Available online at www.sciencedirect.com

ScienceDirect

Procedia Environmental Sciences 28 (2015) 502 – 508

Procedia Environmental Sciences

The 5th Sustainable Future for Human Security (SustaiN 2014)

Sustainability assessment of deep ocean resources

Benjamin C. McLellan[a,b]*

[a]Kyoto University, Graduate School of Energy Science, Yoshida Honmachi, Kyoto 202-8501, Japan.
[b]University of Queensland, Sustainable Minerals Institute, St Lucia 4072, Australia.

Abstract

Critical or strategic minerals are important for the future sustainable energy and economic security. Unconventional resources are being sought to obtain these minerals. Research about the extraction of deep ocean resources (DOR) has increased significantly over the past decades. However, the understanding of social and environmental implications is still very poor – especially for remote, deep deposits where the relevant stakeholders are unclear and the environment is mostly unknown. This research will use reviews of law and literature, workshops interviews, and practitioner interviews to elucidate social acceptance of extracting these resources with web-based approaches. The research will also clarify environmental impacts by undertaking the first full life cycle assessment on DOR extraction to compare with land-based projects.

Peer-review under responsibility of Sustain Society

*Keywords:*Sustainability; minerals; LCA; stakeholder; environment

1. Introduction

Critical minerals have become concerned issues in recent years due to the increasing demand in new energy technologies and the limitations on supply due to price, capacity, and political reasons[1]. Deep ocean resources (DOR) – e.g. rich cobalt crusts, massive sulphide deposits, and manganese nodule deposits – have been of increasing interests to provide secured supply for strategic minerals for future sustainable energy, but are currently inaccessible due to the lack of appropriate technology or being uneconomic to extract. This is despite of the long term (decades) investment and investigation[2]. Moreover, while the setting of international legislation was initially seen as a key

---

* Corresponding author. Tel.: +81-75-753-9173; fax: +75-753-9189.
E-mail address: b-mclellan@energy.kyoto-u.ac.jp.

Peer-review under responsibility of Sustain Society
doi:10.1016/j.proenv.2015.07.060

enabler[3], along with rising demand for metals that could outstrip onshore production capacity, the political will and economic impetus take the plunge into deep ocean to mine.

Japanese government has recently instated policy aiming to extract such resources commercially from 2018 from the deep ocean within Japan's exclusive economic zone (EEZ)[4]. The actualization of this mining activity will be unique given the global status quo, and the social and environmental implications are still unclear.

Nomenclature

DOR	Deep ocean resources
EEZ	Exclusive economic zone
ISA	International Seabed Authority
LCA	Life cycle assessment

Some of the key challenges that must be overcome in determining the sustainability of such deep sea resources are:

1. the limited knowledge of the deep sea environment;
2. the lack of existing technology to a base assessment;
3. the lack of clarity or precedents on the identification of appropriate system boundaries and stakeholders.

The final of these points is very important because the scale and range of impacts from such operations is yet to be demonstrated, and the potential impact on international waters cannot be eliminated.

Globally, the project for undersea minerals extraction that is closest to operation is Nautilus Mining's "Solarus I" project in Papua New Guinea (PNG). The Solarus I project has been the subject of significant protests due to potential environmental impacts, as well as a lack of understanding as to who the permission-giving stakeholders are or should be. Stakeholders in the case of remote EEZ or the "Area" (outside the continental shelf) will be even more difficult to identify, as the locations are largely uninhabited. These areas are also potential for international conflict (Fig. 1). Therefore, new techniques are needed to be developed and employed using internet-based engagement processes in parallel with conventional stakeholder workshops and surveys.

