SUSTAINABILITY AND DESIGN CONSIDERATIONS FOR CRITICAL MINERALS IN CLEAN ENERGY TECHNOLOGIES

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ABSTRACT

In order to address concerns over global warming, and to mitigate localized pollutants and energy security issues, a variety of clean energy technologies are being proposed or proliferated globally. Many of these technologies – e.g. fuel cells, photovoltaics, wind turbines – rely on critical minerals with concerns over physical, economic or politically-driven scarcity. This paper discusses some of the key minerals and technologies, and highlights important strategies for sustainable design considerations. The potential benefits and barriers of alternative sources of relevant minerals are discussed with relation to recycling and deep ocean resources.

INTRODUCTION

The minerals-energy nexus is an increasingly important area of research consideration for the future sustainability of societies. Within this nexus, this paper will consider the important aspect of how to ensure sustainable supply of critical minerals for the clean energy technologies that may be required in the future. Although this is an issue of many facets and complex interactions, the current paper provides a comparison of some of the key elements to be considered in securing supply, including considerations of peak minerals, recycling and unconventional resources such as deep ocean mining. Moreover, the integration with the design process is considered from the perspective of lifecycle sustainability.

Critical minerals have been of particular interest in recent years, with many countries having developed methods and ratings to identify such minerals that are essential to their economic activities (e.g. [1,2]). Table 1 shows some relevant figures regarding important critical minerals relevant to clean energy technologies. Some of the key reasons for elements being designated as critical include: physical scarcity, geological or political centralization of supply, high prices, economic reliance.

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Table 1: Relevant data on selected critical minerals (Data: [3])

Mineral	Global Mine Production[1] 2011 (t)	Single largest supplier		Global reserves			
				Total (t)	Largest	% of total	R/P
Cobalt	110,000	55%	Congo	7,200,000	Congo	47%	65
Copper	16,100,000	33%	Chile	690,000,000	Chile	28%	43
Gallium[2]	474	74%	China	-	-	-	
Indium[3]	738	52%	China	-	-	-	
Lithium	621,000	68%	Australia	13,000,000	Chile	57%	21
Manganese	15,700,000	23%	South Africa	570,000,000	South Africa	26%	36
Nickel	1,960,000	15%	Indonesia	74,000,000	Australia	24%	38
PGMs				66,000	South Africa	95%	136
Platinum	200	74%	South Africa				
Palladium	213	40%	Russia				
Other PGMS	73	80%	South Africa				
Rare Earths	110,000	96%	China	140,000,000	China	39%	1273
Selenium[3]	2,280	33%	Japan	120,000	China	22%	53
Tellurium[3]	83	48%	Japan	24,000	Peru	15%	289
Zinc	12,600,000	32%	China	250,000,000	Australia	26%	20

Notes:

[1]Mine production refers to metric tonnes of contained metal content unless otherwise specified

