Commissioned by

HIGH LEVEL PANEL *for*
A SUSTAINABLE
OCEAN ECONOMY

BLUE PAPER

What Role for Ocean-Based Renewable Energy and Deep-Seabed Minerals in a Sustainable Future?

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About the High Level Panel for a Sustainable Ocean Economy

The High Level Panel for a Sustainable Ocean Economy (Ocean Panel) is a unique initiative by 14 world leaders who are building momentum for a sustainable ocean economy in which effective protection, sustainable production and equitable prosperity go hand in hand. By enhancing humanity's relationship with the ocean, bridging ocean health and wealth, working with diverse stakeholders and harnessing the latest knowledge, the Ocean Panel aims to facilitate a better, more resilient future for people and the planet.

Established in September 2018, the Ocean Panel has been working with government, business, financial institutions, the science community and civil society to catalyse and scale bold, pragmatic solutions across policy, governance, technology and finance to ultimately develop an action agenda for transitioning to a sustainable ocean economy. Co-chaired by Norway and Palau, the Ocean Panel is the only ocean policy body made up of serving world leaders with the authority needed to trigger, amplify and accelerate action worldwide for ocean priorities. The Ocean Panel comprises members from Australia, Canada, Chile, Fiji, Ghana, Indonesia, Jamaica, Japan, Kenya, Mexico, Namibia, Norway, Palau and Portugal and is supported by the UN Secretary-General's Special Envoy for the Ocean.

The Ocean Panel's approach is both ambitious and practical. Collaborative partnerships are essential to converting knowledge into action. To develop a common understanding of what a sustainable ocean economy looks like, the Ocean Panel gathers input from a wide array of stakeholders, including an Expert Group and an Advisory Network. The Secretariat, based at World Resources Institute, assists with analytical work, communications and stakeholder engagement.

In the spirit of achieving the UN Sustainable Development Goals (SDGs), providing value to the UN Decade of Ocean Science for Sustainable Development and meeting the objectives of the Paris Agreement, the Ocean Panel commissioned a comprehensive assessment of ocean science and knowledge that has significant policy relevance. This includes a series of 16 Blue Papers and Special Reports that will ultimately inform the Ocean Panel's action agenda. The Blue Papers and Special Reports are central inputs in shaping the new ocean narrative and identifying opportunities for action.

Ultimately, these papers are an independent input to the Ocean Panel process and do not necessarily represent the thinking of the Ocean Panel, Sherpas or Secretariat.

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Foreword

The High Level Panel for a Sustainable Ocean Economy (Ocean Panel) commissioned us, the co-chairs of the Ocean Panel Expert Group, to produce a series of Blue Papers to explore pressing challenges at the nexus of the ocean and the economy to ultimately inform a new ocean report and the Ocean Panel's action agenda. The Ocean Panel identified 16 specific topics for which it sought a synthesis of knowledge and opportunities for action. In response, we convened 16 teams of global experts—over 200 authors from nearly 50 countries—who reviewed and analysed the latest knowledge. They then provided new thinking and perspectives on how technology, policy, governance and finance can be applied to catalyse a more sustainable and prosperous relationship with the ocean. In short, these Special Reports and Blue Papers provide the information needed to transition to a sustainable ocean economy.

The Expert Group, a global group of over 70 experts, is tasked with helping to ensure the high quality and intellectual integrity of the Ocean Panel's work. All Blue Papers are subject to a rigorous and independent peer-review process. The arguments, findings and opportunities for action represent the views of the authors. The launches of these papers, which are taking place between November 2019 and October 2020, create opportunities for exchange and dialogue between political leaders, policymakers, the financial community, business leaders, the scientific community and civil society.

We are delighted to share the latest in the Blue Paper series, What Role for Ocean-Based Renewable Energy and Deep-Seabed Minerals in a Sustainable Future? Previous analysis prepared by the Expert Group identified the potential for ocean-based renewable energy to deliver up to 5.4 percent of the emissions reductions needed by 2050 to stay within the 1.5°C limit set by the Paris Agreement. This potential makes the role of ocean-based renewable energy in the sustainable transformation of the global energy system irrefutable. This Blue Paper builds on this analysis, further exploring the links between ocean-based renewable energy options and to what extent, if any, minerals and metals found in the deep sea are needed to facilitate this energy transition.

This paper makes a significant contribution to the existing research landscape by considering both the demand and potential for ocean-based renewable energy with the question of whether deep-seabed mining would sustainably bring the technologies required for decarbonisation to scale. It not only unpacks the risks and challenges involved in deep-seabed mining but also proposes a pathway to ensure that the ocean stays healthy and resilient for future generations and that ocean-based renewable energy is harnessed in a sustainable manner. This analysis offers an inspirational perspective on the vital role that resource limitation considerations play in the transition to a more sustainable energy system.

As co-chairs of the Expert Group, we are excited to share this paper and wish to warmly thank the authors, the reviewers and the Secretariat for supporting this research. We are also grateful for the vision of the Ocean Panel members in commissioning this important body of work. We hope they and other parties act on the opportunities identified in this paper.

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Expert Group co-chair P. Haugan served as a co-author and contributor to the report. To ensure the integrity and independence of the review, Dr. Haugan recused himself from participating in the editorial and review process, which is typically overseen by the co-chairs, and was not involved in the arbitration process.

Highlights

- This paper analyses the underlying tension between the need for rapid decarbonisation, including that required for scaling up ocean-based renewable energy, and the resource and environmental implications related to that metal demand, with particular attention on current proposals to mine the deep seabed.