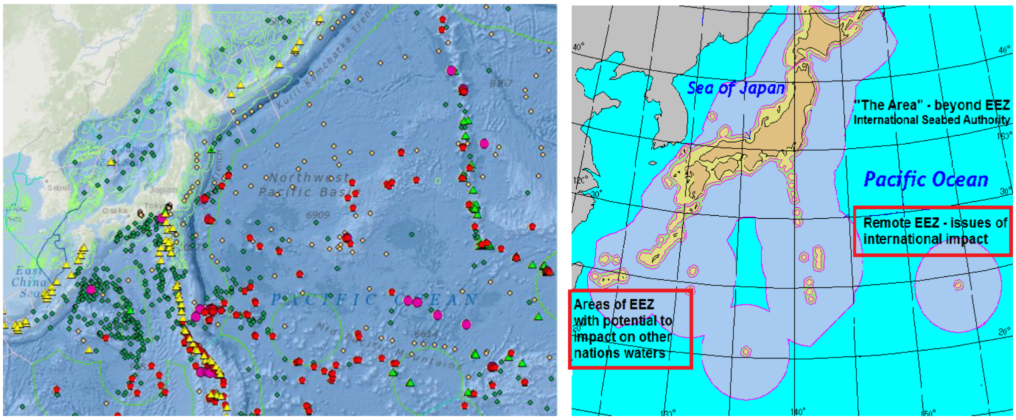

Fig. 1. (a) Japan`s EEZ overlayed with known DOR deposits [International Seabed Authority]; (b) Japan's EEZ (right)

This study aims to identify and quantify (where possible) the impacts of deep ocean resource extraction and utilization with a comparison to land-based resources, as well as testing methods for stakeholder interaction. The current paper will expand on the techno-economic and broad environmental aspects of such resources. The social and economic elements of sustainability will not be covered in this paper. Instead, this paper will present an initial high-level assessment of the life cycle impacts of DOR extraction.

1.1. Background

While it has been known for over a century that certain types of rich mineral deposits are located in the deep ocean, the concept of mining on an industrial scale has only really been contemplated seriously since the 1960`s [5]. The attraction of these deposits continues to grow due to a number of important factors:

- the high grade of metal contained in some seabed deposits compared to onshore ores
- the large untapped seabed resource
- the improvement and proving-up of technologies for extraction
- the constant growing demand for metals.

There are three broad classifications of deep ocean mineral deposits: Cobalt-rich ferromanganese crusts (cobalt-rich crusts), Polymetallic nodules (Manganese nodules), and Polymetallic sulphides. Each of these mineral deposits has different areas of geological occurrence and different requirements for extraction and processing associated with the mineral composition. Manganese nodules are formed at depths of over 4000m by the precipitation of dissolved minerals onto hard substrate – for example sharks` teeth – and can range in size of millimeters to tens of centimetres[6]. They are often being described as “potato-like” minerals. Abundance of nodules in the range of 5-15kg/m^2 is considered commercial[7]. Ferromanganese crusts are layers of precipitated material similar to manganese nodules. They are formed in a continuous layer typically in the size of 4-15cm for commercially considered deposits. They are placed generally in the depths of 800-3000m on the flanks of seamounts, ridges, and undersea volcanoes[6]. Polymetallic sulphides are often associated with active hydrothermal vents, occurring as muds or hard consolidated deposits depending on their mixture with sediments (in the former case) or otherwise[6]. These deposits tend to be at shallower depths – typically 700-2400m[7-8], and some concern has been raised over the potential for mining of these deposits to impact on the unique ecosystems associated with hydrothermal vents (although only inactive vent deposits are currently being considered)[6].

Table 1. Comparison of some typical grades of different seabed minerals.

Deep ocean resource	Metal	Seabed grade (wt%)[3, 9]		Onshore minimum grade (wt%)[10]
Cobalt-rich (ferromanganese) crusts	Fe	12		25
	Co	0.9		
	Mn	25-30		30
	Ni	0.7		1
	Cu	0.1		0.5
Polymetallic (Manganese) nodules[7]	Fe	6		25
	Co	0.2-0.3		
	Mn	25-30		30
	Ni	1.1-1.6		1
	Cu	0.9-1.2		0.5
	Ni/Cu cut-off	2-2.5		
Polymetallic (Seafloor massive) sulfides[11]		General	Solwara I	
	Cu	0.5	6.5	0.5
	Zn	2	0.5	4
	Au		0.00056	0.0004
	Ag	0.004	0.00275	0.01
	Cr			25
	Sn			5
	Mn	2		30

1.2. Environment

Environmental concerns over the impact of deep ocean mining are an important factor in delaying exploitation[12]. The International Seabed Authority (ISA), whose job is to issue exploration and exploitation permits and to ensure appropriate management of international seabed resources, has devised an environmental management plan (EMP) as the potential for mining coming closer to a reality[13]. This EMP calls for various measures, including spatial planning and the maintenance of untouched areas (30-50% of the total managed area) in order to preserve biological diversity. It has been assessed elsewhere that the potential impacts of mining will have locally high severity impacts for cobalt-rich crusts and polymetallic sulphides, and very high severity impacts at a regional-basin level for polymetallic nodule mining[6]. Such impacts are likely to be still relevant under the EMP although others argue that the impacts on biodiversity may be mitigated or relatively small within the context of the entire seabed ecosystem, and that recovery of much of the biodiversity is alike (with significant recovery at test sites within 7 years)[5].

