave many obstacles to be identified through experience of this first effort. Deep-sea mining has not yet been attempted and there are no close analogues compared to the depth, temperature, pH, and mineral content of the surrounding water. The lack of redundancy of the mining fleet is identified as one of the greatest project risks. The Seafloor Production Equipment are unique and without replacement. Any loss of function or catastrophic failure of any of the SPE would cause delay in the mining plan and threaten the economic viability.

While Solwara-1 contains elevated gold and silver grades, it is predominantly a copper deposit. As a result, the economics of mining the deposit are most sensitive to movements in the copper price. As discussed in the above 'Mineral estimates' chapter, the minerology of the deeper parts of the deposits is only identifiable by extensive drilling samples which presents a cost/benefit challenge of identifying these "feeder zones". These zones could hold mineralization even greater than the chimney structures, but its composition remain inconclusive due to a lack of drill sampling.

There exists an uncertainty regarding the abrasiveness of the mineralized material which could cause wear to the production equipment. The Subsea Slurry Lift Pump is designed with this in mind - as a 10-chamber positive displacement pump functioning a nominal rate even with failure of two chambers.

A seismic analysis has identified slope failure as the *"biggest single unknown geotechnical factor"* for the project. The cross-section of the mining method is akin to hilltop removal and seismic activity in the area could cause failure of the weak footwalls of clay-dominated rocks [47].

4.1.7 <u>Environmental and ecological concerns</u>

The Nautilus Minerals - Environmental Impact Statement (EIS) was prepared by the consultancy of Coffey Natural Systems Pty Ltd, Brisbane, Australia, in September 2008 [39], [47]. The Solwara-1 deposit is an active hydrothermal field and home to the type of ecology discussed in the previous chapter. The dewatering plant is the only pre-processing preformed on location with no surfactants, filter aids or other processing chemicals being used in the operation. All hydraulic fluids used in the subsea equipment are biodegradable.

The water quality, sedimentation rates and macro-fauna of active and inactive hydrothermal vents have been studied at the Solwara-1 deposit as well as a nearby SMS deposit known as South SU. The studies show that the sedimentation rate at Solwara-1 is on average 50 times higher than in areas of no hydrothermal and volcanic activity.

The return water from the dewatering plant will discharge material smaller than 8µm at a height of between 40m to 180m above the sea floor increasing the sedimentation rate of the area. The fauna of these areas is already adapted to high sedimentation rates and live naturally in extreme environments of high concentrations of dissolved arsenic, copper, manganese, and zinc with dilution occurring within 85m of the discharge point. The EIS notes that pre-existing water quality standards for other marine life may hold little relevance to the sensitivity of this deep-sea extremophile fauna. The return water sediments is expected to not rise above 1,400mbls in the water column and it is *"envisaged that under normal operation conditions, there will be a negligible impact to the marine life in the mid-water column"* and should not affect pelagic tuna, tuna fisheries, near-shore coral reefs, or traditional fisheries [39], [47].

5 Offshore geothermal power

The geothermal gradients and reservoir conditions may vary greatly along the Mid-Ocean Ridge system but the root-zone magmatic origins is the driving force of the whole system. Predictions for how exploitation of hydrothermal resources can be achieved are difficult to make, but sampling one area can offer an indication for the potential along the system.

The Reykjanes ridge to the south west of Iceland has been continuously studied for a long time and will form the basis of our reservoir assumptions when assessing the hydrothermal power potential along the Mid-Atlantic Ridge. The Reykjanes steam field is the highest temperature steam field in Iceland and has been used for power production for over 30 years without significant depletion of the reservoir [66].

This project will use the average wellhead pressure, temperature and mass flow from Baldur Kárason's 2013 Master's Thesis [66] as a reference when discussing the possibility of having an in-situ power option at these hydrothermal mineral fields. All the offshore geothermal power options presented in chapter 6 are derived from this work, with the exception of Option 5 – The hydrothermal submarine. This dataset is only used as an indicator for the potential but could provide an approximation for how a geothermal reservoir near an active part of the ridge will behave. This data will be referred to as "the Reykjanes average".

5.1 Reservoir conditions

The reservoir conditions will vary from location to location along the ocean ridge system. Below are presented two datasets for the conditions one might expect below the seabed near hydrothermal vents. These two datasets are presented as an indication for the conditions that can be expected when evaluating the potential for an offshore geothermal power plant. Their main difference is the depth of the geothermal reservoir.

5.1.1 **The Reykjanes ridge area**

The Reykjanes geothermal steam field is one of the most studied geothermal fields in Iceland and has the highest temperature of the Icelandic steam fields. *"The actual data for the boreholes located on the Reykjanes peninsula were collected from two companies; ISOR (Icelandic Geosurvey) and HS Orka (the owner of the steam field). From ISOR, information about the productivity curves for the boreholes was collected and analyzed. Power production and enthalpy information was collected form HS Orka."* [66].

The graph below shows the reservoir data collected from the Reykjanes steam field plotted into a pressure-enthalpy chart with the pressure-enthalpy area marked in orange [27].

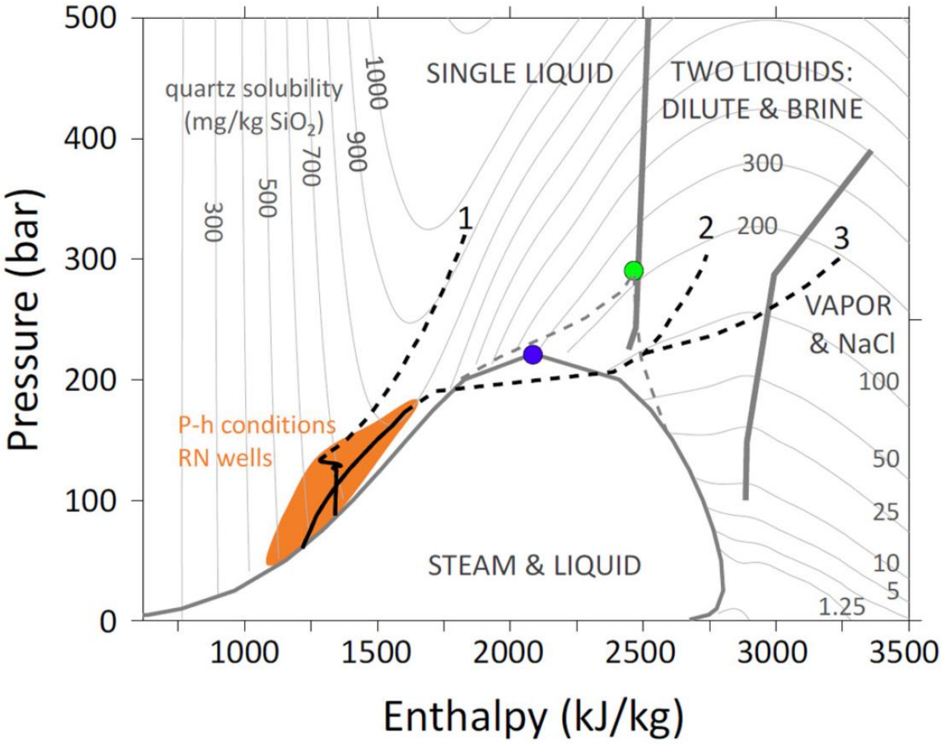


Figure 10 The orange shaded area represents the pressure-enthalpy regime of the existing Reykjanes geothermal production wells [67]

This wellhead data average is collected on land with seawater supplying the hydrothermal system below. The source gives no estimation for the average depth of the reservoir, but process diagrams from the power calculations show a reservoir pressure of 139,9 bar and temperature of 336,6°C [66]. The Reykjanes average is used as an example for the conditions that could be present near hydrothermal wells. The higher wellhead pressure at these temperatures would mean a higher enthalpy. Therefor this average gathered from wells above sea level could be considered a conservative estimate compared to the conditions at ocean depths.