- Building a sustainable global energy system is intimately linked to both scaling up renewable energy and finding a way to source and use rare minerals in a more sustainable way. Questions remain as to whether deep-seabed mining should be heralded as the key to a transition to a sustainable energy sector, based on whether it can be accomplished in a way that appropriately ensures a healthy and resilient ocean.

- Rapid transformation of our energy systems is required if we are to achieve the goals of the Paris Agreement and limit the global average temperature rise to 1.5°C, or even 2°C, above pre-industrial levels. In addition to expanding land-based renewable energy, the ocean offers significant potential for supporting this transition. However, new technologies must be implemented in a sustainable way in order to avoid unintended consequences that could undermine other aspects of ocean health.

- Ocean-based renewable energy sources include offshore wind (near-surface as well as high-altitude), floating solar, marine biomass and ocean energy, which encompasses tidal range, tidal stream, wave, ocean thermal energy conversion (OTEC), current and salinity gradient.

- Offshore wind (near-surface, i.e. based on bottom-fixed or floating support structures) is presently more developed than other marine renewable energy and has reached cost parity with fossil sources of electricity.

- The trend for newer multi-megawatt wind turbine generators is to use direct-drive systems with permanent magnet generators. Since most other ocean-based renewable energy technologies are still in early phases of development with little deployment, few studies have been completed on what materials will be needed to scale up the use of these technologies. If these technologies have similar metal requirements to modern wind turbines, which is likely, implementation will rapidly increase the demand for many metals, such as lithium, cobalt, copper, silver, zinc, nickel and manganese, and rare earth elements (REEs).

- The demand for specific metals to serve the global energy transition is highly dependent on their cost. Often, alternatives to specific metals can be found. The industry is continually developing solutions that can use cheaper and more abundant resources avoiding specific costly metals.

- Selected metals and minerals are increasingly difficult to find in large quantities or high grades on land, but are present in higher concentrations in some parts of the deep seabed. As such, the deep seabed resource potential has attracted interest in mining for copper, cobalt, nickel, zinc, silver, gold, lithium, REEs and phosphorites.

- The potential to mine the deep seabed raises various environmental, legal and governance challenges, as well as possible conflicts with the United Nations Sustainable Development Goals.

- Greater knowledge of the potential environmental impacts and measures to mitigate them to levels acceptable to the global community will be crucial.

- Full analysis of the perceived positive and negative impacts is required before there can be confidence that engaging in industrial-scale deep-seabed mining would achieve a global net benefit.

1. Introduction

Scenarios for sustainable transformation of the global economy to near zero greenhouse gas emissions in 2050 in line with the Paris Agreement and the UN 2030 Agenda for Sustainable Development rely strongly on renewable energy. Offshore wind shows potential to become a globally significant supplier of electricity in these scenarios. Floating solar energy and direct ocean energy sources, such as wave, tidal and ocean thermal energy, may also contribute significantly in a range of locations, but require more policy support and understanding of potential environmental impacts in order to become significant in the transition to a sustainable global energy system.

The expanding use of batteries to electrify the transport sector is leading to increasing demand for a range of rare minerals. Renewable energy technologies, such as solar panels and wind turbines, along with electronic products and cell phones, also use these various minerals. One potential new source of minerals is the deep seabed. But the mining of these minerals raises potentially serious environmental, legal, social and rights-based challenges, as well as potential conflicts with UN Sustainable Development Goals 12, 13 and 14.

This Blue Paper focuses on the extent to which a selected subset of ocean resources, ocean-based renewable energy and deep-seabed minerals can contribute to sustainable development. Options for harvesting ocean-based renewable energy and the needs for ocean-based minerals are reviewed with a focus on scenarios where anthropogenic global warming in the 21st century is limited to 1.5–2°C – in other words, where decarbonisation of the global economy has to happen fast. The deep-seabed minerals case is discussed in some detail in order to spell out the steps that would be required if deep-seabed mining were to be developed, and to weigh up the benefits, risks and alternatives.

The introductory section briefly explains the basic characteristics of ocean-based renewable energy, discusses the expected demands for minerals from ocean-based renewable energy and global energy system transformation, and ends with an introduction to deep-seabed mining. In Section 2, 1.5°C scenarios, both with and without carbon capture and storage (CCS) and negative emissions in the later part of the century, are described. In Section 3, ocean-based renewable energy options, their technological and cost status, and projections for future development are reviewed. In Section 4, deep-seabed minerals and the motivations for mining them are addressed. Section 5 focuses on sustainability, including the environmental impacts of ocean-based renewable energy and deep-seabed mining. Section 6 deals with governance issues, before moving into the opportunities for action in Section 7.

1.1 What is Ocean-Based Renewable Energy?

Ocean-based renewable energy sources (often called marine renewable energy) include offshore wind (near-surface as well as high-altitude), floating solar, marine biomass and ocean energy, which encompasses tidal range, tidal stream, wave, ocean thermal energy conversion (OTEC), current and salinity gradient. All of these are considered in this paper except marine biomass. Harvesting of naturally growing marine biomass, as well as industrial production, is ongoing in several locations, mostly motivated by demands for food, feed or pharmaceuticals. The by-products of such production may be combusted for energy purposes, and thereby reduce the need for other energy sources. However, based on current knowledge, the global long-term significance as an energy source is believed to be limited.

