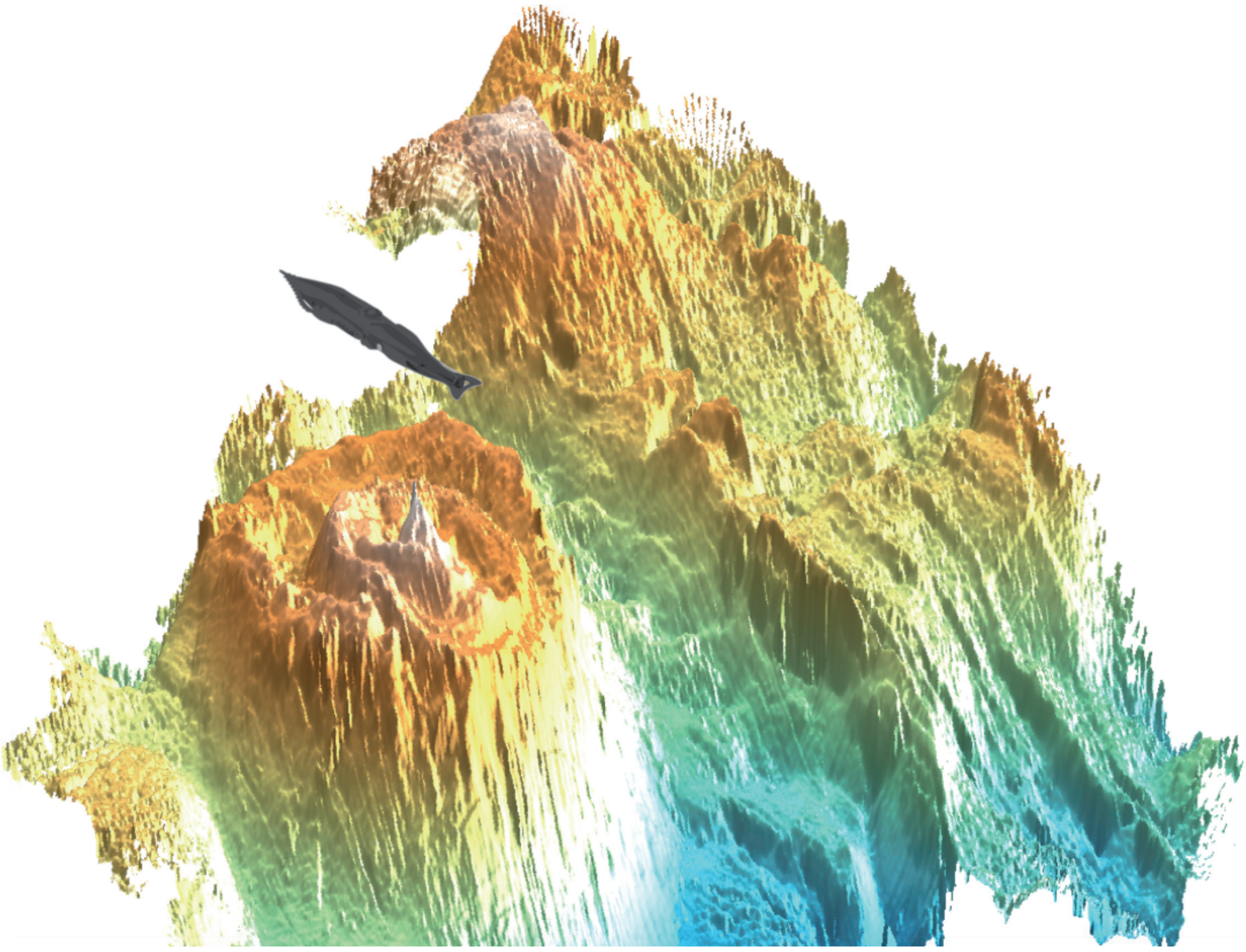
The deep sea energy park: Harvesting hydrothermal energy for seabed exploration



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Lloyd's Register Educational Trust

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- Research – adding value to society by funding research programmes which address fundamental challenges that affect us all."

The deep sea energy park:

Harvesting Hydrothermal Energy For Seabed Exploration

Jorge Parada · Xiangbo Feng · Elena Hauerhof · Ryosuke Suzuki · Usman Abubakar

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ISBN 978-0-854-32953-3

University of Southampton
Highfield, Southampton
SO17 1BJ, England

First published 2012

British Library Cataloguing in Publication Data
A catalogue entry for this title is available from the British Library

ISBN 978-0-854-32951-9

Printed in Great Britain by The Print Centre, University of Southampton

Foreword

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

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

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

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

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

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

Acknowledgements

We are very grateful to all the people that made this book possible. Firstly, we would like to thank Mr Michael Franklin of the LRET for allowing us to pursue this venture. The support of The LRET, and Michael in particular, made this all possible.

We would like to thank Ms Aparna Subaiah-Varma for making our stay in Southampton a rich and memorable experience. Professors Ajit Shenoi and Philip Wilson, our mentors at the University of Southampton, have been responsive in helping and directing our progress. A word of thanks to the group at Ship and Marine Science, and special thanks to Sally, Mirjam, Björn, James, Alex and Richard and special thank for the valuable lessons of Prof. Rachel Mills, Dr. Justin Dix, Dr. Stephen Roberts, Dr. Jon Copley, Prof. Vaughan Pomeroy, Sunil Murlidhar Shastri, Mr. G.S. Chopra and Mr. Mark Stokes.

We appreciate the valuable help from everyone at the National Oceanography Center Southampton (NOCS): Professors Gwen Griffiths, Chief Technologist and Head of the Marine Autonomous and Robotics facility, and Maaten Furlong from the Marine Technology Department; Dr Bramley Murton, Chairman of InterRidge; Prof. Martin Palmer from the School of Ocean and Earth Science; Mr Robin Plumley, Research Ship Manager; Prof. Chia Chuen Kao, Taiwan Ocean Research Institute & National Cheng Kung University.

We had rich discussion and feedback from industry. Martijn Schouten, Managing Director and Rick Lotman, Project Engineer for Deep Sea Dredging & Mining of the IHC Merwede division of Mining; Stef Kapusniak, SMD Project Director for Nautilus Minerals. Also, a word of thanks to the excellent professionals from the oil industry who helped identify and understand the major challenges in deploying our system concepts: Javier Vargas, Senior Technical Professional Cementing, Halliburton; José Luis Pinto Vergara, Wellstream Flexible Products, GE Oil & Gas; and Armando León, from PDVSA Petrocedeño.

Our gratitude also goes out to our fellow scholars of the collegium, for all the time we have enjoyed, on and off topic.

We thank you all,

Jorge, Xiangbo, Elena, Ryosuke and Usman

Executive Summary

Modern society is in growing need of natural resources. Energy security remains one of the greatest challenges that we face. We need increasing amounts of energy, but it is no longer acceptable to supply it at the expense of the environment. In the coming years we will continue our struggle to innovate and discover new sources of clean, cheap and reliable energy. The ocean has vast resources that could contribute to solving our energy needs.

The evolution of the energy market in the coming 50 years requires innovation, strong international cooperation and moderation from consumers. This volume in The LRET collection on seabed exploitation will explore some opportunities of meeting these challenges. The seabed, defined here as the bottom of the ocean, has rich natural reserves including energy, solid minerals, and biogenic resources. Using a scenario planning approach, we determine that energy exploitation from the seabed has the greatest short- and long-term potential.

This volume explores the technological challenges in exploiting the seabed as a source of energy. We show two scenarios exploring an evolution-based strategy for maturing technology needed in seabed energy exploitation. The first is a conservative scenario that imagines the business as usual outcome towards greenhouse gas emissions policy. In this outcome, we imagine the growth of energy technology in ocean research, exploration and prospection. The second scenario explores the outcome of an aggressive policy and integration outcome, reflecting the IEA 450 Scenario. In this outcome, the growth of seabed energy technology derives from offshore geothermal or hydrothermal energy.

Finally, this volume shows the design of a novel application for power generation from the seabed. The system is an Autonomous Observation Node, designed for ocean research, exploration and prospection. Our novel approach for collecting power from the hydrothermal vent fields implements thermoelectric generators. We show preliminary design options, either tapping a temperature gradient directly from the plumes of a hydrothermal vent, or using high-pressure thermosyphons installed in a well on the hydrothermal mounds. These alternatives can provide clean and reliable power with less environmental impact on the surrounding ecosystem. The system design shown in this volume considers the most conservative scenario of growth for energy in the seabed exploitation industry.

We leave the reader with some thoughts. Although the ocean covers approximately 71% of our planet, much of its reserves are yet undiscovered. Any prospect of resource exploitation remains limited by our lack of understanding of the fundamental processes that shape and transform the ocean. Therefore, we need affordable and reliable technology to facilitate long-term scientific observation and exploration of the ocean.

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List of Abbreviations

AUV	Autonomous Underwater Vehicle
BOP	Blow Out Preventer
CDR	Critical Design Review
CS	Continental Shelf
CW	Coastal Waters
CZ	Contiguous Zone
DC	Direct Current
DPS	Dynamic Positioning System
EEZ	Exclusive Economic Zone
EGS	Enhanced or Engineered Geothermal Systems
EIA	Environmental Impact Assessment
EIR	Environmental Inception Report
EIS	Environmental Impact Statement
EL	Exploration Licence
EPR	East Pacific Rise
FAO	Food and Agriculture Organization
ISA	International Seabed Authority
LED	Light Emitting Diode
MAR	Mid-Atlantic Ridge
MD	Measure Depth
MOR	Middle-Ocean Ridge
MRA	Mineral Resources Authority
Ni-MH	Nickel Metal Hydride
NOCS	National Oceanography Centre, Southampton
NWP	North-West Pacific
OH	Open Hole
OOI	Ocean Observatories Initiative

REE	Rare Earth Element
ROV	Remotely Operated Vehicle
RSN	Regional Scale Nodes
SMS	Seafloor Massive Sulphides
SWP	South-West Pacific
TAG	Trans-Atlantic Geotraverse
TEG	Thermoelectric Generator
TRL	Technology Readiness Level
TS	Territorial Sea
TVD	True Vertical Depth
UN	United Nations
UNCLOS	United Nations Convention for the Law of the Sea

1 Resources Needs in the 21st Century

"The ocean is the vast reservoir of Nature"

Jules Verne, Twenty Thousand Leagues Under the Sea

Modern society is in growing need for food, energy, water and minerals. Economic growth and increase in world population are driving demand to the very limits of what the earth can provide for us. Meanwhile, humanity struggles to eradicate hunger, and provide the basic needs of the 1.5 billion people that reportedly live under 1.25 USD per day. For the short term, it seems irremediable that we need more goods and services. However, a long-term outlook requires structural solutions based on sound policies, reliable technologies and social innovation.

Population has reached an astonishing 7 billion[1]. People's basic needs have a marked effect on every level of the world's supply chains. The increasing wealth of emerging economies has evolved into new standards of living, which demand evermore from our planet's land, rivers and forests. We must have an open discussion about our individual roles in the sustainability of our societies. How can we move forward? We have become accustomed to many warnings regarding pollution and global warming and resource scarcity; and social issues like poverty, hunger, crime and traffic. These are only some of the many problems that are common in every country in the world.

Solving our society's intractable problems requires building up more innovative, sustainable and green strategies for development. Sometimes this is within reach of technological breakthroughs. Other times, there is need of new social concepts. In many cases, new political leadership could make great contributions to solving many problems. In retrospect, there has been important progress. Both policies and breakthroughs in technology have influenced an almost twofold increase in the contribution of renewables to the global energy mix from 1999-2009[2]. In the social agenda, for example many regions have made significant progress in eradicating poverty[3]. Much still needs to be done. To tackle our short-term needs, we must look at all opportunities, on land as well as offshore. However, addressing the long-term problems would require a broad view of technology, human behaviour and innovation. We must understand the challenges ahead, when the trends of

[1] http://www.un.org/apps/news/story.asp?NewsID=40257

[2] Eurostat, Renewable energy statistics: *The volume of renewable energy produced within the EU-27 increased overall by 60.2 % between 1999 and 2009, equivalent to an average increase of 4.8 % per annum*

[3] UN Millenium Development Goals Report 2012: *the number of extreme poor in the developing regions fell from over 2 billion in 1990 to less than 1.4 billion in 2008.*

increasing demand and unsustainable production ends. Consumer's attitudes and behaviours in selecting products and facilities also needs guidance, influenced by the more healthy, renewable and recyclable solutions.

The LRET and the University of Southampton have commissioned a group of scholars with the task of exploring the possibilities for seabed exploitation. In the pursuit of this open-ended initiative, the first chapter of this volume summarizes all the resources found in the seabed, detects the issues related to the seabed exploitation, and develops scenarios for the exploitation of these resources. Energy from hydrothermal vents is selected as a target resource, so the second chapter will describe the venting system in detail. In the third chapter, we describe a novel concept to tap the hydrothermal energy using thermoelectric generators. This think-tank exercise will then focus on selecting one of such possible scenarios, and continues by providing a roadmap for technology development. An evolutionary approach is proposed in this roadmap, to expose the challenges and leaps that would be required to achieve such exploitation objective. To conclude our endeavour, the fourth chapter will provide a case application for the concept that could be an instrumental first step, both in the technology direction and in developing our understanding of the vastly unexplored ocean. Chapter 4 will propose an evolutionary approach to solve the exposed challenges in terms of environment assessment, legislation assessment, logistic and costs during the seabed exploitation activities. The conclusions and discussion will end the volume.

This first chapter is structured as follows. The Section 1.1 begins by introducing the definition of seabed and explains the legal context of resource exploitation. The following Section 1.2 presents the resources of the seabed that lie within the initial scope of this volume; it will include energy, minerals and biogenic richness of the seabed. The next Section 1.3 considers all the possible impacts of seabed exploitation to the deep sea environment. Then, the Section 1.4 presents a though experiment, in which the authors try to imagine the possible scenarios in which seabed exploitation could play a role in the world supply chain. Here, the scenario planning approach gives a closer look at the forces that could shape the seabed exploitation industry. We end the Chapter 1 with a discussion and the definition of the scope of this report.

1.1 Defining Seabed Exploitation

The aim of this research is to explore the possibilities for seabed exploitation. A first step in this direction requires a definition of both seabed and exploitation. Firstly, the seabed, also known as the seafloor or ocean floor, is the bottom of the ocean. Secondly, exploitation is any activity aimed at the use of and benefiting from a given resource. Both concepts require further clarification to provide the proper scope to the text that follows.

1.1.1 The Seabed

If we imagine the earth without the ocean, the seabed would be about 71% of the surface. The geographical location of the seabed confines any activity, both legally and technically. Technical limitations arise because the ocean is a challenging environment. Pressure, chemical composition, temperature and light are just a few of the things to consider. Legal limitations exist because the ocean, and the seabed, can be a part of the territorial confines of a country, or is governed by international law. The Law of the Sea is one such international agreement. We use the legal domain in the next lines to help us determine a clear to the question: what is the seabed?

The United Nations Convention on the Law of the Sea is an international agreement established in 1982 resulting from the United Nations Conference on the Law of the Sea (UNCLOS). The Convention defines the legal duties and rights of coastal States extended from an agreed Territorial Sea Baseline (TSB). Each costal State has specific authority within five maritime zones shown in Figure 1-1: Coastal Waters (CW), Territorial Sea (TS), Contiguous Zone (CZ), Exclusive Economic Zone (EEZ), and Continental Shelf (CS). Further, the Convention controls the management of mineral resources and other ocean based activities (UN 1982).

Each coastal State has sovereignty rights to a territorial sea (TS) with a breadth not exceeding 12 nautical miles measured from the baseline. These rights include the marine resources both living and non-living. In addition, a coastal State has certain rights to 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. Hereafter, there is an exclusive economic zone (EEZ) which cannot extend 200 nautical miles from the baseline. The exclusive economic zone 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. Finally, the 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 2500 meter isobath, which is a line connecting the depth of 2500 meters as shown on the Figure 1-2. 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, than the EEZ and the CS cover the same territory (UN 1982).

According to the Convention, the term Area relates to the part of the ocean beyond the legal continental shelf. The Area comprises the seabed and ocean floor and subsoil, which is beyond the limits of national jurisdiction. As stated in the Convention “the Area and its resources are the common heritage of mankind” (UN 1982).

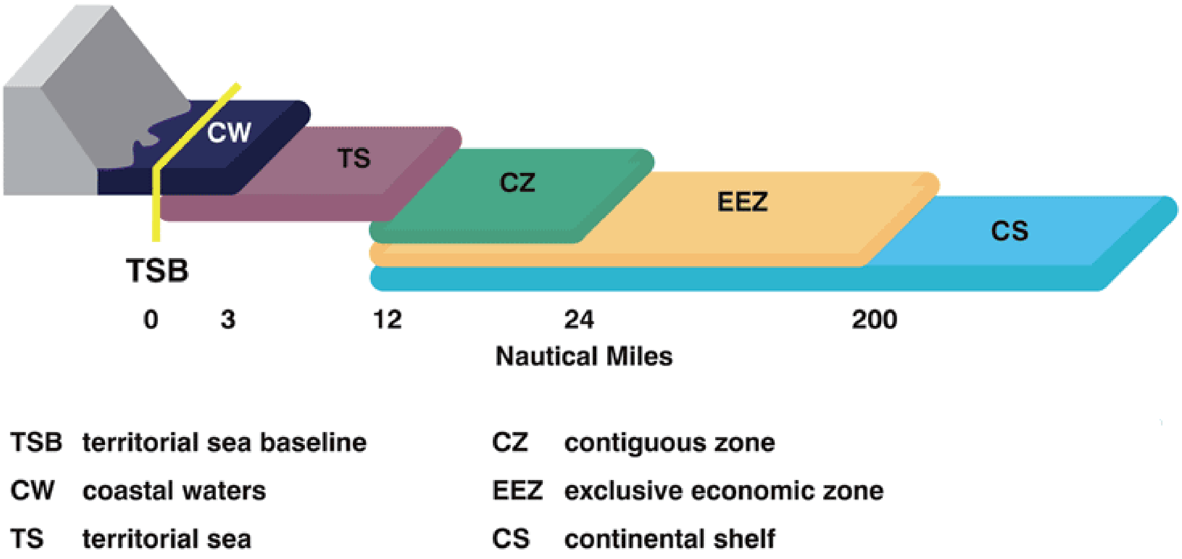


Figure 1-1: Maritime Zones as Defined in the UNCLOS
(Source: http://www.gmat.unsw.edu.au)

The Convention establishes the International Seabed Authority (ISA) in order to organise and control activities in the Area, and in particular to administer its resources. The framework in Figure 1-3 shows the domains of influence of the ISA and its governing regulations. The Authority came into force on the 16th of November of 1994, and its headquarters were based in Kingston, Jamaica. An important role of the International Seabed Authority is to engage in seabed exploration and exploitation activities, employing its commercial arm "Enterprise". Registered organizations, known as *Pioneer Investors*, are allowed to pursuit exploration activities under contract with the Enterprise. No exploitation license has been granted to date for the resources in the Area.

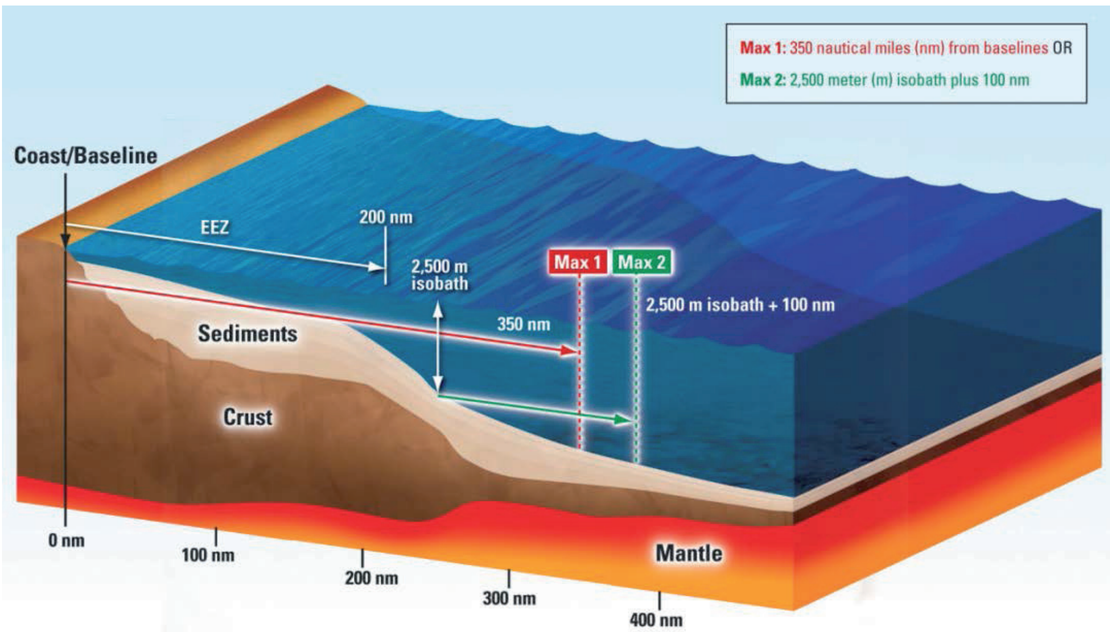


Figure 1-2: Extended Continental Shelf Constrained Lines
(Source: http://continentalshelf.gov)

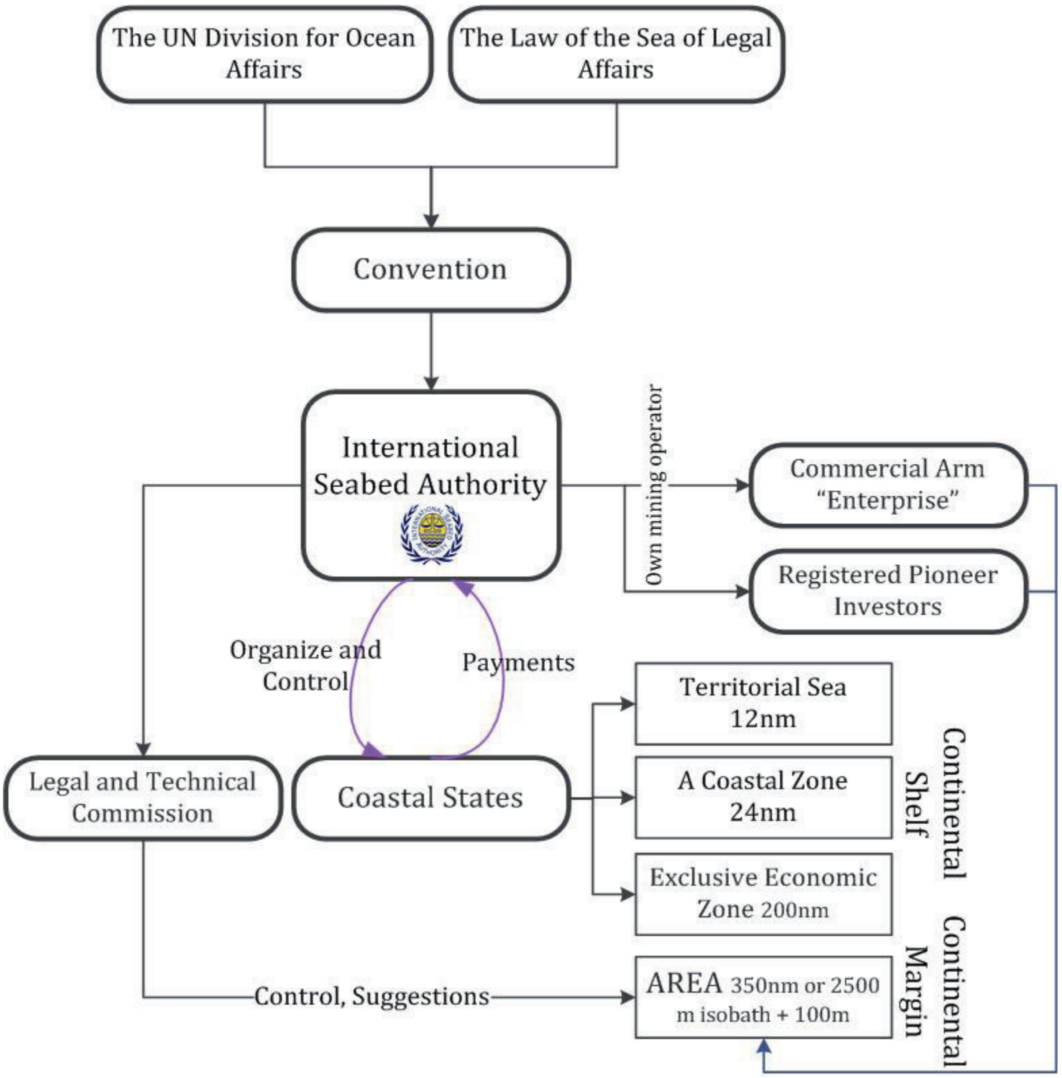


Figure 1-3: International Seabed Authority Framework

1.1.2 Exploitation

Exploitation is the act of using resources for profit. Resources are a means of supporting society and creating wealth. They can be minerals, land, or other natural properties of a country such as water, energy or biological diversity. However, not all resources are economically or technically exploitable. For example, some resources are undiscovered; and others are identified but their exploitation is restricted by legal constraints. The term reserve is used when a resource has been discovered, fully evaluated, and can be commercially and legally extracted. A reserve is a smaller fraction of a country's existing resources, and it is defined as a delineated amount, which we can extract at a profit (Kesler 1994).

Any exploitation activity for seabed resources requires the transformation of the resource into a reserve. Figure 1-4 shows a graphical representation of the relative size of the resources and reserves in the seabed (not scaled). In contrast to onshore resources, a very small part of the seabed resources has been mapped using high-resolution devices.

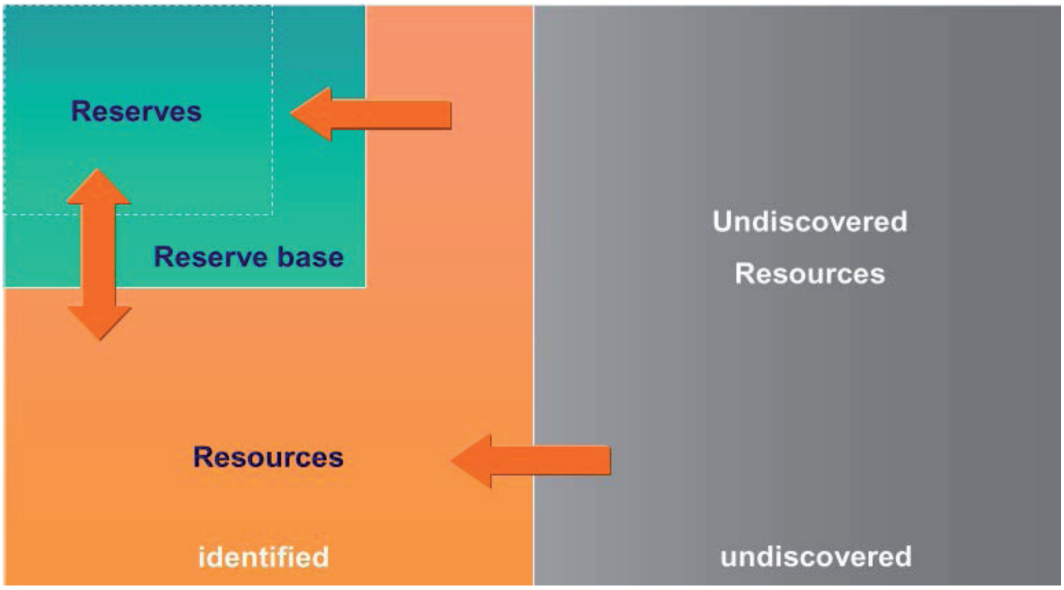


Figure 1-4: Resources and Reserves
(Source: German Federal Institute for Geosciences and Natural Resources)

1.2 Energy, Solid Minerals and Biogenic Resources

This volume will explore the possibilities of seabed exploitation, hydrocarbons excluded. The oil industry was the first to embark in seabed exploitation activities within the EEZ of many nations, and many hydrocarbon resources are already part of national reserves.

We consider the three types of seabed resources listed in Table 1-1: energy, solid minerals and biogenic resources. Firstly, energy in the seabed can be extracted from a wealth of sources: hydrothermal and hydrodynamic energy from hydrothermal vents, hydrostatic pressure from the deep water. Secondly, solid mineral resources include poly-metallic nodules, poly-metallic crusts, poly-metallic massive sulphide deposits, poly-metallic sediments, and marine diamond deposits. Finally, the third type of resource is biogenic, which consists of genetic resources, fisheries and biofuels.

Table 1-1: The Seabed Resources within the Scope of this Research

Major Deep Seabed Recourses	Examples
Energy	• Hydrothermal energy • Geothermal energy • Hydrodynamic • Hydrostatic pressure • Chemical
Solid Minerals	• Poly-metallic nodules • Poly-metallic crusts • Seabed massive sulphides deposits • Poly-metallic sediments • Marine diamonds
Biogenic	• Biogenetic • Biofuels

1.2.1 Energy Resources

Hydrothermal and Geothermal Energy

The water in and around the hydrothermal vent contains vast amount of heat energy. Right under the earth, the molten rock (magma) also contains and stores enormous amount of heat energy termed geothermal energy. This vast source of energy constitutes another form of seabed resource that remains unexploited.

Geothermal energy originates from the Earth's core, which is estimated to have a temperature of about 5,000° C –almost as hot as the surface of the Sun. This energy has been there since the formation of the planet (over 4.5 billion years). Average temperatures increase at a rate of 10° to 30° C for each kilometre of depth in the crust, as shown in Figure 1-5. The rate of increase, called the geothermal gradient, varies considerably among regions. Offshore geothermal power is a possibility, especially in areas where the seabed is already active, making the heat source readily available. It energy source is becoming a reality, and government funding has already started projects, for example in Italy[4].

The process of geothermal power uses drilling to create a deep well. This allows the extraction of hot fluid that is used in a steam cycle. A steam turbine transforms energy in this cycle and generates electricity. Geothermal energy has the potential to become the world's lowest cost source of sustainable, renewable energy. Some estimations suggest that by 2050 they could represent up to 3% of the global energy mix in electricity and account for 5% of the heating (Goldstein et al. 2011).

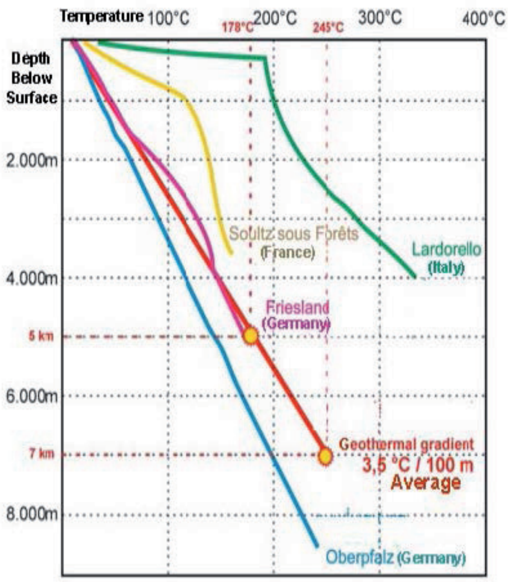


Figure 1-5: Earth's Crust Temperature Profile in Different Places (Adopted from Armani 2012)

[4] www.eurobuilding.it/marsiliproject/

Hydrodynamic

Hydrothermal vents gush high temperature liquid. The possibility to generate electricity from this liquid derives from the extraction of the kinetic energy in the vent fluids. Because vent fumes exit the chimney at flow rates of 2-3m/s, there could be potential for extracting kinetic energy from the fluid.

Hydrostatic Pressure

Water pressure at the deepest point in the ocean is more than 8 tons per square inch. Under the enormous pressures of the deep ocean, seawater can reach very high temperatures without boiling. Temperatures of up to 400°C have been measured at hydrothermal vent sites.

This high pressure is possible because about 362 million square kilometres, or nearly 71% of the Earth's surface is covered by water. More than 97% of our entire planet's water is contained in the ocean. Average ocean depth is about 3,720mbsf, the deepest point is about 11 033mbsf in the Mariana Trench in the western Pacific. One unique feature of this form of resource is that it will continue to avail as long as the water body remains thus relaxing the question of renewability.

1.2.2 Solid Mineral Resources

Figure 1-6 show some major sources of hard minerals on the seabed. Some of the most common sources include. The tables in Appendix A.1-A.5 list some known metal content characteristics of these solid mineral formations.

Polymetallic Nodules

Polymetallic nodules are small potato-sized rocks that contain minerals precipitated from seawater and sediment pore water. The metal accumulation rates are very slow, and it takes millions of years to form a manganese nodule. Figure 1-6 shows these formations partially buried on the surface of sediments, covering vast plains on the deep seafloor at typical water depths of 5 kilometres. Polymetallic nodules can contain up to 40 different metals, including manganese, iron, nickel, copper, aluminium, iron and cobalt. The average concentrations of these metals vary depending of the local characteristics of where they are formed. Table A-1 in Appendix A lists average concentrations of metal content in nodules from different oceans.

Some estimations place the total nodule deposits at 500 billion tons (Archer 1981). In some areas studies assessed the readily recoverable quantities of copper and cobalt to 2.4 billion tons of each element, 3.6 billion tons of nickel, and 96 billion tons of manganese (R. Stein & Walter 1977). The highest metal concentrations in nodules occur in equatorial regions of

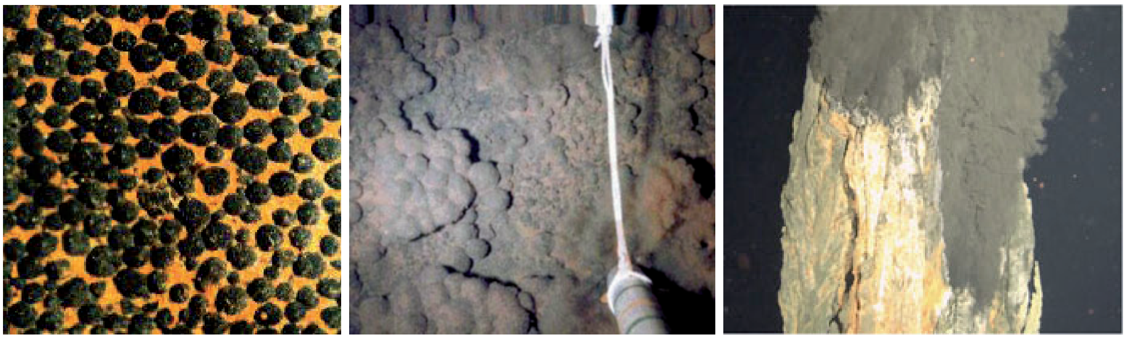


Figure 1-6: Manganese Nodules, Cobalt Crusts and Sulphides on the Seafloor

oceans where the remains of tiny plants and animals sink to the seafloor, dissolve, and release the metals into the pore water of seafloor sediments. Areas of commercial interest include the eastern equatorial Pacific, between the Clarion and Clipperton fracture zones, and the central equatorial Indian Ocean, shown in Figure 1-7 (Rona 2008).