5.1.2 <u>The Icelandic Deep Drilling Project (IDDP) at Reykjanes</u>

The Icelandic Deep Drilling Project aimed to drill deep into the hottest parts of a hydrothermal system to explore the feasibility of producing power from supercritical geothermal resources. The exploratory well IDDP-2 was drilled into the Reykjanes geothermal field and achieved several scientific and engineering records. The exploration well is the deepest and hottest drill-hole so far along the active Mid-Ocean Ridge system. The well was drilled 3km down before being angled towards the main up-flow zone of the system before terminating at 4,5km vertical depth. At 1 – 2.5km the geothermal field produces fluids of <300°C and is unusual for being recharged by sea water. Below 3km the drilling lost circulation due to the temperature, and drill cutting could not be collected for analysis. The drilling continued without mud circulation and the bottom hole temperature is estimated to 535°C [67].

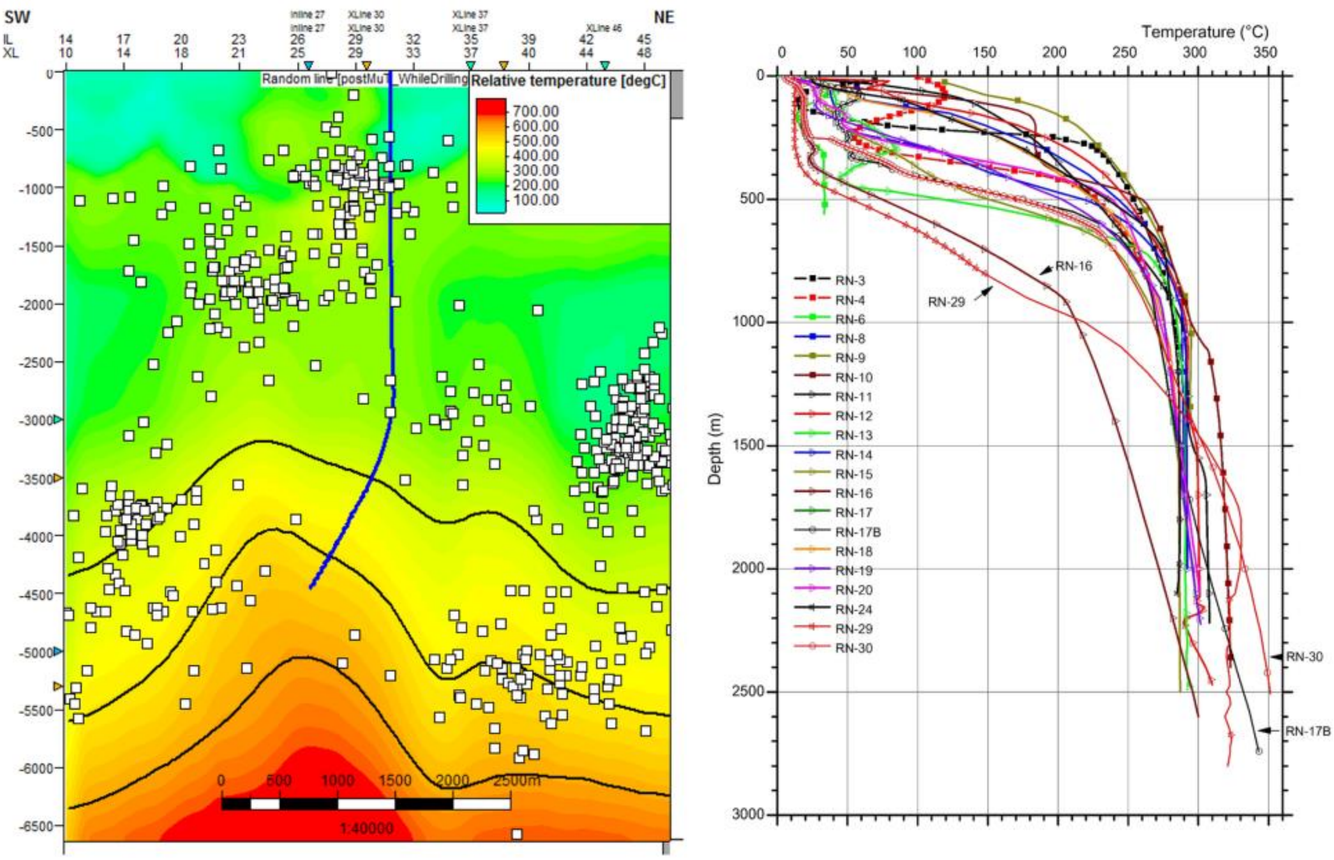


Figure 11. To the left: the temperature prediction based on drilling data from IDDP-2. On the right shows the steady state temperature-depth profile for most of the Reykjanes wells. These well are inferred to be the same well data as the dataset used to analyze the Reykjanes average [67]

"The drilling of the IDDP-2 has achieved number of scientific and engineering firsts. It is the deepest and hottest drill hole so far sited on an active mid-ocean spreading center. It penetrated an active supercritical hydrothermal environment at depths analogous to those postulated as the high temperature reaction zones feeding black smoker systems" [67].

As the name of the article of (Friðleifsson, G.Ó., et al. 2018) implies "Drilling into the root zone of a black smoker analog", the IDDP aimed to drill deep into the Reykjanes geothermal field on land, analogous to the high temperature zones feeding black smokers along the MOR. The project explored the economic potential of supercritical wells at record setting bottom hole temperatures of 535°C. The IDDP was scheduled for gradual warm up in preparation for long-term flow tests in early 2019. The literature search for this project cannot find much in terms of preliminary data for expected enthalpy, pressure and flow rate of IDDP-2 [68], but the results could be very interesting for future work on this subject. A third IDDP-3 well is planned at the Hellisheiði Power Station east of Reykjavik.

By comparison the first IDDP well at Reykjanes in 2005 was considered a failure when drilling encountered >900°C magma at 2.1km, collapsing the uncased well. Subsequent long-term flow rate tests have found the well to have sufficient conditions to supply a geothermal power plant with about $35MW_e$ of power generated [67].

5.2 Location and method

Below are presented six options for generating the power, based either on a surface platform power plant or at the seabed. In the options located at sea level the common denominator of "platform" is used for where the equipment is housed, whether it is a ship, barge or other offshore platform.

One of the hard to define factors when determining placement is the synergy with other processes like ROV-operations to find and mine the minerals, crushing, processing and refining, storage and offloading, etc.