[2]Gallium expressed as capacity for production as it is a by-product mineral

[3]Selenium, Tellurium, Indium figures are the refinery production rate

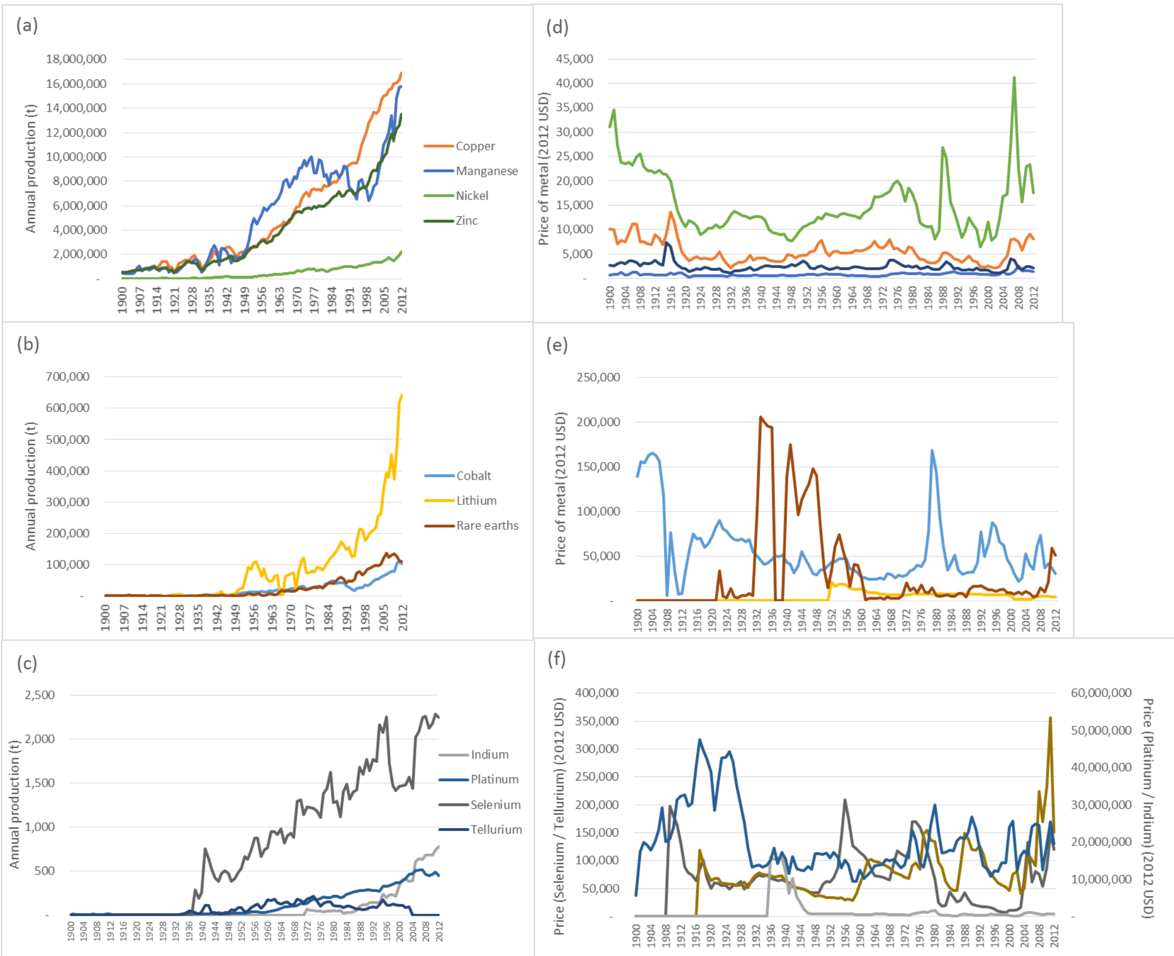

Figure 1: Production (a-c) and prices (d-f) of selected critical minerals (Data: various [4,5])

CRITICAL MINERALS IN CLEAN ENERGY TECHNOLOGY

A review of LCA literature [6] and other technical documentation has been utilized to produce some estimates of the range of materials and the quantities required per kilowatt of installed capacity. This review also identified the typical scale of individual units and power plant scale installations, building on other recent estimates [7]. Table 2 shows the key critical materials, their function within technologies, the range of reported densities of materials per unit generating capacity and typical scale. While details on wind turbine technologies are readily and widely available, the specific quantities and ratios of photo-active materials (PVA) in photovoltaics is often unclear. The estimates here are based on a USGS [8] study as well as the reported total PVA in various LCA studies.