Offshore wind (near-surface, i.e. based on bottom-fixed or floating support structures) is presently much more developed than the others and has reached cost parity with fossil sources of electricity in recent contracts. Offshore wind is therefore dealt with separately in Section 3.1. Of the others, technology for exploiting tidal range is well developed in some locations, tidal stream is developing rapidly now, and wave energy has a long history of research but no clear technology winner. OTEC, which has potential in the tropics, requires significant investment in order to capitalise on the economy of scale. Salinity gradient, which has potential where fresh water meets saline seawater, has only seen experimental-scale testing. Ocean currents, exploiting the energy contained in large-scale thermohaline ocean circulation, has considerable potential, but has challenges relating to proximity to demand, in combination with the early stage of technology. Floating solar has so far been mostly developed in fresh water for reservoirs and dams but has clear potential for ocean scale-up. High-altitude wind can be scaled up offshore once key technology has been validated, presumably first onshore. These energy sources are further described in Section 3.2.

1.2 Renewable Energy and the Demand for Metals

Key elements of a low-carbon emissions future are the accelerated use of wind power, solar energy and the electrification of the energy sector, including use of electric vehicles.

Construction of offshore wind turbines requires significant amounts of conventional materials, in particular steel. However, rare earth elements (REEs) are also needed, in particular in the construction of the direct-drive permanent magnet generators that are currently preferred. For offshore wind, it is the use of REEs in the generators that appears to be the biggest potential challenge when it comes to supply of minerals. Wilburn (2011) states that each megawatt (MW) of installed capacity needs 42 kilograms (kg) of neodymium and 3,000 kg of copper.

Stegen (2015) provides an overview of REEs and permanent magnets in connection with renewable energies. Stegen notes that present wind turbines using direct-drive permanent magnet generators are favoured over conventional heavy gearboxes since the latter require more steel and concrete. The reduced weight of permanent magnet generators and increased reliability and efficiency is particularly attractive offshore. Permanent magnets typically use neodymium, dysprosium, praseodymium and terbium. For turbines above 10 MW, which are now beginning to be applied offshore, superconducting generators may be preferred over permanent magnet generators, again because of costs and weight. However, greater deployment of superconductors will increase demand for yttrium, another element typically considered together with REEs (included in REEs or expressed as REY, rare earths and yttrium).

Pavel et al. (2017) discuss substitution strategies for REEs in wind turbines, noting the variety of designs that are being considered and the potential for material efficiency. They do not consider the deep seabed as a source, but still conclude that the wind industry is well prepared for potential shortages in REEs in both the short and medium term. For the longer term, superconductors are being considered. A considerable amount of REEs, including yttrium at high concentration in seafloor mud, was recently documented in the Japanese exclusive economic zone (EEZ) (Takaya et al. 2018).

Goodenough et al. (2018) note that very little mineral-processing research on REEs took place outside of China during the 1980s, 1990s and 2000s, but this research has been accelerating in recent years after China introduced export restrictions. It remains a challenge to develop the value chain from mining through processing and separation to end-uses. Goodenough et al. (2018) also note that, within 10 years, new technological developments are likely to drive substantial changes in both processing of, and demand for, REEs.

Moving to the further requirements from the energy sector as a whole, a recent IPCC report indicates that 70–85 percent of all electricity must be from renewable sources by 2050 to limit global warming to 1.5°C (IPCC 2018). Implementation of these renewable technologies will rapidly increase demand for many metals, including lithium, cobalt, copper, silver, zinc, nickel and manganese, and REEs and others (Arrobas et al. 2017; Sovacool et al. 2020). The projected metal demand varies greatly for the different energy sources under scenarios involving different amounts of renewable energy at different rates over the next 30 years (Arrobas et al. 2017; Dominish et al. 2019). For example, the demand for metals, such as aluminium, cobalt, nickel, lithium, iron and lead, coming from solar and wind will be twice as high under a 2°C warming scenario than under a 4°C scenario, but the demand from batteries would be more than 10 times higher. Offshore wind energy generation requires more metals than onshore wind due to the use of magnets; differing solar technologies use different amounts of silver, zinc and indium; and for cars, fully electric, hybrid and hydrogen fuel cells differ in their demands for lithium, lead and platinum (Arrobas et al. 2017). There is general agreement that electric car batteries will be the greatest source of increased metal demand.

Deetman et al. (2018) study scenarios for copper, tantalum, neodymium, cobalt and lithium demand up to 2050 and find that in a stringent climate policy scenario (1.5–2°C), the demand from cars rises more rapidly than that from appliances and energy technologies. In particular, this applies to cobalt and lithium. Boubault and Maizi (2019) extend the well-known TIMES energy system model tool for electricity generation to metal requirements for the power sector using a life cycle approach. Cost-optimal deployments of different electricity generation sources in a 2°C scenario to 2100 provide corresponding metal needs. In comparison with the baseline scenario, cobalt and aluminium are among those that increase the most.

Limiting the global average temperature rise to 1.5°C using 100 percent renewable energy is projected to increase demand in 2050 to more than four times the existing reserves for cobalt, almost three times the reserves for lithium, and slightly more than the existing reserves for nickel (Dominish et al. 2019). Cobalt and nickel, whose demand could exceed current production rates by 2030, are driving the rapidly rising interest in mineral mining on the deep seafloor. Cobalt in particular has highly concentrated production and reserves (especially in the Democratic Republic of the Congo) and thus poses the greatest supply risk; cobalt contamination also causes severe health impacts for miners and surrounding communities (Dominish et al. 2019).

Attempts to compare various modelling studies of energy systems and metal needs (Boubault and Maizi 2019) are complicated by the different choices made in terms of scenarios, assumptions and the degree of resolution in the metals covered by each model. In conclusion, there are large uncertainties about metal needs over time horizons of longer than a decade. A hot topic for offshore wind is REEs for permanent magnets. However, this need is expected to diminish as the industry transitions to even larger turbines with superconductors. The energy sector as a whole has a wider set of mineral needs but also larger flexibility to switch between alternative technological solutions. Trends and demands for the coming decade can be estimated, but it is very difficult to deduce a minimal set of required metals to enable energy system transition to a 1.5–2°C global temperature rise across the timeframe of 2050 to 2100. Integrated energy system models that include metal needs in a life cycle approach (Hertwich et al. 2015) are useful tools but rely on bottom-up estimates of costs of energy sources and energy conversion processes. The search for alternative technologies is intense, driven by actual costs as well as projections of future costs.