This project will not focus on these processes, but the two options for location of the power generation will be on the seabed near the wellhead or on a sea-level platform. The determining factor for the location may be what and where the power generated will be utilized for.

The options for how the thermal energy are converted to electrical are:

- Single flash cycle directly utilizing the reservoir steam
- Binary organic Rankine cycle using a heat exchanger as an intermediary
- Thermoelectric using Peltier elements.

There exist more complex power options, but these are the most common methods used in land-based power plants.

5.3 Single flash cycle

The single flash cycle is the most commonly used method of generating electricity form geothermal power. This method requires a geothermal reservoir hotter than 190°C and geothermal fluid hotter than 182°C to run efficiently [69].

As seen in the figure below; the geothermal fluid is brought up through the wellhead and "flashed" by going through an expansion valve. This expansion of the fluid separates it into a gaseous and liquid phase. The phases are separated with the steam going through a demister and the fluid running through the separator for reinjection. The now dry steam drives a turbine which in turn drives a generator producing the electrical power. Exiting the turbine, the steam is condensed before being reinjected together with the separator fluid.

There are options for more advanced versions of the flash cycle like the dual and triple flash cycle, which adds extra separators to get more steam at lower pressure to run a larger turbine with several steam injection points, or to run additional lower pressure turbines.

These options run at a higher efficiency than the single flash and can produce 15-25% more power [69], but comes with a higher cost and lower system reliability due to the added components.

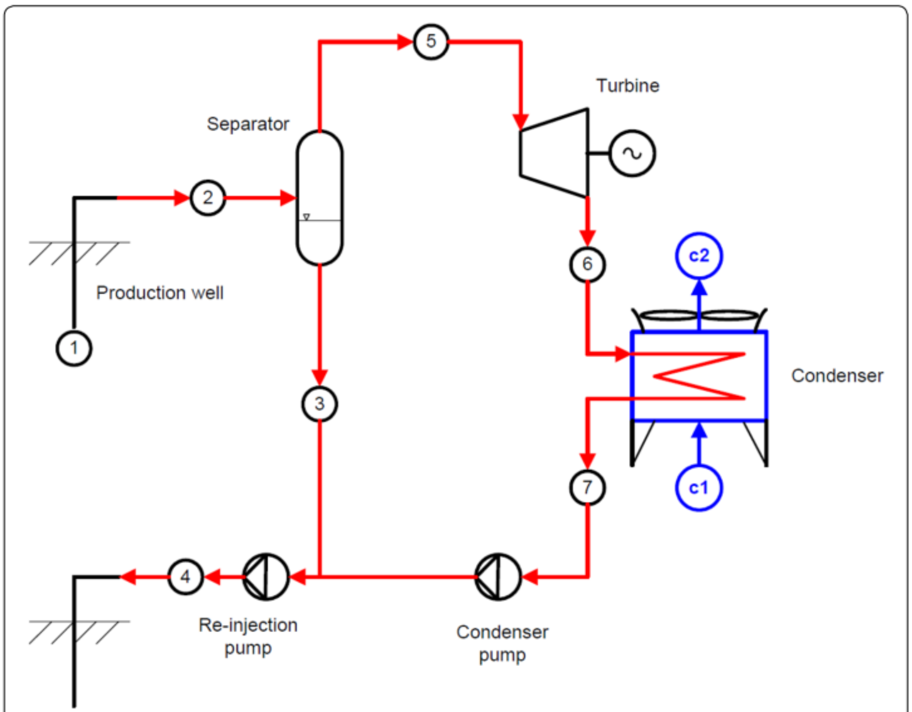


Fig. 1 Single flash power plant (Valdimarsson 2011)

Figure 12 Process diagram of the Single Flash Cycle [66]

As the reservoir fluid is flashed and steam evaporates, the mineral contents are concentrated in the remaining hypersaline fluid. Precipitation, scaling, erosion and corrosion could be major concerns for this hot concentrated brine. The "dry" gas exiting the demister usually contains Non-Condensable Gasses (NCG) like hydrogen sulfide, ammonia, methane, carbon dioxide, carbonic acids, etc. which can severely degrade components over time. The content of NCG in geothermal steam can vary greatly from near zero to as much as 25%wt [70].

The flash cycle is the only of the before mentioned power options that has a problem with Non-Condensable Gasses since the other alternatives will run the reservoir fluid through a heat exchanger before it is reinjected. The NCG contents can interfere with the heat transfer in the condenser, which could raise the pressure at the exit of the turbine, decreasing the pressure difference and efficiency. Going through the turbine the NCGs also contain a lower recoverable specific heat than the steam it displaces. A 1978 study by Khalifa and Michaelides found that *"the presence of 10% NCG in the geothermal steam, results in as much as a 25% decrease in the net work output compared to a clean steam system"* [70].

5.4 Binary organic Rankine cycle

In a binary organic Rankine cycle (ORC) the heat from the reservoir fluid is transferred to an organic working fluid such as hydrocarbons or fluorocarbons. The binary ORC is currently used for lower reservoirs temperature of 150°C and lower, but can be engineered to work with reservoir fluids of 200°C. Numerical calculations for the power output using a geothermal fluid temperature of 200°C and isopentane as a working fluid was performed by (Assad, et al. 2017) [69].

As seen in the figure below the reservoir fluid enters the heat exchanger where it vaporizes the working fluid which in turn drives the turbine. The working fluid in the binary cycle runs in a closed loop with nothing entering or exiting the system. After exiting the turbine, the fluid is condensed and pumped back into the heat exchanger for vaporization.