Table 2: Density of some critical functional materials in distributed energy technologies

Technology	Critical materials	Function	Density (kg / kW)	Typical scale (kW)
Wind turbines	Dysprosium, Neodymium,	Permanent magnets	0.15-0.2 (Dy and Nd combined)	1500 – 5000 (turbines) 15,000 – >1,000,000 (wind farm)
	Copper	Generator windings and wiring	1.2 (turbine only – onshore) 2-5 (windfarm averages onshore) 6-12 (windfarm averages offshore)	
Photovoltaics	Indium, Gallium, Selenium, Tellurium	Photo-active materials (total PVA reported)	0.4 – 1.4 (various LCA studies) 2-3 (USGS)	1 – 5 (residential) 10,000 – 550,000 (solar farm)
	Copper	Electrical connections and power electronics	0.25 (various LCA studies)	
Fuel cells	Platinum	Electrodes / catalysts (PEM FC)	0.0001 – 0.001 (various)	5 - >350,000
	Yttrium, Lanthanum	Electrolyte and electrode materials (SOFC)	0.02-0.2 (Yttrium) (various)	

Pressures on supply from rising demand for such critical minerals has been anticipated to lead to the need to exploit unconventional resources – for example, deep ocean and urban ore deposits. The materials indicated in Table 2 have significant remaining reserves, as indicated by the R/P in Table 1. However, it is still important to consider the limitations to global resources and the specific benefits or barriers to utilising alternative resources as the grades of terrestrial resources continue to degrade [9] and many countries seek to ensure long term security of supply.

UNCONVENTIONAL RESOURCES, RECYCLING AND SUSTAINABILITY

The interest in developing unconventional resources is driven by several factors, including concerns for the lack and/or exhaustion of primary geological resources, security of supply for critical metals vital to modern technologies and military applications, and technological advances allowing to overcome some general economic and environmental burdens. In this section the differences and potentials of deep ocean and recycling from energy technology urban ores are examined briefly.

Primary mining and processing of critical metals usually result in significant environmental impacts. For example, the processing of rare earths is characterised by high levels of water consumption, energy inputs, chemicals use, as well as separate treatment and disposal of radioactive waste materials [10]. The low grade of many deposits of these materials is one factor in this, as is the difficulty of separating chemically and physically similar components – particularly in the case of REEs and PGMs [11]. The high environmental impacts of sourcing rare earths from conventional mining and processing [12] provide an incentive to seek unconventional sources. However, current recycling techniques do not always improve the environmental impacts of production, and the system of waste collection, separation and disassembly require infrastructural, institutional and behavioural adjustments. While recycling could enhance security of supply, the ecological and economic costs can be significant.

The growing application of critical metals in the modern hi-tech products also leads to a larger "resource base" of critical metals in the end-of-life products. In contrast to below-ground deposits, urban mines are growing reserves to be exploited, although the combination of different materials, miniaturisation and the improvement of technologies in the production phase can lead to a decreasing "grade" within these reserves. Importantly, such resources can be more-suitably likened to crops – growing resources that accumulate on land and come to maturity or fruition only at the end of life of the product.

In the case of deep ocean mining, the uncertainties of the operating environment translate into contention and widely varying opinions of the potential sustainability. From the perspective of mining, deep ocean deposits have a number of advantages – they are typically near the surface of the ocean floor requiring minimal overburden removal, explosives are not required, and they often contain high ore grades – including many critical minerals such as cobalt, zinc, copper, PGMs and REEs [13,14]. However, some of the deposits (particularly active hydrothermal vents) are considered to have highly unique, specialised ecosystems – and whilst it is likely that such sites will be preserved and "mined-around", there is still some concern raised [15]. Moreover, the lack of oxygen and light and the high pressure of the deep ocean environment mean that much of the benthic fauna is largely immobile, which implies that rehabilitation can be complex and disturbance is likely to induce irreversible, although localised, change [16].

Early estimations indicate that the mining stage requires significantly more energy than average on-land deposits to extract (due to the pumping of materials from depth and the requirement to keep the production vessel in a relatively fixed location) – this would be at least twice the average energy, and certainly comparable to deep land-based mines [17]. Exacerbating the impact of this energy use is the fact that deep ocean mining operations utilise ship-board power, generated by the use of fuel oil or diesel. Technologies to offset this must be considered in order to improve the overall sustainability of such resources. The advantages of high grades and low wastes may help the life cycle impacts in some cases [18].