Cobalt and nickel, whose demand could exceed current production rates by 2030, are driving the rapidly rising interest in mineral mining on the deep seafloor.

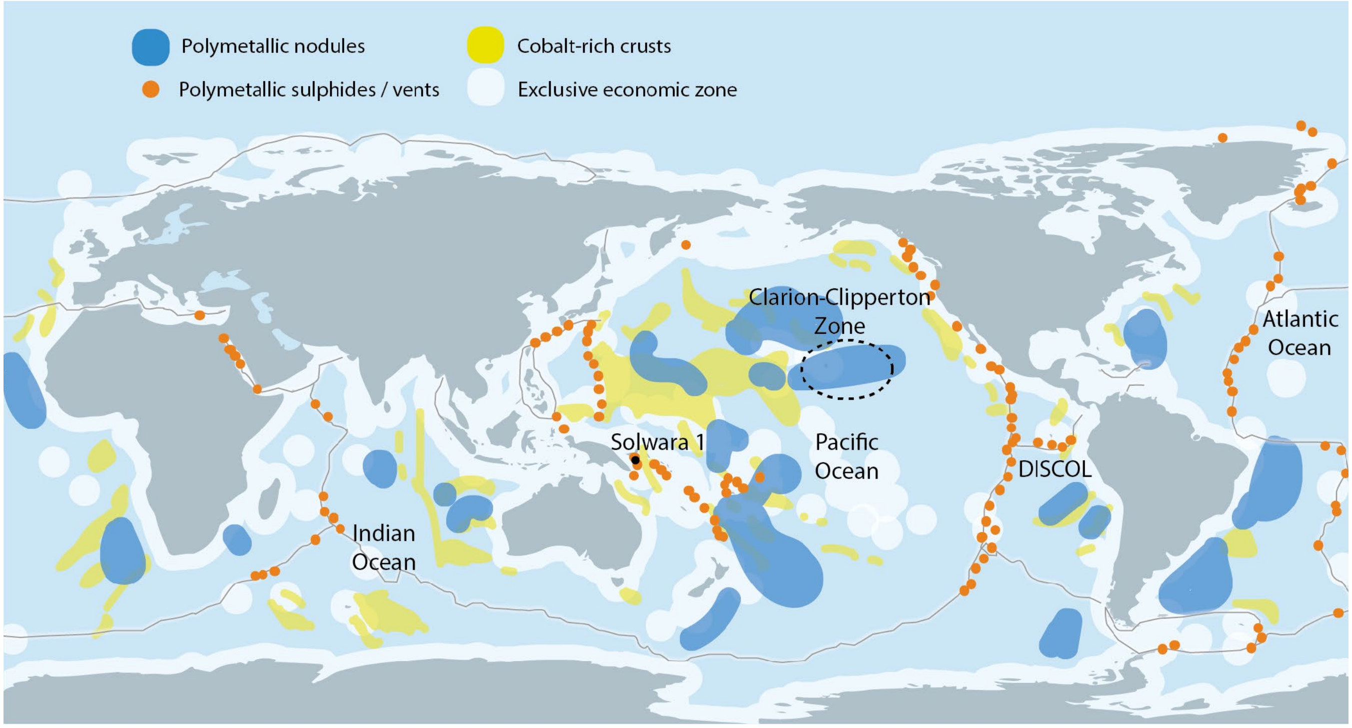
The increase in metal mining needed to address climate change (and the transition to renewable energy) is drawing increasing attention (Arrobas et al. 2017) and has led to a proposal that nationally determined contributions under the Paris Agreement identify critical minerals for energy security options and identify sourcing challenges (Sovacool et al. 2020). Population growth and rising consumption associated with an increased standard of living globally creates additional increased demand for metals, independent of climate change (Graedel et al. 2015; Ali et al. 2017).

1.3 Minerals on the Deep Seafloor

Metals and minerals of interest on the deep seafloor include primarily copper, cobalt, nickel, zinc, silver, gold, lithium, REEs and phosphorites (see Section 4). Many of the metals are found in polymetallic nodules on abyssal plains (covering 38 million square kilometres (km^2) at water depths of 3,000–6,500 metres (m)), on cobalt-rich crusts which occur on seamounts (covering over 1.7 million km^2 at 800–2,500 m), and in polymetallic sulphides near mid-ocean ridges and in back-arc basins (covering 3.2 million km^2) (Figure 1) (Levin et al. 2016; Miller et al. 2018; Hein and Koschinsky 2014; Petersen et al. 2016). Phosphorites, of interest for fertiliser, occur as modern deposits or fossil beds along productive continental margins (slopes) (Baturin 1982). These resources occur both within and beyond national jurisdictions (Figure 1), with the exception of phosphorites, which are targeted only within EEZs. However, while 42 percent of areas with massive sulphides and 54 percent of areas with cobalt-rich crusts fall within EEZs, only 19 percent of known polymetallic nodules are within EEZs. More information on their formation and distribution is provided in Figure 1 and by Petersen et al. (2016) and Jones et al. (2017).