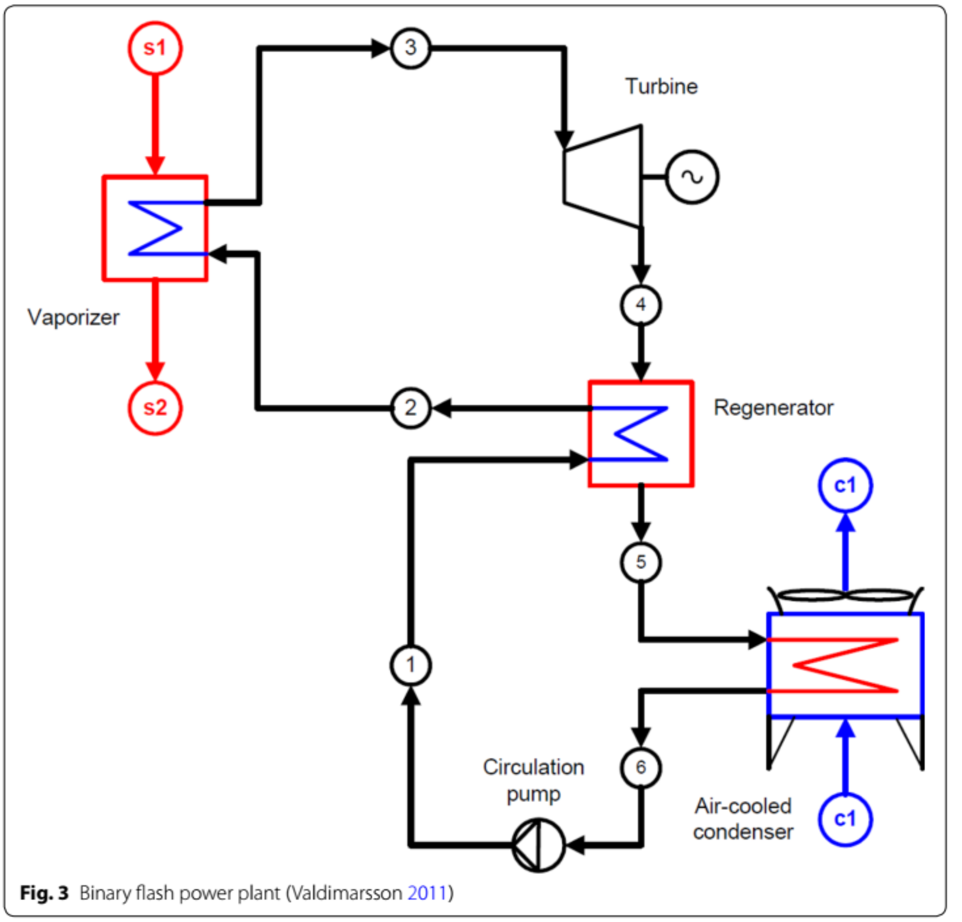


Fig. 3 Binary flash power plant (Valdimarsson 2011)

Figure 13: Process diagram for the binary cycle [66]

The working fluid needs to be evaluated to fit the reservoir conditions and regulations for use in offshore environments. Examples of working fluids can be: Acetone, benzene, cyclohexane, methanol and ethanol, isopropanol, R-113 and R123 [66], [69], [71]. Methanol is widely used in the petroleum industry as a hydrate inhibitor.

Since the heat is transferred from the unseparated reservoir fluid to the working fluid the binary cycle runs at a higher efficiency than the single flash cycle.

The binary cycle has the added benefit of running on a clean predefined working fluid which should not degrade the system as opposed to the problems that arise with the single flash reservoir fluid. The wellhead, heat exchanger, pipes and reinjection pump are the only components in direct contact with the reservoir fluid. Since there is no flashing of the reservoir fluid the brine concentration remains unchanged and the degradation problems mentioned above should be minimal. However, if degradation takes place, the heat exchanger is a much simpler piece of equipment to replace than separators, turbines, condensers, and pumps, which should give the binary cycle better reliability than the single flash cycle.

5.5 Thermoelectric

Thermoelectricity is generated without any moving parts by a temperature difference (ΔT) across a cell. The figure below shows the schematic drawing of a thermoelectric cell called a Peltier element [66]. When electricity flows through a conductor the flow of electrons produce heat. Inversely this phenomenon is called the Seebeck effect where the thermal flow through a cell creates a flow of electrons and in effect an electric current.

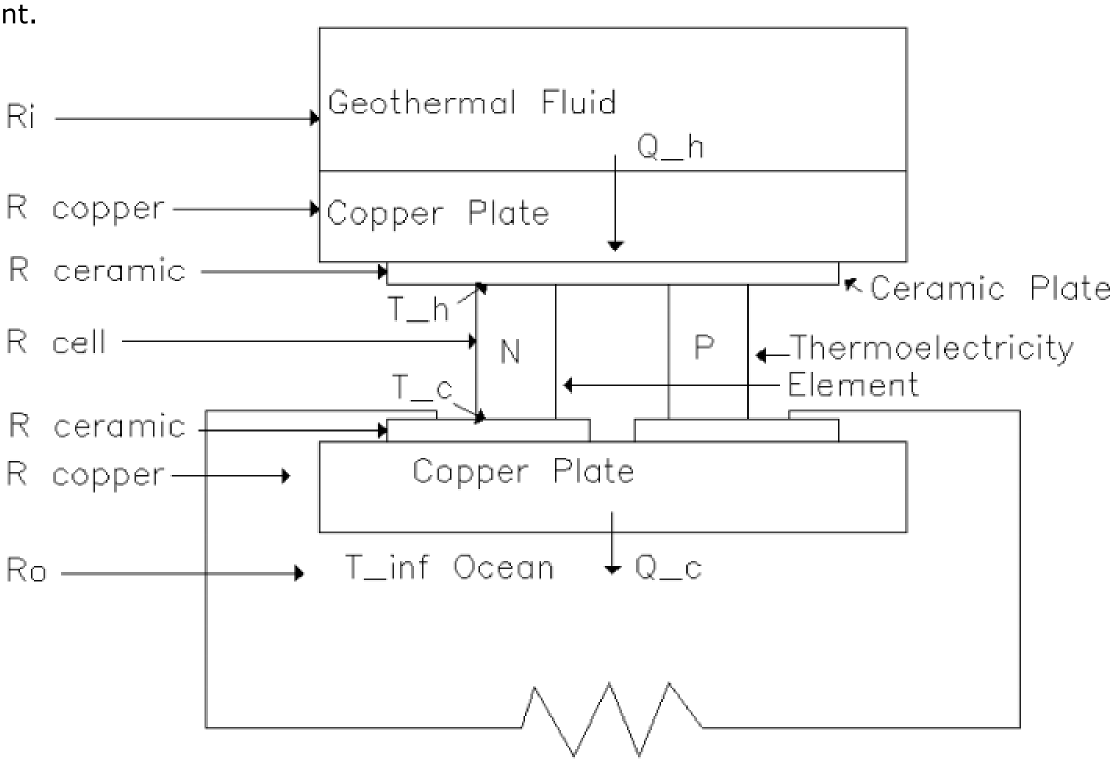


Figure 14: Schematic drawing of a thermoelectric cell [66]

Thermoelectric systems have a high reliability since they contain no movable parts, and the individual cells are all connected in parallel meaning a single cell can malfunction without the system experiencing failure. To increase this reliability the heat flowing into the thermoelectric system should be a clean working fluid like in the binary cycle, separated from the reservoir fluid by a heat exchanger.

Since thermoelectric system are dependent on heat flow and temperature difference, an effective cooling of the heat sinks is of high importance. Local environmental and ecological conditions like ocean currents for cooling and marine growth which can hinder the heat dissipation will be critical factor for system efficiency [19].

6 Power generation options

This chapter will shortly discuss power generation options and locations with their advantages and disadvantages. The results will be presented and compared at the end. The cost, power, and process layout are all, other than Option - 5, based on (Kárason, 2013) [66], where only the depth, location and minor alterations in the setup are changed for the discussion. The cost and performance of each solution will be given based on Kárason's findings, but the aim of this Thesis is only to present the economic feasibility of each solution to give an order of magnitude of the concept and not the finished engineering of them.

The reservoir and wellhead conditions are assumed to be equal to the Reykjanes average the used by Kárason. The casing and wellhead are identical for all the power options.

Assumed wellhead conditions of the Reykjanes average [66]:
Wellhead pressure: 36.2 Bar
Mass flow: 48.1 kg/s
Enthalpy: 1570 kJ/kg
Wellhead depth: 2100 mbsl

6.1 Option 1: Single flash cycle - Platform / FPSO

This option includes the power plant located at sea-level on a platform or Floating Processing, Storage and Offloading (FPSO) ship. These ships are common in the petroleum industry and offer a solution for making mobile non-permanent processing plants.