Similar to deep ocean resources, recycling of urban ores has the advantage of being mostly explosive-free and having minimal (if any) overburden. While not requiring significant vertical transportation of the ore, the distribution of ore across a wide landscape may be an important factor in determining the environmental implications of extraction. Table 3 shows some spatial densities for clean energy technology urban ores. It is apparent that residential or highly distributed use of these technologies will significantly diminish the density, but in this case the power plant scale will be examined in more detail.

Table 3: Estimated range of potential material density and "deposit" size

Technology	Critical materials	Mass density of contained metals (t / km^2)		Size of Deposit (t)
		Residential scale	**Power plant scale**	**Power plant scale**
Wind turbines	Dy, Nd	0.24	6	170
	Cu	1.8	117 (onshore)	3500
			300 (offshore)	9000
Photovoltaics	In, Ga, Se, Te	2.3	83	930
	Cu	0.34	12	140
Fuel cells	Pt	0.001	2	0.2
	Y	0.15	309	40

Table 4: Example grades of conventional and unconventional deposits (various references)

Critical materials	Grade (wt%)			
	Energy system urban ore		**Deep ocean**	**Terrestrial Deposits**
	Component	**System**		
Dy, Nd	30% (magnet) (28% Nd /2% Dy)	0.03%	>0.0023% Nd / >0.0004% Dy (Pacific muds)	0.05% Nd /0.02% Dy ~ 0.8% Nd /0.5% Dy
Cu	~100% (wire / windings)	0.8% (Wind) 0.1% (PV)	6.8% (Solwara I) 0.5% (Izena Cauldron)	>0.5% (typical cut-off grade)
In, Ga, Se, Te	0.5% (panel) 14.5% (panel without glass)	0.3%		In (<0.01%) in Zn ores Se (8%) in Cu slimes Se (<0.00001%) in Cu ores Te (1%) in Cu slimes

Table 3 and Table 4 present some relevant data for consideration of the potential of recycling-based urban ores from clean energy technologies and unconventional deep ocean deposits. It is important to note that deep ocean deposits currently under consideration are typically much smaller than terrestrial deposits (e.g. Solwara I is 1Mt deposit [19] compared with, as an example of a deep onshore mine, Kidd Creek 19Mt [20]), although they can in some cases be very high grading. Energy system ores have three important characteristics in this sense:

1. Low deposit size (orders of magnitude)
2. Low deposit geographical density (material spread out across a wide area, particularly if residential usage is anticipated)
3. Variable deposit grades (not always higher than conventional resources).

The first two of these characteristics are important for the economic feasibility of mining / recovery of the materials at their end of life – these are also affected by the fact that failure of the system is unlikely to occur at the same time, thus implying an irregular period of "harvesting" of these ores. However, it is important to consider the third point a little further. As shown in Table 4, the grade of the critical materials is very high in the components of the technologies, but significantly lower considering the system as a whole. This is an important consideration for the design and end-of-life processing of such technologies. In some cases it is possible to disassemble the unit before recycling – particularly removing parts such as the magnets from generators in wind turbines – in which case the selective separation can enable higher efficiency recycling and a high incoming grade. If it is infeasible to remove components, then there is often a significant grade degradation – e.g. if the glass is effectively separated from PV panels, then the grade rises by almost a factor of 30 for the thin-film components. This is an important consideration to be incorporated in design for sustainability of such technologies.

DESIGN CONSIDERATIONS FOR SUSTAINABILITY

Considering the case of critical minerals used in clean energy technologies, it is clear that the definition of sustainable minerals applied elsewhere as an "appropriate contribution to society"[21] would be met. However, in order to enhance the benefits and reduce the negative impacts of minerals usage, the full lifecycle should be considered. This implies that, among other aspects, the reusability or recyclability of end-of-life products should be taken into account.