Polymetallic Crusts

Polymetallic crusts, also known as cobalt crusts are shown in Figure 1-6. Minerals form pavements up to 250 mm thick on rock outcrops (Severmann et al. 2004) in water depths of 400 to 4,000 m at the seafloor on the flanks and summits of seamounts, ridges, plateaus, and abyssal hills, where the rocks have been swept clean of sediments at least intermittently for millions of years (Source: National Oceanography Centre).

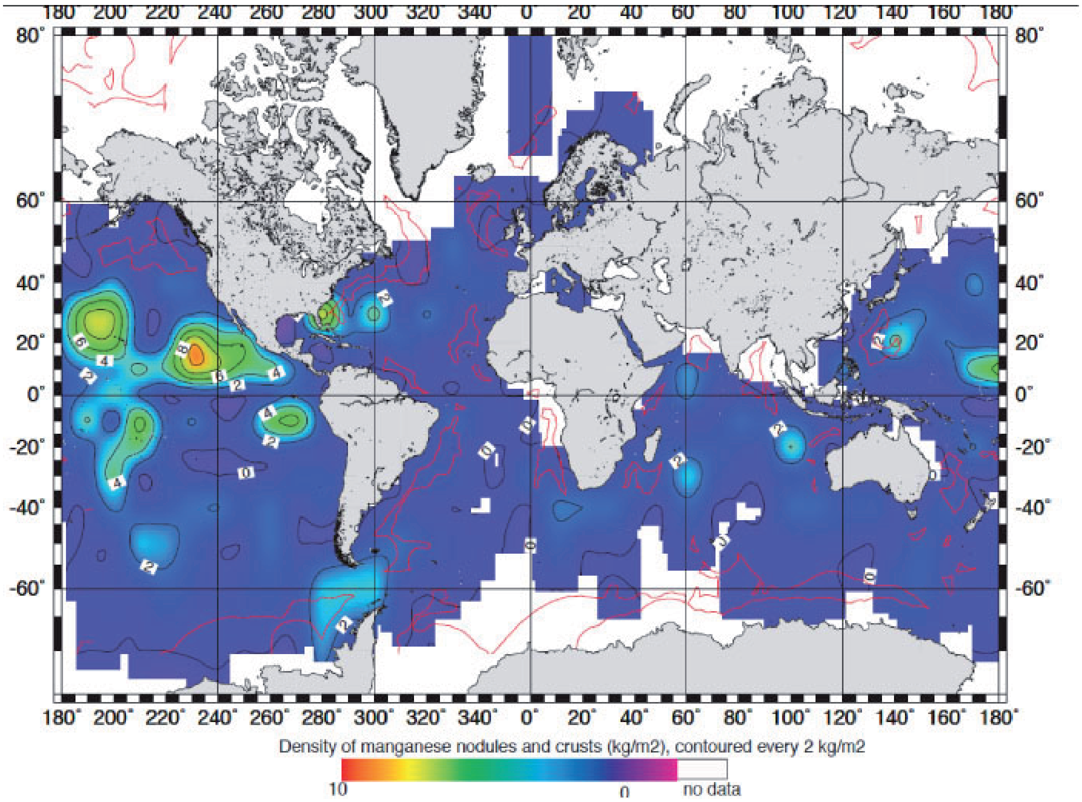


Figure 1-7: Global Distribution of Manganese Nodules and Cobalt Crusts Including the Clarion-Clipperton Zone and Indian Ocean
(Adopted from Rona 2008)

The composition of polymetallic crusts is high in manganese from 13.5 to 26.3 wt. percentage. In addition, crusts can also contain significant amounts of iron, nickel, copper, cobalt, zinc, barium, cerium and other minor metals. The global mean concentration of these elements is listed in Table A-2.

Figure 1-7 shows important areas where rich manganese crusts have been found in the Pacific include the north-west Hawaiian Ridge, Johnston Island, Huwlarid-Baker Islands, Marianas Island, Guam, Marshall Islands, Central Seamounts, Palmyra-Kingman, Micronesia and Wake Island (Manheim 1986).

Seabed Massive Sulphides Deposits

Polymetallic sulphides, also known as massive sulphides, are found at vent fields as shown in Figure 1-6. These formations have high contents of copper, iron, zinc and silver combined as sulphide minerals. They are referred to as massive sulphides, and the term massive pertains to metal content rather than to size or shape of the deposit. Gold and other metals may also be present in lower concentrations. Average concentrations of the minerals in massive sulphide deposits are listed in Appendix A.3.

Massive sulphide bodies are principally found along the earth's major tectonic belts, as indicated in Figure 1-8. Up to 40% of the known deposits occur at shallower depths in back-arc basins and on submarine volcanic ridges within 200 nautical miles of the coast and within the jurisdiction of national exclusive economic zones.

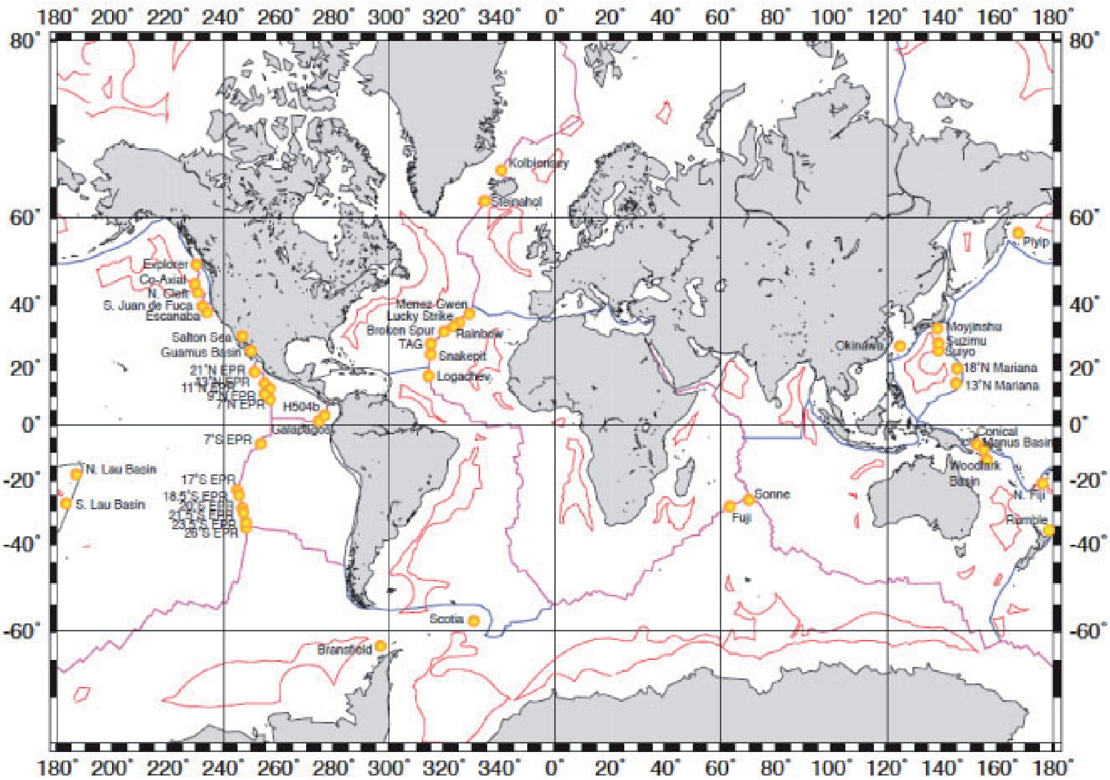


Figure 1-8: Known Occurrences of Polymetallic Sulphide
(Murton 2000)

Polymetallic Sediments

There are many places in the ocean where the processes described above have given rise to metalliferous sediment formation. Most of these are associated with mid-ocean ridge spreading centres, but some have also been found in island arcs. The best examples of metalliferous sediments discovered to date are in the Red Sea where metal rich hydrothermal brines discharge into a number of deeps along the axial rift to give rise, on fractional precipitation, to sulphide deposits containing high grade Cu and Zn, and to metal-rich silicates and oxides precipitated at increasing distances from the sulphides. Resource potential of metalliferous sediments of the Atlantis II Deep, Red Sea, is listed Table A-4.

The metalliferous sediments of the Atlantis II Deep in the northern Red Sea constitute the first hydrothermal deposit (a mineral deposit concentrated by hot, metal rich aqueous solutions) found at a divergent plate boundary in the ocean (Degens and Ross 1970) and remain the most efficient ore-forming system and the largest such deposit found to date. The Atlantis II Deep is a basin roughly 10 kilometres (6.2 miles) in diameter at a water depth of 2 kilometres (1.2 miles). This basin lies on the divergent plate boundary that rifted Africa from the Arabian peninsula about 10 million years ago, and generated lithosphere at a slow full-spreading rate (2 centimetres or 0.8 inches per year) to account for the present width of the northern Red Sea (200 kilometres or 124 miles).

Marine Diamonds

Marine diamond mining takes place primarily along the 1,400 km stretch of coastline of southern Namibia and north-west South Africa. Namibia has the richest known marine diamond deposits in the world, estimated at over 100 million carats. Table A-5 in Appendix A.5 lists some of the operational ocean diamond mining sites.

The diamond content of the deposits varies from 0.15 carat per square metre (ct/m^2) to 2.45 ct/m2 for corresponding sediment thicknesses of 1-6m (UN 2004). Corresponding grades by weight are approximately 0.07 to 0.28 carat per metric ton (ct/t). Richer deposits have been reported with 1.00 ct/t. The diamonds are of 95 per cent gem quality, with the stones weighing 0.3 to 0.7 ct on average, with a value of $150 to $400 per carat.

1.2.3 Biofuels and Biogenetic Resources

As the name suggest, biogenic resources originate from bacteria, plants and animals on the seabed. There is great interest in the unique biodiversity on the seabed particularly in their genetic makeup. It is perceived that this kind of biomass surviving under such extreme conditions could possess some DNA structure and composition that may revolutionize medicine (W Fenical 1996; W Fenical 1993; Bhavya et al. 2012). *Bioprospecting* is a term used to describe the process of exploration for biogenic resource exploitation (UNU-IAS 2005).

The oceans are a cooking pot of life. The largest share of the ocean's biomass lives in the top layers of the oceans. There, it is fuelled by the sun's energy that reaches the shallower water, just hundreds of meters below the surface. At greater depth, biodiversity is constrained by the small amounts of available energy. In the deep sea however, an explosion of life appears in places called the deep ocean ridges. Fields of hydrothermal vents in the deep seas can sustain a wealth of life that is only starting to be understood by the scientific community.

1.3 Environmental Considerations

1.3.1 Protecting the Marine Environment

Van Dover exposes three scientific reasons for deferring commercial exploitation of mineral resources in deep-sea hydrothermal vents: firstly, we still have much to learn about the ocean; secondly, there is a lack of strategies for environmental impact assessment in the deep seas; and thirdly, mitigation strategies do not exist. These reasons could well apply to any exploitation activity in other areas of the sea. Scientists suggest that we still need to place the proper regulations and control mechanisms to guarantee an environmentally conscious and sustainable use of ocean resources.

It is difficult to build up a strategy to assess the environmental impact of any seabed exploitation activity, mainly because operation technologies are different. They remain on a conceptual stage. Even for resources that are closer to our daily life, such as food from fisheries of sea-farming activities, have suffered from a lack of an integrated framework for environmental impact assessment and mitigation. In 2009 for example, 30% of the 395 fish stocks monitored by coastal states were found to be overexploited; and 57% of the catches were very close to the limits of sustainable exploitation (UN 2012).

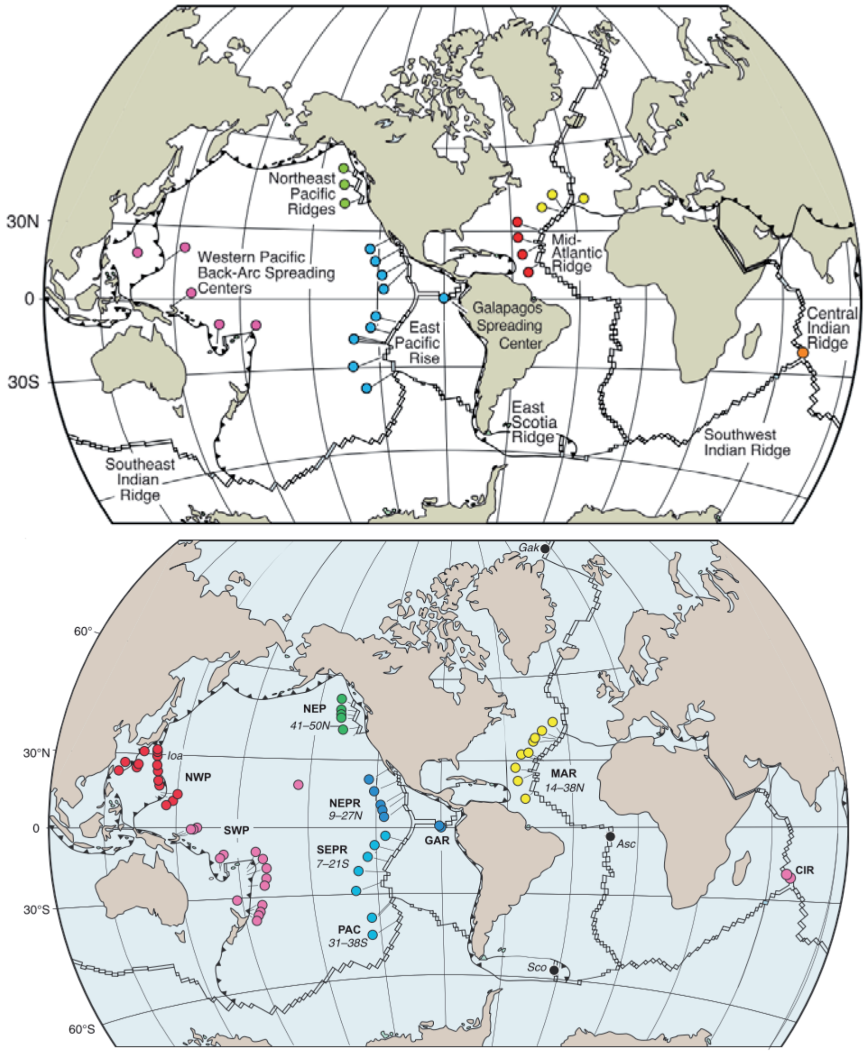
Ecological Issue

Conservation of the marine environment is important. The ocean supports a wealth of creatures that are only beginning to be understood, as is evident in the rate of discovery of these so-called biogeographic provinces shown in Figure 1-9. The maps of Figure 1-9 contrast the data from hydrothermal vents that have been discovered in a period of only eight years between the selected publications. Notice the remarkable rate of discoveries at the North-West Pacific (NWP), the South-West Pacific (SWP) and the Mid-Atlantic Ridge (MAR).

The issue for ecology is the impact of seabed exploitation on the ecosystem and biodiversity. It is still unknown to what extend exploitation will destroy and lead to the reduction of species. In some area of the seabed, the habitants are unique and local. Table 1-2 shows the species found at hydrothermal vent fields in different regions.

Resource Issue

The definition and discovery of a resource sometimes depends on people's recognition on the use of that particular resource. People in the future may very well need a resource of no value or use today. Therefore, all of the resources in the seabed are potentially necessary for society. From food to hydrocarbon fuels, we are already dependant in offshore resources for a good deal of our economies and livelihoods. Preservation is important, and sustainable resource exploitation should be a top priority.



(a)

(b)

Figure 1-9: Maps of Known Hydrothermal Vent Biogeographic Provinces

(a) Known provinces in 2002 and in (b) updated with data from 2009-2010. Legend: green, northeast Pacific (NEP) ridge system; dark blue, northern East Pacific Rise (NEPR) + Galapagos Rift (GAR); lighter blue, southern East Pacific Rise (SEPR) and Pacific-Antarctic Ridge (PAC); red, north-west Pacific (NWP); pink, southwest Pacific (SWP) + central Indian Ridge (CIR)

Table 1-2: The Unique Animals at Hydrothermal Vent Fields

Area	Biomass
East Pacific Rise	Pompeii worm, Siboglinid tubeworm, Bathymodiolin mussel
Mid-Atlantic Ridge	Vent shrimp, Vent anemone, Bathymodiolin mussel
East Scotia Ridge	Hoff crabs, Peltospirid n. sp. Seven-armed seastar, Vulcsnolepas n. sp.
Cayman Trough	Rimicarishybisae, Zoarcid fish, Lysianassoid amphipod
SW Indian Ridge	Scaly-foot, Rimicariskairei

Legal Issue

In order to minimize environmental effects from seabed exploitation, many international organizations have made the first steps in the direction of environmental laws or guidelines. The United Nations Convention on the Law of the Sea (UNCLOS) is an example of a legal framework of international scope that regulates exploitation activities. The International Seabed Authority (ISA) was instituted, which duty is "to ensure effective protection of the marine environment from harmful effects which may arise from mining-related activities in the Area" (UN 1982). In addition, the ISA has already developed regulations to govern prospecting and exploration for polymetallic nodules and is in the process of developing a regulatory regime for exploration for new types of resources, including polymetallic sulphides and cobalt-rich crusts (OREM/ISA 2007; ISA 2011). According to Van Dover (2011), extracting minerals from sea-floor vents should not go ahead without a coherent conservation framework (CL Van Dover 2011).

1.3.2 Exploitation Activities and Impact Assessment

There are many kinds of seabed resources, and in turn, there are many different exploitation activities that might be implemented on the seabed. Table 1-3 shows a summary of the possible impacts of seabed exploitation on the environment.

1.4 When will the time be right for exploiting the seabed?

It is very difficult to identify prospective ventures in seabed exploitation. When will the time be right for exploiting seabed energy? When will the time be right for mining solid minerals from the seabed? When will the time be right for seabed biogenic resource exploitation? We have to know what resources will be more important for the future. In addition, there is a great deal of uncertainty around the prospect of exploiting the proposed resources in the seabed. We use scenario planning as a tool for approaching this problem.

Table 1-3 Environmental Impact of Seabed Exploitation

Resource	Risky operation	Environmental impact	Remarks
Energy (geothermal energy / hydrothermal energy)	• Return waste water to underground • Release of cooled exhaust • Raise of hot liquids	• Landslides; change the underground structure because of raise the hot water and return of waste-water • Earthquake • Pollution of underground water • Air pollution; emission of waste water gas from the seabed cracks • Pollution of surface layer ground; congelation of waste-water • Reduction of hot springs	• Seriousness of poisonous waste water is already known (Japan & Italy, the Philippines) • Thus, the environmental impact of offshore geothermal generation (hydrothermal generation) would be smaller than onshore one.
Mineral (seabed mining)	• Mineral collecting minerals • Transport slurry (riser) • The discharge of waste water from the mining ship • Onshore processing • Operational error	• Buried in and around the tracks • Smothering by sediment resettlement • Change the temperature in ocean surface and seabed • Mix of the biomass • Interfere with light penetration • Reduce photosynthesis • Gas emission (SOx, NOx) • CO2 emission from operation • Noise	• 80 % of the total biomass in the oceans is found in the surface layer • Some seabed species take over a decade to re-colonization • Sudden temperature changes effect on mortality. • Other estimations establish that there is no large impact.
Biogenic	• Indiscriminate harvest • Collector units	• Reduction of oxygen in seabed • Temperature change in the ocean • Destruction of ecosystem • Damage from collector units	• Compared other seabed technology, environmental impact from biofuels would smaller. • Once some species in seabed die out, it takes over a decade to re-colonize.

1.4.1 Scenario Planning

Scenario planning is a tool for strategic planning that allows one to imagine a few possible futures. With this structured approach, one simplifies the avalanche of data into a number of possible states. The scenarios obtained using this tool represent extreme worlds that can help us understand how the future may unfold (Schoemaker 1995).

Figure 1-10 shows the scenario planning process used in this research. Firstly, we define the scope, and set the period for the analysis. Next, we identify the stakeholders, basic trends and key uncertainties. Stakeholders are those individuals or organizations who will have an interest in the problem. The basic trends are those that affect the problem, and they can be political, economic, social, environmental, legal, technological and industry trends. Key uncertainties are events whose put comes are uncertain. Existing relevant scenarios can be used to assist the identification process.

Following step three of the scenario planning process, we construct extreme worlds and business as usual scenarios. In extreme worlds, we separate the negative trends and the positive trends relative to business as usual –how things would be if current trends remain. We check for consistency by performing expert interviews and group meetings in step 4. Finally, in step five one attempts to quantify and qualify the key forces of each scenario to develop the final scenarios.

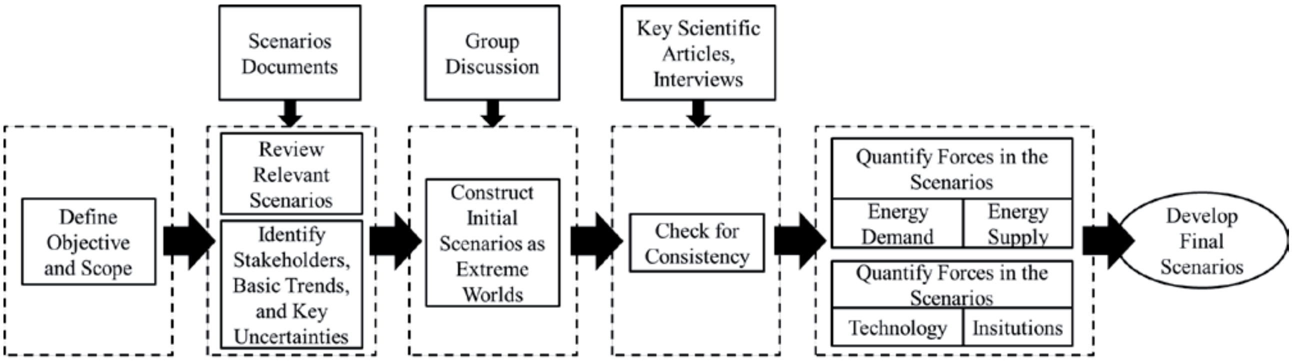


Figure 1-10: The Scenario Planning Process
(Modified from Weidenaar et al. 2012)

1.4.2 Objective and Scope

The scenario planning approach will be used to develop scenarios that help determine the opportunities for seabed exploitation within the timeframe of 2050. The benefits of this approach for the current research are threefold. Firstly, with these scenarios one can establish clear research objectives around a particular resource, and therefore fulfil the project requirement of seabed exploitation. Secondly, it will help this research group to establish a technology baseline needed for exploiting an identified resource, and therefore engage in the system development process. Finally, with the scenario results the research will develop a technology maturity framework to guide the evolution of the required technology for by 2050.

1.4.3 Existing Scenarios

Energy Scenarios

Figure 1-11 shows several projected scenarios for future energy supply. Shell proposed two scenarios called *Scramble* and *Blueprint* (Shell International BV 2008). The key force in these scenarios is the degree of international cooperation that would actively seek solutions to the problems of global warming, resource scarcity and population growth. The 2011

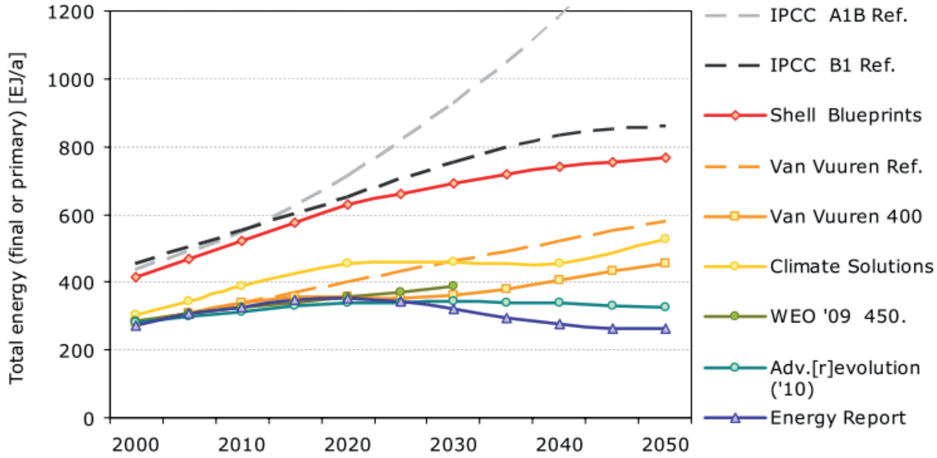


Figure 1-11: Comparison of Demand and Supply in Energy Scenarios

(Adopted from WWF 2010)

revision of the Shell scenarios introduces four key forces: (environmental) regulation –after the Macondo incident, restoration of Iraq, natural gas and the economic crisis (Shell International BV. 2011).

BP's most likely scenario proposes evolution of the energy market for the year 2030 (BP 2012). Policy, technology, the economy appear as key forces around the uncertain growth of China and India in the energy market, the exports of the Middle East and the impact of clean transportation as a driver for energy demand.

The IEA proposes four scenarios in each of their Market Outlook & Technology Perspectives (IEA 2011; IEA 2012). These scenarios are built around mitigation of GHG emissions. The central scenario of the WEO-2011 is the New Policies Scenario. Key forces are the implementation of government policies.

On technology perspectives IEA, propose a BLUE Map Scenario, and other three scenarios limiting long-term global temperature increases of 2°C, 4°C and 6°C. Major uncertainties include maturity of clean energy technology, policy and investment.

The WWF Ecofys Scenario explores an aggressive option for total substitution of non-renewable fuels for the year 2050 (WWF 2010). Bioenergy sustainability is a key factor of the Ecofys scenario. Key actors to enable this scenario include two main stakeholders: public bodies and private actors. Public bodies have the role of levelling the playing field and investment, while private actors have the role of channelling investments and following best practices for energy efficiency.

Mineral Resource Scenarios

Outlooks on mineral resource scenarios generally consider resource scarcity as key force acting on the market. Some commodities are affected by the surge of new clean energy technologies, around which there still remains a great deal of uncertainty, for example market penetration for electric cars. Around the specific theme of mineral resource exploitation key forces such as policy, investment, exploration, technology and social acceptance appear as the key forces, both uncertain and with high impact, that determine the start-up of the industry.

In the case of mineral resources, uncertainties in the playing field are much higher. Each country, depending on the local and regional characteristics of their industry, has a different assessment of criticality fort the market of mineral commodities. A general approach is to consider two drivers: economic attractiveness and supply risk.

The US Department of Energy (DOE) Reference & Policy Based scenarios explore the role of rare earth metals and other materials in the clean energy economy. DOE scenarios base some of their assumptions on IEA's ETP 2012 and WEO 2009 scenarios, because of the interactions of clean energy initiatives and the materials required for implementing clean energy technologies. The key force is resource scarcity (DOE 2010).

The EU scenario (EC 2010) presents a similar analysis on the perspective of mineral commodities which are linked to clean energy technologies. For example, a scenario analysis for Lithium in transportation technology provides input for determining the possible scenarios for 2030 lithium demand. Technological change is seen as the key force driving criticality of raw materials.

Finally, the Blue Growth report scenarios give a relevant perspective specific to the seabed exploitation industry. Four scenarios explore the possible outcomes of EU policy-making towards the seabed exploitation industry. The key forces identified are EU policy, risk investment, uncharted exploration results, technology, social acceptance (EC 2012). Table 1-4 lists the non-exhaustive review of some existing relevant scenarios. The research was unfruitful in identifying existing studies with scenarios that relate to exploitation of biogenic resources.

Biogenic Resource Scenarios

Our research did not find existing scenarios that could be linked directly to the exploitation of seabed biogenic resources. The word bio-prospecting is used to describe the search for economically valuable genetic and biochemical resources from nature (UNU-IAS 2005). The UNU-IAS Report (2005) discussed the role of scientific knowledge and active exploration as a necessary step for the identification of the biogenic resources of the seas. This activity is gaining importance and we identify some possible trends, forces and key forces in Figure 1-17. However, lack of substantial reference data has dimmed it impossible for the research to develop a full scenario for analysis.

Table 1-4: Existing Scenarios for Energy, Mineral and Biogenic Resources

Resource	Organization	Description	Scenarios	Key forces
Energy	Shell	Shell Energy Scenarios to 2050	Scramble & blueprint	Global warming, resource scarcity, population growth
	BP	BP Energy Outlook	Most likely	Policy, technology, economy
	IEA	World Energy Outlook	450, current policies, new policies, deferred investment, low nuclear	Policy action
	IEA	Energy Technology Perspectives	6°C Scenario (6DS), 4°C Scenario (4DS), 2°C Scenario (2DS), BLUE Map Scenario	GHG emissions, energy efficiency
	WWF	The renewable energy report. 100% renewable energy by 2050	Ecofys Scenario	Lifestyles, energy efficiency, electrification, sustainable sourcing of bioenergy, cost advantages
Mineral	DOE	US Department of Energy Critical Materials Strategy	Reference & policy based Scenarios	Perceived resource scarcity
	ECEI	Critical raw materials for the EU	EU scenario	Perceived resource scarcity, future of technological change
	Fraunhofer ISI	Lithium für Zukunftstechnologien	Pluralism & dominance scenarios	Market penetration for electric cars
	EC/DG MARE	Blue Growth	Nothing, squeeze out, EU supplier & EU control Scenarios	EU policy, risk investment, uncharted exploration results, technology, social acceptance
Biogenic	-	-	-	-

1.4.4 Trends, Forces and Key Forces Affecting Seabed Exploitation

Trends forces and key forces shape the scenario planning process. Trends are patterns that can be found in data about the scenarios. Trends have the least amount of uncertainty and can have a high impact. Forces are those factors that can modify trends. Key uncertainties appear when the impact of a force is high and we look far into the future, introducing more uncertainty. These definitions are graphically represented in **Figure 1-12**.

Global Trends

Two global trends considered are the increase in population and growth. The steep ascent of population following WWII has continued to the almost 7 billion people in our planet today.

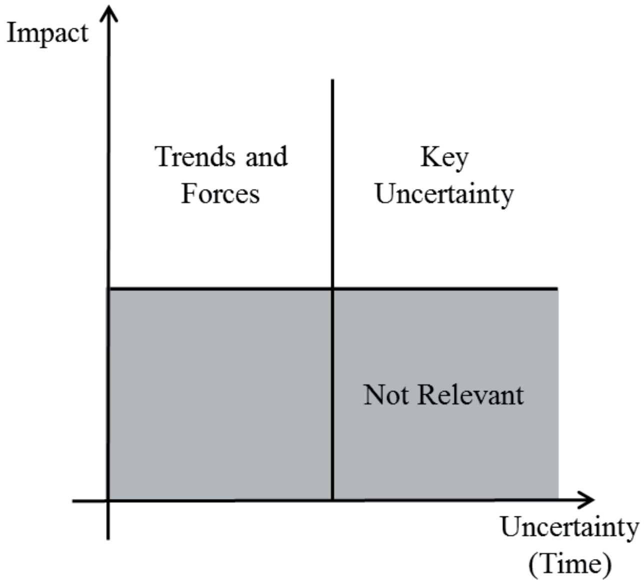


Figure 1-12: Trends, Forces and Key Forces in the Scenario Planning Method

The so-called developing economies, such as China and India, have grown in population much more than the developed nations of the world. Figure 1-13 shows a rough estimation of population growth starting around 2 billion people in the turn of the 1900s until in 1950 the first UN world data estimation was available. By the year 1987 population had doubled.

According to the UN World Population Prospects 2010 Revision, population could keep growing to 9.3 billion in 2050, as shown in the medium variant of Figure 1-13. In this estimate, population growth should stabilize around the year 2050. A low variant suggests a decline in population growth starting in the second quarter of the 21st century. High variant and constant fertility estimates suggest an explosion in population growth, which could reach more than 25 billion people by the turn of the century (UN/DESA 2010).

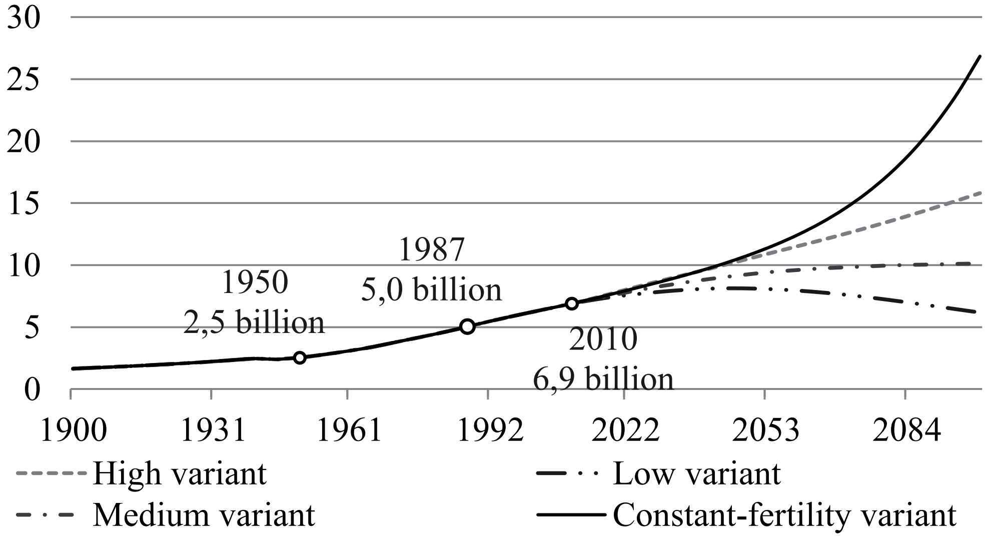


Figure 1-13: World Population Estimates
(Source: UN/DESA, 2010)

Demographics are an important part of world demand for food, water, minerals and energy. A good example of the impact of demographics on demand for biogenic resources is agriculture. Increase in population has undoubtedly been a major driver of demand for food, water and many other goods and services. This has a direct effect on the food supply chain; for example, demand for nitrogen, phosphorus and potassium provided by the fertilizer industry for agriculture is expected to increased 9% by 2016 compared to 2011 production (Heffer & Prud'homme 2012). According the United Nations Food and Agriculture Organization (FAO) a "slowdown in world population growth and the attainment of a peak of total population shortly after the middle of this century will certainly contribute to easing the rate at which pressures are mounting on resources and the broader environment from the expansion and intensification of agriculture" (FAO 2006).

The growth of wealth in the past decade has reflected in an increasing need for more of our natural resources. Economic growth starts in a household, where a family can perhaps have a better job, increased pay, or where perhaps more than one individual can work to provide a living. The increase in income could for example afford a house, white line, or jewellery. These goods in turn create demand for steel, copper, nickel, gold, silver or diamonds. As the market keeps purchasing, industry will respond with a steady flow of supply.