The single flash power cycle is the most common method of generating electric power from geothermal resources on land [69]. This option places the power plant at sea level on a platform or ship. Two methods for this are discussed below:

- Extending the pipeline up from the wellhead to the power plant at sea level
- Flashing and separating the phases at the seabed

Extending the reservoir pipeline: No flashing is intended as the pipeline up from the wellhead lets the reservoir fluid flow uninterrupted. This option is proposed in [66] with calculation made for a water depth of 300m from the platform to the wellhead. The average depth of oceanic hydrothermal vents is around 2100m [10] so flashing due to pressure loss in the fluid column must be evaluated.

Assuming reservoir conditions as the Reykjanes average and the process cycle shown in the figure below illustrates the process stages of the geothermal fluid coming up from the reservoir, getting separated, drive the turbine, get condensed and reinjected.
The optimal mass flow and pressure for single flash cycle are estimated as [66]:
Optimal turbine inlet pressure: 12,06 bar
Optimal wellhead mass flow: 46,12 kg/s
Optimal turbine steam mass flow: 17,89 kg/s

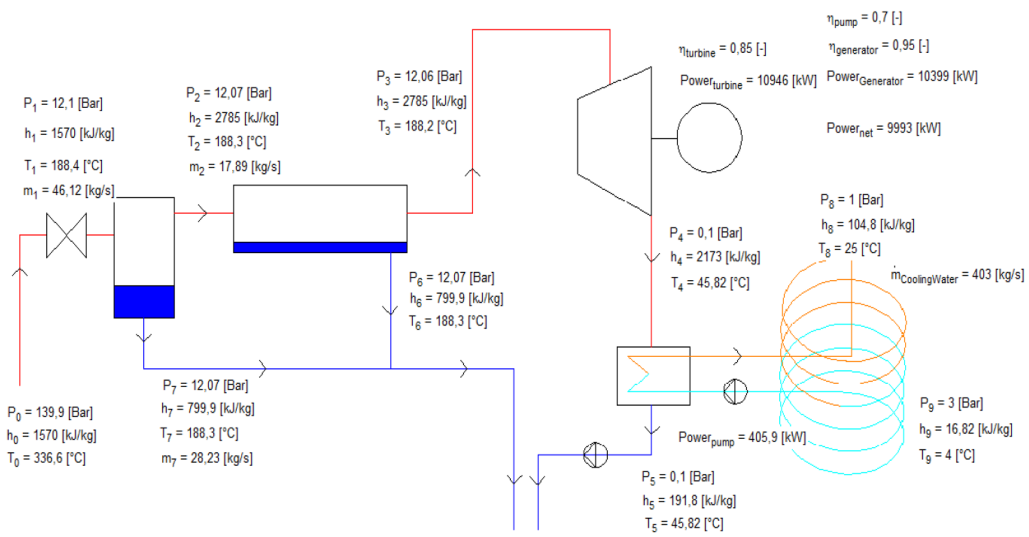


Figure 15 Diagram of the single flash cycle with process data [66]

The depth from the platform to well head is much greater than in the Reykjanes ridge so the pressure drop must be assessed. The pipeline from wellhead to platform is viewed as an extension of the reservoir flow, so a static gas column assessment is made for the 2100m from wellhead to platform. Equation 1 makes the assumptions of ideal gas and constant temperature with clean dry steam [72].

$$P_{top} = P_{bottom} * e^{-\frac{M*g*h}{R*T}} \qquad (1)$$

Using wellhead pressure as stated above, h = 2100m column, molar mass of steam (neglecting brine and NCG) M = 18 kg/kmol, R = 8134 J/kmol*K, and temperature T = 610K.

$$P_{top} = P_{bottom} * e^{-\frac{M*g*h}{R*T}} == 36{,}2 * e^{-\frac{18*9{,}81*2100}{8134*(336{,}6+273)}} = 33{,}6\ bar$$

The turbine on the platform needs 12,06 bar for optimal performance. The pressure drop in the super-heated fluid column is calculated to 2,6 bar.

This analysis is crude and makes assumptions which we know are rough, but a top pressure of 33,6 bar is well above the 12,7 bar needed for the separator inlet. The increased depth is not viewed as a problem for the gas column.
However, the depth will be a challenge due to the hydrostatic depth of:

$$P_{water} = P_{atm} + \rho g h \qquad (2)$$
$$P_{water} = P_{atm} + \rho g h = 101325 + 1028 * 9{,}81 * 2100 = 21.279.153 Pa = 212{,}8 bar$$

The pressure on the riser will need to be addressed in the design.

Once on the platform the process will be the same as in the Reykjanes example [66]. The difference will be in the length of the riser and reinjection line which will increase the cost of the pipeline but should not influence the performance.

The net power of the single flash cycle on platform is calculated under these conditions to be 9,993kW.
Factoring the increased pipeline into the total cost calculated for the single flash platform solution. The cost is $91.501.607 and cost per kW_e is 9156,6$/$kW_e$.

Subsea separation for flashed gas lift:

An alternative to the single flash platform option would be to have the expansion valve and separator located near the wellhead and bring up the flashed fluid to the turbine on the platform. This would require the reinjection pump and infrastructure to be close to the separator. It would possibly be less expensive to install equipment to purify and release the fluid exiting the turbine rather than pipeline for reinjection. Such a system would have to filter 17,89 kg/s at optimal conditions. An extra step in the subsea separator could allow the separation of NCG from the flashed fluid which would both increase turbine performance and reduce the amount of gasses like hydrogen sulfide, ammonia, methane, carbon dioxide, carbonic acids which would have to be dealt with on the platform.

Using the same equation as above and assuming the demister is located near the separator. The pressure out of the seabed demister needs to be 13 bar for the turbine inlet to receive 12,06 bar.

This system alternative is more vulnerable to degradation due to the difficulty of intervention of the separators and injection pump. The turbine, being be the most expensive piece of equipment and the one requiring the most maintenance and monitoring would be on the platform.

The only benefit of this option would be the immediate reinjection of the separated brine and NGC and the freed-up space on the platform. Separators, demister, and pump are relatively simple and could be designed for scheduled replacement to keep system reliability high. The power generated should be unchanged with only the cost/benefit of an extra reinjection pipeline vs the subsea separators and lower platform infrastructure being discussed.

6.2 Option 2: Single flash cycle - Subsea

This alternative has the entire power cycle on the seabed near the wellhead.
This would increase the cost on engineering and manufacturing of the whole system due to the hydrostatic pressure of ~213bar and this is represented with a cost-factor in the final cost estimation. The cost of intervention and replacement will not be covered, but the concerns of corrosion, erosion, scaling and other degradation mechanisms makes this option vulnerable since the whole cycle is in contact with the hot brine reservoir fluid.

The process here is identical to option 1, but with negligible pipelines for transporting the geothermal fluid. The calculations for the power output are identical with the only difference to the net power being reducing the pump head for the cooling water from 50 meters on the platform to 0 meters on the seabed.
The potential benefit of this option will be entirely dependent on how the power is integrated into a subsea field. The value of having it supply processes locally with few transmission cables would be weighed against the increased cost.