The life cycle impacts of deep ocean resource extraction have been less widely examined, and a detailed examination is warranted. Much of the life cycle impact (apart from the mining impact on the deep ocean ecosystem directly) can be considered or associated with the economic feasibility of the operation. Although it is not an accurate measure, if the cost of equipment and operation of that equipment is too expensive, this generally implies the use of higher intensity materials and fabrication processes, and greater use of energy and other feedstock in the operation, which in turn requires a higher environmental burden. The key trade-offs in the case of minerals are that generally higher grades will imply lower impacts in processing and waste[14], while complex ores will increase the processing requirements[15]. There have also been studies into the use of tailings associated with the processing of ocean minerals[16] which could potentially have industrial ecology solutions to offset lifecycle emissions by use in other industries, such as cement substitutes as demonstrated with other mineral wastes[17].

2. Methodology

Due to the many facets of sustainability, this study will utilize a number of different techniques with the aim of getting a clearer picture of the overall sustainability of DOR. The first stage is a life cycle assessment (LCA) baseline study which will be used to compare conventional critical minerals and the extraction of DOR, based on available technology specifications. The LCA will be utilized to examine the environmental impacts. It will also function as a help to be the educational tool in stakeholder consultation. In this paper, a high-level first-cut LCA is utilized, identifying the energy impacts of DOR extraction for some typical conditions. This will be further refined as the project progresses.

2.1. Goal, scope and system boundaries

This study takes the system boundary of the extraction of materials from the deep ocean – the mining stage through the surface of the ocean, onboard the mining ship. The subsequent stages of mineral processing, and the disposal of waste or integration into final products are not included at this stage. The impacts being considered are the material throughput, energy use, and the subsequent greenhouse gas (GHG) emissions.

The extraction of seafloor massive sulphides (SMS) will be the focus, and the data from the Nautilus Minerals Solwara I operation[18] and literature[19] will be used as the basis for calculations. Fig. 1 shows the general seabed mining system layout. The material is extracted and collected from the seafloor by seabed mining tools. They are then crushed and screened before being pumped to the surface as a slurry.

3. Results

In the case of the Nautilus project, the power requirements of the major elements are shown in Table 2. At the design basis of 1.8 Mtpa of ore, this average power usage equivalent to 123-136 GWh is around 68-75 kWh /t of ore. Without even considering the minerals processing component, this is significantly higher than the world average energy usage per ton of mined or quarried material (around 20-36 kWh / t based on previous studies[20]). This energy is provided as electricity, generated on-board by a fuel-oil driven generator, leading to emissions of 22-25 kg CO_2-eq

/ t based on emissions factors[21] and an efficiency of 80%. Again, in comparison with land-based ores[20] (6 – 12 kg CO_2-eq / t) this is exacerbated by the utilization of the onboard, highly-polluting fuel oil. This is still a significant lower emission compared to the entire life cycle of the metal, but important as a point of comparison – particularly in considering future risks and stewardship of resources.

Table 2. Equipment power usage for the Solwara I project – design basis

Equipment	Power usage (MW)		
	Average	Worst case	Capacity
Mining system	13.8	13.8	13.8
Positioning system	3.6	7.2	12
Ship services	1.1	1.1	1.1
Total	*18.5*	*22.1*	*26.9*