Figure 1-14 shows how the global GDP has almost doubled in the last 10 years. Economic growth has been traditionally skewed towards the US and Europe. Economies in East Asia & Pacific region, Latin America & Caribbean and the Middle East & North Africa represent about 30% of the total World GDP. The fastest growing economies are Brazil, Russia, India, China and South Africa (BRICS).

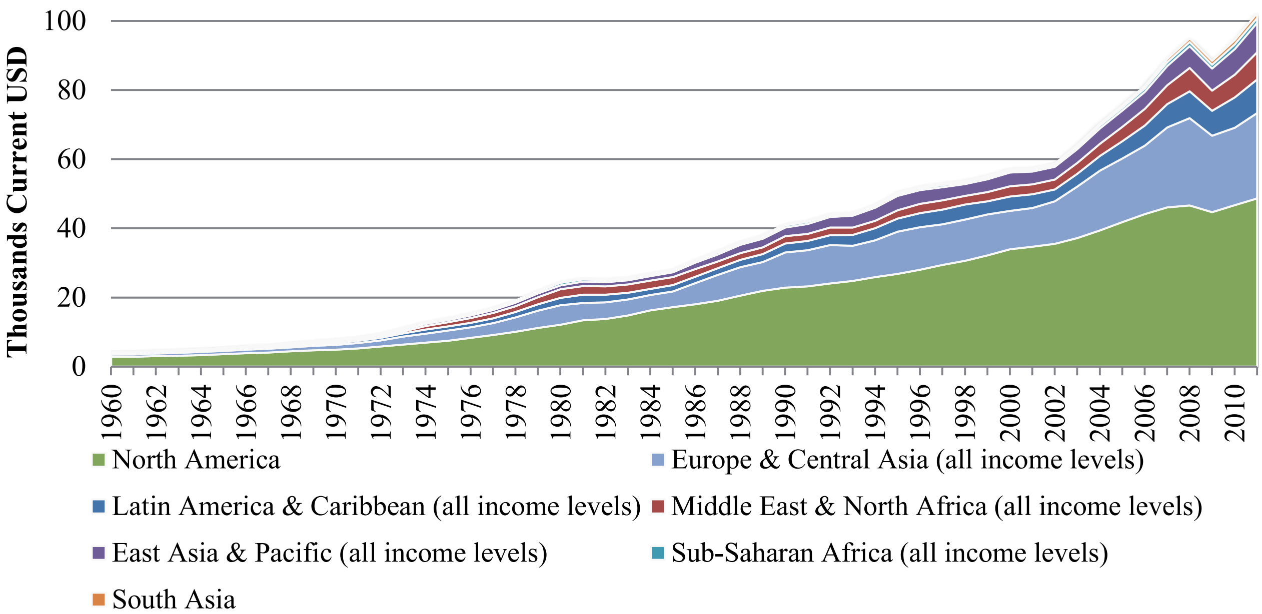


Figure 1-14: GDP per Capita
(Source: World Bank, 2011).

Forces and Key Forces

From the cited energy scenarios, we identify in Figure 1-16 the following key forces that have both a high impact and high uncertainty. Perceived resource scarcity; mitigation of GHG emissions; the role of emerging economies in the balance of demand; influence on the global energy mix; the role of renewable technologies; and the success of new ventures in the exploitation of seabed energy resources. For mineral exploitation, the driving forces are listed in Figure 1-16. Respectively, we identify in Figure 1-17 the trends, forces, and key forces acting on the prospect of seabed biogenic exploitation.

Trends	Forces	Key forces
Increasing population	World energy demand	Scarcity
Increasing GDP	Supply availability	Green House Gas (GHG) mitigation
Increasing electricity demand	Technology evolution	Emerging economies
Construction industry growing	Policy evolution	Renewables
No cheap oil	Changes in lifestyle	Success of new ventures
Increasing renewables in energy mix		

Figure 1-15: Trends, Forces and Key Uncertainties Around the Exploitation of Energy Resources from the Seabed

Trends	Forces	Key forces
Increasing population	Scarcity	Political determination
Increasing GDP	Supply availability	Discoveries of new deposits
Increasing market share of clean energy technologies	Technology evolution	Success of new ventures
Increase in mineral commodity demand	Policy evolution	Legal framework
Increasing interest on seabed exploitation	Price spikes & hog cycles	Financial risk
	Renewables	Technology markets affecting demand
	Environmental	
	Mining technology	

Figure 1-16: Trends, Forces and Key Uncertainties around the Exploitation of Mineral Resources from the Seabed

Trends	Forces	Key forces
Increasing population	Policy evolution	Political determination
Increasing GDP	Disease control	Discoveries
Increasing antibiotic resistance	Environmental	Legal framework
Aging population	Exploration technology	
Infant mortality		

Figure 1-17: Trends, Forces and Key Uncertainties around the Exploitation of Biogenic Resources from the Seabed

1.4.5 Scenarios for Seabed Exploitation

Seabed Energy Scenarios

Figure 1-18 shows two examples of scenarios for the energy market. We use two extreme energy scenarios to show how these renewable sources could shape the future of the energy market.

The business as usual scenario is marked by a very slow growth of alternative energy technologies. On land, geothermal energy keeps a steady growth but unsuccessful performance of cost reduction projects impacts government interest in new ventures. Hydrocarbon exploitation is still the only important economy of the seabed and research for new offshore energy alternatives receives poor government funding. Pilot projects for offshore geothermal are implemented in their initial phase, but suffer from lack of a fair playing ground in the energy market. Investment in seabed exploration continues, mainly fuelled by national interests within the EEZ. A clear legislation governing the use of the Area prevents investment and growth in clean energy technology, pilot research projects limited to the EEZ.

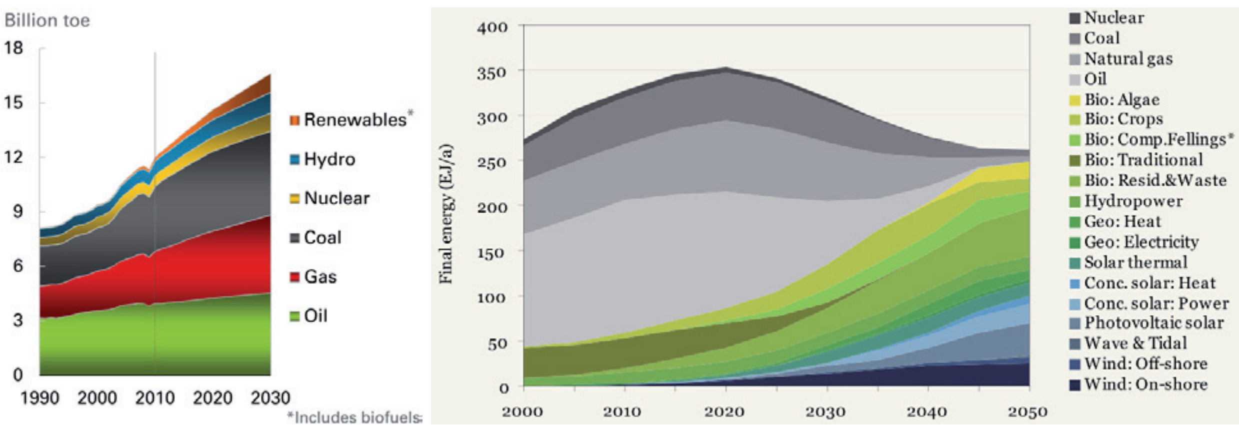


Figure 1-18: World Energy Supply by Source. BP (left) vs. Ecofys (right) Scenarios (Adopted from BP 2011; WWF 2010)

In the Ecofys scenario onshore geothermal represents 4% of the total electricity supply of 2050. To achieve the annual 5% growth of the geothermal energy industry, growth must be doubled to a rate of 10% per year. The successful implementation of the initial stages of the offshore geothermal plants in Italy and a strong commitment to reduction of GHG emissions drives public investment in new ventures. Policy makers approach international law as a fundamental step in managing the resources of the sea; a clear framework exists by 2015 allowing extensive progress in exploration of the Area. The public understands the value of developing offshore energy, aided by the successful deployment of scientific observation networks in the deep sea. New developments in thermoelectric energy conversion for hydrothermal vent fields make the cost reduction targets for deep sea exploration in remote areas.

Seabed Mining Scenarios

The exploitation of mineral commodities from the seabed presents similar challenges. Political support, due to the financial risks of these ventures, can be a driving force for the industry. However, as long as new mining ventures show a limited success, the risks will outweigh the benefits for private or public support. The seabed mining industry lags behind onshore projects and recycling. Several technical challenges, including the transport of ores and the logistics of the mining operation would limit any short-term ventures to the EEZ. The Blue Growth scenarios for seabed mineral exploitation represent plausible outcomes that are corroborated by interviews and research by the authors of this volume.

Figure 1-19 shows the critical commodities reported by several countries. Of the total amount of critical commodities, the most important resources appear to be rare earth elements (cerium, dysprosium, erbium, europium, gadolinium, holmium, lanthanum, lutetium, neodymium, praseodymium, samarium, terbium, thulium, ytterbium, yttrium, ferrocerium, monazite, bastnasite, mischmetal) and vanadium (V). While the four scenarios of the EC show outcomes dependant on the success of one project, it should be noted that countries like India, Japan and China are already embarking in the quest for deep sea minerals.

1.4.6 Quantification of Forces around the Seabed Exploitation Industry

Forces in Energy scenarios

Figure 1-20 shows the growth of installed operating capacity for onshore geothermal energy from 1950-2010. A 4% growth of installed capacity per annual is much less than predicted by several energy scenarios of Table 1-4. The sector has experimented slow growth, mainly due to difficulties in finding new sites. Engineered geothermal systems (EGS) could be a possible *known* technological solution for 2050 and beyond (Shell International BV. 2011).

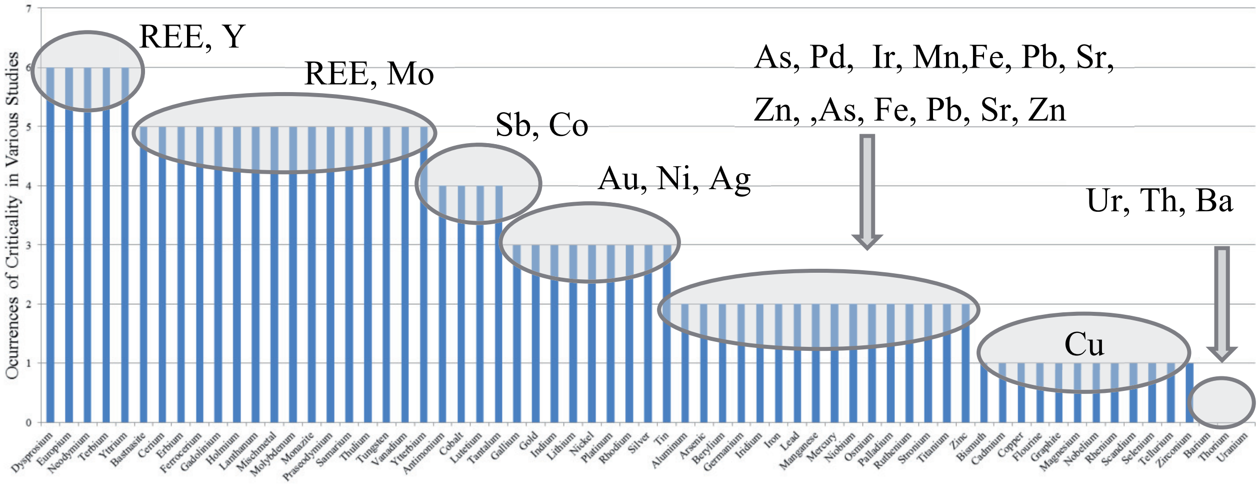


Figure 1-19: Critical Commodities Found on the Seabed
(Sources: DOE 2010; EC 2010)

Technology for offshore geothermal remains in its infancy. The work with offshore supercritical fluid in hydrothermal is tangentially mentioned in the IEA-IGC report, and the authors have only found two proposals for such developments (Marshall Hydrothermal n.d.; Hiriart & Hernández 2010).

Forces in Mining Scenarios

We show in Figure 1-21 the world production and pricing for rare earth elements (REE). This behaviour is evident in many commodities in the manufacturing industry. We shoe this particular group of materials because they are reportedly critical in all of the criticality analysis found in the literature for mineral commodities. These elements exists in deep sea mud, and have been estimated by Kato et al. (2011). However, the conditions in which there will be a real scarcity are not clear, especially when REE can be readily extracted from the waste from ore processing of other minerals.

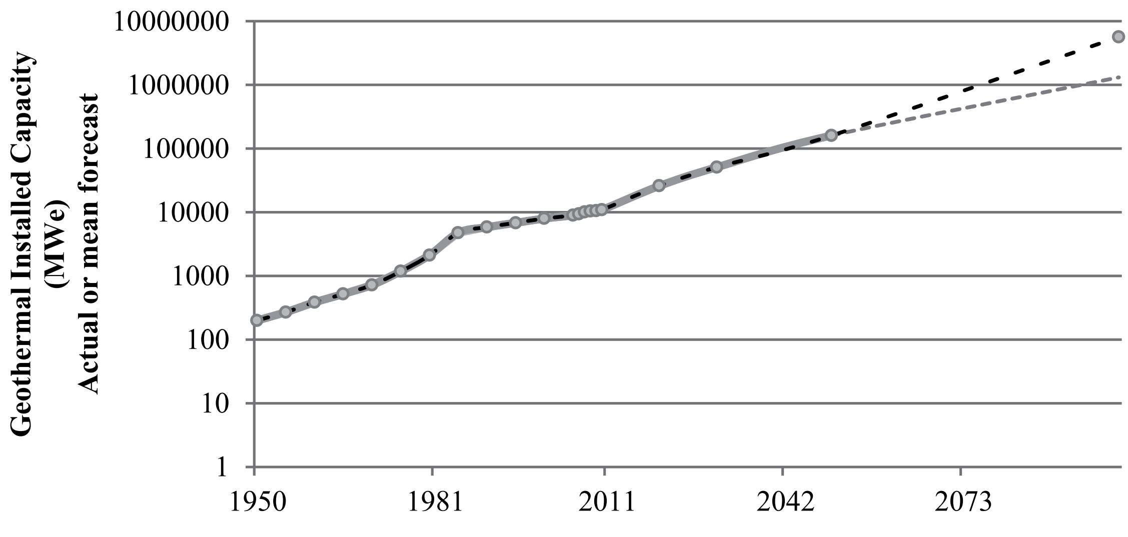


Figure 1-20: Geothermal Electricity Generating Capacity and Forecast
(Data: IEA-GIA 2012, Projections for 2010-2100 by Goldstein et al. 2011)

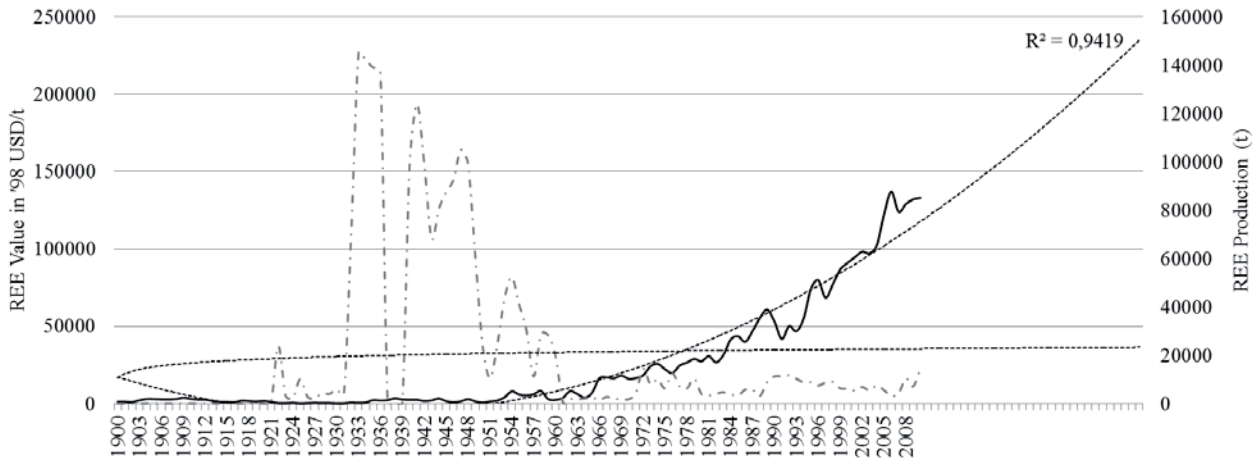


Figure 1-21: World REE Cumulative Prices and Production per Year 1900-2010 (Data USGS)

1.5 Evaluation of Seabed Exploitation

Renewability

None of these types of minerals can be considered a renewable source. They all require thousands to millions of years to accumulate in economically interesting grades and tonnages. Polymetallic massive sulphides require thousands to tens of thousands of years to concentrate from hot metal-rich solutions into large deposits while individual mineralized chimneys have been observed to grow quickly (days to years). Polymetallic manganese nodules (manganese, nickel, iron, copper, cobalt) which lie on and in sediment that covers the vast abyssal plains of the deep ocean, take millions of years to accumulate slowly by precipitation from seawater. Cobalt-rich ferromanganese crusts that accumulate on the bare rock outcrops of seamounts and submerged volcanic mountain ranges, take millions of years to accumulate slowly by precipitation from seawater. While hydrocarbons have been used for over a century, the reader should consider that they also take years in the order of millions to develop.

Financials and Risk

A closer look at the mineral market and the mining industry on land gives the impression that, given the existing known mineral resources of the seabed, the prospect for economic gain are small. Our interview results show that the general expert opinion is aligned around the fact that even though the grade of the ores appears large, when compared to onshore reserves, the total size of the known deposits –like SMS and sediments– or the technical difficulty to exploit them –crusts and nodules– will deny any prospect of a substantial profit, if any. The concerns for all the minerals exploitation are concluded as follows.

Firstly, mining seafloor massive sulphides deposits (SMS) is likely to begin within the coming years. However, the success of such venture still raises many questions about the profitability of similar ventures elsewhere. Drilling is necessary to determine grade and tonnage of a deposit, and favourable market conditions relative to land sources must evolve. Furthermore, the grade and size of SMS in the worldwide is not worth to exploit it as a common resource currently.

Secondly, the Atlantis II Deep zinc-silver-copper metalliferous sediment deposit of the Red Sea is the only seafloor hydrothermal deposit in which grade and tonnage are anywhere near to mining standards on land. Legally its recovery rests with the bordering coastal States (Saudi Arabia and Sudan), with overlapping exclusive economic zones. The grade of other areas of metalliferous sediment deposit is too small to exploit compared to the resources on land.

Finally, cobalt-rich ferromanganese crusts are within the scope of many projected critical resource analysis. However, the prospect of recovery and refining from a hard-rock substrate adds an extra challenge.

Technical Challenges

Technical limitations in processing, deep sea excavation, cutting, collecting, and power supply have been tackled by some specialized companies in the past years. Most machines derive from land mining operations, and are designed for service in relatively deep regimes. However, only ocean diamond mining operations have seen industrial scale service, and the deposits lie in relatively shallow waters as shown in Appendix B. For deeper waters, the technical solutions will have to be proven, and favourable market conditions relative to land sources must be within sight.

Environmental Challenge

While there is pressing interest in exploiting the vast energy resources in the seabed, there are also both legal and moral requirements for protecting the environment, especially around the unique hydrothermal communities. This is not a threat to take lightly, especially when pressing environmental concerns begin to drive policy making and international cooperation.

In the meantime, energy security remains one of the greatest challenges facing our society. Inasmuch as there are dependencies between development of clean energy and mineral resource availability, this analysis leads us to believe that in the business as usual case; seabed energy would still have a chance of slow but steady growth, following any of the existing scenarios for renewables in the energy mix prospects until 2035. Tapping the vast renewable energy resources of the seabed promises a much kinder approach to resource exploitation. In the following chapter, we characterize the energy content of the resources of the seabed. Chapters 2 to 4 will be devoted to a technology discussion, and analysis of economic, logistic and environmental challenges of a case study on seabed energy exploitation.

2 Hydrothermal Vents

2.1 Geological System of Hydrothermal Vent

2.1.1 Hydrothermal Circulation

Hydrothermal vent is a kind of submarine volcano on the sea floor of over thousand meters depth, spewing hot, reach in minerals and low pH water. Hydrothermal circulation, which is schematically represented on Figure 2-1, plays a significant role in the forming of hydrothermal vents. Hydrothermal circulation occurs when cold deep seawater of about 2°C percolates down through fractured ocean crust along the middle-ocean ridge (MOR). The cold seawater, which is heated by the hot magma, takes a chemical reaction with the mineral compositions within the magma. The hot water can reach over 400°C when it continues to go down. At these temperatures, the fluids become extremely buoyant and rise at a rapid speed back to the seafloor where they are expelled into the overlying water column.

The first investigation of the seabed hydrothermal activities was undertaken in the Red Sea in 1960s, finding the deep basins filled with warm salty water of 40–60°C and rich-mineral sediments (Degens E. T 1967). In 1977, the first high-temperature hydrothermal vent was discovered on the Galapagos Rift at 21°N on the East Pacific Rise (EPR). Two years later, the scientific expedition on the submersible Alvin made a spectacular discovery. They found a vent fluid of about 380°C, chimneys with black smoker and exuberant oases of exotic animal life (Spiess et al. 1980). That was a beginning of the vent time. Thereafter, scientists started to pay more attention to the vent research and discovered other active fields in the Pacific, North Atlantic, and Indian Oceans.

Recent hydrothermal research brought a great contribution to the understanding of hydrothermal activity by proving that hydrothermal vents may occur in reasonable abundance along slow-spreading ridges (C.R. German et al. 1996) and not only in fast- and intermediate-ridges, which have significantly greater magmatic heat fluxes. According to (M. Hannington et al. 2011), the abundance of venting along any section of ridge crest links with the available magmatic heat flux and with ridge spreading rate. This theory was proved by the other discoveries of hydrothermal vents along some of the world's slowest spreading ridges, namely the Southwest Indian Ridge (C. German et al. 1998; Bach 2002) and the Gakkel Ridge in the Arctic Ocean (Edmonds, H. N., P. J. Michael 2003).

2.1.2 Generation of Vent Deposits

There are three kinds of the hydrothermal vent deposits: black smoker deposits, white smoker deposits and mound deposits. The black smoker's deposit is represented as a

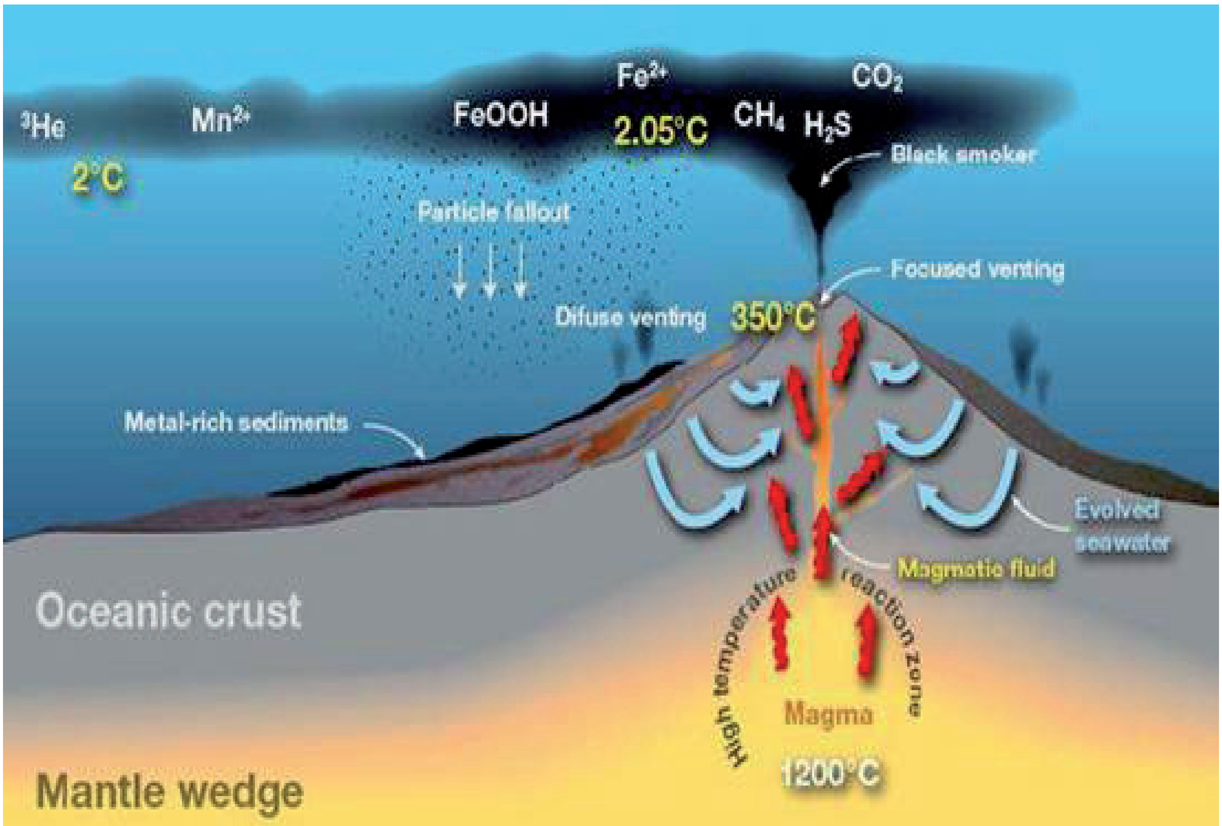


Figure 2-1: Diagram of Hydrothermal Vent System
(Source: www.gns.cri.nz)

chimney that consists of the minerals and sulphides. In 1983, Haymon first introduced the circulation process and explained how chimney usually forms (R. M. Haymon 1983):

- As a result of mixture between the superhot vent fluid and the cold seawater, an anhydrite ($CaSO_4$) forms around the vent fluid;
- The anhydrite walls then protect subsequent hydrothermal fluids from the mixture with the seawater, as well as provide a base for the precipitation of the sulphide minerals coming from the vent flow;
- As long as the chimney remains open, the majority of vent fluid coming out from the top into seawater and then rises in a large plume where abundant metals precipitate.

The real formation process of the black smoker chimney is also shown on the Figure 2-2. Black smokers together with superheated vent fluids can reach hundreds of meters wide as well as chimneys could be up to 60 m height. It should be noted that the maximum growth rate of the black smoker's chimney is 9 meters in 18 months as was discovered by scientists at the University of Washington.

Although, white smokers usually emit relatively lighter concentrated chemical fluids, they also have rich composition deposits including manganese, iron, barium, calcium, and silicon. These vents tend to have a lower temperature plumes of about 250-300°C but still

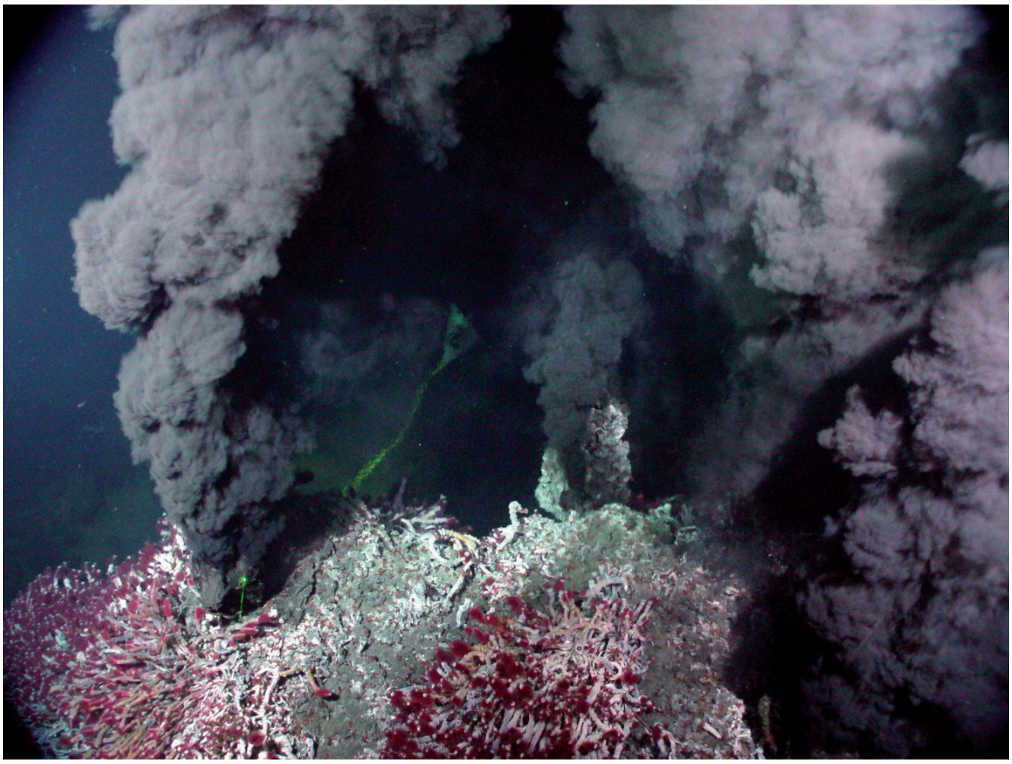


Figure 2-2: Development of Active Black Smoker Chimneys
(Source: http://www.visions05.washington.edu)

continuously provide the starting point for more complex organic molecules as well as the energy needed to produce it. Microscopic structures of the white smokers "show interconnected compartments that provide an ideal hatchery for the origin of life"(Lane 2010).

When high-temperature vent flow mix with much colder oceanic water, it becomes buoyant and begin to rise. A shear flow between rising fluid and ambient water becomes turbulent and forms the vortices or eddies. These eddies act to entrain the material from the ambient water column, which result in continuous dilution of the original vent fluid as the plume rises up. Such fluids together with the low-temperature vent fluids, for example white smokers, and diffuse fluids existing on the surface of the vent fields spread out at its appropriate density level. Moreover, biogeochemical transformations, namely, the sorption of aqueous oxyanions may occur onto the vent-derived particles such as phosphate, vanadium, and arsenic. Therefore, these particles form metalliferous sediments on the seafloor and generate a mound deposit around the vent complex. However, it was discovered that largest mound deposits usually appears on the slow-spreading ridges (Margaret Tivey 2007).

2.1.3 Types of the Hydrothermal Systems

Magma wells up from the underneath of the Earth along spreading centres or middle-ocean ridge (MOR) and produces fresh ocean crust at a rate of 20 $km^3\ yr^{-1}$ and, therefore, forming new seafloor at a rate of about 3.3 km^2 yr^{-1} (Parsons 1981; White et al. 1992). However, the young oceanic lithosphere formed in this way cools down because it also moves away from the ridge crest.

Depending on the spreading rate of the ridges, three types of the hydrothermal vents are classified (C. German & Lin 2004). The fast-spreading rate of ridges is in Pacific at rates from full opening rate of 15 cm yr-[1] to a minimum of 2.4 cm yr^{-1} on parts of the Gorda Ridge. In the Atlantic Ocean, the ridge systems have slow-spreading rate. Consequently, the hydrothermal vents in the Atlantic Ocean are low active and more stable. In the Indian Ocean, the ridge spreading varies between intermediate in range of 6 cm yr^{-1} and very slow rates of about 2.0 cm yr^{-1}. However, the Arctic Ocean ridges rate is the slowest known of 1.0 cm yr^{-1}. German and Lin (C. German & Lin 2004) propose a simple conceptual model, which is illustrated on the Figure 2-3. The ridge extension is achieved via episodic diking, with a repeat of the period at any given location within 50 years. Removal of the heat follows, using the following three stages: (a) near-instantaneous generation of "event plumes" (~5% of total heat available); (b) an "evolving" period (5 years) of relatively fast heat discharge (~20%); (c) a decadal "quiescent" period (~75%).

On the slow-spreading Mid Atlantic Ridge, the mechanisms for formation of the long-lived, tectonically-hosted hydrothermal vent fields such as TAG and especially Rainbow showed that slow-spreading ridges have much greater irregularity of episodic activation of the heat sources in terms of time and region.

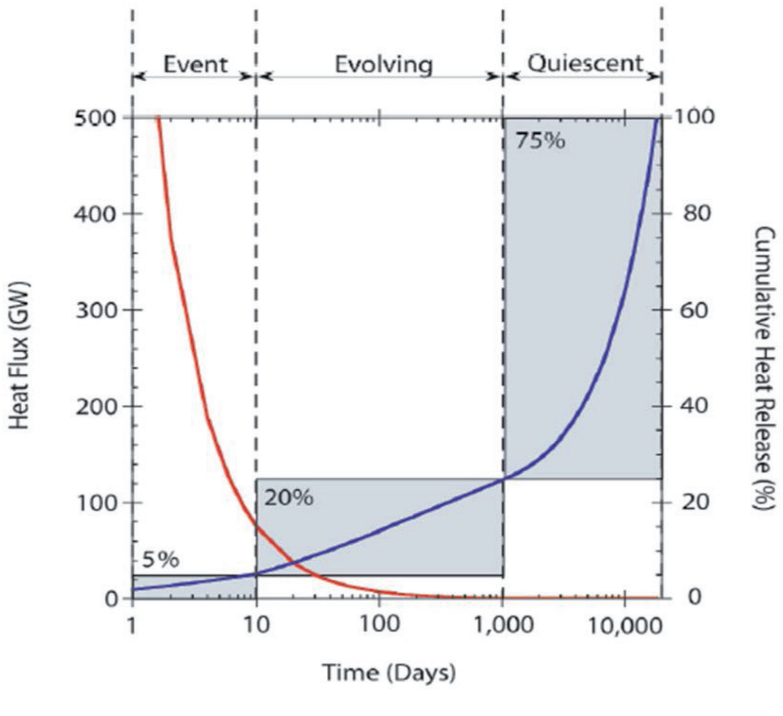


Figure 2-3: Graphical Representation of the Heat Flux (red curve) and Corresponding Cumulative Heat Release (blue curve) as a Function of Time at a Fast- or Medium-Spreading Ridge Crest
(C. German & Lin 2004)

2.1.4 Chemical Compositions of Hydrothermal Vent Fluids

The chemical composition of hydrothermal fluids depends on many factors. These include initial composition of the cold seawater, the composition and structure of the crusts that react with the circulating fluids and the morphology of heat source –for example temperature, size, depth and shape as well as the volatiles of the percolating fluids heated by the magma such as He, CO_2 CH_4 and H_2 (MK Tivey 2007). Therefore, the composition of venting fluids depends on the locations and surrounded environmental systems of the hydrothermal vent. The general chemical composition of several hydrothermal fluids is represented in Appendix A, Section A-6 .

2.2 Ecosystem of the Hydrothermal Vent

Back in 1977, during the scientific expedition to the seabed of the Pacific Ocean in the deep-submersible vehicle Alvin, scientists discovered a first hydrothermal vents (black smokers) which pouring a hot fluids with a mineral rich composition from underneath of the surface. Moreover, the vents were inhabited by previously unknown organisms, which can survive without the presence of the sunlight.