Mining of the deep seabed (below 200 m) has not yet taken place. Extraction of minerals from the seafloor is planned to involve either modified dredging (for nodules) or cutting (for massive sulphides and crusts), and transport of the material as a slurry in a riser or basket system to a surface support vessel (Figure 2). The mineral-bearing material will be processed on board a ship (cleaning and dewatering – with the waste water and sediment being returned to the ocean) and transferred to a barge for transport to shore where it will be further processed to extract the target metals (Collins et al. 2013; Brown 2018) (Figure 2). Relative to mining on land, there is less overburden to remove and no permanent mining infrastructure required for deep-seabed mining (Lodge and Verlaan 2018). However, there is likely to be solid waste material left after metal extraction, and disposal mechanisms for this waste could be comparable with those used for terrestrial mine tailings, some of which are introduced into the deep ocean via pipe (Ramirez-Llodra et al. 2015; Vare et al. 2018).

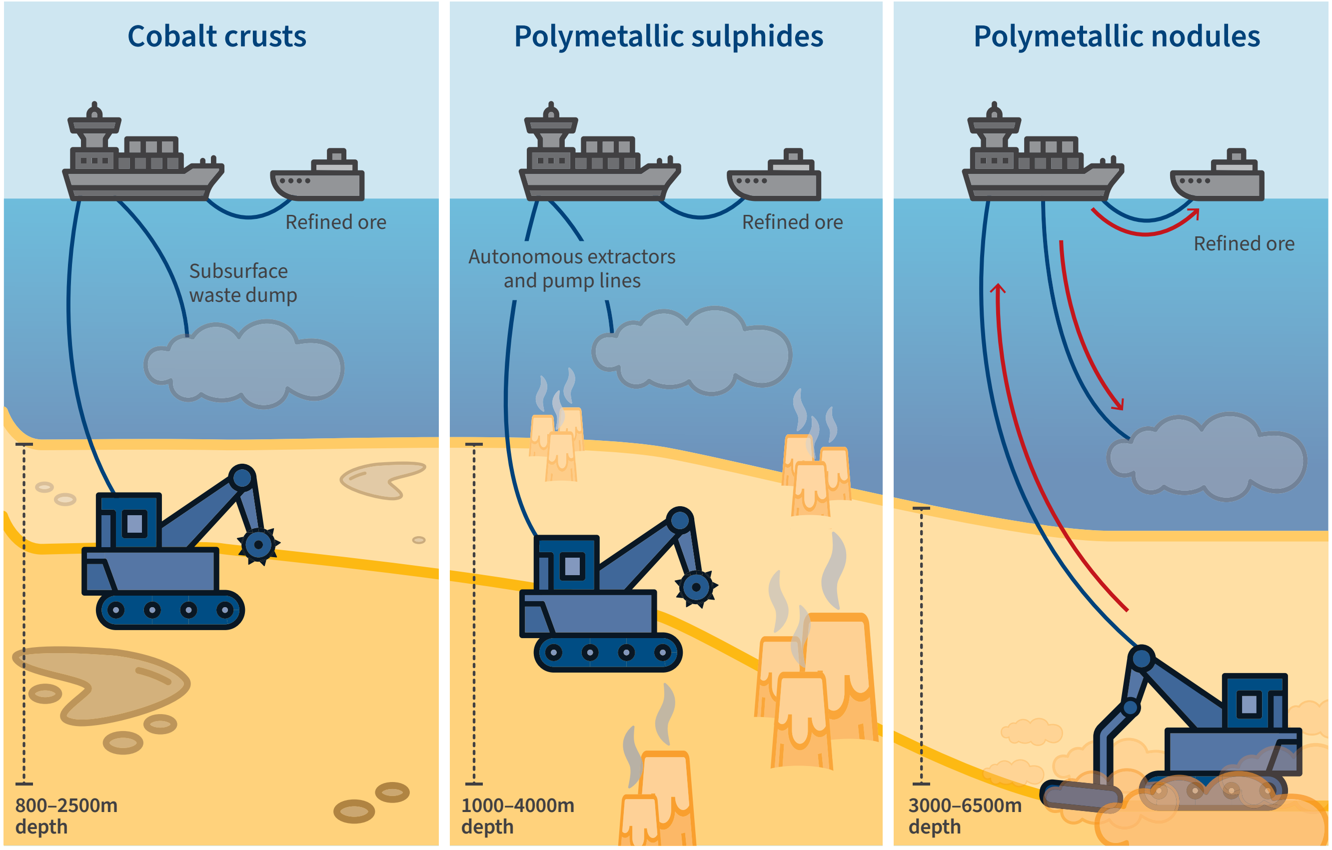
Figure 1. Distribution of Polymetallic Nodules, Polymetallic Sulphides and Cobalt-Rich Crust Resources in the Deep Sea



Note: The white area around Antarctica is not an exclusive economic zone but rather governed by an international commission.

Source: Miller et al. 2018; Hein et al. 2013.