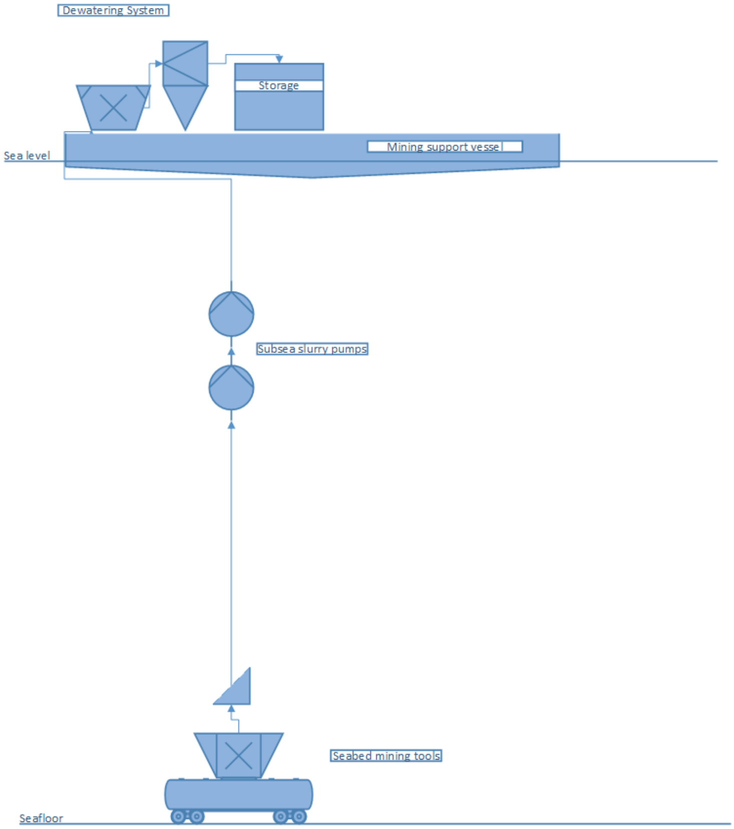

Fig. 2. General seabed mining flowsheet

When these figures are converted to a rough-estimate of final metal based on ore content and the stated recoveries of up to 75-90%, the mining component contributes 1000-1400 kWh / t metal, and 350 – 460 kg CO_2-eq/t metal (across all combined major contained metals).

Table 3 shows the variation of these figures with depth, assuming that the major variation is the pumping energy usage. This indicates that increasing depth would have significant impacts on economic feasibility as well as the environmental impacts associated with extraction of alternative resources.

Table 3. Energy and emissions for ore mining variation with depth (estimate)

	Energy (kWh / t)		Emissions (kg CO2 / t)	
Depth (m)	Average	Max	Average	Max
1500	69	76	23	25
3000	113	125	37	41
4500	158	174	52	57

The lifetime assumed for the mining system by Nautilus minerals is 10 years. The embodied emissions of the mining system in a given short lifetime are potential to the impact of the environment lifecycle. As a rough initial calculation, the weight of major equipment is shown in Table 4, with the assumption that the materials used are general steel[20] or stainless steel[22]. It is needed to acknowledge that this is an oversimplification.

Table 4. Mass of key mining system elements and lifecycle impacts

Item	Mass (t)	Embodied energy (MWh)	Embodied emissions (t CO_2-eq)
Tool 1	150	780 – 3130	288 – 1020
Tool 2	250	1310 – 5210	480 – 1700
Tool 3	100	520 – 2080	192 – 680
Lift pump	129	670 – 2690	248 – 880
Pipe	694	3620 - 14460	1332 - 4720

In total, this equates to an equivalent of 0.4-1.5 kWh / t ore and 0.1-0.5 kg CO2-eq / t ore, these figures indicate that the equipment-related to embodied emissions are likely to be quite minimal.

4. Conclusions

This study indicates that high-level life cycle affects the mining of deep ocean minerals. The study is highly limited due to the restrictions of time, but the project will still go on greater levels of detail and broader scope in the upcoming months.

Importantly, the study indicates that the energy associated with the mining stage of deep ocean resources is likely to be significantly higher than onshore deposits. In this case, they should be taken care of very carefully to identify whether the remainder of the life cycle and the associated environmental impacts are equivalent or improved. It is if they are compared to on land resources. The aim is to increase the argument for their exploitation.

Acknowledgements

This project is being undertaken with the support of a grant-in-aid from the Japan Society for the Promotion of Science (JSPS), and with assistance from the University of Queensland.

References

1. McLellan, B.; Corder, G.; Ali, S., Sustainability of Rare Earths—An Overview of the State of Knowledge. *Minerals* **2013,** *3* (3), 304-317.
2. Cronan, D. S., *Marine minerals in exclusive economic zones*. Springer: 1992; Vol. 5.
3. Wiltshire, J.; Yao, D. In *Mineralogy and geochemistry of ferromanganese crusts from Johnston Island EEZ*, OCEANS '96. MTS/IEEE. Prospects for the 21st Century. Conference Proceedings, 23-26 Sep 1996; 1996; pp 1360-1365 vol.3.
4. Government of Japan, Basic Plan on Ocean Policy [April, 2013] (in Japanese). Policy, H. f. O., Ed. Government of Japan: Tokyo, 2013.