The vent ecosystems are rich in carbon dioxide, hydrogen sulphide, organic carbon compounds, methane, hydrogen, and ammonium (Birney et al. 2006). The mineral rich venting fluid creates the fundamental principle of the surrounded food chain.

The microorganisms discovered in the hydrothermal vent system are chemoautotrophic and can be found living inside the vent, on the surface around the vent, as well as inside of the vent organisms. They use the hydrogen sulphide, oxygen and carbon dioxide from the water around the vent. Generally, bacteria get energy by breaking down the hydrogen sulphide and then use this energy and oxygen to produce sugars from the carbon dioxide and release sulphur and water. These microorganisms are adapted for extreme conditions, for example, hyper thermophiles can be found in high temperatures over 80°C, barophiles survive at high pressure, and acidophiles survive in acidic conditions (Birney et al. 2006).

Moreover, biological diversity increases during the formation of the vent chimney, which can reach up to 100 m high. The chimney also becomes colonised by bacteria as well as other vent organisms that can remain attached to chimney for the whole period of their life. Therefore, if the chimney will collapse many of these organisms will no longer be able to live.

The hydrothermal vent bacteria form symbiotic relationships with other deep-sea animals. The symbiotic relationships can be considered using the example of the Giant Tubeworm, which is obligatory, in other words essential for both host and symbiont. The tubeworms are a large organism, shown in Figure 2-4, one or two meters in length and several centimetres

Figure 2-4: The Giant Tubeworm
(Source: www.divediscover.whoi.edu)

in diameter (Cindy Van Dover 2000). Adult tubeworms completely lack a mouth and digestive system and have a specialized organ named throphosome, which is packed with bacteria. The bacteria manufacture sugars through chemosynthesis. The tubeworm absorbs some of these sugars and uses it as a food. Other symbiotic dependent organisms include the Giant White Clams, mussels and snails, which host bacteria in the gill filaments.

However, the bacteria also form the basis of the food chain as primary producers, as can be seen in Figure 2-5. For instance, the blind Atlantic vent shrimp and worms feed directly on the mats of sulphur bacteria, and have been discovered with bacteria in their gut. In turn, larger organisms, such as crabs, octopus and fishes are opportunistic feeders and feed on other vent organisms (Birney et al. 2006). Therefore, these facts lead to the establishment of a food chain, which include primary producers (chemoautotrophic bacteria), the secondary producers (tubeworms, mussels, clams, and shrimp), predators (fishes, octopus) and scavengers (dandelions, crabs).

2.3 Energy Potential in Hydrothermal Vents

In the hydrothermal venting system, there are two potential energies: hydrodynamic (kinetic) energy and hydrothermal energy. Hydrodynamic energy from the chimney fluid is defined by velocity of fluid and diameter of chimney. We assume that diameter of hydrothermal vent chimney is 20cm and the fluid velocity is 3 to 5 m/s (Marshall Hydrothermal n.d.). According to the calculations shown in the Appendix B, it can be

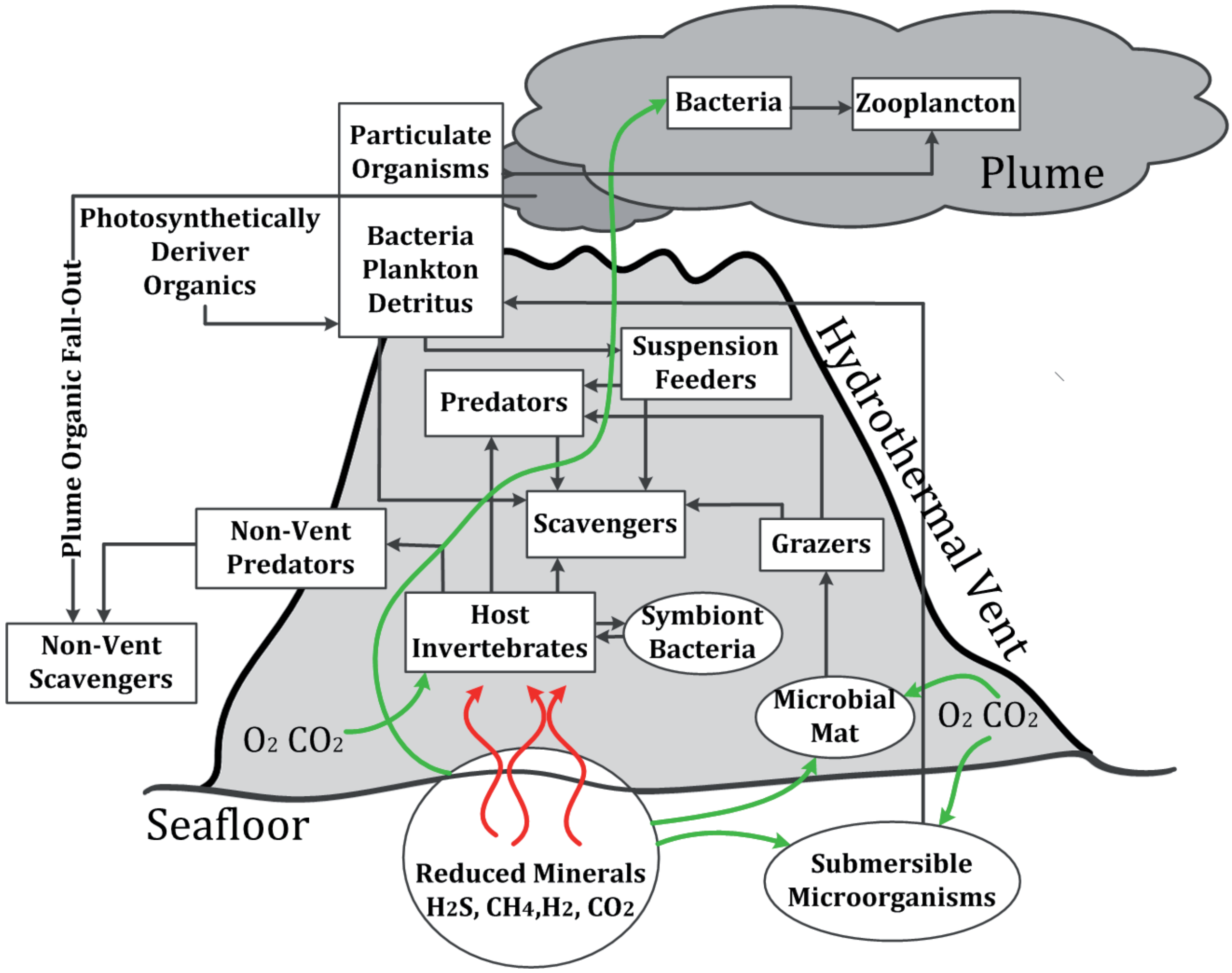


Figure 2-5: The Trophic Interactions in Vent Ecosystem
(Based on Van Dover 2000)

concluded that the hydrodynamic energy from the standard vent will be around 0.4-2 kW.

Currently, two methods exist to estimate the hydrothermal fluxes: geophysical and geochemical estimations. Geophysical estimation is based on the calculation of the required amount of the heat flux when the crust is formed in different age (C. A. Stein & S. Stein 1994). In regards to geochemical estimation, the element or isotope that has an anomalous concentration in hydrothermal fluids in comparison to seawater is used to estimate the hydrothermal fluxes (Lupton et al. 1995). Global hydrothermal heat fluxes from geophysical and geochemical estimates are 2-4 TW and 1-18 TW relatively (H. Elderfield & a. Schultz 1996). In addition, National Oceanic and Atmospheric Administration (NOAA) qualifies several vents along the areas of MOR, excluding western Pacific back-arc basins, and then makes an estimation of global convective heat flux with different spreading rate shown on Figure 2-6.

In the hydrothermal circulation, the venting heat could be released in three different ways: black smoker, white smoker and diffuse heat flux on the mound. Most of the attention focuses on the high-temperature fluids rising sharply as black smokers, which are normally

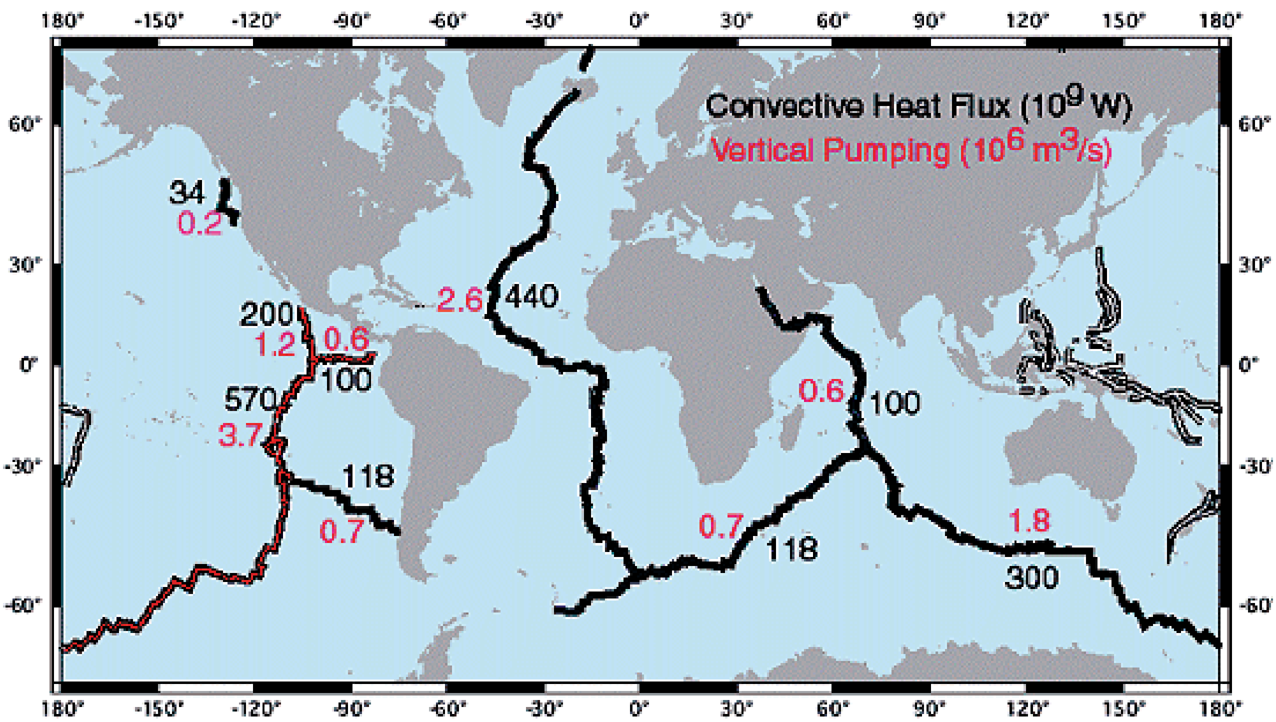


Figure 2-6: Heat Flux and Vertical Pumping along the Mid-Ocean Ridge (Source: NOAA)

over 350°C. However, studies and estimations show that high-temperature black smoker takes about 10% of total hydrothermal heat energy close to the ridge axes (C R German & Von Damm 2003). The diffuse flux of the low-temperature fluid (0.2°C -81°C) or flank flux may take 70% or more of the total heat energy hydrothermal mound. For example on the MAR, the speed of low-temperature (4.5 °C –16.4°C) diffuse flow measured range from 1.1 to 4.9 mm/s (Sarrazin et al. 2009). Therefore, the diffuse heat flux has a main contribution to the energy amount in the hydrothermal vent system. The properties of diffuse flow are summarized in Appendix A, Section A-7 (Bemis et al. 2012).

2.4 World distribution of the hydrothermal vents

In general, hydrothermal vents occurs along the global MOR crest for over 60,000 km (C R German & Von Damm 2003). Based on the latest InterRidge Cruise Database 2011, the known number of hydrothermal vent sites is 592, from which 257 vent sites are hydrothermally active, 56 are inactive and the geological activity of 279 vent sites is unconfirmed. Vents are different in tectonic settings, mineral composition as well as occur in different depths in the ocean. The global distribution of the hydrothermal vent fields is shown on Figure 2-7. In 2010, scientists from the National Oceanography Centre, UK discovered the deepest vent systems of the 5,000m deep in the Caribbean Sea floor.

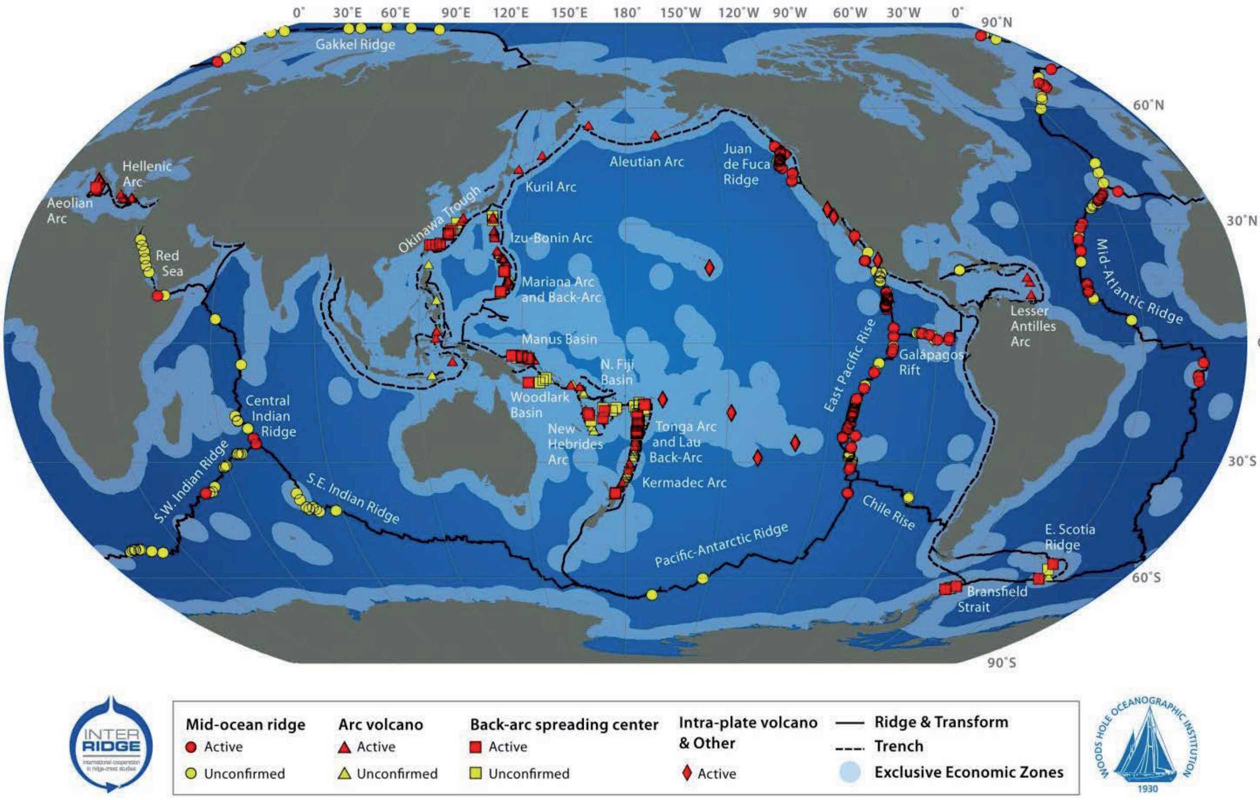


Figure 2-7: Known Sites of Hydrothermal Venting along Mid-Ocean Ridges, Arc Volcano, Back-Arc Spreading Centre and Inter-Plate
(Source: the InterRidge Cruise Database, http://www.interridge.org/)

2.5 TAG Hydrothermal Vent Field

2.5.1 Morphology

The TAG (Trans-Atlantic Geotraverse) hydrothermal field extends over 25km^2 and lies at 26°08'N of the base of the eastern median valley wall on the Mid-Atlantic Ridge (MAR). TAG mound is the largest volcanic-hosted hydrothermal deposits yet discovered along the global mid-ocean ridge system. In addition to the high-temperature TAG mound, there are at least six inactive sulphide mounds and one vent with the low-temperature activity.

Seafloor spreading rates at the TAG segment are known to be asymmetric, with half-spreading rates of 13mm/yr. on the east and 11mm/yr. on the west side (McGregor & Rona 1975; McGregor et al. 1977). Generally, the TAG mound is a circular mineral deposit of 150m in diameter and 50m high that is being formed at the seafloor in a water depth of approximately 3,650m as could be seen from Figure 2-8. The TAG mound has two approximately circular, superimposed platforms. The lower platform is about150m in diameter in water depth of 3,650–3,655m.

On the southeast side of lower platform, there are a number of white smokers. The upper platform of 90m in diameter spans over the NNW part of the lower platform. On the top of this platform could be seen a black smoker chimney of 10 to 15m in height and 10 to

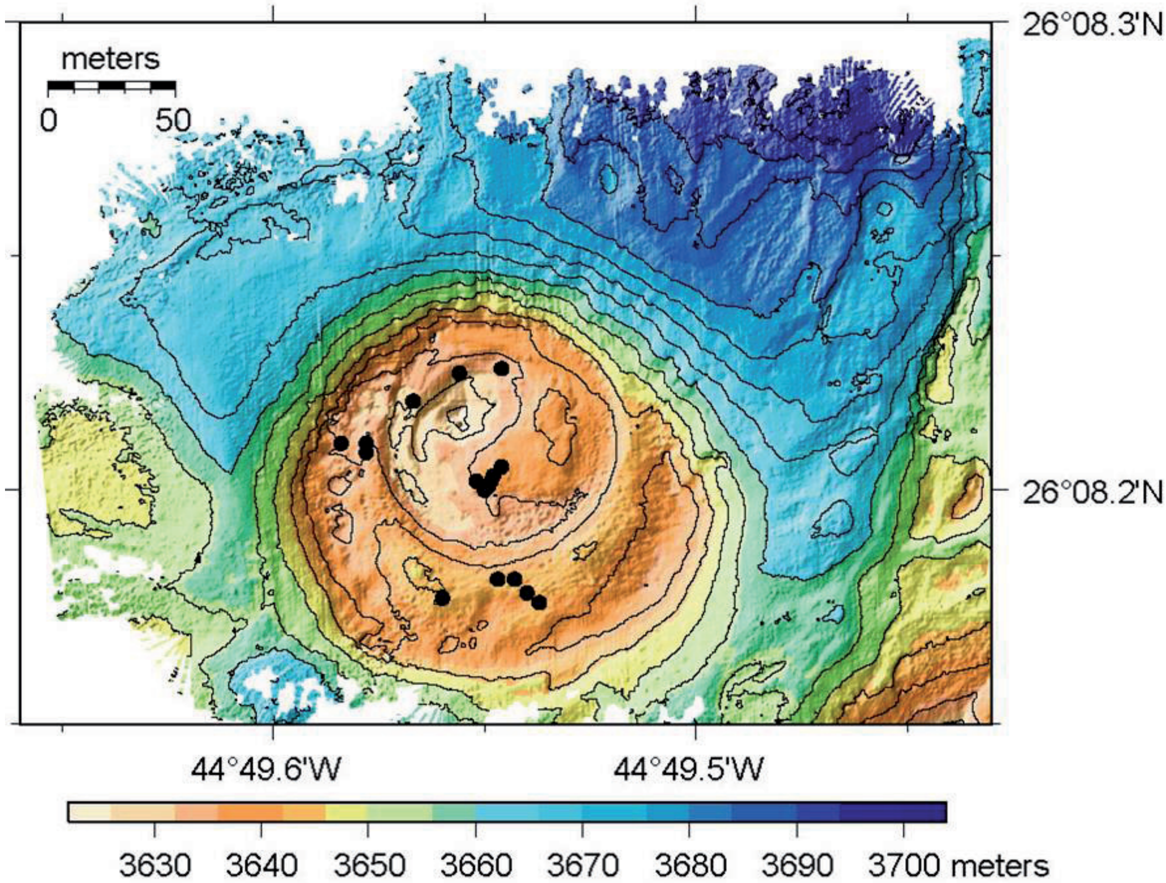


Figure 2-8: Bathymetry of the TAG Active Hydrothermal Mound, Mid-Atlantic Ridge 26N (Source: Data courtesy of Rob Sohn, WHOI)

20m in diameter discharging the high-temperature fluid of 363-366°C through the multiple clustered vent chimneys (Edmonds et al. 1996). The diameter of black smoker chimney at the top of the TAG mound was estimated as 3 m and the vent orifice is 5.19 cm IN radius.

White smoker chimneys of 1-2m high are localized in 20-50m diameter area in the southeaster quadrant of the mound at the ocean depth of 3,662-3,665m and approximately 70m away from the black smoker complex. Lighter-mineral fluid with measured temperatures ranging from 260 to 300°C comes from the chimneys. Twelve white smokers were discovered ranging in height from 11 to 53cm. As to the tallest one, the diameters of the lower stalk and of the widest part of the dome are 10 and 17 cm respectively (Margaret Kingston Tivey et al. 1995). The bottom current minimum, maximum and average velocities of over 16-day measurement are 1.0, 28.3 and 7.3 cm/s respectively. The current direction is from eastward to northwest (Kinoshita et al. 1998).

2.5.2 Heat Release

A central area of TAG vent field discharges the black smoker fluid of high-temperature 363-366°C. A small, but apparently waning (Edmonds et al. 1996), region on the southeast of the mound has a white smokers which discharge lower-temperature 260-300°C fluids. It also has a diffuse flow of up to 50°C on of the rest of the mound (E. Humphris & Cann 2000).

The energy flux associated with TAG activity have been estimated by (Rona et al. 1993). They calculated the output of the energy to be 225 MW based on the temperature measurements in the buoyant plume above the black smoker. However, according to (Goto 2003) the lower value is 200 MW based on the measurement with vertical thermal arrays. The total energy from the whole mound including black smoker, white smokers and diffuse flow could reach up to 2000 MW. It should be noted that about 50-90% of the energy are released from white smokers and diffuse flow (James & Henry Elderfield 1996; E. Humphris & Cann 2000).

Very high values of heat flow (250–25,000 MWm^{-2}) were measured on the southeast side of the mound as well as heat flow is extremely variable (100–100,000 $MW\ m^{-2}$) within 20m of black smoker chimney (Becker et al. 1996). Becker et al. (Becker et al. 1996) concluded that such high, variable heat flow values are result of complex fluid advection in the vicinity of the black smoker chimney. High heat flow was also measured near the periphery of the mound (300-3000MW/m^2). On the other hand, a low heat flow zone (< 20 MWm^2) is located on the western side of the mound (Becker et al. 1996).

3 System concepts for energy extraction

The development of a system to achieve exploitation of the energy resource from the seabed will require a structured systems engineering approach. In Chapter 1 we identified possible sources of renewable power from the seabed: hydrothermal/geothermal, hydrodynamic, hydrostatic pressure and chemical compounds. Most sources of seabed energy exist around hydrothermal vents, and their characteristics were discussed in Chapter 2. The goal of this chapter is to expose the possible architectures of a system that achieves energy exploitation. The development of the architecture concepts follows a technology evolution approach shown in Figure 3-1.

To fulfil the energy needs for the future offshore energy industry one must think of evolving capabilities based on short-term needs. Today, renewable offshore power could be a major driver of cost reduction, even for the oil industry. Potential clients to evolve such capabilities are shown in Figure 3-1. They represent changes in power demand in orders of magnitude from tens of KW, to tens of MW, to GW installations.

For kilowatt demand, we have a fundamental and very immediate need: seabed exploration. If any venture in seabed exploitation is to take place in the future, it is clear that we are in urgent need of understanding the complex processes of the ocean. Exploration is an expensive activity, but we show in the next chapter that technical developments existing today could be close to delivering solutions for clean and reliable power in the seabed that could easily supply demand for deep sea observatories.

A leap to a megawatt scale in the medium term could include clients from an emerging seabed mining industry, CCS platforms or small coastal cities. While many technical constraints still exist, as we will show in the coming pages, many of them could develop rapidly given that short-term applications prove successful.

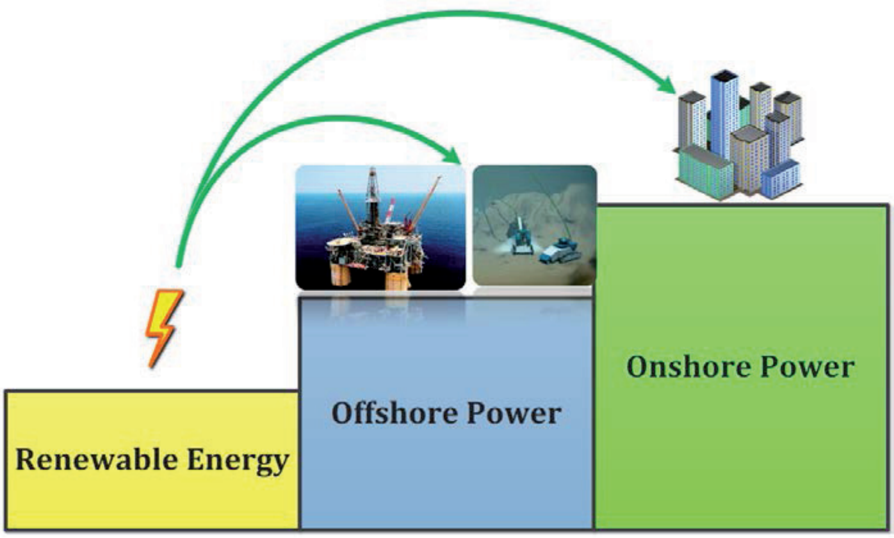


Figure 3-1: Evolving Renewable Energy Technology for Offshore and Onshore Power

Giga Watt power demands could come from coastal states or offshore processing plants. These are the most ambitious applications for seabed energy. Large investments in R&D could facilitate the process, but risk is still a major barrier for such undertakings.

3.1 Qualitative Technology Readiness Assessment

To determine what technologies could have the potential of delivering the three levels of power in our evolutionary approach, we use the technology readiness framework (Mankins 1995). Five functions were identified that could define the energy conversion process, given the energy sources described in Chapter 1.

The critical function of the system is the conversion of one of the forms of energy found on the seabed. One can imagine the conversion of thermal-electrical, thermal-mechanical-electrical, hydrodynamic-mechanical-electrical and thermal-chemical-electrical. A functional analysis of the energy conversion sub-system is shown in Figure 3-2. This focus on electrical power output results from two sources: almost all offshore and subsea systems, including exploration systems rely on electrical power for operation or power storage functions. A few examples exist in the use of fuel cells for AUVs (Bradley et al. 2001). Table 3-1 lists the functions selected in the scope of this research for energy exploitation from the seabed. Unfortunately, the short or medium term possibilities for direct conversion of thermal energy to chemical energy remain in the realm of theory. While living organisms are very good at achieving this function, the authors could not find a viable technology for implementing such a system. Further, the use of hydrostatic pressure is a plausible means of storing energy. However, existing prototypes have only achieved operating cycles in the order of minutes (F. Wang et al. 2008).

Table 3-1: Assessment of Subsystem Functions for Seabed Exploitation

Sub-System	TRL	Power (kW/unit)	Remark
Thermal=>Mechanical=>Electric	5	>4,000	Cheap Complexity Supportability Challenge
Thermal=> Electric	5	5.0	Reliable Expensive 4,400units= 22MW
Hydrodynamic=>Mechanical=>Electric	5	0.3 – 1.2	Low power 165,000units= 22MW
Hydrostatic/Pressure=>Electric	6	1.2	Depth 2,400m 48min/cycle Efficiency 63.8%
Thermal=>Chemical=>Electric	2	---	---

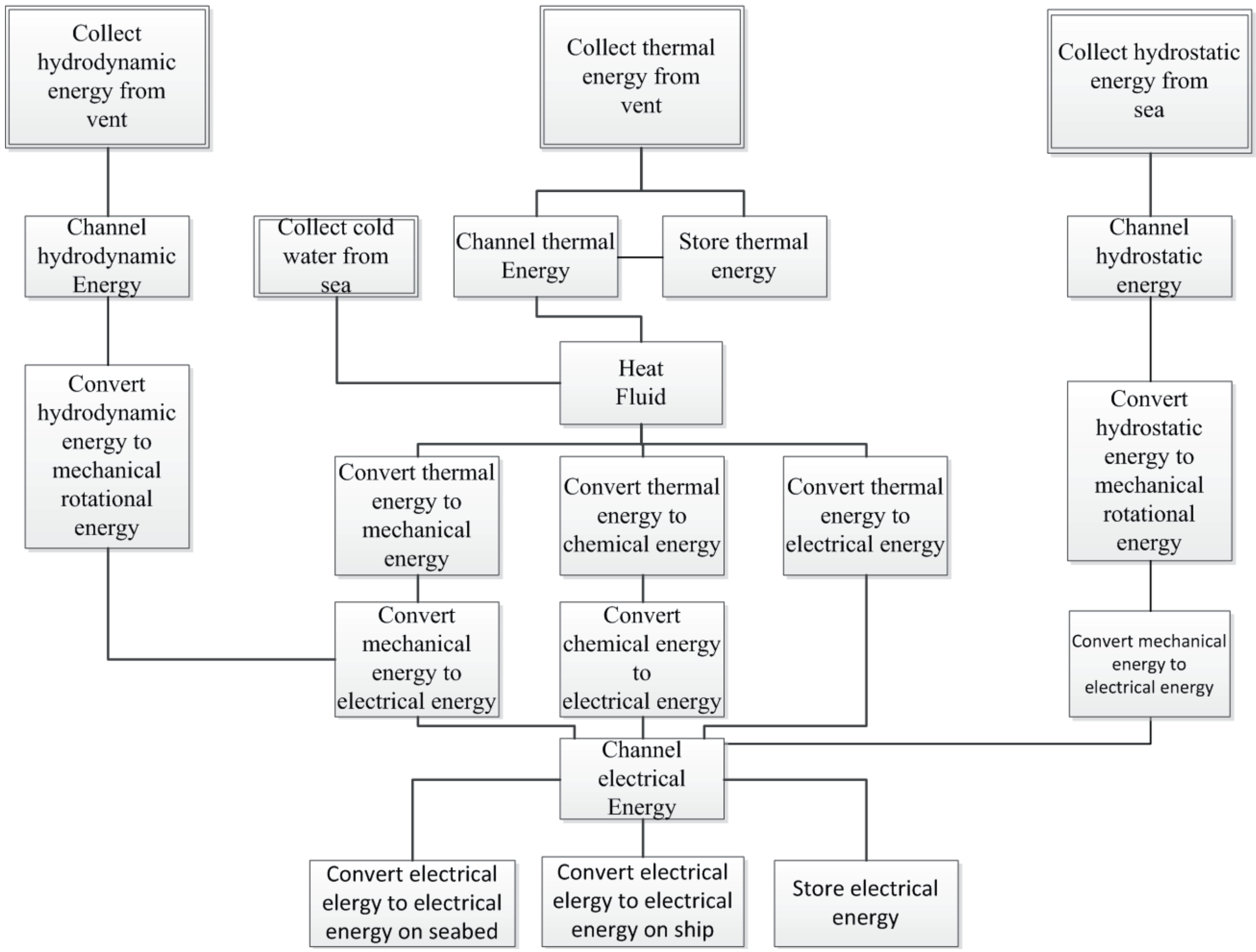


Figure 3-2: Functional Analysis of the Energy Conversion Sub-System

The hydrodynamic potential of the deep sea vents derives from the gush of supercritical fluid. This kinetic energy could be transformed to electricity, but the power offer was found to be quite low. The two competing alternatives remaining are the thermal-mechanical-electrical conversion, and the thermal-electrical conversion. For the base client of low power demand both options could become technically feasible in the short term. However, for megawatt power demand both alternatives have technical disadvantages. Next, two scenarios are proposed employing one such function, respectively.

3.2 Technology Evolution Scenarios

3.2.1 Controlled Growth Scenario

The controlled growth scenario is a reflection of the precautionary principle in the seabed energy industry. Hydrothermal vents are a source of power supply for scientific research and public engagement. Controlled growth provides an alternative to cabled ocean observatories like NEPTUNE in Canada, MARS in the Monterrey bay area, or the Pioneer Array in the East coast of the US, following the Ocean Observation Initiative. Deployment of the first unit in 2015 opens the doors for research. The business-as-usual effect in the energy industry distracts the efforts of developing the seabed energy industry. Slow growth into 2025 limits extensive applications beyond scientific interest.

By 2025, increased understanding of the thermal vent environment and technological developments like deep-sea reverse osmosis installations facilitates the first operational mineral concentration facility for hydrothermal vent fluids. Megawatt power generation is possible using the mature TEG technology. By 2050, the base technology for seabed energy generation is ready to reach Giga Watt power. Storage media for seabed energy has developed concepts like concentrated biotic hydrolysis farms and hydrogen is a prospect for next-generation energy storage systems. The main system components in this scenario are listed in Table 3-2.

The casing, Wellhead, BOP, riser pipe, other piping and the support vessel have been determined from existing oil industry operations. A short discussion of the perceived challenges follows. Stage 2 represents a possible mid-term future. Separation and concentration of minerals from the hydrothermal fumes opens the possibilities of a new and cleaner seabed mining industry. Mining lies outside of the scope of this volume, but it is worth noting that the main contribution of this development is the separation of clean water. A distant future could see this development as a possible source for seabed hydrolysis and Hydrogen storage in the deep sea. Mining operations would benefit if the subsea power supply drives slurry pumps to surface the concentrated mineral slurry that results from the cyclone or reverse osmosis filters. More on this will be discussed in the coming lines.