With the cooling-pump head reduced from 50m to 0m the net power output at optimal conditions is calculated at 10,269 kW. The cost of transmission lines is neglected in the source calculations, so the total cost is assumed to be the same [66]. The offshore cost factor of 4 is revised to 5 because of the increased depth and pressure when moving from 300mbsl to 2100mbsl. A cost factor of 5 for the power plant increases the total cost to $18.126.576 with the rest of the calculations remaining unchanged.

The new total to $124.576.288 with a total cost per kW_e of 11,381$/$kW_e$.

6.3 Option 3: Binary Rankine cycle - Platform / FPSO

This option has the reservoir fluid flow through a heat exchanger located on the seabed near the wellhead. The heat exchanger vaporizes an organic fluid which flows up to a platform floating at sea level above. The turbine/generator is located on the platform with a riser pipeline circulating the working fluid from the wellhead to the platform.

The benefits of having a closed binary cycle are many, but most of all it makes the concerns of internal material degradation negligible as opposed to the single flash cycle. The binary cycle can be run at a much lower temperature than the single flash cycle [66], [69], and since the heat exchanger utilize the whole reservoir fluid without separation it leads to a higher exergy efficiency. The exergy efficiency of the single flash cycles is <50% compared to 65% for the binary cycle [66].

The figure below shows the process diagram of the binary cycle [66]. The heat exchanger is located on the seabed near the wellhead with methanol as the organic working fluid.

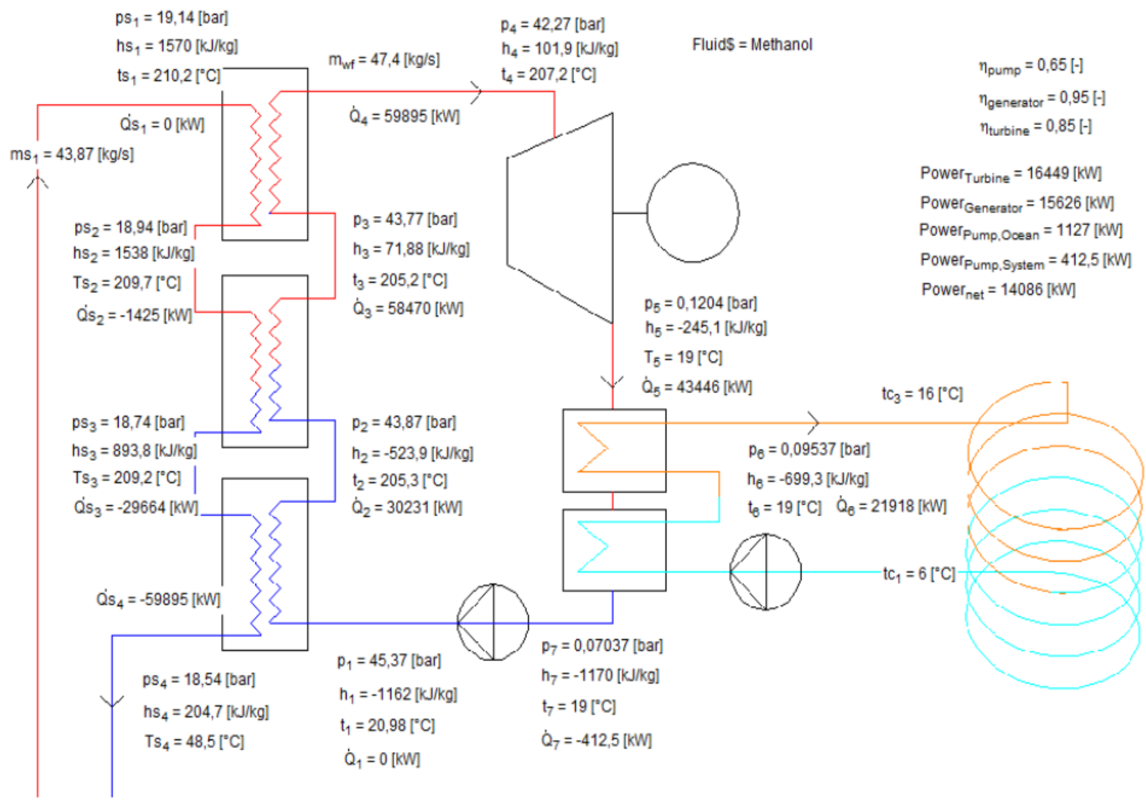


Figure 16: Diagram of the binary cycle with process data [66]

The turbine inlet pressure and pressure differential are higher than in the single flash cycle. Methanol has a higher molecular mass than steam which leads to increased kinetic energy in the fluid.

Performing the same crude pressure analysis using equation 1, the fluid pressure coming out of the heat exchanger needs to be 49,86 bar to give a turbine inlet pressure of 42,27 bar. Pressure drop due to the depth should be negligible, but a concern will be thermal insulation for the riser pipeline.

The topside pressure, enthalpy and mass flow should remain mostly unaffected by the changes in the heat exchanger. At these conditions, the net power output is calculated to 14,086kW. At 2100mbsl the binary cycle would need two lengths of riser pipe to circulate the working fluid. The riser pipe is estimated at 520$/m and the length are 2 * 2100m [66].

The revised cost for pipes is $2.184.000 and an offshore cost factor of 3, the new total cost is then $105.729.601 with a cost per kilowatt of 7506$/$kW_e$.

6.4 Option 4: Binary Rankine cycle - Subsea

This option is not described in (Kárason, 2013) [66]. Estimations for the performance and cost are made based on the assumptions made in the other options.

This option places the entire power plant on the seabed near the wellhead. The Rankine cycle is a closed loop which can be engineered for a high reliability of the internal components. The external concerns are hydrostatic pressure and material degradation. Once in place the system should be considered divided into two major components: The heat exchanger and the Rankine cycle.

The Rankine cycle will be a closed system encapsulated with only the heat exchanger, condenser and reinjection system exposed to seawater. This should give the power plant a high reliability which will be important due to the cost and complexity of intervention.

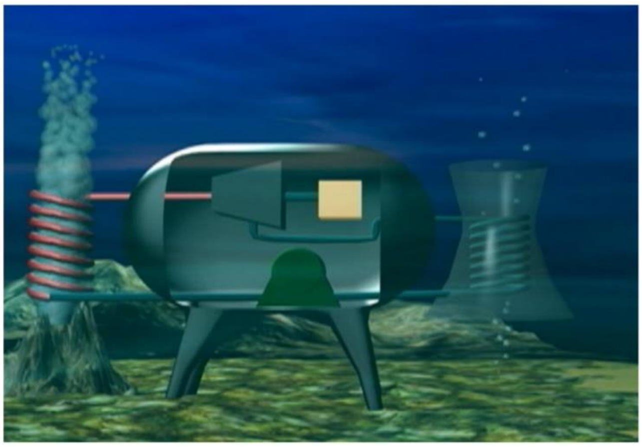
The heat exchanger is as mentioned above, a simpler piece of equipment and will along with the wellheads and reinjection system be the only equipment in direct contact with the reservoir fluid. The reservoir fluid can lead to material degradation like erosion and corrosion, or scaling from minerals like silica (SiO_2) and calcite ($CaCO_3$) [73].