Green engineering is described exhaustively in a variety of resources [22,23] and is utilized here as an example methodology for design for sustainability. Table 5 shows some of the most relevant principles with regards to the critical minerals – clean energy nexus. Regarding principles 1 and 2, the outputs from production of minerals are an important consideration. Particularly, the wastes associated with processing minerals – in the case of the Izena Cauldron (deep ocean deposit) for example, high concentrations of Arsenic make an inevitable hazardous input and output [24], while recycling or even other conventional deposits are not subject to this restriction. Choice of whether or not to mine such a deposit is an important consideration. These principles also favour recycling, as it is removing a potentially hazardous waste in the process of production. Principles 9 and 11 have implications that are apparent in the limitations of recycling waste energy technology – often the incorporation of critical function materials in small quantities makes end-of-life separation a challenging task. In some cases, reuse (as preferable to recycling) could be utilised with certain components – although this requires consideration of the level of standardisation appropriate to the product type and market. The final principle is of importance to energy technology seeking to utilise renewable energy, but at the same time including non-renewable minerals resources in the generating technology. Without such technology, the use of renewable energy is limited, but to the extent that materials can be recovered at the end of life of the product, the benefits of utilising a non-renewable mineral resource may outweigh the depletion constraints.

Table 5: A selection of the twelve principles of Green Engineering [25]

1. Designers need to strive to ensure that all material and energy inputs and outputs are as inherently nonhazardous as possible.
2. It is better to prevent waste than to treat or clean up waste after it is formed.
…
9. Material diversity in multi-component products should be minimised to promote disassembly and value retention.
…
11. Products, processes and systems should be designed for performance in a commercial "afterlife".
12. Material and energy inputs should be renewable rather than depleting.

Sustainability in the minerals industry has been largely examined as a mitigation of negative impacts, but the benefits attributable to using minerals to produce clean energy must be adequately considered as well. From the perspective of societal stakeholders, unconventional resources are typically considered quite differently from conventional resources. The recycling of end-of-life products is often also supported by general public opinion, thus can be considered as a part of responsible manufacturing to meet customers' expectations. By contrast, public support for deep ocean mining is less certain, and perhaps less likely – particularly in near-shore projects [26]. The specific stakeholders needing to be consulted within the deep ocean context are also uncertain, particularly in the remote exclusive economic zone or in international waters. The procedures for environmental impact assessment, and the associated social impact assessment and consultation are still in development at the international level.

CONCLUSIONS

This paper has presented a variety of key issues associated with the use of critical minerals in clean energy technologies. It is important that, as the world`s demand for such minerals increases, the considerations of sustainability are integrated with a lifecycle viewpoint. Deep ocean deposits and the recycling of minerals utilised in clean energy technologies themselves may be future options for the extension of global reserve life. Deep ocean resources may be expected to have higher impacts than terrestrial resources in many categories – despite having relatively high grades. On the other hand, recycled urban energy system ores can be better-engineered or designed for end-of-life so that the invested value that has contributed to their construction can be recapitalised – for example, by enabling effective disassembly and separation of high value components to present a high grade stream.

REFERENCES

1. USDOE. *Critical materials strategy*; DOE PI-0009; United States Department of Energy: Washington D.C., January 10, 2012, 2012; p 190.
2. European Commission. *Critical raw materials for the eu*; European Commission: 30th July, 2010.
3. USGS. *Mineral commodity summaries 2013*; United States Geological Survey: Washington, January, 2013, 2013.
4. USGS. *Metal prices in the united states through 2010: U.S. Geological survey scientific investigations report 2012–5188*; 2013; p 204.
5. USGS. *Mineral commodity summaries 2015*; United States Geological Survey: Washington, February, 2015, 2015.
6. Chapman, A.J.; McLellan, B.C.; Tezuka, T. In *Life cycle assessment inventory of energy technologies – survey and application to energy technologies*, EcoBalance 2014, 2014; The Institute of Life Cycle Assessment Japan.
7. McLellan, B.C.; Florin, N.; Giurco, D.P.; Kishita, Y.; Itaoka, K.; Tezuka, T. Decentralised energy futures: The changing emissions reduction landscape. In *The 22nd CIRP conference on Life Cycle Engineering*, Kara, S.; Li, W.; Vongbunyong, S.; Ibbotson, S., Eds. Sydney, Australia, 2015.
8. Bleiwas, D.I.; USGS. *Byproduct mineral commodities used for the production of photovoltaic cells*; United States Geological Survey: Virginia, USA, 2010.
9. Mudd, G.M. The environmental sustainability of mining in australia: Key mega-trends and looming constraints. *Resources Policy* **2010**, *35*, 98-115.