Table 3-2: Main System Components in the Controlled Growth Scenario

Stage 2015	Stage 2015-2025	Stage 2025-2050
Casing	Casing	Casing
Wellhead	Wellhead	Wellhead
BOP	BOP	BOP
TEG System	TEG unit	TEG unit
Piping	Piping	Piping
-	Reverse Osmosis / Cyclone unit	Reverse Osmosis / Cyclone Unit
-	Slurry pump	Seabed hydrolysis unit
-	Riser pipe	Slurry pump
-	Support vessel	Seabed H_2 storage
-	-	Riser pipe
-	-	Support vessel

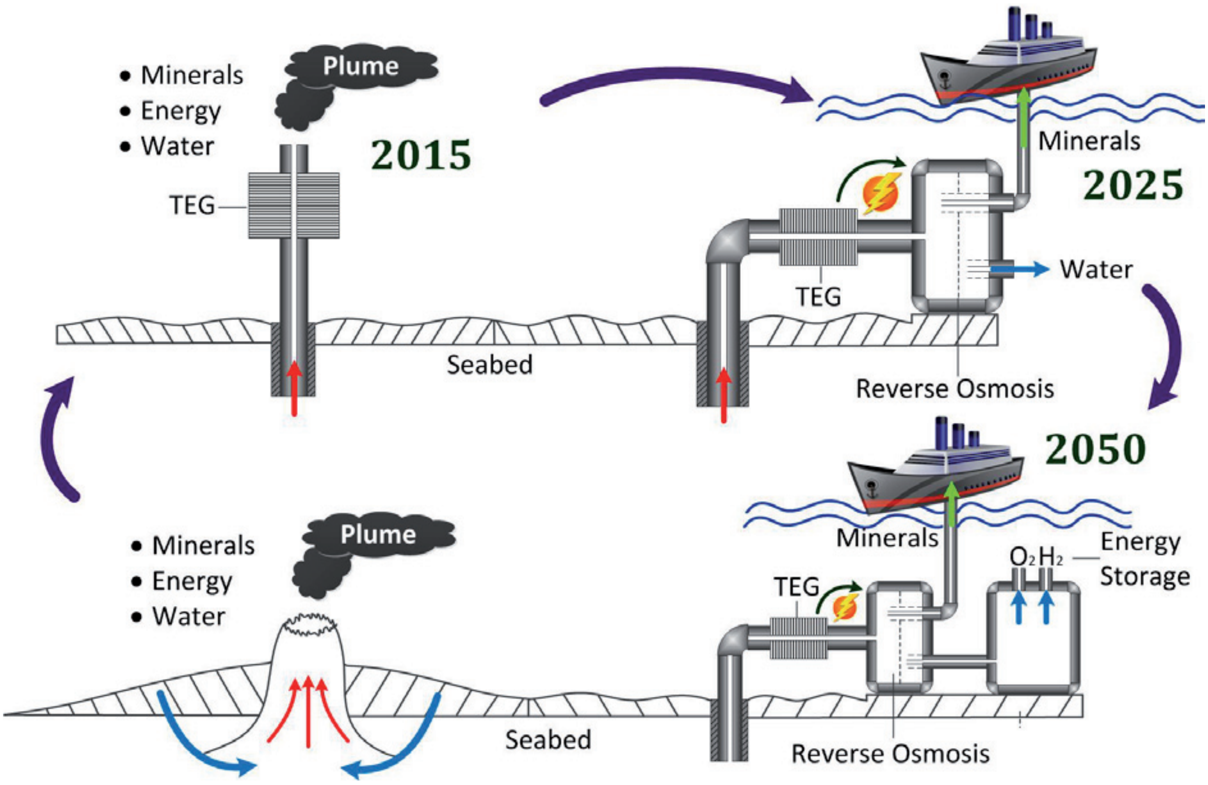


Figure 3-3: High Tech, but Business as Usual Scenario

Subsurface Power Challenge

The main technical challenge involved in the deployment and operation of the business as usual concept is the subsurface power solution. TEGs appear to have very good behaviour under compression. However, the expectation for high power outputs can be a big restriction into MW sizes. The exploration of the alternative function *thermal-mechanical-electrical* has been explored by some authors (Hiriart & Hernández 2010; Hiriart et al. 2010).

The literature has proposed cases for subsea binary cycle, operated inside a pressure resistant chamber. At deep waters, this solution would require a large installation, with many moving parts and the logistics could be considerably complex, with due high costs. Evaluating such undertaking is beyond the scope of this research, and further research must be developed to refine the design of the application. The subsurface binary cycle would be a plausible solution for vent systems located in shallow waters, looking forward into 2025-2050.

3.2.2 Run for the Gold Scenario

The pressure to lower emissions increases. The turnout of 2015 appears close to the IEA 450 Scenario. Energy policy is strong and the playing field begins to level for renewables. Successful deployment of the first offshore geothermal project leads to a boom in the market. Prospecting activities begin and new sites for offshore geothermal power in the pacific are in sight. The success boosts government investment. By 2025, having overcome the technical limitations, the scale up begins. The first Giga Watt central is deployed by 2050, and megawatt offshore power is ubiquitous. Offshore process industry and CCS costs are reduced significantly by the new developments. Clean mining, by concentration and separation of hydrothermal fluids, becomes a reality. A short discussion of the perceived challenges follows.

The offshore hydrothermal (OHT) system is the result of the implementation of the first stage of this rapid growth scenario. Supercritical fluid from the hydrothermal well is captured using modified oil and gas industry technology. In Stage 2, the scale-up permits extension to MW power supply. Stage 3 employs offshore enhanced geothermal system (OEGS), considerably increasing the amount of possible applications for offshore power, and allowing introduction in the offshore operational scenario an emerging offshore process industry.

Some of the components of this system are standard components that already exist and are in operation in some parts of the world. Power conditioning, subsea cables and ocean cooling systems are common in other industry. A return injection pipe is normally used in geothermal energy systems. This avoids pollution and a wealth of other problems. Similar approaches result in this scenario. Next, we briefly discuss some of the technical challenges facing the development of this scenario.

Table 3-3: Main System Components in the Run for the Gold Scenario

Stage 2015 (OHT)	**Stage 2015-2025 (OHT)**	**Stage 2025-2050 (OEGS)**
Supercritical well	Enhanced supercritical well	Enhanced supercritical well
Casing	Casing	Casing
Wellhead	Wellhead	Wellhead
BOP	BOP	BOP
Riser pipe	Riser pipe	Riser pipe
Generation Rig	Generation Rig	Generation Rig
Generation system	Generation system	Generation system
Power conditioning	Power conditioning	Power conditioning
Cooling system	Cooling system	Cooling system
Return injection	Return injection	Return injection
Subsea cable	Subsea cable	Subsea cable
-	-	Offshore process vessel

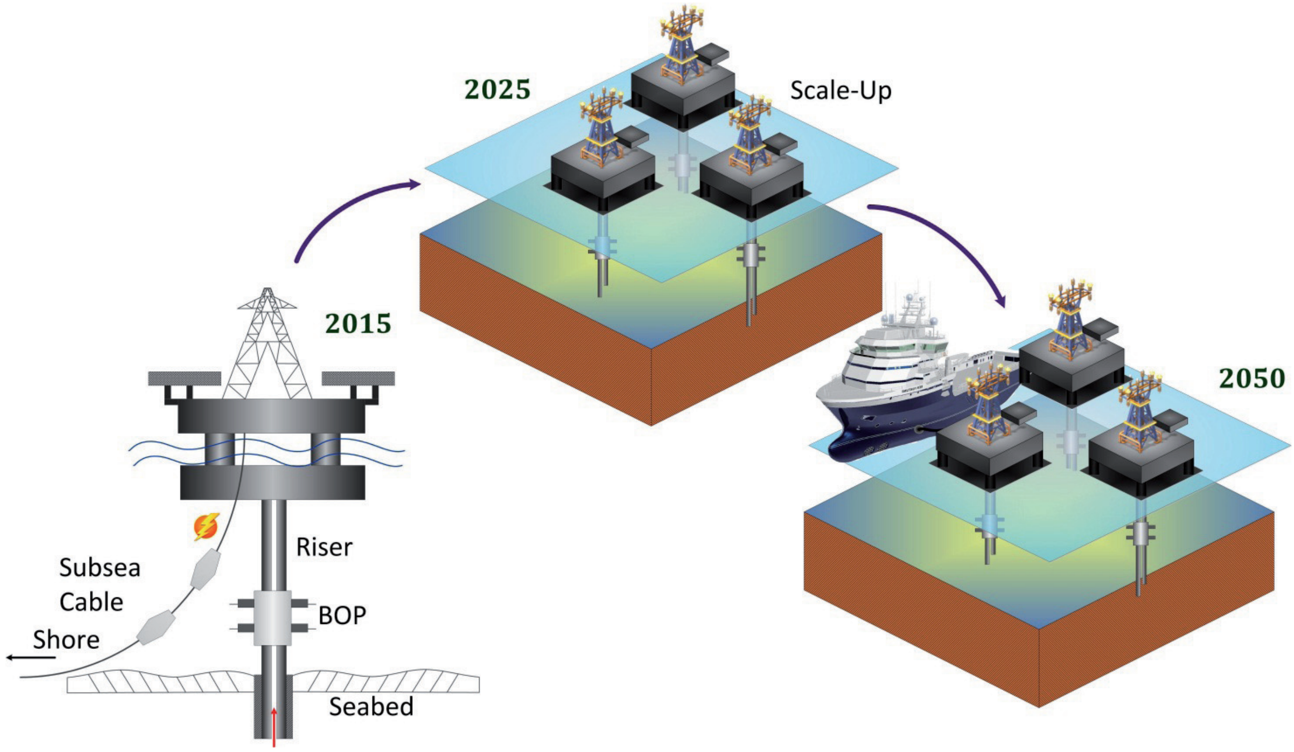


Figure 3-4: Run for the Gold Scenario

Riser Pipe Challenge

On the one hand, existing flexible production riser pipes used in the oil industry have maximum operating temperatures of 130-150 degrees Celsius. This includes supply from leading manufacturers such as Wellstream, Technip or NKT. The main limitations are in the mechanical structures of the pipes. Specifically, the polymer layer that isolates the pipe outer ring from the internal pipe. The water depth on the other hand poses another limitation. For working depths of over 3500, no flexible risers are qualified, nor exist in oil industry standards. Aggressive R&D investments are needed in this directions for a *rush for the gold* scenario. Flexible pipe technology using composite materials is on the way.

Operation Rig Challenge

Dynamic positioning rigs exist within the oil industry and DP can be considered mature technology. However, an industrial scale power plant would be installed on the rig. These developments have been proposed in the Marsili Project, currently in early stages[5].

Generation and Power Conditioning Challenge

Power generation for high temperature geothermal systems has had limited success on land, but promises large benefits for the future. Very high efficiencies can be achieved with Enhanced geothermal systems (EGS) as reported in the MIT-led panel study for geothermal

[5] www.eurobuilding.it/marsiliproject/

(MIT 2006). If the hydrothermal fluid is captured on the seabed, the supercritical fluid has an equivalent power delivery potential offshore; this also suggested but coarsely explored in the Marshal Project[6]. Vent plumes are sometimes found with temperatures of over 400°C, but the vents themselves are not a good source of the fluid, as the chimneys are unstable and collapse rather regularly.

The MIT study proposed two alternatives shown in Figure 3-5 for power generation using supercritical geothermal fluids. They could be equally deployed in offshore hydrothermal power with some adaptations. The triple expansion plant would reportedly have high thermal and utilization efficiencies. For high-pressure supercritical fluid, an alternative approach is the single expansion ultra-high pressure single expansion cycle. A critical factor to consider however is the amount of dissolved minerals in the hydrothermal supercritical fluid. Two approaches could deal with this problem: reverse osmosis or wet cyclone filtering. Both have technical advantages. The reverse osmosis application was implemented at the Lawrence Livermore Laboratories for silica extraction (Parker 2005). Liquid-liquid cyclone separation would be equally enabling technology.

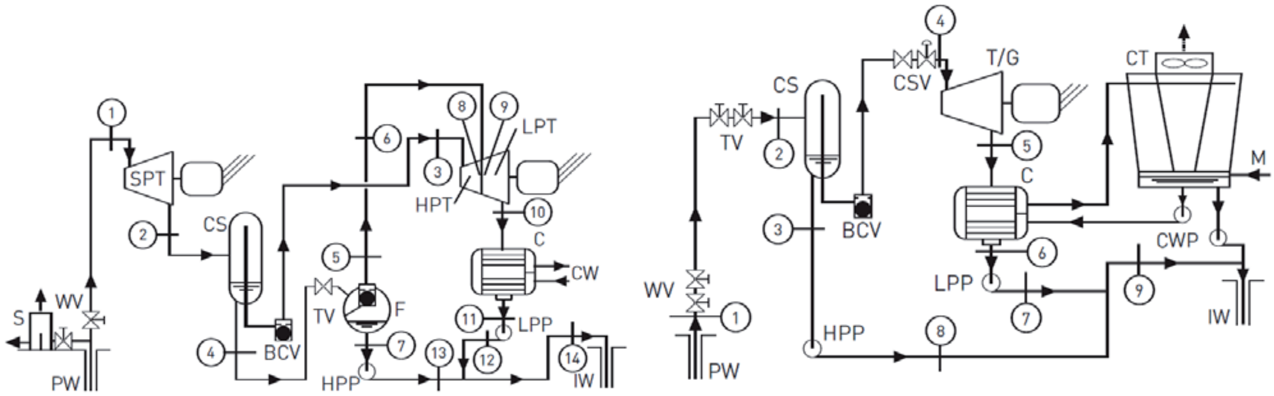


Figure 3-5: Plants for Supercritical Separated Hydrothermal Fluids; Triple-Expansion (left), and Single-Expansion for Ultra-High Inlet Pressures (right)
(Adopted from MIT 2006)

Legend: CS=Cyclone separator; PW=Production well; S=Silencer; WV=Wellhead valve; SPT=Super-pressure turbine; CS=Cyclone separator; BCV=Ball check valve; TV=Throttle valve; HPP=High-pressure pump; HPT=High-pressure turbine; LPT=Low-pressure turbine; C=Condenser; compressor; CW=Cooling water; LPP=Low-pressure pump; IW=Injection well; M=Make-up water; CT=Cooling tower; T/G=Turbine/generator.

[6] www.marshallhydrothermal.com

3.3 Functional Analysis

To achieve energy exploitation from the seabed several main functions are required. This section will cover some of the main technical systems in the power generation function.

3.3.1 TEG: Old Concept, New Application?

Thermoelectric technology has been around for a long time. In the 1820s, Thomas Johann Seebeck first discovered a phenomenon where two dissimilar metals connected in a circuit would deflect a compass if the junctions had different temperatures. Almost two hundred years later, commercial applications of thermoelectric materials have come a long way. Applications range from satellites to wristwatches, from the climate control seat in cars to the new Mars rover.

The thermoelectric effect, also known as the Seebeck effect, is the electric potential produced in thermoelectric materials by the temperature difference. There are two types of materials used as *legs* for producing the thermoelectric effect, shown in Figure 3-6 as p-type and n-type legs. A positive charge builds on the cold side of p-type semiconductors. Conversely, n-type semiconductors are negatively charged at the cold junction.

Recent advances in nanotechnology opened new possibilities for thermoelectric (M. S. Dresselhaus et al. 2007). The efficiency of a thermoelectric generator is characterized by a non-dimensional figure-of-merit, $ZT=S^2\sigma T/k$. The Seebeck coefficient is S, the electrical conductivity of the leg is σ, the thermal conductivity is k, and T is the absolute temperature. New materials developed with Nano-technology and there have been important breakthroughs, such as increasing *ZT* above 1 (Snyder & Toberer 2008). New

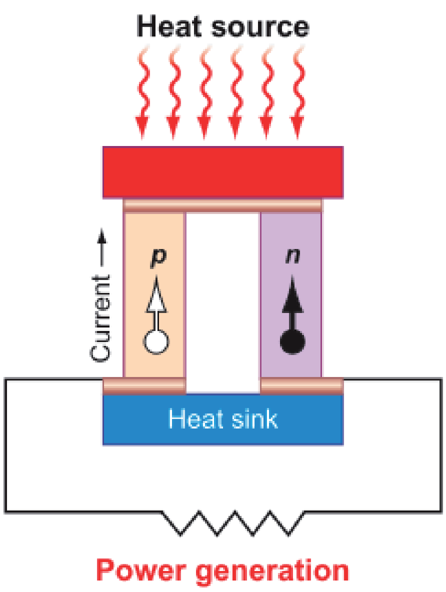


Figure 3-6: A Thermoelectric Couple to Achieve Power Generation
(Source Sales 2002)

thermoelectric materials like bismuth antimony telluride (BiSbTe) have shown laboratory performances with figure of merit *ZT* of 1.4 at 100°*C* (Poudel et al. 2008). Bell discusses the possible use of thermoelectric for a global scale energy alternative (Bell 2008). However, detractors are highlighting the shortcomings of thermoelectric as a real option for solving the world's energy problem (Vining 2009).

Thermoelectric generators are certainly not a panacea. The problem of low efficiency and high initial cost has restricted their commercial applications for many years. In Table 3-4 we list some of the reported benefits and shortcomings of thermoelectric technology. There are two common ways to improve thermoelectric efficiency: decrease thermal conductivity, or increase the product of $S^2\sigma$.

This discussion inevitably leads to the following exploratory question: *Under what conditions could thermoelectric provide a competitive advantage for energy generation in the deep sea?* To answer this question we should make the following considerations. Existing commercial TEG units have limited performance; they supply small amounts of power and are costly. In what timescale could thermoelectric technology mature to provide the required power for a high impact application?

In Figure 3-7, we show the evolution in time of the thermoelectric figure of merit *ZT* as appearing in scientific publications since the year 2000. A second point to consider, is that thermoelectric are reliable sources of power. Thermoelectric materials have been used in many applications that require autonomy and reliability.

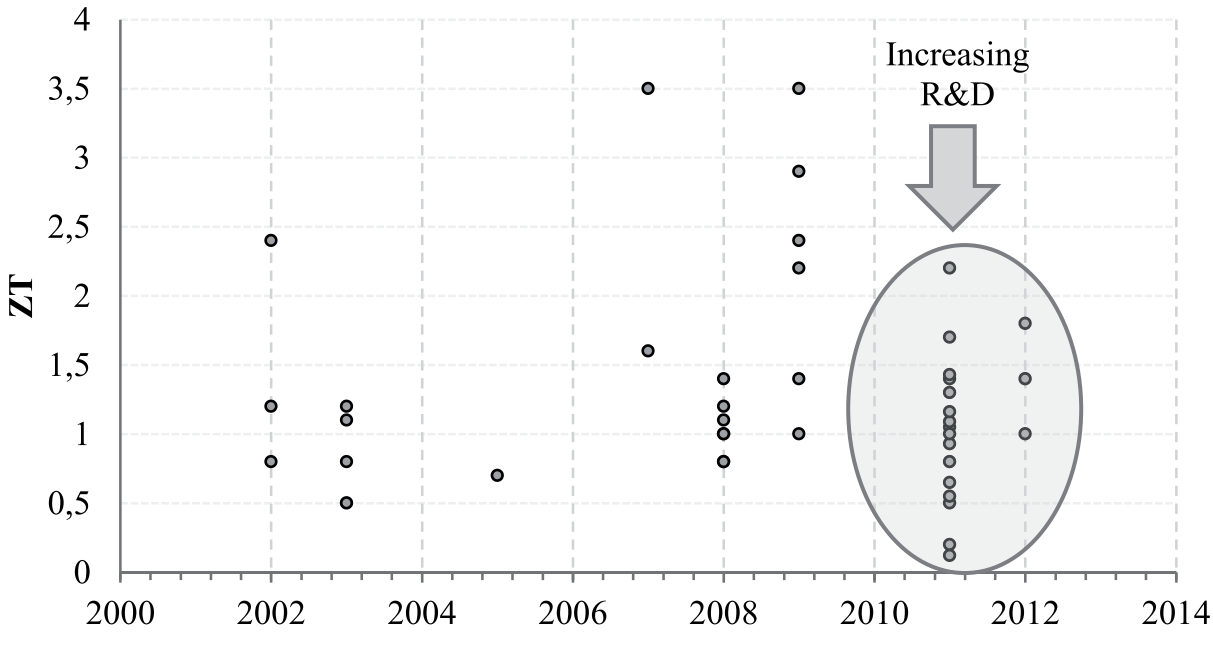


Figure 3-7: Evolution *ZT* in Thermoelectric Materials Research During 2002-2012

Table 3-4: The Benefits and Shortcomings of Thermoelectric

TEG Benefits	TEG Shortcomings
No moving parts, low maintenance demand Reliability Quiet Environmentally safe	Limited theoretical efficiency for available temperature difference at hydrothermal vents Costly (price per Watt) when compared to other renewable solutions

3.3.2 Collection of Energy from Hydrothermal Vents

Efficient energy collection from the hydrothermal vent (HTV) is a major functional requirement in the proposed concept for power generation using Thermoelectric Generator (TEG). The turbulent hot fluid, together with the dissolved minerals needs to be collected and transported across the power generation system. To achieve that, quite a number of issues have to be factored into the decision making process. First, the entire system will be located deep on the seabed where the hydrostatic pressure could be in the order of hundreds of bars. Also, there are technical issues that need to be addressed including: fouling/scale deposition both inside and outside the pipe work constituting the generation plant, fatigue and fracture failure due to temperature swings, corrosion & erosion. The suitable construction materials and optimum configuration to maximize power production at reduced cost need to be determined. Weight of the entire power generating plant also needs to be assessed against the shear/bearing strength of the seafloor; topography of the area around the vent is another important factor to consider in selecting the best energy collection strategy.

There is the legal and moral responsibility for minimising damage to both physical and biological environment on the ocean floor. The marine community around the HTV needs to be protected. One must weigh these factors to decide the right site and energy collection system. Figure 3-8 shows some candidate energy collection concepts each with its merits and demerits. To conduct a coarse assessment of the impact of possible alternative configurations we list 13 criteria in Table 3-5, grouped in two categories: cost and unreliability. The assessment scale bears numbers 0-10, with zero suggesting best and ten worst in terms of costs, environmental impact and reliability, these points are then summed up for each of the six energy collection concepts to determine (subjectively) the viable options. This is however only a guide, and should be validated during detail design.

Site clearing effort refers to the cost due to excavation works, trimming work and levelling when the seabed topography is poor. Thermal gradient is necessary, and heat losses in transporting the vent fluid to the TEGs could affect the efficiency of the units. Portability refers to the ease with which the entire system can be moved from one site to another.

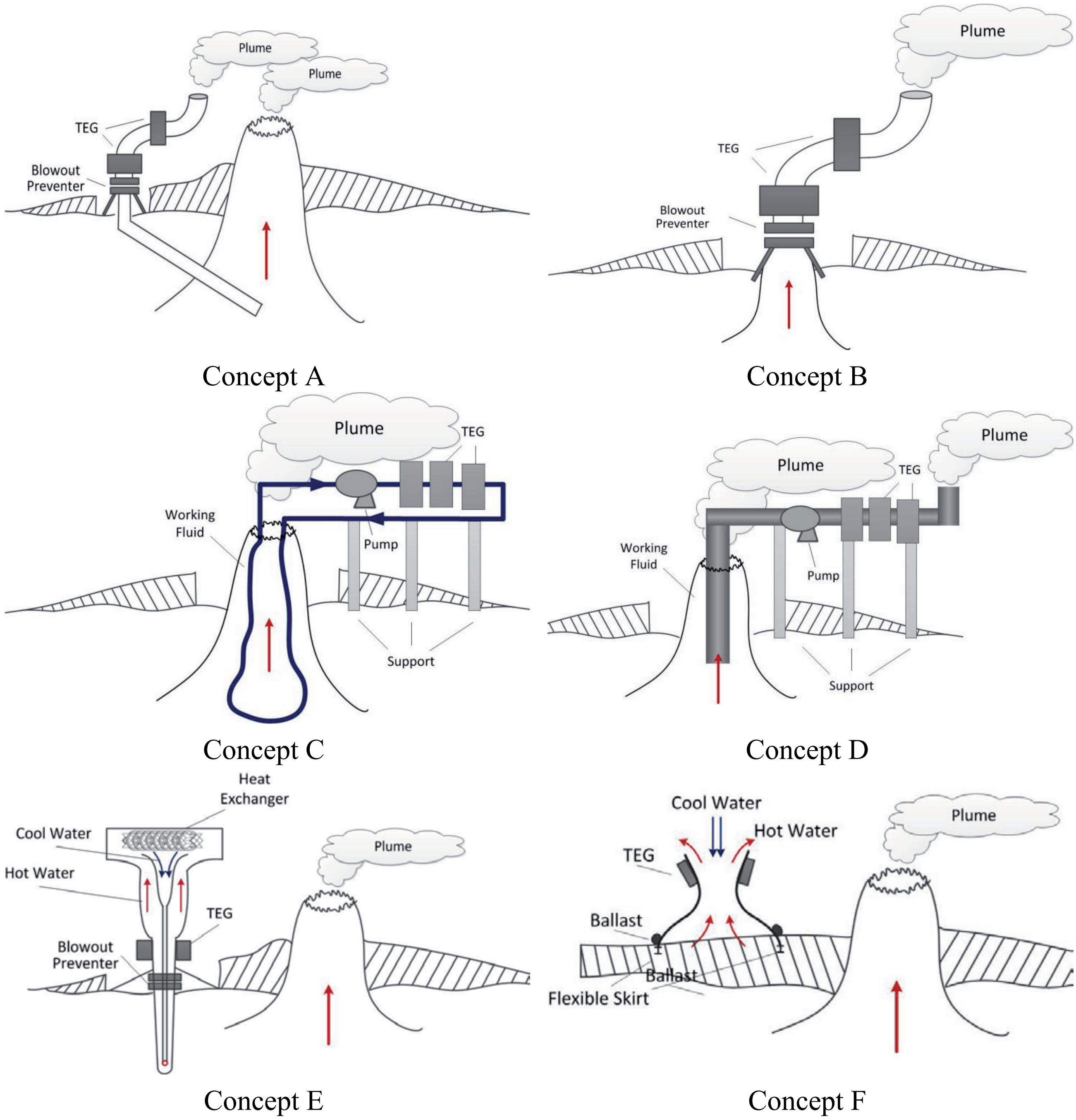


Figure 3-8: Candidate Concepts for Energy Collection from HTF

Preventing fouling (mineral sedimentation) within the power plant

Supercritical hydrothermal fluids dissolve a large amount of minerals. Channelling this fluid through pipe will result in precipitation if the fluid leaves the supercritical condition. The result is clogged pipes, or at least pipe work coated with mineral deposits. This will affect heat transfer at the hot side of the thermoelectric couples. Consequently, the overall efficiency of the power plant decreases and the frequency of turnaround maintenance activities will increase. Fundamental research is needed for understanding the mechanisms and conditions giving rise to the fouling in the pipe work as well as the chimney –for seabed conditions in deep sea.

Table 3-5: Criteria for Performance Analysis of the System Architecture

CRITERIA		CANDIDATE CONCEPTS					
		A	**B**	**C**	**D**	**E**	**F**
Cost	Borehole drilling requirement	10	0	0	0	8	0
	Need for special construction material type	10	10	10	10	10	8
	Quantity of material needed	10	6	9	7	8	0
	Site clearing/preparations	0	9	10	10	0	0
	Expected thermal gradient (efficiency)	1	0	5	2	5	10
	Portability	10	10	5	5	8	2
Unreliability	Internal fouling/ mineral deposition	10	10	0	10	0	2
	External sedimentation on pipe work	5	5	5	5	5	7
	Number of moving components	0	0	10	10	0	0
	Potential for fatigue/fracture failure	10	10	10	10	8	0
	Maintainability vs. design configuration	10	10	10	10	10	0
	System stability against seabed dynamics	0	10	10	10	0	5
	Chimney build up system exit	10	10	0	10	0	2
TOTAL POINTS		86	90	84	99	57	36

The chimney-like structure is formed by Calcium and sulphate rich hydrothermal fluid being exposed to the seawater[7]. During the turbulent mixing, two major events happen. The first is the formation of a ring-like-structure made up of calcium sulphate. The second is the development of smoke, which could be black or white depending on the chemical composition of the plume. The ring-like structure provides a surface for chalcopyrite (which is copper–iron sulphide) to start precipitating, this builds up gradually resulting into the so called chimney structure. On the other hand, the metal sulphides, oxides and other minerals present in the plume help in chimney plating and the remaining minerals deposited close to the chimney or further away depending on particle size and hydro/thermodynamics.

[7] http://www.whoi.edu/oceanus/viewArticle.do?id=2400&archives=true

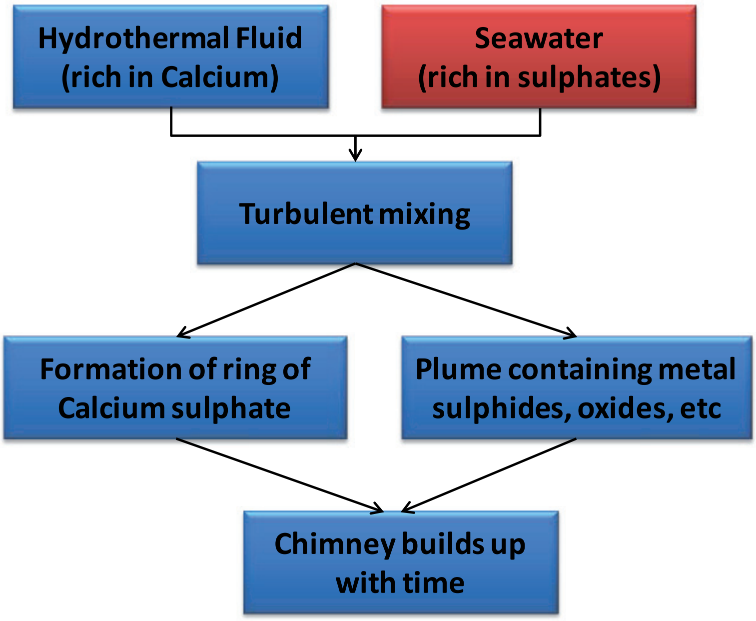


Figure 3-9: Mineral Sedimentation Process around a Hydrothermal Vent

Therefore, a possible approach for minimizing mineral sedimentation, which eventually leads to chimney formation, is to prevent the hydrothermal fluid from coming into contact with the seawater before getting into the pipe network leading to the TEG. Given the conditions at the HTV (Turbulent, high velocity, hot fluid) mild temperature gradient is not expected to have significant impact on the sedimentation, nevertheless, good lagging material is used to coat the pipe work to minimize whatever effect there may be.

Combining the two actions above within the pipe work create conditions similar to what is obtainable down the hydrothermal vent which is why sulphate ring precipitation and black smoke are not there, consequently no mineralization on is observed down the vent.

On a separate note, for soil with poor bearing strength, each or both of these measures can be adopted: using supports with flat-based pillars to distribute the weight of the power plant structure and/or introduce some form of buoyancy to the plant. Therefore, the key points in this section are:

- The hydrothermal fluid is not allowed to come in contact with seawater before getting into the power plant so that no sulphate ring is formed.
- Use good internal isolation in the TEG assembly to minimize the effect of the temperature gradient on particle deposition.
- Use flat bottom pillars and/or incorporation of buoyancy to support the weight of the power plant where the seabed bearing strength is not sustainable.

3.3.3 Channelling Fluids

Candidate Concepts for Energy Collection: Brief description

Concept A involves diagonal drilling. After site preparation, a borehole is drilled to divert part of the superheated water, which can subsequently be used in power generation. While this concept does not involve physical damage to the HTV itself, it involves diagonal drilling which is expensive. A blowout Preventer (BOP) is also necessary to check against pressure swings. Maintenance cost for the borehole in case of fatigue or fracture failure of the borehole is also another factor to consider.

Concept B involves capping the HTV and routing the fluid a few meters away from its original position. As in the previous case, a BOP is needed, mounting the power plant around the vent could be present some technical challenges.

Closed Loop System

Concept C involves use two separate flow lines. Pumps are needed to provide the pressure head to circulate the working fluid. With slight inclination of one of the loop arms, a convective current could be set which may suggest that smaller or no pump may be needed depending on the overall size of the system as well as the working temperature. However, the HTV may need to be especially prepared/trimmed to allow for the part of the loop to come in contact with the superheated vent fluid, this may be quite demanding.

Concept D is similar to the concepts shown in Concept C but does not need a working fluid and is open ended. The same technical issues apply here.

Thermosyphon Based Concept

Concept E features a concept that exploits the working principle of a thermosyphon. The system involves a centrally positioned pipe through which cold water gravitates downward. The descending cold water displaces hot (lighter) water stream upward. This concept also requires drilling but in a vertical direction as opposed to the case in Concept A where diagonal drilling is required. Near the HTV, the temperature a few metres down the seabed meet the thermal requirement of the power plant. A BOP is also needed and working fluid and heat exchangers form part of the system. It should be noted that in this case there is no need for a pump as convective current is in effect; of course, this depends on the size and temperature below the seabed. However, as with concept A, in an event of borehole failure, cost of maintaining the system could be high.

Venturi System Based Concepts

Concept F uses energy dissipated in the area around the mound. While the HTV vent may be described as giving focused power output at higher temperature and velocities, cracks, bacterial mats and other openings expel hot fluid but in a more diffuse sense, with lower velocity as well, these are referred to as diffuse Flows. This concept exploits the energy in the diffuse flows on the mound.

'Diffuse flow' is fluids discharged along mid-ocean ridge (MAR) axes that have low temperatures, low flow rates, and broad spatial distributions. In particular, for the TAG area, the temperature has been found to be between 13.5 to 14.5°C, flow velocity between 1 to 9E-04 m/s, total diffuse heat output between 250 to 470 MW (Bemis et al. 2012). Generally, the temperature could range between 0.2 to 100°C (Sarrazin et al. 2009).

In this case, the energy collection system is placed on top of a suitable diffuse flow; ballast is used to provide stability against the seabed topography, and mild tectonic activities. Flexible skirt is also used to ensure good contact between the system and the seabed (Sarrazin et al. 2009).

While the power system traps the hot gushing fluid, denser cold seawater descends displacing the hot and less dense fluid. The hot water comes into contact with inner part of the TEG module providing the needed thermal potential for power generation.

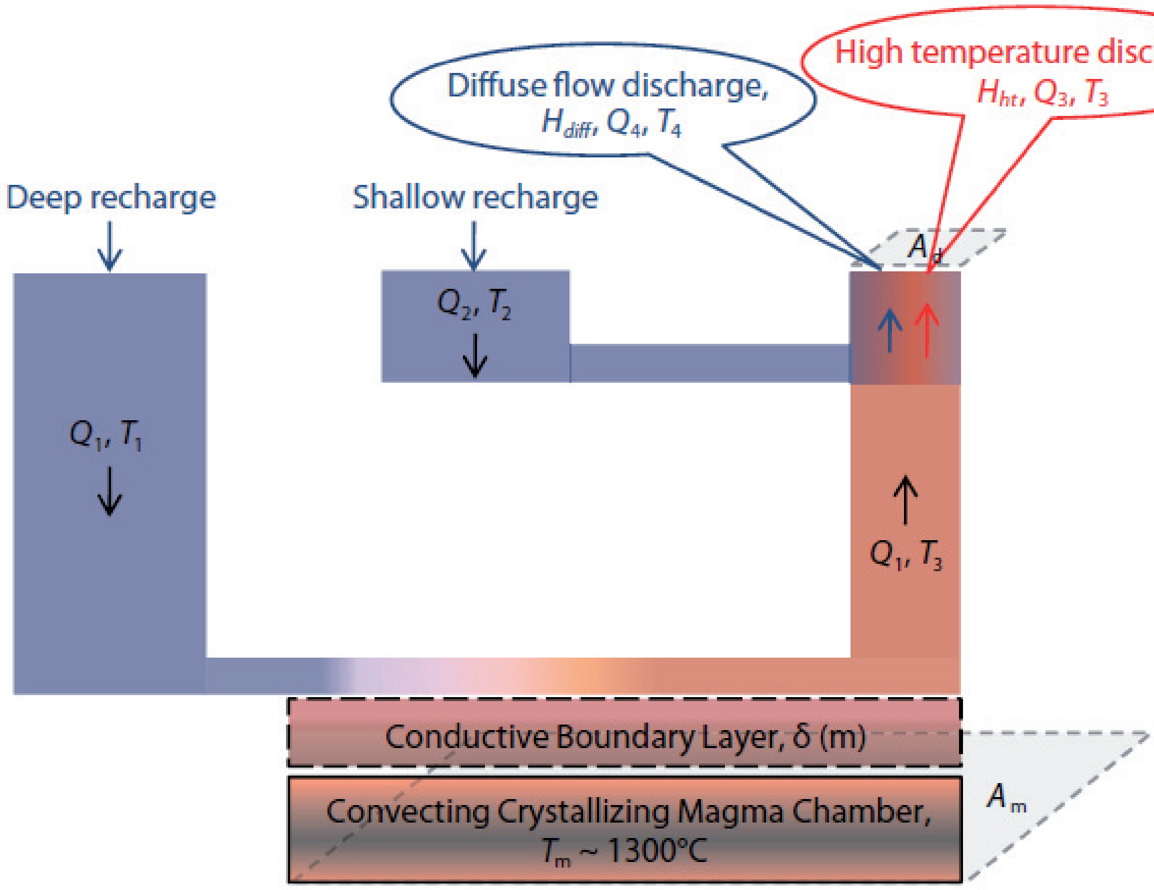


Figure 3-10: Schematic of a Cross Section of a Two-Limb, Single-Pass Hydrothermal Circulation Model for Understanding the Partitioning Between Focused and Diffuse Flows at the Vent-Field Scale
(Bemis et al. 2012).