In this design everything is located near the wellhead.
The power generated will be assumed as the same as in the binary cycle on the platform of 14,086 kW_e.

There is negligible cost from pipes and the cost of binary power plant will be the cost of the platform power plant multiplied by and offshore cost factor of 4 like in the single flash calculation. The platform binary plant has an estimated capital cost of $43.014.135. The total cost of a subsea binary power plant is $206.712.938 with a cost per kilowatt of 14,675 $/kW_e$.

6.5 Option 5: Binary Rankine cycle – Hydrothermal submarine

This proposal is based on the IMPULSA project at the Universidad Nacional Autonoma de México (UNAM) which focused on finding new renewable energy sources for desalinating seawater [71]. While the other power options require drilling into a hydrothermal reservoir to extract geothermal fluid, the UNAM project proposes a submarine with an organic Rankine cycle inside. The submarine is to be semi-permanently placed with a heat exchanger above an active hydrothermal vent as illustrated below.



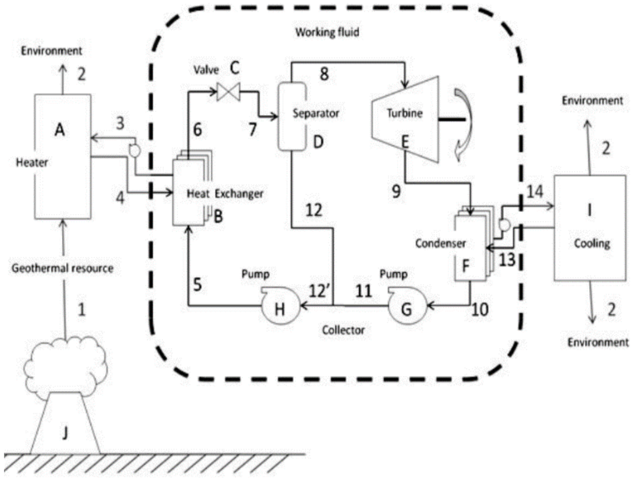


Figure 17 Showing the concept sketch on the left and the concept process diagram on the right of the geothermal submarine power plant [71]

The project focusing on the *"abundance of submarine hydrothermal systems"* within the Mexican EEZ with the intended area of exploitation being the Gulf of California. Based on their consideration that only 1% of the already known sites can be exploited an estimated 130.000MW of potential electric power can be generated using this method [71].

The benefits of using geothermal submarines for power generation is not only the reduced exploration and drilling cost. The sites remain mostly undisturbed since the installation is not permanent. As previously mentioned, active hydrothermal systems are home to unique ecosystems which would be subject to environmental and ecological regulations. The submarine having all its moving components encased inside should be a negligible disturbance to the local ecology.

Since the submarine relies on two heat exchangers the ecology could however be a disturbance to the performance of the power cycle due to marine growth and fouling. This would decrease the heat conduction and potentially reduce performance.

The conclusion of this project was that the potential for electricity generation from one hydrothermal vent is estimated to be up to 20MW using this method. The project makes no estimates towards the cost but mentions a prototype which the literature study for this Thesis can find no results from. If the estimate of 20MW is to be accepted and comparing it to the lowest cost per kilowatt estimated from the other options: the price for the submarine to be competitive with the other options must be: 20.000kW_e * 7506$/$kW_e$= 150 million dollars or less.

6.6 Option 6: Thermoelectric generator

Thermoelectric elements also known as Peltier elements have no moving parts which contributes to its high reliability. Perhaps the best-known use for thermoelectricity is in radioisotope thermoelectric generators which powers satellites, space probes and exploration rovers through the heat form radioactive decay. However, the high reliability of the Peltier element is only contrasted by its low efficiency.

The calculations use data collected at Cardiff University to make assumptions for how much power 1m^2 of thermoelectric elements can produce when supplied by 180°C geothermal fluid and having a 5°C heatsink from sea water [66].
This would be conservative since at wellhead pressure the vapor temperature of water is 244.6°C [74]. At 180°C and expecting mass flow to keep the hot side of the element at this constant temperature an estimated 3,6kW/m^2 is calculated. The thesis assumes that three wells are needed for the mass flow to be enough for the temperature gradient to sustain this performance and this is reflected in the cost analysis [66].

Since circulating geothermal fluid may lead the internal degradation of an otherwise highly reliable system; adding a heat exchanger like in the binary cycles could make this the most reliable of the proposed power solutions. The fluid which circulates within the thermoelectric cell array could be a high boiling point oil or a vaporization cycle at lower pressure.

The area of thermoelectric cells needed to supply power equal to the highest of the other power options would be that of the binary cycle at 14.086kW.
Estimated at 14,086 * 10^3 W_e / 3645,7W/m^2 = 3863m^2

Each cell is 40mm x 40mm. Put into a larger cell the cost for 1m^2 is estimated to 7,368\$/m^2. The total cost is estimated to \$110.270.233 with a cost per kilowatt of 7,828\$/kW_e.

This estimate does not include power needed for circulation or reinjection pumps, or the cost for a heat exchanger or reinjection system.

6.7 Results from power options

The power calculations make many assumptions both for existing and un-developed technologies. For the platform solutions, no riser pipes currently exist which have a maximum operating temperature above 130°C - 150°C [19]. The results of 10MW – 14MW of electrical power being obtainable from one hydrothermal well on the seabed give an order or magnitude indicator for the concept potential. The table below shows the summary of results gathered from the power options.

Power option	Total effect [kW]	Total cost (Dollars)	Cost per kW [$/$\boldsymbol{kW_e}$]
Option 1: Single flash cycle - Platform	9993	91.501.607	9156,6
Option 2: Single flash cycle – Subsea	10.269	124.576.288	11.381
Option 3: Binary cycle - Platform	14.086	105.729.601	7506
Option 4: Binary cycle - Subsea	14.086	206.712.938	14.675
Option 5: Binary cycle - Submarine	20.000	~150.000.000*	7506
Option 6: Thermoelectric	14.086	110.270.233	7828

Table 3 Results from power options.

*The basis for total cost of option 5 is estimated to be competitive with the lowest cost per kW of the other options

The cost of offshore geothermal will have to be compared against the investment and operational cost of other more conventional power alternatives to give a scope of the viability. At 7506 $\$/kW_e$ the binary cycle platform power plant would be the most cost effective if it could be implemented. The table below compares total capacity to completion cost of new land-based power plants reported by the U.S. Energy Information Administration [75]:

Technology	Size [MW]	Total cost per kW [$\$/\boldsymbol{kW_e}$]
Conventional combustion turbine	100	1126
Geothermal (land based):	50	2787
Wind offshore	400	6542
Advanced nuclear	2234	6034

Table 4 Shows cost comparison for different power plant technologies [75]

Conventional combustion turbines are often used to power ship and may be employed to power mineral extraction. They are relatively cheap compared to other power technologies. A 50MW land-based geothermal power plant would cost about 37% of the proposed offshore binary power plant on a platform.