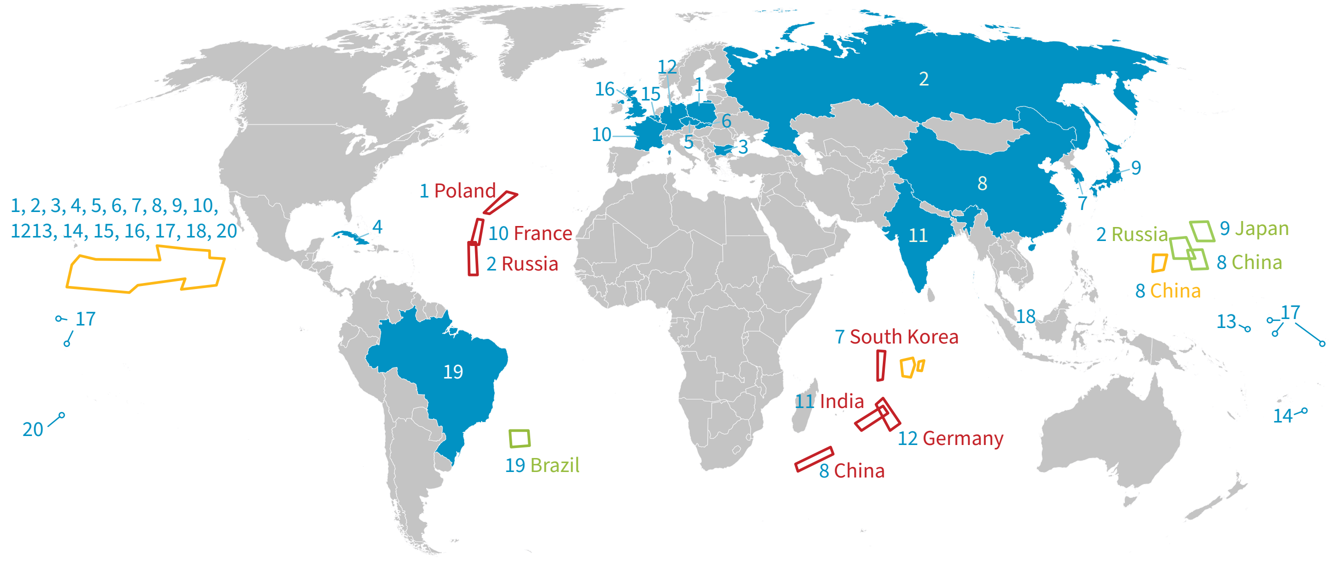
Figure 2. Schematic Illustrating Deep-Seabed Mining for the Three Resources



Source: Modified from Fleming et al. 2019.

The current governance structure under the UN Convention on the Law of the Sea (UNCLOS; UN 1982) gives the International Seabed Authority (ISA) regulatory responsibility for both the minerals on the seafloor in international waters (the Area) *and* the protection of the marine environment from the effects of mining in the Area. The minerals of the Area are designated as "the common heritage of [hu]mankind" (UN 1982). Since 2001, 30 *exploration* contracts for deep-seabed minerals in the Area have been approved. These were granted initially for 15 years each, and those contracts which have expired have been renewed for a 5-year extension. Seventeen of the ISA contracts are for polymetallic nodules in the Clarion-Clipperton Zone (CCZ) and two are for nodules elsewhere; others are for crusts and seafloor massive sulphides, and occur on West Pacific Seamounts (in the Prime Crust Zone), the Mid-Atlantic and Southwest Indian Ridges, the Rio Grande Rise off Brazil,[1] and in the Central Indian Ocean (Figure 3). The exploration contract areas are granted to individual states, consortia of states, state-owned enterprises or companies working with states. At the time of writing this paper, the contracts cover more than 1.3 million km^2 (or 500,000 sq miles), equivalent to about 0.3 percent of the abyssal seabed (Petersen et al. 2016). No contracts for mineral *exploitation* in the Area exist. Regulations for the exploitation of seabed minerals and for associated environmental management are currently under development by the ISA.

Figure 3. International Exploration Contracts from the ISA



🟦 Countries with ISA exploration contract areas

☐ Polymetallic sulphide ISA exploration contract areas

☐ Cobalt-rich ferromanganese crust ISA exploration contract areas

☐ Polymetallic nodule ISA exploration contract areas

COUNTRY

1	Poland	(2)	6	Slovakia	(1)	11	India	(2)	16	UK	(2)
2	Russia	(4)	7	South Korea	(3)	12	Germany	(2)	17	Kiribati	(1)
3	Bulgaria	(1)	8	China	(5)	13	Nauru	(1)	18	Singapore	(1)
4	Cuba	(1)	9	Japan	(2)	14	Tonga	(1)	19	Brazil	(1)
5	Czech Republic	(1)	10	France	(2)	15	Belgium	(1)	20	Cook Islands	(1)

Note: Countries with international exploration contracts from the ISA are shown in blue, the number of contracts per country (as of 2019 is depicted in the legend), and the general location of contracts in the Area is shown schematically for different resources.

Source: Authors.

Roughly 70 percent of the 154 coastal states have significant deep ocean within their EEZs; many of these contain mineral resources. Licences for deep-seabed mineral exploitation within national jurisdictions have been granted by Papua New Guinea (to Nautilus Minerals) and by Sudan/Saudi Arabia (Diamond Fields International) (Miller et al. 2018). Additionally, New Zealand, the Kingdom of Tonga, Japan, Fiji, the Solomon Islands and Vanuatu have permitted research to assess the mining viability or issued exploration permits for national seafloor polymetallic sulphides, although some of them have lapsed. Exploration for polymetallic nodules in the Cook Islands (Cook Islands News 2018), cobalt crusts and polymetallic nodules in Brazil (Marques and Araújo 2019), and phosphorites in Namibia and South Africa (NMP n.d.; Levin et al. 2016) are also under consideration.

Sand is another resource mined in the ocean. Demand for sand, used in building and transportation, has increased 23-fold from 1900 to 2010, and is now seen as a scarce resource, the extraction of which can cause environmental degradation, health risks and social disruption (Torres et al. 2017). Sand occurs in shallow marine waters, is not closely tied to energy industries and is not a mineral per se, so will not be considered further here.