Some of the issues with this concept include low temperature gradient between inner part of the TEG and the surrounding water. Stability of the module due to poor shear strength of the seabed as well as the geodynamic process is also another source of concern.

In conclusion, each of the six energy collection concepts proposed here has its merits and demerits. It can also be seen that each of the concepts involves some kind of site preparations/excavation with the exception of the concept shown in Concept E, which may require relatively mild or none at all. Each of them is also under the effect of hydrostatic pressure, and could be in the order of hundreds of bars at the sea bed. Low pH and the heat content of the environment also means that special construction materials are necessary. This requirement could increase the cost of the project. The energy source however, is quite vast, renewable and sustainable. The entire process also features relatively mild environmental impacts.

3.3.4 Converting hydrothermal energy to electrical energy

This section presents a method for estimating theoretical energy obtainable from a HTV, actual electrical energy realizable as well as the factors affecting thermal efficiency of the TEG.

Average (theoretical) power obtainable from a typical HTV

The available thermal power Q in a hydrothermal vent can be estimated by:

$$Q = \frac{\pi D^2}{4}.v.\rho_{avg}.C_v.(T_h - T_c) \tag{3.1}$$

where D is the average diameter of the vent expressed in meters; v is the linear flow speed of the fluid gushing from the vent measured in m/s; ρ_{avg} is the average density of hydrothermal fluid measured in kg/m^3; C_v is the average heat capacity of the hydrothermal fluid; T_h is the temperature (hot) of the vent fluid measured in °C. Finally, T_c is the surrounding cold water temperature. Values for the parameters in Equation 3.1 vary from chimney to chimney, and between hydrothermal fields. Flow speeds between $1m/s$ and $2m/s$ and temperature ranges between 25°C and 405°C are common.

The actual available power will be reduced because of losses. For a single power unit one multiplies the available power by the heat transfer efficiency η_{HEX} and by the thermoelectric efficiency η_{TEG}. One obtains:

$$P_E = Q \times (\eta_{HEX}) \times (\eta_{TEG}). \tag{3.2}$$

Heat transfer efficiency depends on the configuration of the heat exchange regimes. Given Equation 3.2, one can determine the efficiency of the TEG by:

$$\eta_{TEG} = \frac{Energy\ provided\ to\ the\ load}{Heat\ energy\ absorbed\ at\ the\ hot\ junction}. \quad (3.3)$$

Heat absorbed at hot junction here refers to the effective heat from a hydrothermal vent, which was computed earlier. The following expression has been used to estimate the maximum TEG efficiency:

$$\eta_{max} = \frac{T_h - T_c}{T_h} \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_c}{T_h}} \quad (3.4)$$

Z is the figure of merit of a thermoelectric couple, and is given by:

$$Z = \frac{\sigma S^2}{\kappa}, \quad (3.5)$$

where σ is the electrical conductivity, κ is the thermal conductivity, and S is the Seebeck coefficient. The dimensionless figure of merit ZT is formed by multiplying Z with the average temperature.

$$T = \frac{T_h + T_c}{2} \quad (3.6)$$

T_h is the temperature of the hydrothermal vent fluid; T_c is the temperature of the cold sea water (Fergus 2012). Some of the factors that affect the thermoelectric figure of merit are shown in Table 3-6.

Table 3-6: Factors Affecting the Efficiency of a TEG
(Source: Bell et al. 2011)

Factors affecting generator performance	Remark
Intrinsic material performance	Obtain the best materials, optimize stack design for compatibility
Thermal leaks: conduction, convection, radiation	Minimize exposed areas Suppress leaks by Insulation/shielding
Interfacial losses within thermoelectric stack, thermal and electrical	Characterize contact resistance Develop metallization solutions Develop bonding solutions
Interfacial losses between thermoelectric shunts, both thermal and electrical	Investigate joining approaches

Table 3-7: Efficiency Losses as Contributed by Different Factors
(Source: Bell et al. 2011)

Element	Loss (%) Net	Efficiency (%)
Ideal device efficiency	baseline	13.37
External thermal leaks	3.05	10.32
Interfacial losses between segments (0.32 μΩcm2)	0.03	10.29
External interfacial losses (0.32 μΩcm2)	0.06	10.23
Device net efficiency	n/a	10.23

As a reference,

Table 3-7 outlines the contributions of individual loss mechanisms in a 10% efficient generator recently developed at BSST[8]. This template can be used as one of the bases for estimating the efficiency of HTV- based TEGs.

Many factors affect the efficiency of thermoelectric devices. Note that the Figure of merit Z is essentially a function of thermal conductivity of the material, electrical conductivity and Seebeck coefficient. However, the efficiency of a thermoelectric device for hydrothermal vent applications depends on the average vent temperature. The exact calculation of TEG efficiency requires consideration of the compatibility of the two thermoelectric legs. Compatibility for the P and N-type semiconductors has to be considered (Snyder & Caillat 2003). The maximum efficiency Z is only achieved when the relative current density u, (ratio of the electrical current density to the heat flux by conduction) is equal to the compatibility factor:

$$C = \frac{\sqrt{1+ZT}-1}{ST} \tag{3.7}$$

Therefore, the central goal is to find materials with high figure of merit and similar compatibility factors. Semiconductors of high mean atomic weight are likely to have good thermoelectric properties. In particular, n-type legs using Lead, Tin and Tellurium have been extensively studied because of high temperature resistance and energy gap. The corresponding p-type legs are formulated from alloys that contain the elements Te, Ag, Ge, and Sb –also known as TAGS.

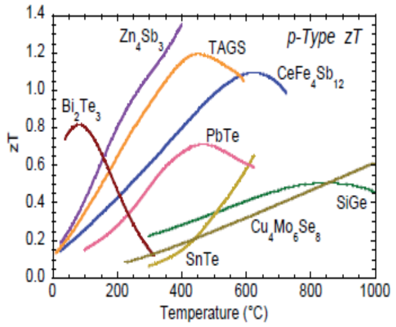
[8] Details about BSST available at: http://www.bsst.com/about.php

Example on How to Improve PbTe-TAGS

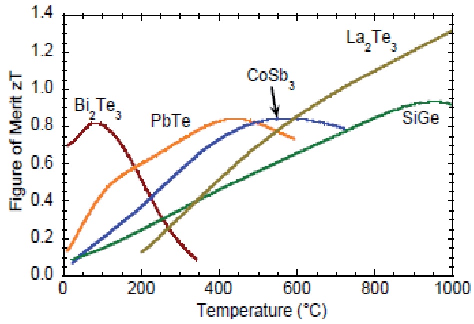
The [9] TAGS material $((AgSbTe2)_{0.15}(GeTe)_{0.85})$ must be maintained below 525°*C* while the PbTe n-type element can operate to 600°*C*. To achieve a 600°*C* system, a segment of another p-type material is added to the TAGS p-leg. The charts in Figure 3-11 show different compatibility factors. For instance, it can be seen that the TAGS and the PbTe have high ZT, their compatibility factor is not good. To address this problem, the material is segmented with SnTe, which result in higher compatibility, and acceptable ZT. With TAGS-SnTe, the efficiency increases from 10.33 to 11.09%. A fully segmented generator using Bi_2Te_3-type, PbTe, TAGS, Zn_4Sb_3, skutterudite, La_2Te_3, and Chevrel compounds between 25°*C* and 1000°*C* achieves 18.1% conversion efficiency (Snyder & Caillat, 2000).

3.3.5 Electrical Energy Storage

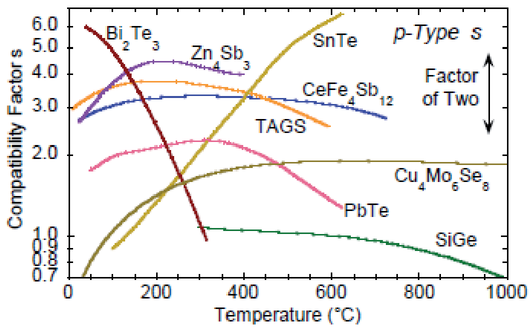
Electrical power generation should usually be bigger than the power consumption of the subsea equipment. For reasons of redundancy or to improve equipment utilization, one must analyse the alternatives to store the electrical power generated by the thermoelectric unit. Figure 3-12 shows a range of rechargeable batteries and fuels that could be used for subsea power generation. Next, we introduce rechargeable batteries that are used in deep sea.



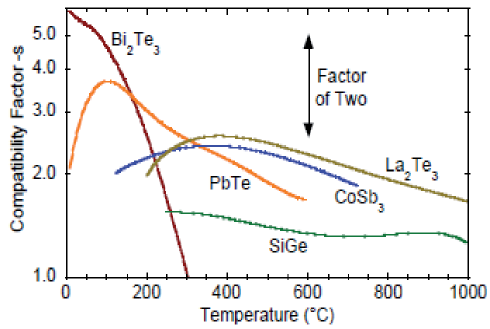
a: P-type materials



b: n-type materials



a: P-type materials (positive)



b: n-type materials (negative)

Figure 3-11: Compatibility Factors *(below)* and Figure of Merit *(above)* for Different *(a)* p-type and *(b)* n-type Semiconductors

[9] General formula for TAGS is: $((AgSbTe2)_x(GeTe)_{1-x})$

Table 3-8: Maximum Single Element Efficiency for Thermoelectric Generators (Snyder & Caillat, 2000)

Material	Efficiency (%)	T_c (C)	$T_{Interface}$ (C)	T_h (C)	$u(T_c)$ (V^{-1})
p-TAGS	10.45	100		525	2.97
p-TAGS/PbTe	10.33	100	525	600	2.33
p-TAGS/SnTe	11.09	100	525	600	2.84
p-TAGS/$CeFe_4Sb_{12}$	11.87	100	525	600	2.94
p-TAGS/$CeFe_4Sb_{12}$	13.56	100	525	700	2.88
p-SiGe	4.23	525		1000	0.85
p-TAGS/SiGe	9.89	100	525	1000	1.12
p-$Cu_4Mo_6Se_8$	4.00	525		1000	1.78
p-TAGS/$Cu_4Mo_6Se_8$	11.48	100	525	1000	2.77
n-PbTe	9.87	100		600	-2.00
n-PbTe/$CoSb_3$	11.30	100	600	700	-1.96
n-PbTe/SiGe	13.76	100	600	1000	-1.46
n-PbTe/La_2Te_3	15.56	100	600	1000	-1.80
n-SiGe	5.44	600		1000	-1.29
p-Bi_2Te_3/Zn_4Sb_3 /TAGS/$CeFe_4Sb_{12}$ /$Cu_4Mo_6Se_8$	18.57	25	170/400 525/700	1000	2.94
n-Bi_2Te_3/PbTe /$CoSb_3$/La_2Te_3	17.83	25	190/480 600	1000	-2.01

Key Factors to Consider in Deciding Batteries Characteristics

In order to decide the batteries to use for storing energy on the seabed, we must consider the maximum working depth, energy capacity, power density, power capacity, charging time and cost per kWh among others. Firstly, the maximum working depth is determined after site location. Most hydrothermal fields exist above 4000mbsf. Energy capacity is the total amount of energy that a battery can store when it is fully charged. Power density is the amount of power available per unit volume or weight. Power capacity refers to the power that the battery can deliver. Appendix B.2 shows some basic criteria. The summarized performance of batteries is represented in Table 3-9.

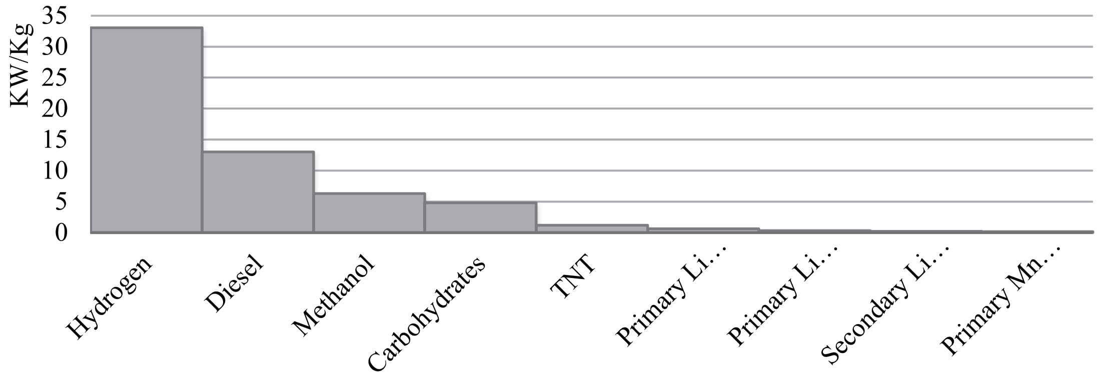


Figure 3-12: Specific Energy and Specific Power
(Data: Griffiths 2004)

Comparison and Summary

From the Table 3-9, we can know that lead acid battery has highest energy/cost performance of the four. It means that it cost the lowest in order to store same amount of electrical energy. However, lead acid battery has less power density than that of lithium polymer battery. Therefore, it needs to take larger space to store a lot of energy.

Lithium polymer has lowest energy/cost performance of the four, and there is less attractiveness in cost. However, it has highest power density, and high energy efficiency. Thus, if it is affordable, lithium polymer battery has highest performance. Lithium ion battery has similar performance to lithium polymer battery. However, it is inferior to lithium polymer battery in power density. Therefore, there is no attractiveness to use Lithium ion battery for energy storage. Ni-MH battery also has no attractiveness, because it has lowest energy/cost and lower power density than that of lithium polymer battery. All the mentioned battery technologies are already in use in deep sea, mostly in AUV. Thus, the applicable depth is not a problem.

Every battery has a different environmental impact. Lead acid batteries leak sulphuric acid when ruptured. Lithium polymer batteries and lithium ion batteries are known to explode. Once destruction of batteries happens, damage to the ecosystem can occur. However, all of them are avoidable by monitoring battery current and by packing batteries tightly. Table 3-9 shows summary of the performance of each type of battery; and Table 3-10 shows the related benefits and disadvantages.

In summary, when the priority is on the cost rather than battery size, or the amount of energy storage required is small, lead acid batteries can be a good option. If emphasis is on space minimization and efficiency rather than battery cost, or when the amount of energy storage required is big, lithium polymer batteries are a better option. From the above comparison, one finds the following tradeoffs:

- When we prioritize the cost over battery space, or when the amount of storage energy is small, lead acid battery is a good option.
- When we prioritize the minimum space and efficiency over battery cost, or when the amount of energy storage requirement is big, lithium polymer battery could be employed.

3.3.6 Supply Electrical Energy

In this section, means of power transmission from the battery to a given destination are discussed. Potential subjects are: AUV, mining collectors/cutters, and cities, power demands of each of these are different. AUV for exploration purpose needs 1kW- 10kW, mining units need approximately 2*MW* and DPS system of mining ship needs approximately *20MW*

(Jankowski et al. 2010), city requires power in the order of hundreds of *MW*. In this work, the focus is on AUV which have relatively low energy requirement.

Figure 3-13 shows the power supply map, from storage battery to an AUV. In this section, we discuss energy supply from storage battery to each client. In this work, we focus on AUVs, as shown in Figure 3.13.

Table 3-9: Performance of Each Battery

	BATTERY TYPE			
PARAMETER	Lead acid battery	Ni-MH battery	Lithium ion battery	Lithium polymer battery
Capacity	960Wh 12V-80Ah	N/A	N/A	4500Wh 56V-80Ah
Power	Max 16A 192W	N/A	N/A	Max 18A 1008W
Application (product name)	SeaBattery (Deep Sea Power & light)	Diving pump, AUV	Diving pump, AUV (Urashima)	AUV (Autsub6000)
Depth	Max 6,000m	N/A	Max 3,5 00m (case of Urashima)	Max 6,000m (case of Autsub6000)
Power density	20Wh/kg	Higher than lead acid battery, but lower than li-po and li-ion battery	Higher than lead acid battery, but lower than li-po battery	102Wh/kg
Charging time	10h or 20h	Rapid recharge is possible	1-5h	1-5h
Cost	$2,700	N/A	N/A	$27,000
Capacity/cost	0.36Wh/$	Lowest of the four	Almost same as li-po battery	0.167Wh/$
Environmental Impact	Leakage of sulphuric acid	Explosion (less than li-po or li-ion battery)	Explosion	Explosion

Table 3-10: Benefit and Disadvantage of Each Battery

	BATTERY TYPE			
	Lead acid battery	Ni-MH battery	Lithium ion battery	Lithium polymer battery
Benefit	• Cheapest	• Rapid recharge is possible	• High energy density, but less than that of li-po battery. • High cost	• Most highest energy density • Easy to package than li-ion battery
Disadvantage	• Low power density • Leakage of sulphuric acid is common	• Low efficiency • Low capacity/cost • Possibility of explosion but less than li-po battery	• Expensive • Hard to package • Possibility of explosion • Flammable electrolyte	• Expensive • Possibility of explosion • Flammable electrolyte

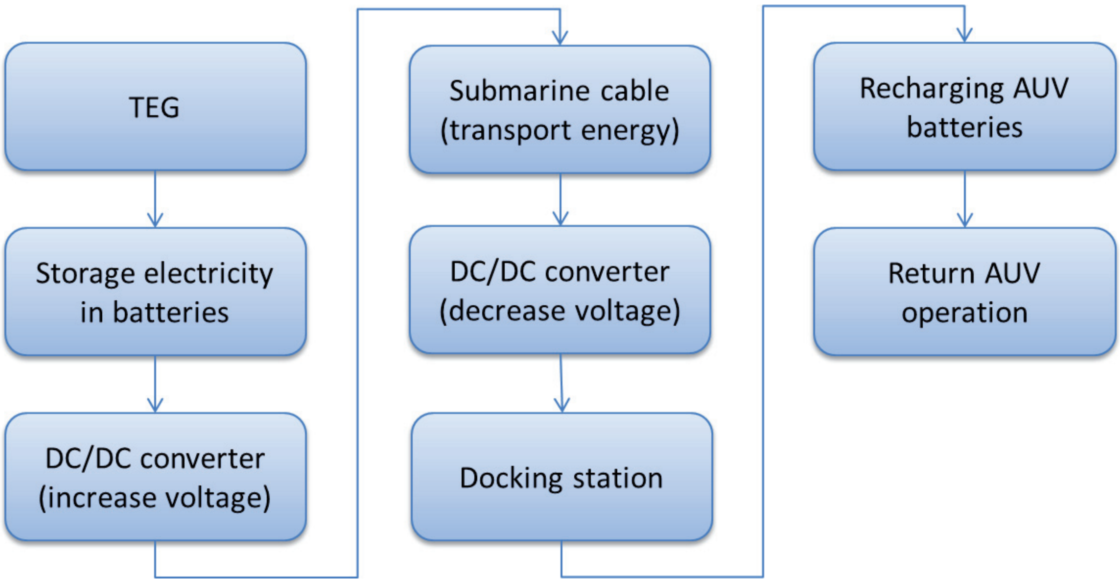


Figure 3-13: Electrical Energy Supply Map

Below are some steps involved in energy supply from storage battery to an AUV. Each of the following needs to be clearly defined:

- A target AUV
- Recharging energy (Docking station)
- DC/DC converter1 (decrease the voltage)
- Cable
- DC/DC converter2 (increase the voltage)
- Storage battery

Defining AUV Performance

In order to define a target AUV, the following information, and evaluation methods are necessary. Operation depth should be equivalent to or deeper hydrothermal vent depth, because energy transportation systems like docking stations are near the storage batteries. Thus, AUVs must have the capability to submerge to docking station depth. Operation depth will depend on each vent location, and the maximum operation depth of the selected AUVs must be larger than the vent depth.

AUVs must have lithium ion battery or lithium polymer battery, when we use inductive charger. It is because inductive charge experiment has already conducted in case of lithium ion battery. Thus, AUV should have it, or similar battery: lithium polymer battery.

Battery type is not a limitation in case of plug-in charge, because batteries are normally recharged by using plug-in cable on the ship. Thus, the only thing required is that AUV uses rechargeable battery. Battery data is used to determine charging time of AUV. Some technical improvements to AUV are required in order to be able to recharge the battery on the seabed. For example, in case of inductive charge, AUV must be equipped with the coupler secondary core. To calculate the output power and required input power of docking station one must know the power required for charging the AUV batteries. AUV size data is also used to calculate the size of the docking station.

Defining the Energy Transport System

Two things define energy transport system: both the form of docking station and the recharging method. They need to be considered carefully. The docking station must be designed for suit AUV positioning to achieve good recharging efficiency. Thus, entrance of docking station has the role to guide that place. Now we can design two docking stations based on this principle. They are shown in **Figure 3-14** *(a)* and *(b)*. Both forms are also designed to have simple shape and less moving parts. The entrance to the docking station has conical shape and transport tool like inductive chargers are equipped in the fiberglass cylinder (McEwen et al. 2008). It is not necessary for AUV to require high accuracy operation, because this conical entrance guides AUV to transport flat. Because we require 1cm-10cm accuracy, the sound sonar is enough to achieve entrance (Toshihiro Naki 2011).

The entrance diameter is 2m, when the AUV diameter is 54 cm. Thus, when our target AUV diameter is given (D_{auv}[cm]) the entrance diameter is calculated by:

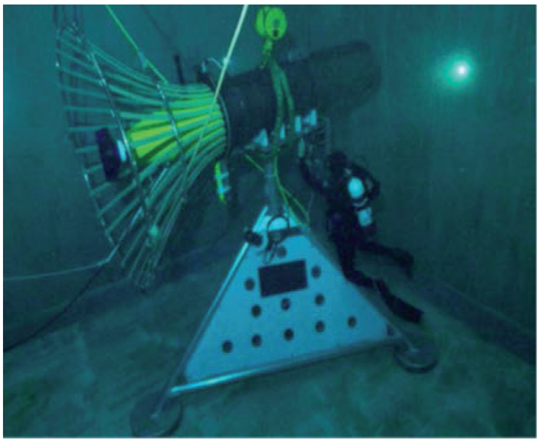
$$D_{en} = \frac{D_{auv}}{54} \times 2.0 \quad (3.8)$$

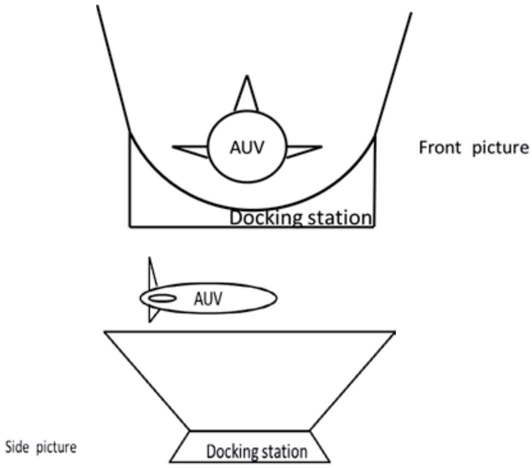
where D_{en} is the entrancediameter, and D_{auv} is the target AUV diameter. The cylinder diameter is designed to be about 3cm bigger than that of the AUV diameter. In the concept shown in Figure 3.2b, the docking station is designed with a parabolic shaped section. This also makes for proper energy transportation area and does not require high accuracy-operation as in the case of conical entrance. In order to keep the same guide performance with conical one, the entrance width and length should be calculated:

$$L_{en} = \frac{L_{AUV}}{54} \times 2.0\ ,\ W_{en} = \frac{D_{AUV}}{54} \times 2.0 \quad (3.9)$$

Where L_{en} *is the e*ntrance length; L_{AUV} is our target AUV length and W_{en} is the entrance width [m]. The two forms are assessed in terms of technology maturity, cost and accuracy.

The conical entrance form has high technical readiness: Experimentations in shallow water depth has already been conducted successfully (McEwen et al. 2008). The form shown in **Figure 3-14** *(b)* is also another possible alternative but there is the fear that particle sediments from the black smoker may affect it, especially if the plant is sited close to the HTV. In this last option, the system is open-ended, and it will require more frequent maintenance services.





(a) *(b)*

Figure 3-14: Form of Docking Station: *(a)* Conical and *(b)* Parabola Type (McEwen et al. 2008)

If we assume that same materials are used for both forms, the parabolic form will cost more than the conical design. Concerning accuracy, no large difference is expected between the two forms. Consequently, it can be concluded that the conical form of **Figure 3-14** *(a)* is superior to the parabola type docking station.

There are two possible recharging methods: inductive and plug-in method. Using the inductive method, the battery is charged by electromagnetic induction; the inductive coupler has a primary side that is fixed to the docking station and a secondary side that is mounted on the AUV. When the battery needs charging, the AUV with the coupler secondary core will dock and make contact with and coupler primary core. As soon as the primary and secondary cores are engaged, as indicated by a limit switch, the system will be ready for charging. Then AUV batteries start recharging by the electromagnetic induction. The electrical energy for the coupler primary core comes from batteries stored energy near the hydrothermal electrical generator. This is shown on the Figure 3-15. The plug system is quite common, and will not be expanded here.

In terms of charging simplicity, the inductive charger is superior to the plug in concept. In inductive charging, high tapping accuracy is not required, so no need for sonar or highly sophisticated dynamic positioning system as it is the case with plug in device,(Toshihiro Naki 2011). For this reason, inductive charging system is quite suitable for charging AUVs and ROVs.

The required input power to the docking station [W] can be calculated from:

$$P_{in-dock} = \frac{P_{out-dock}}{E_{dock}} = \frac{P_{in-AUV}}{E_{dock}} \quad (3.10)$$

Where $P_{in-dock}$ is input power to docking station, $E_{dock}$is energy efficiency of docking station (This is given charging system and gap) and $P_{out-dock}$ is input power from docking station., P_{in-AUV} is required power of our target AUV (This is decided by the target AUV), $P_{in-DC/DC2}$ is input power to DC/DC converter2, $P_{battery}$ is power of storage battery per 1 battery .

From the table below, it can be seen that the cost is directly proportional to performance, capacity and efficiency requirements, which is to be expected; this therefore is a question of optimization.

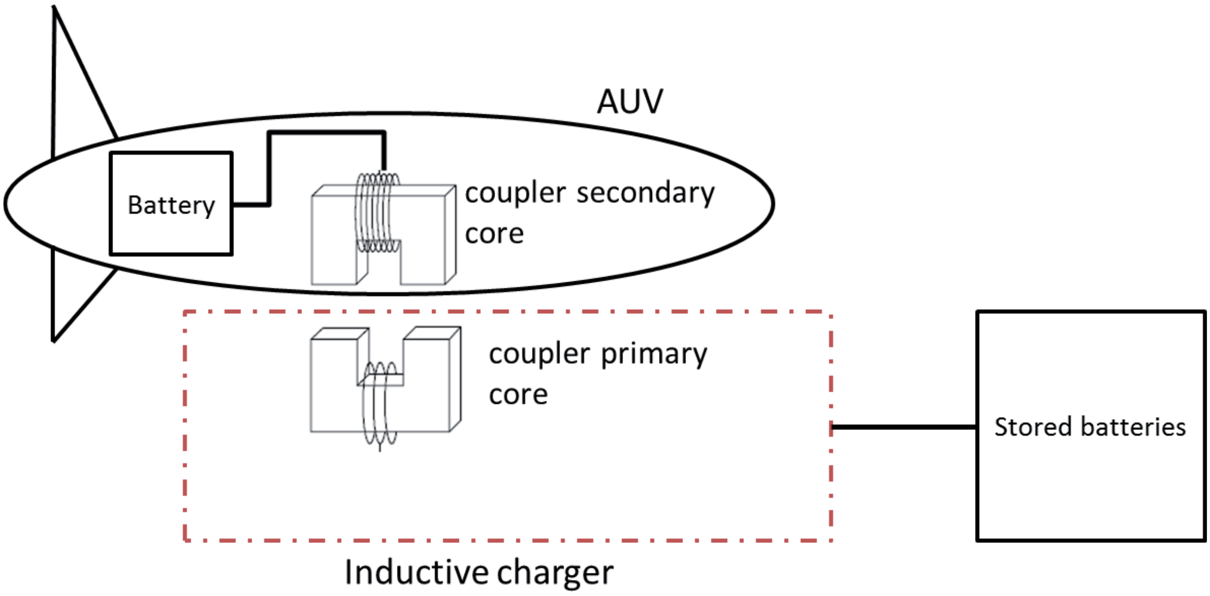


Figure 3-15: Inductive Charging System

Table **3-15**: Influenced Parameters by Defining Each Function

Function	What parameters are decided by this function	Notice
AUV	Power [W], [A] Capacity for charging [Wh], [V] Maximum operation depth Cost for AUV Cost for improvement	Depth should be defined based on vent depth.
Transport system	Energy transportation efficiency Cost	Transportation method and gap decide efficiency. When we try to higher the efficiency, cost also becomes higher. Thus, this balance should be considered.
DC/DC converter 1 (decrease voltage)	Output power [W] Output voltage[V] Input Voltage [V] Energy efficiency Cost	Input voltage should be higher to minimize cable energy loss. Output power and voltage are decided based on transportation data. When we try to higher the efficiency and input voltage, cost also becomes higher. Thus, this balance should be considered.
Cable	Resistance Cost	Resistance should be smaller to reduce cable energy loss. Cable length is decided by location of vents.
DC/DC converter 2 (increase voltage)	Output power [W] Output voltage[V] Input Voltage [V] Energy efficiency Cost	Output power and voltage are decided based on cable data.
Storage battery	Energy [Wh] Power[W] Power density[Wh/kg] 4. Cost Energy/Cost[Wh/$]	The balance of energy and cost is important. Required total power is calculated in this step. Required number of battery is decided by battery data and AUV data.

4 A case of Deep Sea Energy Exploitation

"We know less about the ocean's bottom than the moon's behind"

Roger Revelle (1909-1991)

Deep sea energy exploitation is presented in this chapter as a case study for the Stage 1 of the slow growth scenario. Specific operational scenarios could include general exploratory missions (scientific), exploration companies doing mineral prospecting or government agencies enforcing monitoring regulations over the resources of the EEZ. The novel concept in this application is the use of a thermoelectric generator for the energy conversion of the hydrothermal well. Figure 4-1 shows a system concept for deep sea exploration. This chapter is dedicated to describing this concept, and exposing the many challenges involved in the implementation stage of such a system. The focus of the following concept exploration is on the energy demands of the system, and the engineering of critical subsystems that could deliver the power required.

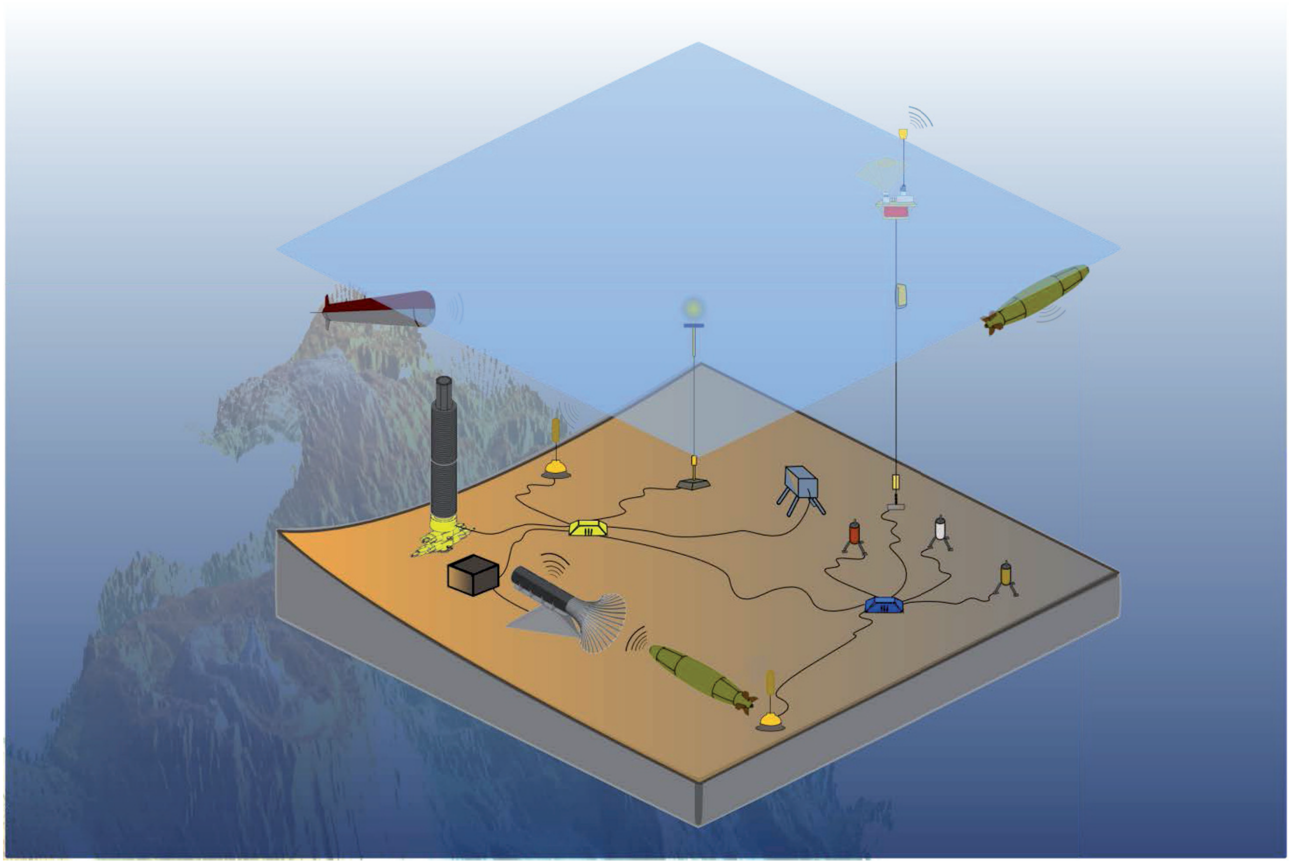


Figure 4-1: Case Study for Deep Sea Exploration

4.1 Deep Sea Exploration

The power demand for the power subsystem in this deep sea exploration concept is 10-12kW. This requirement derives from the power requirements established in the Systems Requirements Document of the Ocean Observatories Initiative. The OOI project has specified requirements for two types of nodes in their system. The main system components are listed in Table 4-1.