5. Thiel, H.; Schriever, G.; Foell, E. J., Polymetallic Nodule Mining, Waste Disposal, and Species Extinction at the Abyssal Seafloor. *Marine Georesources & Geotechnology* **2005,** *23* (3), 209-220.
6. Glover, A. G.; Smith, C. R., The deep-sea floor ecosystem: current status and prospects of anthropogenic change by the year 2025. *Environmental Conservation* **2003,** *30* (03), 219-241.
7. ISA In *Proposed technologies for mining deep-seabed polymetallic nodules*, Proposed technologies for mining deep-seabed polymetallic nodules: proceedings of the International Seabed Authority's workshop held in Kingston, Jamaica, August 3-6, 1999, Kingston, Jamaica, The International Seabed Authority: Kingston, Jamaica, 2001; p 464.
8. Yamazaki, T.; Nakatani, N.; Nakatani, T.; Arai, R. In *Seafloor Primary Ore Dressing System for Economic Sulfide Mining*, Emerging Trends in Engineering and Technology (ICETET), 2012 Fifth International Conference on, 5-7 Nov. 2012; 2012; pp 152-156.
9. Marjoram, T.; Cameron, H.; Ford, G.; Garner, A.; Gibbons, M., Manganese nodules and marine technology. *Resources Policy* **1981,** *7* (1), 45-57.
10. Rankin, W. J., *Minerals, metals and sustainability : meeting future material needs*. CRC Press: Boca Raton, 2011.
11. Bertram, C.; Krätschell, A.; O'Brien, K.; Brückmann, W.; Proelss, A.; Rehdanz, K., Metalliferous sediments in the Atlantis II Deep—Assessing the geological and economic resource potential and legal constraints. *Resources Policy* **2011,** *36* (4), 315-329.
12. L. Morgan, N. A. O. A. T. J. C., Synthesis of Environmental Impacts of Deep Seabed Mining. *Marine Georesources & Geotechnology* **1999,** *17* (4), 307-356.
13. Lodge, M.; Johnson, D.; Le Gurun, G.; Wengler, M.; Weaver, P.; Gunn, V., Seabed mining: International Seabed Authority environmental management plan for the Clarion–Clipperton Zone. A partnership approach. *Marine Policy* **2014,** *49* (0), 66-72.
14. Mudd, G. M., The Environmental sustainability of mining in Australia: key mega-trends and looming constraints. *Resources Policy* **2010,** *35* (2), 98-115.
15. Cooper, C.; Giurco, D., Mineral resources landscape: reconciling complexity, sustainability and technology. *International Journal of Technology Intelligence and Planning* **2011,** *7* (1), 1-18.
16. Bai, Z.; Wiltshire, J. C., Composition and useful properties of tailings of marine manganese nodules and crusts. *Marine Georesources and Geotechnology* **2005,** *23* (1-2), 13-24.
17. McLellan, B. C.; Williams, R. P.; Lay, J.; van Riessen, A.; Corder, G. D., Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement. *Journal of Cleaner Production* **2011,** *19* (9-10), 1080-1090.
18. Nautilus Minerals Nautilus Minerals Inc. - Solwara I Project. http://www.nautilusminerals.com/s/Projects-Solwara.asp (accessed April 8).
19. Charles L. Morgan, N. A. O., Anthony T. Jones, Synthesis of environmental impacts of deep seabed mining. *Marine Georesources and Geotechnology* **1999,** *17* (4), 307-356.
20. McLellan, B. C.; Corder, G. D.; Giurco, D. P.; Ishihara, K. N., Renewable energy in the minerals industry: a review of global potential. *Journal of Cleaner Production* **2012,** *32* (0), 32-44.
21. DCC *National Greenhouse Accounts (NGA) Factors*; Department of Climate Change, Australian Government: Canberra, July 2014, 2014.
22. Norgate, T. E.; Jahanshahi, S.; Rankin, W. J., Assessing the environmental impact of metal production processes. *Journal of Cleaner Production* **2007,** *15* (8-9), 838-848.