Offshore wind and advanced nuclear would be within the same cost range as offshore geothermal. The Russian nuclear power plant barge Akademik Lomonosov being an example of offshore nuclear power generation. This floating nuclear power plant is powered by two 35MW reactors and has a reported cost of 274 million dollars which gives it a cost per kilowatt of 3914$\$/kW_e$ [76].

7 Discussion

Deep-Sea Mining:

There remains a great deal of uncertainty regarding the environmental and ecological impact from Deep-Sea Mining, as well as the nature of state sponsorship of private companies exploring in international waters and the involvement of private interests in shaping the regulation for exploitation in these waters. The ISA Mining Code still awaiting completion before exploitation contracts can be issued within the international seabed Area. Jamaica is expected to soon be the twenty-second nation involved in exploring marine minerals in the Area. Within territorial waters of coastal states, the Government of Norway is increasingly investing in mapping its marine mineral deposits, and the EU is furthering its Blue Mining project with the current Blue Nodule project viewing marine minerals as a potential sector in its Blue Economy.

The economical cost versus benefit of deep-sea mining has yet to be proven. The literature study of this Thesis could only identify two previous drill sample assays from the mineralized SMS deposits precipitated away from the hydrothermal vent chimney edifices. This precipitant domain makes up most of the area of SMS deposits and non-drilling electromagnetic and seismic mapping are unreliable for determining the thickness and composition of these areas. The two mentioned drill sample assays of this main part of the deposits show lower mineralization than the chimney structure but still within profitable margins for exploitation. More drilling data or data gained from experience through mining efforts will be needed to show if deposits along the Mid-Ocean Ridge system conform to a uniformity or if each deposit will need rigorous drilling programs to assess individually.

The environmental concerns most mentioned are the increase in sedimentation from the mining operation, the noise levels affecting the local fauna, the air-emissions from the mining vessels, and the ecological concerns on ecosystems surrounding the deposits. The ecosystems of active and inactive hydrothermal systems as well as the abyssal plains are not well studied and could be permanently disrupted by mining operations. The unstudied nature of these regions poses the paradox of not knowing how common these unique ecosystems are. As exploration into the size and distribution of marine minerals progress, we are likely to learn more about the ecosystem surrounding them.

Offshore geothermal power:

The cost for the proposed solutions is high but within the order of magnitude of existing power options. The prospect is interesting, but much work needs to be done before offshore geothermal power is more than a fantasy. The Reykjanes ridge average gives a glimpse into what conditions may look like at other locations along the mid-ocean ridge system. At 14MW the binary power options is within the range of a single offshore wind turbine. The remoteness of intervention is a concern even at sea-level so a single power station at 2100mbsl generating the same as a single topside wind turbine would make no sense.

The thermoelectric option is interesting since it has no moving components and could be engineered for high reliability and low intervention. At a comparable price to the binary power cycle on platform, further research could make this viable despite its cost due to the benefit of reliability.

The results of the IDDP-2 and the continuation with the IDDP-3 wells in Iceland will be very interesting when discussing future power generation options with dryer and hotter reservoir steam. If the drilling and exploration costs are reduced while the cost for the subsea power plant stays unchanged and power generated is increased by two- or three-fold. The prospect of these supercritical dry steam wells is interesting for land-based options if scaling and material concern can be addressed.

8 Conclusion

The interest for deep-sea mining and marine minerals seems high from both commercial actors and governments. The potential to find new sources of mineralized materials is evident with observed marine deposits in cases like cobalt. Even at this preliminary exploration stage, by one estimate 1 billion tonnes of cobalt could be present in polymetallic nodules and crusts on the seafloor, with 120 million tonnes observed. Comparing this to the known terrestrial mine deposits of 7 million tonnes we get a sense of the scale of marine minerals. However, no commercial exploitation has so far taken place either in the international Area or within the seabed of costal states. The Government of Papua New Guinea which granted licenses within its territory has since supported a moratorium on mining marine minerals until environmental, ecological, and economical concerns are addressed. Within international waters, Greenpeace in a December 2020 report, raised concerns about the nature of state sponsorship of private companies within the Area and the inclusion of private interest when developing the Mining Code that will govern exploitation in what the U.N. calls *"the common heritage of mankind".* The Mining Code is still unfinished, but the newly reelected Secretary-General of the ISA Michael Lodge has indicated the work progressing. While the potential is apparent the field of deep-sea mining is still in its infancy.

The concept of offshore geothermal power seems technically possible, but with many uncertainties. The technology is missing for the platform-based power options, given that no riser pipes exist for this temperature range of hydrothermal fluid. The results show that the potential from one subsea hydrothermal well can be around the 10MW range for single flash and 14MW for binary cycle given similar conditions as the ones round in the Reykjanes ridge area. If hotter dry steam wells can be constructed, like the one envisioned in the Icelandic Deep Drilling Project, then 35MW to 50MW power stations might possibly be constructed at comparable cost. At its present cost all the power options are unlikely to be competitive with combustion turbine generators which are a proven and reliable, less expensive technology used for power generation offshore. This is unlikely to change in the foreseeable future given the price, government subsidies, and availability of fossil fuel sources. An interesting compassion, however, was that offshore wind and the least expensive of the above-mentioned geothermal power options are withing the same order or magnitude cost range. With its reliability issues, high investment cost, and remoteness in case of intervention, offshore geothermal seems an unlikely candidate for future power generation, at least at large depths.

9 Future work

Deep-Sea Mining:

Development within deep-sea mining seems likely to continue given its current trajectory both with the involvement of governments looking to participate in activities in the international Area and within their own territory. Corporations are being sponsored by national governments to map the feasibility of exploitation and in the case of Papua New Guinea the Government has elected to halt the process to protect its own marine interests. Further studies along the seabed will map both the economic aspects of marine minerals and give a better view into the ecosystem surrounding them.

Future work that would benefit the field:

- The zinc content of SMS deposits is relatively high but have so far not been deemed economically viable for processing due to the low metal price. This may change as terrestrial deposit diminish. An attempt at making zinc concentrate has had encouraging results, with a product high in precious metals that might be upgraded by the established technique of reverse flotation [47]
- New electromagnetic and seismic measuring techniques could identify more inactive SMS deposits. These deposits are often larger than active deposits, but harder to identify
- The total cost for the Nautilus's deep-sea mining system is estimated at 530million dollars. The mining equipment is designed to be reusable and would be financed by the successful completion of the Solwara-1 mining operation. This could increase the profitability of future ventures if the project ever resumes.

Offshore geothermal power:

Offshore geothermal seems unlikely to progress but there is interest in land-based geothermal power with promising results from Iceland where deeper and hotter dry steam wells are being researched.

The calculations for the thermoelectric power plant could be revised to accommodate a heat exchanger and circulation fluid as well as revising the 180°C temperature of the fluid. The Reykjavik Ridge average wellhead pressure of 36.2bar gives an evaporation temperature of 244°C at the given enthalpy. The conservative estimate of the thermoelectric power plant needing three geothermal wells to supply itself also seems high. Adding a heat exchanger could make such a thermoelectric power plant very reliable. The calculations for the thermoelectric option would be interesting to revise with more fidelity. At the expected 14MW for 3863m^2 of cells, a stacked array of 10x10m with 40 layers gives a scale for the size of this power option.

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