The challenge for research and exploration in the area lies in the logistics of the operation, the costs and reliability of the deep-sea subsystems. Because of the distance to the shoreline of coastal states, power supply becomes a problem for autonomous operation. This is the problem we address in the next lines: the design of a novel, clean and reliable energy supply sub-system for the remote Autonomous Observation Nodes (AON).

Figure 4.1 shows the Autonomous exploration nodes. The concept enables seabed photography, hi-resolution bathymetry, magnetic survey and sub-bottom profiling capabilities mounted on AUVs that could be deployed for short or very long missions without a surface vessel around. Using a surface vessel with deployment capability (drill <200 meters close to the active vent site) the system is installed. Maintenance demands return to the site for extraction *(i)* when maintenance is required or *(ii)* when the mission is complete. The system must have the ability to send real time data for monitoring operations and scientific measurement instruments, while it could send block-data once downloaded from the AUVs – upon docking.

Table 4-1: Main System Components for Deep Sea Exploration and Monitoring Using Autonomous Observation Nodes (AON)

	Primary Node	Secondary Node
Level 1 User	Scientific themes Programme requirements	Policy structure Programme Requirements
Level 2 Program Management	Scientific requirements Education requirements Cyber-User requirements Common requirements Supportability requirements Operational requirements	Oversight requirements Exploitation operator requirements Common requirements Supportability requirements Operational requirements
Level 3 System	Cyber-Infrastructure requirements Main node requirements Interface requirements	Cyber Infrastructure requirements Secondary node requirements Interface requirements
Level 4 Subsystem	Surface Buoys, Data Infrastructure, Moorings, Profiler, Power system, Telemetry System, Instrument package, Autonomous Underwater Vehicle (AUV)	Vertical Moorings, Data Infrastructure, Profiler, Subsea cable, Power System, Telemetry System, Instrument Package, Autonomous Underwater Vehicle (AUV)

4.2 Case study: TAG Vent Fields

These two cases were selected because they represent extreme use cases for an Autonomous Observation Network in the deep sea. An implementation on TAG enables exploration of the area. Future implementation in Solwara (Papua New Guinea) could enable monitoring of mining prospects, accelerating the learning curves for future environmental impact assessments.

4.2.1 TEG Characteristics

Appendix E shows schematic drawings representing the design of the energy harvesting system. The main challenge for this preliminary conceptual design lies in the deployment constraints for the system. Appendix E contains the system requirements for the power generation unit and the General Requirements (GR) for the Autonomous Observation Nodes.

4.2.2 Deployment

Drilling at the TAG site is feasible. Both the existing rigs ant the Ocean Drilling Program assets have the capability for the 3500 meter depth. Major challenges for drilling in deep sea are (a) water temperature and (b) hydrostatic pressure. A drilling riser pipe is used to reach the required depth. Normally it consists of a pipe of approximately 19" inner diameter, and 22" outer diameter. In a first stage of the drilling process, a wellhead is installed. Then the process consists of drilling, controlling the well, casing and cementing.

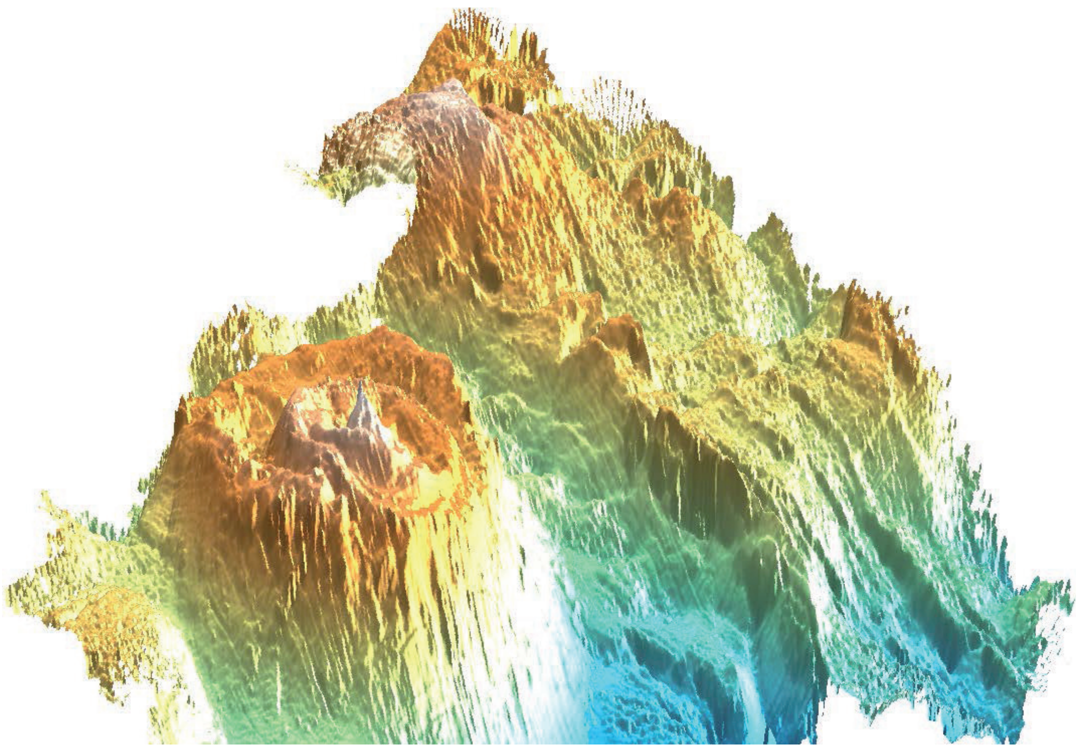


Figure 4-2: Topography of the TAG Vent Systems.

The drilling process continues and casing and cementing are performed to hold the walls and preserve the well. A Blow Out Preventer (BOP) is used in the oil industry to retain control of the well in case of an accident or failure. The BOP is installed on the wellhead, and will remain there after closing of the well. Tools, drill bits and drill fluids go on the inside of the casing during the drilling process, and on the outside the connections for activating the valves that control the BOP.

For shallow wells, seawater could be used as drilling fluid and some additives could be used to increase the viscosity of the solids removed during drilling. It could also be that a "Jetting" process is preferred to drilling. A pipe section is lowered to the seabed and the hole is carved using a high-pressure flow. After jetting, you cement and use a casing. Another option is to use jetting in the first stage and drilling in a second stage.

Drilling Rigs

Drilling is feasible in the deep waters of many ocean ridges. The list of drilling rigs from the oil industry with existing capabilities to drill in deep waters is listed in Table 4-2. Notice that many of these rigs have design capabilities to drill in deeper waters, but equipment is not certified for all of them. However, a deep-water drilling platform costs between USD 500K and USD 1M per day including personnel, equipment and operating expenditures. However, this costs do not include external services like drill fluids, directional drilling, logging, cementing and finishing. An alternative to oil drilling platforms is the type of equipment that is already in active use for ocean research. The like of ships used in the Ocean Drilling Program, such as the JOIDES Resolution[10] shown in Figure 4-3, or the Glomar Challenger used in the Deep Sea Drilling Program, would have the necessary capability to perform the deployment operation for this case. This alternative would bring down the costs for the drilling operation to an approximate USD 100K per day.

Wellhead, BOP and Other Subsea Equipment

Several technological restrictions exist regarding the deployment operation Most of the tools used in offshore oil have not been certified to work in depths of 3500 meters. The drill bits, casing, wellhead, BOP, trees, subsea compressors, PLET, flexible piping or umbilicals have to face one main challenge: hydrostatic pressure.

[10] Vessel specs: http://www-odp.tamu.edu/publications/tnotes/tn31/jr/jr.htm

Table 4-2: Dynamic Positioned Drilling Rigs with Deep Water Capability (Greenberg 2010)

Vessel Name	Maximum Water Depth Equipped	Maximum Water Depth Certified
Noble Danny Adkins	12 000ft (3 657.6m)	12,000ft (3 657.6m)
Noble Jim Day	12 000ft (3 657.6m)	12,000ft (3 657.6m)
Sevan Driller	12 500ft (3 810m)	12,500ft (3 810m)
Discoverer Clear Leader	10 000ft (3 048m)	12,000ft (3 657.6m)
Discoverer Americas	10 000ft (3 048m)	12,000ft (3 657.6m)
Discoverer Inspiration	10 000ft (3 048m)	12,000ft (3 657.6m)
Petrobras 10000	10 000ft (3 048m)	12,000ft (3 657.6m)
Dhirubhai Deepwater Kg1	10 000ft (3 048m)	12,000ft (3 657.6m)
Dhirubhai Deepwater Kg2	12 000ft (3 657.6m)	12,000ft (3 657.6m)
Discoverer Luanda	7 500ft (2 286m)	12,000ft (3 657.6m)

Figure 4-3: JOIDES Resolution Vessel from the Ocean Drilling Program, and the SEVAN Driller from Petrobras.
(Adopted from: www-odp.tamu.edu, www.dynamicpositioningnews.com)

Cementing

Casing prevents the collapse of the well. The casing process isolates the ring between the casing and the open hole to secure the hole, preventing collapse or introduction of non-desired fluids into the well. Special cement is designed according to the properties of the well. The properties of the cement are adjusted for controlling density, loss of fluid (cement dehydration), resistance to compression and setting time. Special additives are added as required: accelerator/retardant, expander, filter control, antifoam, etc. Depending on the well depth, drilling is performed in stages and cementing is done at each stage to prevent collapse of the well. It is the geologist's responsibility to determine the depth of each drilling stage depending on the type of formation.

The biggest challenge for the cementing operation lies with the characteristics of the sub seabed fluids and geology. Two types of cements can be used in this operation, given the composition of the vent fluids: acid cement or foamy cement. Cement is mixed with fly ash to produce acid cement. This helps avoid dissolving cement and corrosion in the casing pipes. Foamy cement is produced by using a dense mixture of standard cement (15.4-15.8ppg) and injecting Nitrogen during the pumping operation.

Piping

Piping diameters and casings change according to *(i)* the total depth of the well, *(ii)* the distance of each drilling stage and *(iii)* type of reservoir. Pipes will vary in thickness, materials and accessories. Expert consultation determined that the case at TAG may be drilled at 36" for outer diameter (OD) casing in the first stage and 20" inches outer diameter for the second stage. In case it is needed, a third stage could be in place for either 13-3/8" or 13-5/8" OD. It could be feasible to drill 20" OD for the first stage and finish with 13-5/8" on the second. Common hole diameters/Casing (OD) for the oil industry, from shallow to deep water: 42"/36" - 26"/20" - 17.5"/13-3/8" or 13-5/8" - 12.25"/9-5/8" or 9-7/8" - 8.5"/7" - 6.5"/3.5" or 4.5". In contrast, casings reported from the ocean drilling program reached a maximum depth slightly under 1 000mbsf using 10 3/4" Casings.

The casing material is also an important consideration, and there are existing solutions that can be readily used. The use of high nickel alloys and titanium is advised, given the chemical composition and the temperature and pressure conditions of the supercritical hydrothermal vent fluid. Examples of corrosion resistant casing materials include Inconel 625, Hastelloy/HPAlloy C-276, super duplex 2205, 2507 and Al 2003. Alloy C-276 is a nickel-molybdenum chromium wrought alloy that is typically used in the refining industry for chemical characteristics similar to those found in the vent. This was corroborated in consultation with industry experts. For high pressures around 450atm however, it appears that successful applications in geothermal production have only been made with titanium.

Well Enhancement

In the oil industry, it is common practice to stimulate a well by a process known as *shooting* the well. It consists of placing a pipe with explosive charges inside the cemented well. Such practice is also common in EGS, and perhaps could be useful in developing HTV fields for energy extraction. However, vent fields, and particularly hydrothermal mounds, are known to be unstable. In time, chimneys are known to die out, and the channels often change in structure. Possibly this natural process could destabilize an enhanced hydrothermal well. The implications of shooting a well under the vent environment however, are not known.

4.3 Environmental Assessment

4.3.1 The Potential Environmental Impacts of the Hydrothermal Energy Harvesting System

In comparison to the mining of manganese nodules and massive polymetallic sulphide deposits, the harvesting of the hydrothermal energy has not been explored by researches or environmental organizations. Therefore, in this chapter the possible environmental impact discussions primarily based on the previous research of impact studies from mining and exploration projects with added personal views and assumptions of the LRET research group members.

The principle difference between the mineral mining and the energy harvesting system is that the mining operations intend to cause a physical disturbance and resurfacing of the hydrothermal vent deep-sea area. However, in order to assess a possible environmental impact, the proposed energy system has been divided into two general segments such as harvesting of the hydrothermal energy from the active vent and charging of the autonomous underwater vehicles (AUVs) at the underwater docking stations powered by that hydrothermal energy.

The energy collection system from the hydrothermal vent is the major critical principle that has to be considered in terms of the possible environmental impact. Therefore, several different strategies have been outlined: drilling, covering of the chimney, closed or opened systems as well as installation of the venturi unit on the side of the vent.

Drilling on the Side of the Hydrothermal Vent

Drilling allows the extraction of hot fluid that is used in power generation cycle. Generally, the drilling process on the side of the hydrothermal vent is very similar to the functions used in geothermal power generation onshore. The difference is that created onshore well is much deeper (1000s meters) than proposed system requires (100s meters).

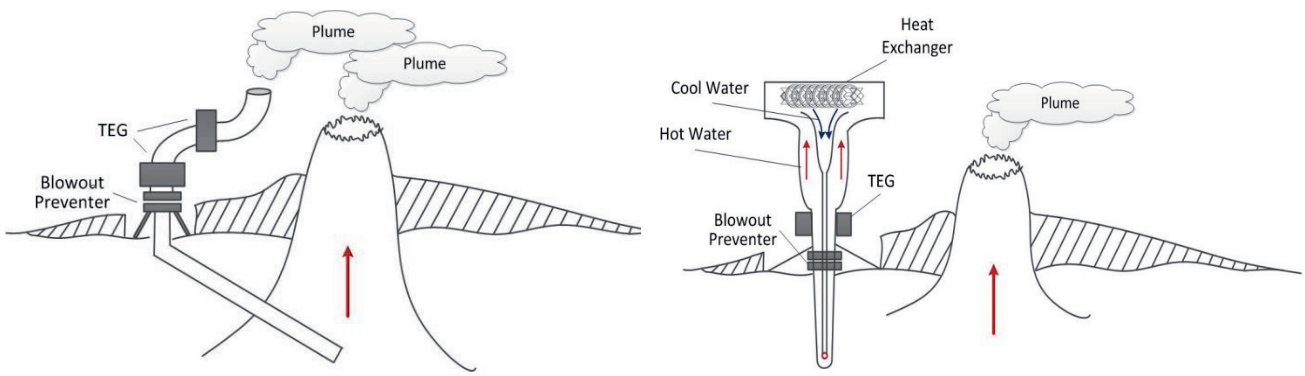


Figure 4-4: Drilling-Based Energy Collecting Systems

The main benefits of the hydrothermal energy collection system placed on the side of the vent are the maintenance of the integrity of the vents chimney and protection of the surrounded area from the damage. Therefore, it provides relatively safe subsistence of the vent ecosystem.

The other important point is the structure of the vent. In accordance to (C R German & Von Damm 2003), ocean water percolates into the crust through cracks. It provides a circulation of the water and the appearance of the black or white plume. Therefore, the drilling of the surface around the chimney can disturb the water circuit in the vent system. In addition, the splitting of the hydrothermal flow may lead to demineralization of the main vent flow, which may affect the chemoautotrophic bacteria and the food chain of the vent ecosystem.

Installation of the Venturi Unit on the Side of the Hydrothermal Vent

The installation of the venturi unit on the side of the vent should not provide any physical damage to the surrounded ecosystem. It should be mentioned that the proposed unit has an open top, which may attract some species to get inside of the energy collection system, producing failur

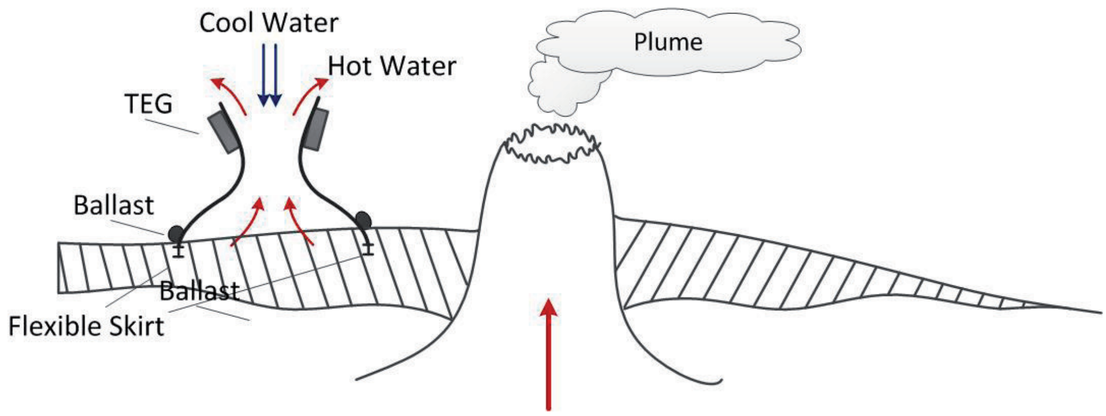


Figure 4-5: Hydrothermal Energy Collection by Venturi Unit

Hydrothermal Energy Collection by Covering of the Chimney

The covering of the hydrothermal vent with the energy-collecting cup will totally absorb the hydrothermal plume. It may be very dangerous for organisms living on and around the chimney as it can seriously affect its habitual duty. For example, mussels can also filter the food from the water fluid, so if the hydrothermal fluid will stop flowing, the mussels can survive only for a short time period.

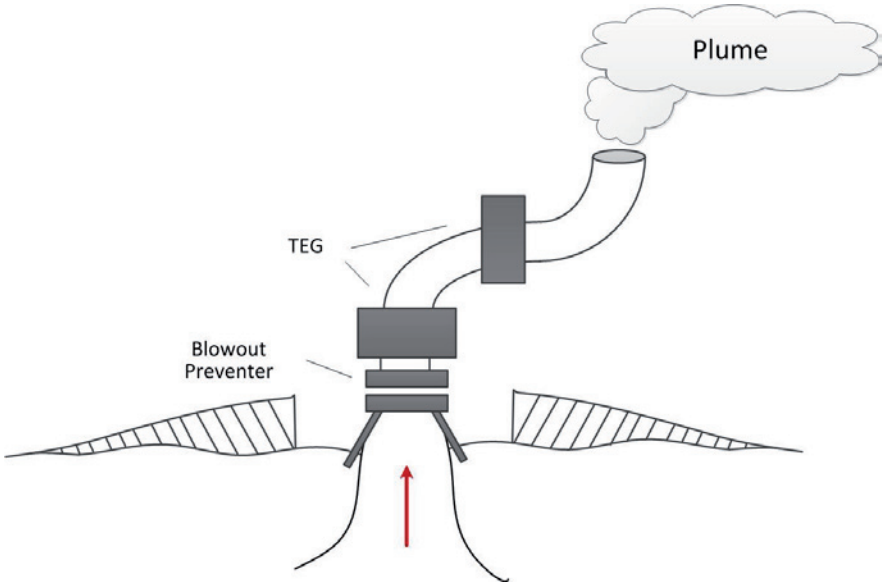


Figure 4-6: Energy Collection by Covering of the Hydrothermal Vent

Closed and Open Cycle Energy Collecting Systems

Closed and open loop energy collection systems have similar construction structures but different working principles described in the Chapter 3. The environmental impact to the hydrothermal vent ecosystem may be characterised by a physical damage of the heat-collecting pipe to the chimney. The open system has also a waste fluid coming out from the energy generation unit. The discharge fluid is toxic but no likely to be very harmful to the surrounded fauna as the hydrothermal flow also consists of the toxic elements (Ramirez-Llodra et al. 2011), which is habitual for the hydrothermal species.

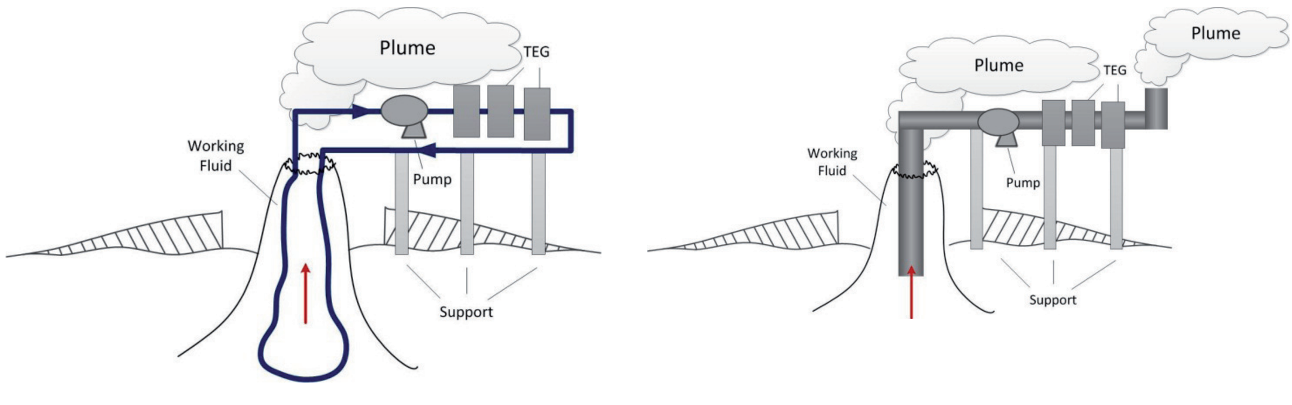


Figure 4 -7: Closed and Open Cycle Systems for Hydrothermal Energy Collection

However, the difference between chemical compositions of the original and processed fluid flows is inexplicit and needs further research. In addition, the distance between hydrothermal vent and the waste discharging pipe should be considered in order to prevent infection of the non-vent living species from the toxic waste fluids.

In order to summarise and compare an environmental impact from listed energy collecting scenarios to hydrothermal vent ecosystem a specified scoring system needs to be applied. In this case the scoring system based on the SYNDEEOP workshop (September 2008) has been chosen with the estimated impact level scored from 0 to 5, which are detailed described in Table 4-3 (Ramirez-Llodra et al. 2011). However, an important factor affecting the estimating capacity in order to assess the impact in the deep sea is our limited knowledge on biodiversity and functioning of the ecosystem.

Using the criteria in Table 4-3, the environmental impact of the energy collecting scenarios to the hydrothermal fauna has been critically analysed by the group members. The results of the assessment are listed in the Table 4-4 below.

Table 4-3: Scoring System for the Environmental Assessment (Ramirez-Llodra et al. 2011)

Score	Explanation
5	▪ Major anthropogenic impact including death of all life at the point of impact ▪ Likely to have subsequent regional effects
4	▪ Major anthropogenic impact with very few species surviving with some or no regional effects
3	▪ Moderate impact causing possible reduction on the biodiversity and potential reduction in biomass in productivity on a local basis
2	▪ Minor impact on fauna or habitat, partially cosmetic but not easily rectified
1	▪ No discernible impact or reduction/increase on biodiversity
N/A	▪ Impact are not applicable to the ecosystem in question
?	▪ No evidence or unknown effect of impact

Table 4-4: Environmental Assessment of the Energy Collecting Scenarios

Energy Harvesting Scenario	Score	Possible Direct Impacts
Drilling on the side of the vent	2	▪ Physical damage ▪ Water demineralization ▪ Waste fluid
Covering of the Chimney	3	▪ Physical damage ▪ Waste fluid ▪ Isolation of the organisms from food and life source
Venturi Unit on the Side of the Vent	1	▪ Physical danger for individual animals
Closed and Open Cycle Systems	?	▪ Possible physical damage ▪ Waste water (In the case of Open Cycle)

4.3.2 The Potential Environmental Impacts of the AUVs Docking

The proposed energy harvesting system is designed to provide a power for autonomous underwater vehicles (AUVs) by charging it in the docking stations. The possible environmental impact, which can be caused by the docking station, is difficult to estimate, but possible failures could occur from nesting of deep sea life. However, the existence of the docking station may cause disturbances and destroy habitat of the vent organisms but it is unlikely to affect big colonies and populations. In addition, the docking station has an acoustic beacon, which may confuse the animals adapted to hear this type of sound.

The other environmental issue could be attributed to lights on the docking station as well as to high-energy floodlights on AUVs. In accordance to (Godet et al. 2011) at Atlantic hydrothermal vents, there was concern about the effect of submersible lights on the sensitivity and integrity of the dorsal photoreceptor of the vent shrimp *Rimicaris exoculata*. From the other side, no changes to shrimp population at a shrimp dominated Trans-Atlantic Geotraverse (TAG) on the Mid-Atlantic Ridge have been detected during the more than 20 years since observation expeditions have been started (Copley et al. 2007). Therefore, although a percentage of the ship population is likely to have been blinded during the exploration activity, the negative effect of light in the survival of shrimp colonies is minimal (Ramirez-Llodra et al. 2011).

4.3.3 Environmental Recommendations

The maximum magnitude of environmental impact of the energy harvesting, charging and exploration activities is assumed to be even less than the natural disturbances, such as volcanic activity which may cause local extinction over the large areas (Godet et al. 2011).

However, in order to protect the hydrothermal fauna it is important to identify and preserve some active sites with rich ecosystem from potential exploitation (C. L. Van Dover 2010). In this case, first the natural conservation units, for example genetic, species specific and biogeographic should be recognised in the areas targeted for energy extraction such as TAG vent fields. Second, there is a need to develop a set of design recommendations for preservation reference areas and conservation areas that can be applied to active or inactive vent fields. In addition, it is also important to develop methods for effective mitigation and restoration strategies to insure the recovery of biodiversity in areas that have been exploited.

However, by the review of the deep-sea impact experiments (Ramirez-Llodra et al. 2011), it may be concluded that environmental assessments would be more effective and accurate if it will be done at a scale similar to real operations, which includes using of the equipment with the real time monitoring of the activity.

4.4 Legislation Assessment

A compliance with legal requirements is a core of the successful implementation of a new project. In the case of proposed hydrothermal energy harvesting system, the legislation procedure is completely unclear, as there are no existing rules and policies, which may cover this type of seabed exploitation. Therefore, the only chance to make any assessment and identify the potential legislation issues is to consider the existing policies and regulation regarding the exploration and exploitation of the seafloor massive sulphides (SMS) in the Exclusive Economic Zone and High Seas according to proposed scenario of harvesting energy from the TAG vent fields.

Nowadays, there are at least two mining companies Australian Bluewater Metals and Nautilus Minerals that pursue the mining exploration within Exclusive Economic Zone (EEZ) in the southwest Pacific Ocean (CL Van Dover 2011). Nautilus Minerals undertook several exploration expeditions in the waters of Papua New Guinea, while Bluewater Metals is concentrated on Solomon Islands waters. Moreover, in beginning of 2011, Nautilus Minerals received a 20-year mining licence from the government of Papua New Guinea for the extraction of SMS at a Solwara 1 vent field in the Manus Basin.

In regards to exploration and exploitation in the High Seas, the International Seabed Authority (ISA), being responsible over mineral resources in international waters, reviewed the first license applications for exploration of sea-floor deposits on mid-ocean ridges from the China Ocean Mineral Resources Research and Development Association and Russia.

In order to have an idea of possible issues and requirements that may face in the future for proposed energy harvesting system it is essential to consider and analyse the existence legal requirements and to identify the legal parties that might be important.

4.4.1 Offshore Legal Framework in Papa New Guinea

To date no nation in the world has created a comprehensive policy or legislative regime to manage the development of offshore exploration and exploitation activities within their territorial waters and exclusive economic zones. In many coastal state cases, including Papa New Guinea, offshore mining activities are governed by onshore mineral management regimes (Birney et al. 2006). As the ocean is a complex ecosystem, the onshore mining policies do not suit well to the exploration and exploitation of deep-sea resources.

The major legal parties related to deep-sea exploitation in Papua New Guinea are the Mining Act 1992, the Mining Safety Act 1977, the Mineral Resources Authority Act 2005 and the Environment Act 2000.

The Papua New Guinea Mining Act 1992 is the principal policy and regulatory document governing the exploration, development, processing and transportation of minerals below the surface of land. It also allows exploration activities and mining of minerals on the seabed within PNG territorial waters (Jankowski et al. 2010). The purpose of the Mineral Resources Authority (MRA) Act 2005 is to provide guidelines for the development of new mining sector governance and administrative structures. The regulations related to the inspections of the exploration and exploitation activity is covered in the Mining Safety Act and considered as a part of the Mining Act 1992 (Pennington 2004). In turn, the Environment Act 2000 defines the activities, which are required by an Environmental Impact Assessment (EIA) process. EIA should be undertaken and considered before the actual approval of an Environmental Permit.

In order to receive the Environmental Permit several steps should be considered. The first step in this process is to prepare and submit an Environmental Inception Report (EIR) in accordance with Section 52 of the Environment Act 2000 (PNG 2000). Once the EIR is approved, the next step is to submit an Environmental Impact Statement (EIS). EIS will be assessed by the Department of Environment and Conservation and other parties and if approval is recommended the Environmental Permit may be issued.

The Environmental Permit is essential for successful grand of an exploration licence and mining leases. The exploration license allows the holder to have an access to the resources in terms of exploration and sampling. An Exploration Licence (EL) will be granted for a period of two years and is renewable for a further period of two years, with a 50% reduction in area at the end of the initial period. The EL could be received by the submission of the application to Mineral Resource Authority. The fees, area and time period regulated by Mining Act 1992 and Mineral Resource Authority are listed in Table 4-5. It is to mention that a security deposit of PGK 6,000 ($2,823.6) is lodged upon grant for each Exploration Licence in PNG. When a Mining Lease is granted, a security deposit of PGK 48,000 ($22,588.8) applies.

Table 4-5: Exploration License Requirements in PNG Mineral Resources Authority (Adopted from MRA 2012)

Security Deposit		Amount per Term		Area	Period
PGK	**US**	**PGK**	**US**		
PGK6,000	$2,823.6	PGK90	$42.35	1 Sub Block ($3.41 km^2$)	Term 1 Year 1 & 2
		PGK180	$84.7		Term 2 Year 2 & 3
		PGK470	$221.18		Term 3 onwards Year 3 & 4 onwards

In the case of Mining Lease, the royalty is also should be paid to the State of PNG under the Papua New Guinea Mining Act 1992. There is 2% of the net smelter return on all minerals produced, and 0.25% for the Mining Resource Authority.

4.4.2 Seabed Exploration in High Seas

Considering the international waters, there are gaps with regard to regulation, governance and conservation of special habitats in the deep sea (CL Van Dover 2011). As it was described in the Chapter 1, the main international body, which is responsible for governing, regulating and establishing of policies covering exploration and exploitation of the resources in the international waters is the International Seabed Authority. As to date, the ISA has been working on the Mining Code, which comprises competitive set regulations, rules and procedures. The establishment of the Mining Code is aimed to prospecting, exploration and exploitation of marine resources in the international seabed Area. The Mining Code is not yet complete. However, the Authority has issued Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area (adopted 13 July 2000) and the Regulations on Prospecting and Exploration for Polymetallic Sulphides in the Area (adopted 7 May 2010) (ISA 2010). These regulations include the forms necessary to apply for exploration rights as well as standard terms of exploration contracts. The third set of regulations, the Regulations on Prospecting and Exploration for Cobalt-Rich Crusts is still being under the process.

The application for exploration licence can be applied by the Enterprise (ISA) or States Parties and natural or juridical persons which possess the nationality of States. Each application shall be supported by the required documents, which include a general description and a schedule of the proposed exploration programme, oceanographic and environmental baseline studies, an environmental assessment and a description of proposed measures for the reduction and prevention of the environmental impact (ISA 2010).

According to the Mining Code, the area covered by the application is divided on “polymetallic sulphide blocks”, which are approximately 10 kilometres by 10 kilometres and no greater than 100 square kilometres. The area covered by the application for the exploration of the polymetallic sulphides should not exceed more than 100 polymetallic blocks (ISA 2010).

As can be seen from Table 4-6, the application is quite expensive but it could be granted for the period of 15 years. Currently, there is no State or organization, who has received the exploration licence yet.

Table 4-6: License Requirements for Exploration of Polymetallic Sulphides, ISA (Based on (Convention et al., 1982, § 21, § 27, §28)

Application Fee	Successful Election Fee	Annual Fee	Max Contract Area	Contract Period
$500,000	$50,000	First Anniversary $5*Area ($km^2$)	10,000 km^2	15 years
		8^{th} Year Relinquishment $10*Area ($km^2$)		
		10^{th} Year Relinquishment $20*Area ($km^2$)		

4.4.3 Legal Conclusion

As we have seen from the previous sections, the legislation framework for the exploitation (mining or energy harvesting) is not established yet. The regulations that can be used to receive the exploration licence in territorial waters are mainly based on legislation policies of Coastal States, and often no legislative frameworks exist. The policies regarding exploration in the high seas are under development but first applications are already submitted and probably exploration license will be graded soon. However, the exploitation lease is still being unattainable task.

Therefore, the recommendation for the hydrothermal energy-harvesting project is to start the exploration of the vent fields located in the territorial waters, because to date, in regards to experience of Nautilus Minerals, it is only real legal procedure.

4.5 Logistic challenges

4.5.1 Deployment

Iceland is one of the countries in the world with a larger share of geothermal energy in the country's energy mix. 27% of Iceland's energy comes from geothermal sources (IEA-GIA 2012). Active research is looking for ways to improve the economics of geothermal energy[11]. The *Deep Vision* consortium is working to tap supercritical water at 450 °C and a flow rate of 0.67 cubic metres per second to generate around 45 MW. On land, recognizing when the supercritical conditions are reached is best done by coring (Fridleifsson & Elders 2007).

For enhanced geothermal systems, the drilling problem has posed many challenges, and the suitable geological formations are dodgy at best. The prospect of offshore hydrothermal power would face similar challenges. Although suitable temperatures can be readily found

[11] www.iddp.is

beneath the hydrothermal mounds, conditioning the mound for production would be an expensive and complex operation.