2. Transition to a Sustainable Global Energy System – 1.5°C Scenarios

2.1 Characteristics of 1.5°C Scenarios

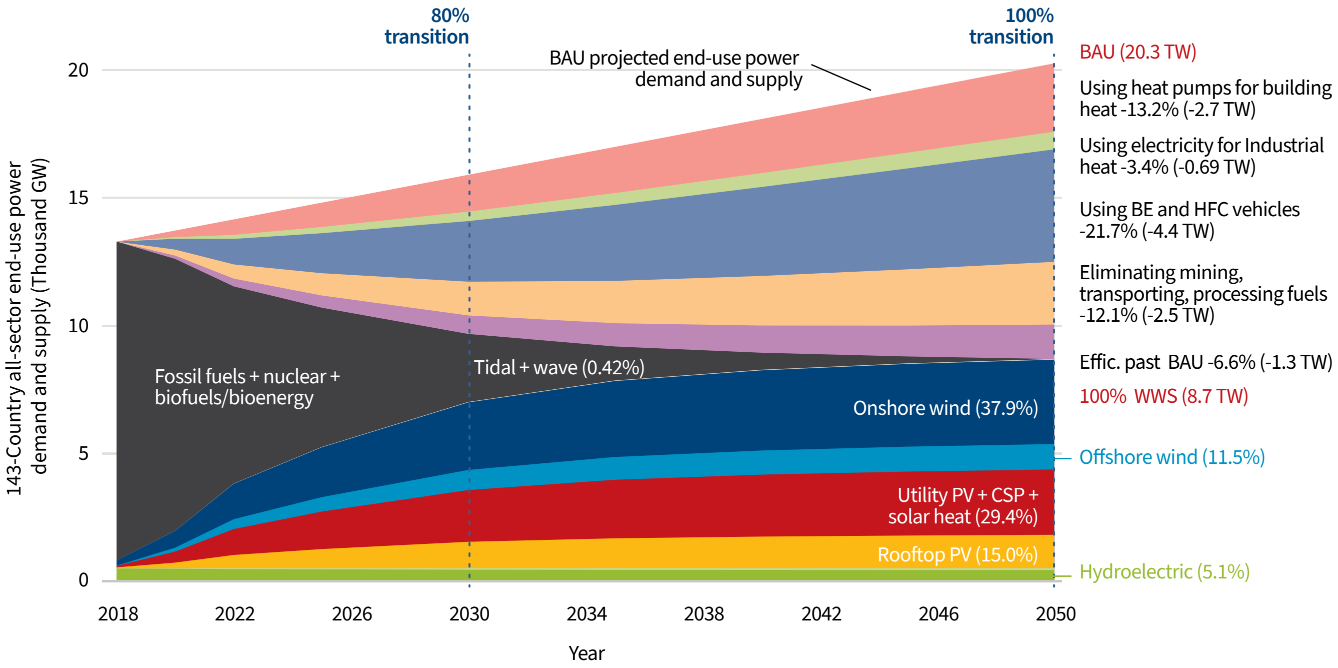
A recent special report from the Intergovernmental Panel on Climate Change (IPCC 2018) describes two main pathways to a 1.5°C global average temperature rise by 2100. In the first pathway, global warming stabilises and stays at or below 1.5°C. The second pathway sees some overshoot around mid-century before returning to a 1.5°C rise. Scenarios with long and large overshoot typically rely heavily on technologies for removing CO_2 from the atmosphere. Such negative emission scenarios are treated in Section 2.2, but it should be noted that related technologies have not yet been deployed at scale and it remains to be seen if they will be applicable and cost-competitive. For example, Reid et al. (2019) raise a series of issues with bioenergy and argue against a path dependency and lock-in that would be implicated by substituting bioenergy for fossil fuel in scenarios involving bioenergy with carbon capture and storage (BECCS). Scenarios that do stay continuously below a rise of 1.5°C typically require more rapid and larger deployment of renewable energy, as well as stronger energy efficiency and demand-side measures. Such scenarios are characterised by electrification of the global energy system and the stabilisation in or even reduction of global final energy use, despite delivering modern and sufficient energy to a growing world population (IPCC 2018). They are therefore low energy demand (LED) scenarios compared with fossil-based business-as-usual scenarios even if they deliver the same energy services.

IPCC LED scenarios (IPCC 2018) typically see a reduction in final energy use of 15 percent in 2030 and 30 percent in 2050, compared with 2010. Renewables deliver approximately 60 percent of electricity in 2030 and 80 percent in 2050. This translates to an increase of more than 400 percent in non-biomass renewables from 2010 to 2030 and more than 800 percent from 2010 to 2050 (IPCC 2018). IPCC LED scenarios (IPCC 2018) with no overshoot show 10–15 percent reduction in the global use of biomass renewables for energy, and employ a limited amount of afforestation but use no other carbon dioxide removal (CDR) technologies.

Jacobson and colleagues in a series of publications (most recently Jacobson et al. 2017, 2018, 2019) construct scenarios requiring 100 percent of global energy to come from wind, water (including ocean energy, hydropower and geothermal) and solar energy by 2050 (Figure 4).

Jacobson et al. (2017) provide detailed specifications of their modelled contributions from different energy sources and grid components, such as batteries, heat and cold storage and heat pumps. Jacobson et al. (2018) confirm that the energy systems modelled provide stable energy services, despite relying heavily on variable wind and solar. While the scenarios by Jacobson et al. (2017, 2018) have previously been considered extreme and have been criticised (Clack et al. 2017), other recent studies, notably Grubler et al. (2018) with a different modelling

Figure 4. Development of Wind, Solar and Other Energy Sources in a Low Energy Demand Transition to 100 Percent Wind, Water and Solar



Note: An earlier study (Jacobson et al. 2017) gave less drastic reductions in final energy use to 11.8 TW in 2050, of which 13.6% or 1.6 TW was offshore wind.