10. EPA. *Rare earth elements: A review of production, processing, recycling, and associated environmental issues*; US Environmental Protection Agency: Cincinnati, OH, 2012.
11. Gupta, C.K.; Krishnamurthy, N. *Extractive metallurgy of rare earths*. CRC Press: 2005.
12. Tharumarajah, R.; Koltun, P. Cradle to gate assessment of environmental impact of rare earth metals. In *ALCAS Conference 2011*, Australian Life Cycle Assessment Society: Melbourne, 2011.
13. Siddiquie, H.N.; Gujar, A.R.; Hashimi, N.H.; Valsangkar, A.B. Superficial mineral resources of the indian ocean. *Deep Sea Research Part A. Oceanographic Research Papers* **1984**, *31*, 763-812.
14. Kato, Y.; Fujinaga, K.; Nakamura, K.; Takaya, Y.; Kitamura, K.; Ohta, J.; Toda, R.; Nakashima, T.; Iwamori, H. Deep-sea mud in the pacific ocean as a potential resource for rare-earth elements. *Nature Geosci* **2011**, *4*, 535-539.
15. Ellis, D.V.; Macdonald, V.I. Rapid preliminary assessment of seabed biodiversity for the marine and coastal mining industries. *Marine Georesources & Geotechnology* **1998**, *16*, 307-319.
16. Sharma, R.; Nagendernath, B.; Valsangkar, A.B.; Parthiban, G.; Sivakolundu, K.M.; Walker, G. Benthic disturbance and impact experiments in the central indian ocean basin. *Marine Georesources & Geotechnology* **2000**, *18*, 209-221.
17. McLellan, B.C. Sustainability of deep ocean resources. In *5th International Conference on a Sustainable Future for Human Security*, Bali, Indonesia, 2014.
18. McLellan, B.C.; Motoori, R.; Tezuka, T. Comparison of lifecycle impacts of seafloor mining with onshore equivalents. In *ISOPE 2015*, Chung, J.S., Ed. Kona, Hawaii, 2015.
19. Nautilus Minerals. Nautilus minerals inc. - solwara i project. http://www.nautilusminerals.com/s/Projects-Solwara.asp (April 8),
20. Xstrata Copper Canada. *Xstrata copper canada sustainability report 2012*; Available through the Global Reporting Initiative Disclosure Database: Toronto, Canada, 2013.
21. Corder, G.D.; McLellan, B.C.; Bangerter, P.J.; van Beers, D.; Green, S.R. Engineering-in sustainability through the application of susop®. *Chemical Engineering Research and Design* **2012**, *90*, 98-109.
22. Allen, D. In *Green engineering education in the united states*, International Conference on Sustainability Engineering and Science, Auckland, NZ, 6-9 July, 2004; Auckland, NZ.
23. Allen, D.; Shonnard, D. Green engineering: Environmentally conscious design of chemical processes. New york, USA. John Wiley & Sons: 2002.
24. Motoori, R.; McLellan, B.C.; Tezuka, T. Economic feasibility impacts of waste and waste water treatment regulations

for deep ocean hydrothermal ore mining in japan. In *ISOPE 2015*, Chung, J.S., Ed. Kona, Hawaii, 2015.
25. Anastas, P.T.; Zimmerman, J.B. Design through the 12 principles of green engineering. *Environ. Sci. Technol* **2003**, *37*, 94A-101A.
26. Mason, C.; Paxton, G.; Parr, J.; Boughen, N. Charting the territory: Exploring stakeholder reactions to the prospect of seafloor exploration and mining in australia. *Marine Policy* **2010**, *34*, 1374-1380.