4.5.2 Downtime

A maintenance intervention frequency of one year is suggested for the application of thermoelectrics on land-based remote locations. Thermoelectrics can be reliable sources of power, as they have no moving components. However, failures can appear by thermal fatigue of the units, or lack of controls and monitoring loops. Table 4-7 and Table 4-8 show a preliminary Failure Modes and Effects Analysis (FMEA) of the submarine thermoelectric generator concept.

4.6 Project Costs

This section features project cost estimates, and the major cost drivers are first identified. Secondly, initial cost due to these drivers is determined. Thirdly, we calculate implementation cost, which refers to the cost for building and running the project. Therefore, it includes operations cost and maintenance cost among others. Finally, we also calculate the total project cost, which consists of implementation cost and system project cost. System project cost is the cost to run a project less implementation cost; for example, project support cost and facility cost. In order to calculate these costs, some assumptions are necessary.

The project cost comes from five major aspects: Setting up Hydrothermal vents; site preparations, excavation, and drilling may be required in this step. Secondly, the TEG has to be installed; this is where the Hydrothermal energy is actually converted into electrical enerThe Third aspect involves power storage. The electricity Generated is stored in rechargeable batteries. Fourthly, there is the supply of energy from batteries to AUV via the docking station and cable. Lastly, there is the cost of AUV operation for survey purposes. Table 4-9 shows the required equipment and functions associated with each step. The major cost drivers are further highlighted in Table 4-10 below.

Table 4-7: Systems, Subsystems and Performance

Failure Mode and Effect Analysis	
System	Autonomous observation node
Subsystem	Power supply
Subsystem function description	Convert thermal energy to electrical energy
Subsystem function performance	Convert thermal energy from fluid between 350-400 degrees Celcius and flow rate of 1-5 m/s to Set-Power (max. 12kW)

Table 4-8: Preliminary Failure mode and effects analysis (FMEA)

Failure Mode	Failure cause	Failure effect	Design approach	Recommended action
F1: Convert thermal energy from fluid between 350-400 degrees Celsius and flow rate of 1-5 m/s to Set-Power (max. 12kW)				
Power output higher (+10W) than set point	Vent temperature higher than 400 degrees Celsius	-	design out	Implement control mechanisms for excessive heat
	Flow rate higher than 5+0.01x m/s	-	design out	Implement control mechanisms for excessive heat
Power output lower (-10W) than set point	Low or inefficient heating. Vent temperature lower than 350 degrees Celsius	mission compromised	-	Possible extinction of vent field. Inspect.
	Low or inefficient heating. Flow rate lower than 1-0.01x m/s	mission compromised	-	Obstructed heat flow through pipes
	Poor or inefficient cooling. Temperature gradient in cold side heat exchanger below 1 degree Celsius.	-	design out	Otherwise, maintenance action must be in place. Check organic growth at thermosyphon. Monitoring possible (measure temperature gradient) Check for sediment deposition at thermosyphon. Monitoring possible (measure temperature gradient)
	Faulty or damaged power unit	Critical failure	-	Monitoring required for: a. Open circuit voltage b. Current c. Internal resistance (determined if the other two parameters known)

4.6.1 Initial Cost

The Initial cost refers to the cost to build product. System running period in this project is estimated at 20 years.

Deployment Cost

Preliminary exploration of the seabed is required in order have details on vent locations and to decide drilling point as well as depth. The details in TAG are already known, as this particular area has been extensively investigated over the last twenty years. For this reason, exploration cost here is not a key.

Table 4-9: Required Functions in Each Step

Step	Function
Setup	Drilling
	Exploration
TEG	Thermoelectric couple
	Casing
	Heat exchanger
	Valves
Storage	Battery
Supply	Docking station
	AUV improvement
	Cable
	DC/DC convertor
Operation	AUV

Table 4-10: Cost Driver Functions in Each Step

Step	Cost driver function
Setup	Drilling
	Exploration
TEG	Thermoelectric couple
Storage	Battery
Supply	Docking station
	AUV improvement
Operation	AUV

There nearer the drill point to the HTV, the shorter the borehole needed to reach the superheated water but the more the impact on the HTV itself, so there is a trade. Therefore, drilling is conducted very near to the vent only when larger amount of power is needed.

There is no significant thermal gradient up to a few meters down the seabed near the HTV, which is good news. This means that drilling does not have to be very deep to achieve the needed thermal potential. In our concept, maximum drilling depth has been estimated at about 300m. And industrial sea floor drilling depth per day is estimated approximately 70m to 170m in North Sea (Osmundsen et al. 2009). In addition, we assume that drilling depth per day in North Sea is equivalent to that of our project. Thus, drilling time ranges from 1 day to 5 days. The drilling cost is different from platform to another. In case of rigs, it is estimated from Section 4.5 that approximate cost per day is between $US\$500{,}000\ and\ 1{,}000{,}000$. On the other hand, it is estimated to be approximately US$100,000 when drilling ship is used. Thus, we can assume that drilling cost is approximately $US\$100{,}000 \sim 1{,}000{,}000$. Thus, the total cost is estimated as follows:

$$Drilling\ cost[\$] = Drilling\ per\ day \times drilling\ tim \quad (4.1)$$

Equation 4.1 results in a total cost range between $US\$100{,}000\ and\ 5{,}000{,}000$. This cost is classified not initial cost, but the other implementation cost, for example, operation cost and maintenance cost, because projector usually uses existing drilling ship and platform.

TEG Costs

Thermoelectric couples are used to generate electricity from thermal energy, and the unit costs are shown in Table 4-11. If we take the average price ratio, it is 0.176[W/$], and 10 to 12kW power can be generated. Therefore, the costs can be calculated as

$$C_{TEG} = \frac{Total\ generated\ power}{price\ ratio} \tag{4.2}$$

where C_{TEG} is total cost of TEG. Equation 4.2 results in a total cost range between US$56700 and US$68000, and these batteries have 20 years life cycle.

Battery Cost

If we prioritize cost to power density, lead acid battery is superior to lithium polymer battery (from the assessment in 3.3.4). Lead acid battery manufactured by Deepsea Power & Light (DeepSea Power & Light 1990a) is US$2,700 per one battery; and power is 192W. The cost of batteries is calculated as shown equation 4.3.

$$C_{Baterry} = \frac{Total\ generated\ power}{power\ of\ battery\ per\ unit} \tag{4.3}$$

where $C_{Baterry}$ is the total cost of batteries. Equation 4.3 results in a total cost range of US$141,000 to US$169,000, and this battery is designed for 3 years life cycle expectation (DeepSea Power & Light 1990b). Therefore, the 20 years life cycle cost becomes $US\$940{,}000 \sim 1{,}127{,}000$

Table 4-11: Costs of Thermoelectric Couple
(TEG POWER 2012; Custom Thermoelectric 2005)

Supplier	**Unit Name**	**Watt [W]**	**Unit Price [$]**	**Price Ratio[W/$]**
TEG Power	F2F200	200	1919.99	0.104
TEG Power	TEGP15	15	79.99	0.188
TEG Power	HTTEM	5	17.99	0.278
Custom Thermoelectric	1261G-7L31-04CL Power Generation Module	5.2	30	0.173
Custom Thermoelectric	1261G-7L31-04CQ Power Generation Module	5	50	0.100
Custom Thermoelectric	1261G-7L31-05CQ Power Generation Module	7.15	50	0.143
Custom Thermoelectric	1261G-7L31-10CX1 Power Generation Module	14.7	79.5	0.185
Custom Thermoelectric	1261G-7L31-24CX1 Power Generation Module	19.1	79.5	0.240

Docking Station and AUV Improvement Cost

The AUV must be equipped with an inductive charging system. The costs of inductive charge docking station and AUV modification for inductive charge are estimated at US$250,000. Although the docking station form is different from our docking station (Source: (B. Miller 2005). It was assumed that docking station cost does not depend significantly on the form. Life cycle of that docking station is estimated at 5 years. Thus, if we assume that our docking station also costs US$250,000, in the space of 20 years, the life cycle costs will be about US$1,000,000.

AUV Operation Cost

As we said in chapter3 (3.5.4 and 3.5.5), target AUV should have capability to dive over the depth where hydrothermal vents are located. The vents in our project are located around 3,500m depth. And AUV should also load lithium ion batteries, because inductive charging system for lithium ion batteries is in high technological readiness (McEwen et al. 2008). For these reasons, we define REMUS6000 as our target AUV. The specification is listed in Table 4-12.

It is difficult to estimate AUV initial cost. But, for the AUV named Autosub6000, whose maximum operation depth is 6,000m and being used in the National Oceanography Centre, Southampton, the cost is approximately US$10,000 based on an expert view (NOCS 2012). Since REMUS6000 also has same maximum operation depth, we assume that the cost of REMUS6000 is also US$10,000,000.

4.6.1 Implementation Cost

Implementation cost is the cost due to building and running the system. Therefore, implementation cost consists mainly of initial cost (production cost), operation cost, maintenance cost, disposal cost. This cost is calculated as shown equation 4.4.

Table 4-12: Specification of REMUS6000
(Hydroid Inc 2012)

Information	Detail
Supplier	Kongsberg Maritime
Vehicle diameter	71cm
Vehicle length	3.84m
Weight in air	862kg
Maximum operation depth	6000m
Energy	11kWh rechargeable lithium ion battery
Charging time	8hours
Battery life cycle	5years
Endurance	Mission duration of 22hours Maximum mileage 125km

$$\text{Implementation cost} = (\text{Initial cost}) + (\text{Operation cost}) + (\text{Maintenance cost}) + (\text{Disposal cost}) \quad (4.4)$$

It is traditional to assumed that initial cost about 30% of implementation cost in onshore production facilities (Jones 2006). Thus, implementation cost is estimated as:

$$\text{Implementation cost} = \frac{100\%}{30\%} \times (\text{Initial cost}) \quad (4.5)$$

Table 4-13 gives a summary of the above details.

4.6.2 Total Project Cost

The Total project cost consists mainly of implementation cost and system project cost.

$$\text{Total project cost} = (\text{Implementation cost}) + (\text{System project cost}) \quad (4.6)$$

It can be assumed that implementation cost composes 50% of total project cost from Table 4-14. So, total project cost is calculated thus:

$$\text{Total project cost} = \frac{100\%}{50\%} \times (\text{Implementation cost}) \quad (4.7)$$

From equation 4.7, the total project cost was estimated at US$80million~US$91million.

4.6.3 Summary

Thus, total project cost ranges approximately from US$80milliom to US$91million with a 20-year life cycle. The price ratio [$/kWh], is given by.

$$\frac{\mathit{Proiect\ costs}\ \text{from drilling to storage [\$]}}{\mathit{Power}[kW] \times \mathit{Generation\ period}[hours]} \quad (4.8)$$

The price ratio was obtained as- 3.91: 8.55[$\$/kWh$].

Table 4-13: Implementation Cost

Step	Function	Minimum initial cost [$K]	Maximum initial cost [$K]	Minimum Implementation cost [$K]	Maximum Implementation cost [$K]
Setup	Drilling	0	0	100	5,000
TEG	Thermoelectric couple	57	68	189	226
Storage	Battery	940	1,130	3,133	3,766
Supply	Docking station AUV improvement	1,000	1,000	3,333	3,333
Operation	AUV	10,000	10,000	33,333	33,333
Total		12,000	12,200	40,100	45,700

Table4-14: Apportioned Budget
(Rosie Heatley Lunde 2011)

	Budget[$M]	Assignment	Contingency [$M]
Project Support	19	25%	4.8
Systems Engineering	25	30%	7.5
Software	16	20%, 30% for Cyber Infrastructure	4
Hardware	11	30%	3.3
Shore Facilities	10.1	15%	1.5
Implementation	168.1	20%, 30% for Cyber infrastructure	34.3
Education	5	0%	0
contingency	55.3		
total	309.5		55.4

This price ratio is higher than that of European wind farming which is approximately $0.1[\$/kWh]$. This mainlyi due to the restriction we place on the amount of power to be generated (10kW – 12kW). It should however be noted that production of energy in the order of hundreds of MW is obtainable from the HTV but his is not necessary for the kind of systems being considered here. This power is smaller than the power generated by one wind power farming plant. Therefore, with bigger power generation, which is feasible, this concept could be highly competitive. Below are some of the major assumptions used in the above computations.

- Only the major cost drivers were considered
- There is no need for extensive exploration for reason mentioned earlier.
- From 10kw to 12kW power can be generated by the TEG concept.
- Ratio of initial cost to the implementation cost is 3:7.
- Ratio of implementation cost to system project cost is 5:5.
- Docking station cost does not depend much on its form.
- Drilling depth per day in our project is equivalent to that of North Sea.
- Our target AUV, which is REMUS6000, has the same cost as that of Autosub6000.

4.7 Risk Analysis

As in any venture, there are certain risk factors associated with energy production at the seabed. Some of the risk may be seen around equipment deployment to the seafloor, installation, operations and maintenance works which have to be done on the seafloor where the temperatures can be anywhere between 0-500^{o}C asides the high hydrostatic pressure and very low *PH*/high salinity. Some of the hazards here include human errors, epistemic and random component failures. Maintenance work around HTV in the kind of conditions described above could be quite hazardous. An obvious mitigation here is to engage the services of certified experts with proven record of excellence. Training and retraining of operators and provision of well-documented operation procedure are also essential.

On the other hand, the technology for deep sea energy exploitation is still young, lack of in-depth knowledge/uncertainty in hydro, thermo and geodynamic behaviours of the ocean floor constitute another source of hazard in terms of equipment safety, reliability, investment security and environmental impacts. To minimize the risk, the proposed concepts was crafted after detailed study of the facilities that have already been validated and certified for use at some lower depths in the ocean. This way, a slight adjustment in material of construction, system configuration, the operational strategy and maintenance regime could provide the new system the needed reliability, and cost efficiency.

However, a major driver for this venture is that the risk associated with future energy market is quite negligible. Global energy requirement has been on the rise and is almost certain to remain as such for at least decades ahead. Today's generation capacity cannot meet the rising energy profile. This problem requires more research into alternative energy sources; seabed is one of these possible sources, providing not only green but also renewable energy capable of sustaining human demands for centuries.

5 Conclusions and Discussion

The seabed holds vast and diverse resources capable of sustaining human demands for centuries ahead. Key among these resources are solid minerals, biogenic and energy resources. This volume focused on developing concepts for exploiting renewable energy resources from the seabed. In particular, the target is the generation of electrical energy from the hydrothermal fields found in mid-ocean ridges.

Seabed Resources and the Scope of this Volume

The first part of this volume examined the characteristics of the resources found on the seabed. An exploratory research methodology was used, mainly based on interviews and a literature survey. The main question addressed is: when will the time be right for exploiting the seabed? The formulation of this question was the result of interviews and expert assessments. The general opinion was that seabed exploitation for any of the three prospective resources is going to happen, it is only a matter of when. The authors use scenario analysis to help determine some key factors that influence the development of the seabed industry. To *imagine* possible future developments, we explore existing scenarios published by reputable organizations in the energy and commodities market, and NGOs.

Throughout our research we have found a general feeling of expectation towards the results of seabed mining operations in Papua New Guinea. However, we have also encountered many challenges for seabed mining, which in order of importance are: *(i)* the small economic prospect of the ventures relative to the size of onshore mining operations, *(ii)* the geopolitical and economic uncertainties around the commodities market and *(iii)* the lack of confidence for private investment. We conclude that coastal states may be candidates to pursuit the development of local seabed mining industry in the Exclusive Economic Zone. However, a shortage of government backing and non-subsidiary policies would place any undertaking in seabed mining in financial problems.

Environmental concerns are a final aspect to consider around the prospect of a seabed mining industry. Public acceptance was seen in one of the studies as a key force, with both high impact and high uncertainty. This acceptance is in large measure subject to the environmental impact of any mining operation. There is still a lack of fundamental research to facilitate impact assessment and development of mitigation strategies. More ocean exploration is necessary.

Scenarios for Energy Industry Development

The exploitation of energy resources from the seabed was selected as a focus area. This industry has challenging but important prospects of growth in the mid-term and long-term. Most scenarios found in the literature suggest promising growth of renewables beyond 2030. The authors propose two prospective scenarios for the development of the seabed energy industry, considering a worst case vs. best case. The development of the offshore geothermal industry is explored within these scenarios, and an evolutionary technology maturity process is proposed. The optimistic scenario, based on the International Energy Agency‘s 450 Scenario, expects a rapid growth and maturation of high power offshore hydrothermal plants. In the most conservative case, this project suggests that smaller but widespread applications of subsea power will be a first step in maturing deep ocean energy technology.

Novel Approach to Hydrothermal Energy

To help the developments in scientific ocean exploration, the authors propose a novel approach for energy generation from the seabed. The system is intended to meet the energy demands for offshore equipment such as the Remotely Operated Vehicles (ROVs), Autonomous Underwater Vehicles (AUVs) and other submarine facilities. In the long term, the proposed concept is intended to evolve to meet the higher power demand onshore, and futuristic technologies like hydrogen storage from deep sea hydrolysis could help this goal.

Taking into account energy collection, transmission, transformation and supply efficiency, a hydrothermal field can potentially provide electrical energy in the order of hundreds of megawatts. The proposed design uses a modest portion of this potential: in the order kilowatts and this is one requirement imposed on the system described in this volume. The locations selected as case studies involve two possible applications for the technology: power supply for exploration in Autonomous Observation Nodes (AON), and in the mid-term, monitoring seabed exploitation or prospecting activities. The Nodes are the extension of the Ocean Observatories Initiative programme for the high seas. This novelty would allow location of remotely operated stations in the mid-ocean ridges, where the possibility of establishing cabled observation networks powered from shore would be very costly.

Power Generation and the Technical Issues

The technical challenges emanate mainly from three key functions: energy collection from the hydrothermal field, generating electrical power from the collected heat energy and channelling the generated power to a given client. What each of these functions share is the harsh seabed environment. In this report, six different energy collection methods have been proposed, each with its merits and demerits. A qualitative method was used to assess the candidate solutions, though subjectively. Thermoelectric generators (TEG) are used for power generation from the thermal energy; this device is capable of exceeding the power requirement for seabed observatories. Similar technology has been deployed in space, on land and at sea, but will have to be readapted for the conditions of the hydrothermal vents.

Environmental Considerations

While there is pressing interest in exploiting the vast energy resources in the seabed, there are also both legal and moral requirements for protecting the environment especially in the unique hydrothermal communities. Each of the functions spelt out in the proposed concept is assessed against these conflicting forces –the need for seabed exploitation and requirement for environmental protection. A number of functions were set aside because of environmental issues even though they appeared viable economically. In particular, significant physical damage to the hydrothermal field, use of toxic chemicals and functions capable of exterminating the smokers were avoided.

Energy Generation from the Seabed: The Economic Prospects

One of the major cost drivers in power generation on the seabed is the need for investing in research and development. Targeted site excavation and drilling may be necessary but there are no readily available solutions. Cost of equipment deployment to the seabed, installation and maintenance is additional cost driver. Existing onshore geothermal has very competitive costs.

The amount of energy at the seabed is vast and renewable, and the proposed concept for power generation entails a small environmental impact; further, it could be concluded that exploiting the seabed for power generation is a viable economical prospect. It has the potential to support seabed exploratory and observatory missions, and possible future mining activities. As described earlier, in the long term, the power generation concept is intended to be stepped up to meet higher energy demands onshore. Therefore, the proposed concept results in clean and sustainable power production; the energy produced stalls as a nerve centre, supporting various human developmental activities both offshore and onshore.

Appendix

Appendix A: Data from mining and energy statistics

Appendix B: Data from offshore resource estimations

Appendix A

A.1 Chemical Compositions of the Polymetallic Nodules

Table A-1: Average Concentration of Metals in Manganese Nodules from the Pacific, Atlantic and Indian Oceans (UN 2004)

Element	Atlantic	Pacific	Indian	World Ocean
Manganese (wt%)	13.25	20.10	15.25	18.60
Iron	16.97	11.40	14.23	12.40
Nickel	0.32	0.76	0.43	0.66
Copper	0.13	0.54	0.25	0.45
Cobalt	0.27	0.27	0.21	0.27
Zinc	0.12	0.16	0.15	0.12
Lead	0.14	0.08	0.10	0.09
Iridium	9.32	6.64	3.48	-
Uranium	9.32	6.64	3.48	-
Palladium (ppm)	5.11	72	8.76	-
Thorium	55.00	32.06	40.75	-
Gold (ppm)	14.82	3.27	3.59	-

A.2 Chemical Compositions of the Polymetallic Crusts

Table A-2: Range of Mean Concentration of Metals in Polymetallic Crusts from the Pacific, Atlantic and Indian Oceans (UN 2004)

Iron (wt%)	**15.1 -22.9**
Manganese	13.5- 26.3
Nickel (parts per million)	3,255- 5,716
Copper	713-1,075
Cobalt	3,006-7,888
Zinc	512-864
Barium	1,494-4,085
Molybdenum	334-569
Strontium	1,066-1,848
Cerium	696-1,684

A.3 Chemical Compositions of the Polymetallic Crusts

Table A-3: Range of Mean Concentration of Metals in Polymetallic Crusts from the Pacific, Atlantic and Indian Oceans (UN 2004)

Element	Mid-Ocean Ridges at Divergent Plate Boundaries	Volcanic Island Chains at Convergent Plate Boundaries
Lead (wt%)	0.1	0.4-11.8
Iron	26.4	6.2-13
Zinc	8.5	16.5-20.2
Copper	4.8	3.3-4.0
Barium	1.8	7.2-12.6
Arsenic(parts/Million)	235	845-17,500
Antimony(parts/Million)	46	106-6,710
Silver(parts/Million)	113	217-2,304
Gold	1.2	4.5-3.1

A.4 Chemical Compositions of the Sediments

Table A-4: Resource Potential of Metalliferous Sediments of the Atlantis II Deep, Red Sea

Metal	Grade (wt%; dry saltfree basis)	Weight (metric tons; dry salt-free basis)
Metalliferous sediments		89,500,000
Zn	2.06	1,838,000
Cu	0.45	402,000
Ag	38 grams/metric ton	3,432

A.5 Marine Diamonds

Table A-5: Operational Marine Diamond in the World

Coastal Location	Country	Depth(m)
Groen River	South Africa,	25
Chameis Bay	Namibia,	25
Broadacres	South Africa,	0.5
Casuarinas Prospect	Australia,	30

A.6 Chemical Compositions of the Hydrothermal Vent Fluids

Table A-6: Ranges of chemical composition of the vent fluids (Margaret Tivey 2007)

	Mid-Ocean Ridge	Back-Arc	Rainbow	Lost City	Sediment-Hosted	Seawater
T(°C)	≤ 405	278–334	365	≤ 91	100–315	2
pH(25°C)	2.8–4.5	< 1–5.0	2.8	10–11	5.1–5.9	8
Cl, mmol/kg	30.5-1245	255-790	750	548	412-668	545
Na, mmol/kg	10.6-983	210-590	553	479-485	315-560	464
Ca, mmol/kg	4.02-109	6.5-89	67	<30	160-257	10.2
K, mmol/kg	-1.17–58.7	10.5–79	20	-	13.5–49.2	10.1
Ba, mmol/kg	1.64–18.6	5.9–100	> 67	-	> 12	0.14
H_2S, mmol/kg	0–19.5	1.3–13.1	1	< 0.064	1.10–5.98	-
H_2, mmol/kg	0.0005–38	0.035–0.5	13	< 1–15	-	-
CO_2, mmol/kg	3.56–39.9	14.4–200	na	Bdl	-	2.36
CH_4, mmol/kg	0.007–2.58	.005–.06	0.13–2.2	1–2	-	-
Fe, µmol/kg	7–18700	13–2500	24000 - 0	-	180	-
Mn, µmol/kg	59–3300	12–7100	2250	-	10–236	-
Cu, µmol/kg	0–150	.003–34	140	-	< 0.02–1.1	-
Zn, µmol/kg	0–780	7.6–3000	160	–	0.1-140	-
Pb, µmol/kg	0.183–0.1630	0.036–3.900	0.148	-	< 0.02–0.652	-
Co, µmol/kg	0.02–1.43	-	13	< 0.005	-	-
Cd, µmol/kg	0–0.910	-	0.130	-	< 0.010–0.046	
SO_4, mmol/kg	0	0	0	1-4	0	28
Mg, mmol/kg	0	0	0	<1	0	53

A.7 Summary of Hydrothermal Energy Found

Table A-7: Summary of published data on diffuse flow in Mid-Ocean Ridge (Bemis et al. 2012)

Location	Type of diffuse structure	T(°C)	Diffuse flow velocity ($m\ s^{-1}$)	Area of diffuse flow (m^2)	Total diffuse heat output (MW)	Ratio of diffuse to total heat flux
Juan de Fuca Ridge (JdFR)						
Axial Seamount	Fracture networks, discrete cracks or holes, sulphide edifices	< 27	5×10^{-4}- 0.14	2.4×10^5	0.2-75	0.9
Main Endeavour Field (MEF)	Sulphide edifice, tubeworms patches	7-13	0.07-0.15	20	0.5-300	0.5-0.9
MEF and Mothra	Varies	9-81	0.01-0.1	-	-	-
Cleft site	Sulphide mounds	2-15	-	-	534	0.7
Southern JdFR	Fracture	1.88-1.98	-	-	12, 125	-
Mid-Atlantic Ridge (MAR)						
Trans-Atlantic Geotraverse (TAG)	Discrete cracks and vents on sulphide mound	14 ± 0.5	$(5 \pm 4) \times 10^{-4}$	-	250-470	0.8
Lucky Strike	Tour Eiffel sulphide edifice	4.5-16.4	$>1 \times 10^{-4}$	-	-	-
East Pacific Rise (EPR)						
9°50'N	Patches, low sulphide mounds, cracks, collapse features	10	0.04	175	285	0.9
21°N	-	20	0.1	80-700	11-900	-
Galápagos Spreading Centre (GSC)						
Rose Garden, 86°W	Cracks between pillows and talus blocks	10.5	2-10 $L\ s^{-1}$	-	-	-

Appendix B

B.1 System Requirements Document

This appendix presents the Preliminary System Requirements Document (SR) for the *Slow Growth Scenario* of Chapter 3. These requirements derive mainly from the scientific requirements presented in the Oceans Observatories Initiative program development. Requirements in this document are limited to the General Requirements (GR) and the Power Network (PN) requirements for a deep sea exploration system (OOI 2007). These are the principal requirements needed to develop a robust Autonomous Observation Nodes (AON) for deep sea exploration.

Scope

Because the scientific requirements of a similar system have been developed in the OOI program, our purpose here is to develop a case for substituting the power network components using a novel subsystem. The Power Network (PN) in the OOI project is designed to provide the necessary power for all the science nodes in the array, each of which has a demand of 10kW.

System Requirements

ID	Requirement
General Requirements	
	The Primary AON shall provide a complete observing system providing both a real-time bi-directional link between users on the Internet anywhere in the world and a wide variety of current and next generation instruments
	The Primary AON shall include a combination of fixed, moored and mobile observing platforms and infrastructure, in-situ and cabled power supplies; a communications network providing high bandwidth communications from surface expressions and in the water acoustic and cabled communications to underwater instrumentation; functional control of accessible infrastructure components.
	The Primary AON shall be designed to be expandable, so that additional Secondary AONs, instruments, and sensors can be readily connected to the system at a future date
	The Primary AON shall support observations across the full depth of the water column, from the sea surface to the sea floor.

	The Primary AON will use Autonomous Underwater Vehicles (AUVs) to sample in space and time to complement the time series and fixed array sampling of the moorings.
	The CGSN nodes shall support the multidisciplinary core sensor packages identified for deployment on its fixed and mobile platforms.
	The Primary AON shall provide extra power and bandwidth beyond that need by the core sensor packages in order to provide the capability of hosting additional instruments and sensors.
	The Primary AON shall be designed for an operational life of at least 20 years
	The AON shall be designed with commonality across Primary and Secondary nodes in order to minimize life cycle costs over the 20 year design life
	The Primary AON power and communication systems shall be designed to be upgradeable over the life of the system
Secondary AON	
	The Secondary AON shall include a power network delivering power to all instruments and infrastructure; a communications network providing high bandwidth communications to all instruments and infrastructure; functional control of all infrastructure components; and time distribution
	The Secondary AON shall be designed to be expandable, so that additional infrastructure and sensors can be readily connected to the system at a future date
	The Secondary AON infrastructure shall be designed to use electrical wet-mateable connectors accessible by academic class remotely operated vehicles (ROVs) e.g., Ventana, Jason II and ROPOS to enable system maintenance and expansion.
	The Secondary AON infrastructure shall support individual instruments or clusters of instruments at locations up to 40km around Primary and Secondary Nodes. Remote sites may have reduced power, communications bandwidth and reliability
	The Secondary AON shall be designed for an operational life of at least 20 years
	The Secondary AON shall be designed to minimize life cycle costs over the 20 year design life

	The Secondary AON power and communication network shall be designed to be upgradeable over the life of the system
	The Secondary AON shall provide a complete observing system providing both a real- time bi-directional link between users on the Internet anywhere in the world and a wide variety of current and next generation instruments and delivery following instrument recovery of calibrated, original sampling rate data from a wide variety of current and next generation instruments through the CI
Primary AON Power Sub System	
	The Primary AON shall provide a power network capable of delivering 10-12 kW of shared power to AON Subsystems including one Primary and one Secondary node.
	Power provided by the Primary AON shall be provided to Secondary AON at 375/400VDC and to Primary AON components at 48VDC.
	Power will be provided by backup storage in absence of connection to the Primary AON Power Subsystem.
	Power generation shall be autonomous, and provide continuous duty power. Capability to provide 10 kW to 12 kW shall be a goal of the Primary AON.
	Power will be provided to recharge AUVs at select docking stations within the AON.
	The Primary AON power network shall be designed to have electrical noise levels that do not prevent oceanographic sensors making low signal level measurements.
	The Primary AON power generation systems shall be designed not to interfere with either atmospheric observations on surface platforms or with oceanographic measurements.
	The Secondary AON shall provide a power network capable of delivering a maximum of 10kW of power shared between each of the node components.
	The Secondary AON power network shall be designed to have electrical noise levels that do not prevent oceanographic sensors making low signal level measurements.

B.2 Battery Characteristics

Key factors to consider in deciding batteries characteristics

Factors to consider include maximum applicable depth, which in this case goes to kilometres below the sea level, amount of energy to be stored; this is in the order of tens of kilometres. Cost of the batteries, charging/ recharging time and environmental impacts are also factors to take into consideration.

Performance of each battery

Nowadays, mainly four kinds of batteries are used to sustain submarine machineries such as or AUV: Lead acid battery, $Ni - MH$ battery, lithium ion battery, lithium polymer battery. In the following, a brief description of each of them is given.

(a) Lead acid battery

This battery has been validated for use at the seabed. (DeepSea Power & Light 1990a).The most common type is 12V – 80AH model, weighing about 49kg in air, maximum applicable depth is 6,000m, maximum charge/discharge current is 16A. It cost is estimated at US$2,700 per unit. Thus, energy and energy/cost, power density can be calculated follow:

$$\boldsymbol{Enegy}[\boldsymbol{Wh}] = \mathbf{12}[\boldsymbol{V}] \times \mathbf{80}[\boldsymbol{Ah}] = \mathbf{960}[\boldsymbol{Wh}]$$

$$\boldsymbol{Energy/cost}\ [\boldsymbol{Wh}/\$] = \frac{\mathbf{960}[\boldsymbol{Wh}]}{\mathbf{2,700}[\$]} = \mathbf{0.36}[\boldsymbol{Wh}/\$]$$

$$\boldsymbol{power\ dencity}[\boldsymbol{Wh/kg}] = \frac{\mathbf{960}[\boldsymbol{Wh}]}{\mathbf{49}[\boldsymbol{kg}]} = \mathbf{20}[\boldsymbol{Wh/kg}]$$

In case of charging time is recommended 20h or 10h. The possible environment problem is water pollution because of sulphuric acid leakage. In addition, it might lead death of organisms on the seabed. Nevertheless, it can be minimized by packing these batteries.

(b) Lithium polymer battery

This battery is already used in AUV, for example Auto sub 6000 (Rutherford & Doerffel 2005). Its energy per one battery is 56V – 80Ah and weight is 44 kg in air maximum applicable depth is over 6,000m, maximum charge/discharge current is 18A. (Source: (Rutherford & Doerffel 2005). Its cost is estimated approximately US$27,000 by calculation:

Small battery:

$$\mathbf{22.2V \times 2.2Ah = 48Wh}$$

The costs is thus US$71, so that:

$$\mathbf{US\$71 \times \frac{1000Wh}{120W} \approx US\$1500}$$

Then, US$1500 cost per 1kWh (rcmodelcentre 2007).

However, this is an "unhoused" price. This is multiplied by four to get $6000 per kWh and this is when they are made up into batteries, with monitoring, charge control circuitry, housing etc. Thus, one lithium-polymer battery for Auto sub (in the ratio 6000: $4.5kWh$) is roughly estimated to cost US$27,000.

Energy and energy/cost ratio, and power density can be calculated as follows:

$$\mathbf{Energy}[\boldsymbol{Wh}] = \mathbf{56}[\boldsymbol{V}] \times \mathbf{80}[\boldsymbol{Ah}] = \mathbf{4500}[\boldsymbol{Wh}]$$

$$\mathbf{Energy}/\boldsymbol{cost}\ [\boldsymbol{Wh}/\$] = \frac{\mathbf{4500}[\boldsymbol{Wh}]}{\mathbf{27000}[\$]} = \mathbf{0.17}[\boldsymbol{Wh}/\$]$$

$$\boldsymbol{Power\ dencity}[\boldsymbol{Wh}/\boldsymbol{kg}] = \frac{\mathbf{4500}[\boldsymbol{Wh}]}{\mathbf{44}[\boldsymbol{kg}]} = \mathbf{100}[\boldsymbol{Wh}/\boldsymbol{kg}]$$

The charging time of lithium polymer battery for Auto sub 6000 is 5hours per battery. A possible environmental problem is explosion of lithium-polymer batteries caused by over discharge. It is because lithium-polymer batteries include flammable electrolyte. However, frequent monitoring of the battery current can control this.

(c) Lithium ion battery

This battery is already used in AUVs (Murashima et al. 2002). Structure and regenerate system of this battery are similar to lithium polymer battery, because lithium polymer battery is developed based on lithium ion battery. The big difference is that liquid is used as electrolyte in lithium ion battery, but gel is used as electrolyte in lithium polymer battery. Thus, it is said that the energy density of lithium ion battery is smaller than that of lithium polymer battery (approximately 2/3). The other parameters and environmental impact is almost equivalent to lithium polymer battery.

(d) Ni-MH battery

Like Lithium ion battery, this battery has also been used in AUVs. However, it has lowest energy /cost out of the four options mentioned. This battery is rarely employed in AUVs, as it has lowest efficiency (approximately 66%). On the other hand, this battery can be rapidly recharged (Lund 2012).

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ISBN 978-0-854-32951-9