Source: Jacobson et al. 2019.

approach, achieve even larger reduction in global final energy demand in 2050, based on improved service efficiencies and demand-side transformation. Beneficial effects on other UN Sustainable Development Goals (SDGs) include better health via reduced pollution (SDG 3), reduced bioenergy and larger forest areas (SDG 15) and reduced ocean acidification (SDG 14). Environmental impacts are discussed in Section 5. Grubler et al. (2018) allow for some bioenergy, fossil fuel and nuclear energy. Their requirements for solar and wind energy are therefore lower than those of Jacobson et al. (2017, 2018, 2019), even though they deal with all countries and regions of the world.

Solar photovoltaic (PV) and wind energy are particularly implicated in use of certain minerals (Section 1.2). The installed capacities (i.e. nameplate capacities or full-load outputs) of solar PV and wind in 2050 from Jacobson et al. (2018) of approximately 30 and 17 terawatts (TW), respectively, are assumed to be upper bounds on the possible demands for installed solar PV and wind in a sustainable energy future. This includes onshore and offshore installations. The installed offshore wind capacity is estimated at about 4 TW. Note that these installed capacities are 2.5 to 6 times larger than the average utilised capacities in Figure 4, reflecting a varying capacity factor (ratio between the energy delivered over a time period and the energy that would have been delivered if the turbine was running at maximum, i.e. installed capacity) due to variable winds and sun. In comparison, Teske et al. (2015), in their Advanced Energy [R]evolution scenario (ADV ER) arrive at approximately 9 TW installed capacity for solar PV and 8 TW installed capacity for wind in 2050. Teske et al. (2016) claim that this scenario is ambitious and may not guarantee to keep the global temperature rise below 1.5°C, but may be the maximum transformation that is realistically achievable.

IEA (2019a) presents two scenarios, a stated policy scenario (SPS) and a sustainable development scenario (SDS). In the two cases, the global installed capacity of offshore wind in 2040 is estimated to be 340 and 560 gigawatts (GW), respectively. With a significant improvement in the capacity factors over the coming 20 years, the annual energy contribution from offshore wind in 2040 is estimated to be 1,400 and 2,350 terawatt-hours (TWh) per year for the two scenarios respectively.

2.2 Negative Emissions and Carbon Capture and Storage

As mentioned in Section 2.1, many of the scenarios in the IPCC report (IPCC 2018) rely on negative emissions in the later part of the present century in order to repair the overshoot and get back to a global temperature rise of less than 1.5°C. Overshoot would imply potentially damaging impacts on the ocean and its ecosystems. Geoengineering through solar radiation management would, if successful, limit global warming, but to avoid ocean acidification atmospheric CO_2 needs to be limited too. Several CDR technologies which would capture CO_2 from the air have been proposed. However, IPCC (2018) states, with high confidence, that: "CDR deployment of several hundreds of $GtCO_2$ is subject to multiple feasibility and sustainability constraints." Afforestation and BECCS are the options most widely studied.

BECCS consists of harvesting biological material, burning it for energy purposes in an energy plant (power or combined heat and power) and adding facilities for CCS. A few BECCS pilot plants exist (IPCC 2018). More research experience is available on CCS from fossil fuel power plants and some from transport and storage of CO_2 for other purposes or from other sources (IPCC 2005). Storage of CO_2 is taking place also in the subseabed, notably for more than two decades on the Norwegian continental shelf (Furre et al. 2017). While CCS research and application has been promoted in several countries over the past decades, questions still remain on the practicality and cost-competitiveness. In Europe, developments in new renewable energy, notably wind for production of electricity, mean that it is steadily becoming cheaper and is already cost-competitive with fossil fuel without CCS.

With CCS, there is the added investment in capture facility, transport and storage, and the related energy penalty (increase in energy and fuel use for running the CCS process) which tends to sit around 20–25 percent (IPCC 2005). Research and development continues, however. Active projects in Norway are directed at CO_2 from other industries like cement and incineration of waste. There are also studies on the separation of CO_2 from natural gas and on delivering hydrogen for energy purposes. Related efforts may lead to an increase in the interest in storing CO_2 offshore in the subseabed and development of technology that could be transferred to BECCS. However, the energy penalty (use of more biological material to provide energy to run the process) and investments in facilities cannot be avoided. In view of the diminishing costs of electricity based on renewables, competition on cost appears to be difficult. Furthermore, the carbon capture process is never 100 percent effective so some CO_2 release has to be accepted. In a sustainable energy future with very tight restrictions on CO_2 emissions, it appears that non-biomass renewables – wind, water, solar and in some locations geothermal – have to replace the lion's share of the energy services presently served by fossil fuel.

Overshoot in itself may lead to irreversible damage to the climate system. No CDR technologies have yet been scaled up. Costs and environmental implications are uncertain. The modelling approaches used in scenario calculations assume learning curves and discount rates that tend to favour shifting of costs to the distant future. Ethical and hard science aspects of these questions are interlinked and hotly debated in the popular media as well as scientific forums (Anderson and Peters 2016). It appears that relying on negative emission technologies in the future is optimistic and could be deemed irresponsible. In the context of this report, the 1.5°C scenarios discussed in Section 2.1. are those considered to be representative of a sustainable future.

3. Ocean-Based Renewable Energy

The status and costs of the various technologies – in other words, their technical and economic potential – are addressed in this section, while the environmental impacts and wider sustainability issues are discussed in Section 5. Since offshore wind is considerably further advanced in its implementation than the other technologies, offshore wind is treated separately.

3.1 Offshore Wind

Technical potential

When considering the available wind energy resources across the global ocean, a geophysical potential may be estimated from knowledge of the global wind field. This global potential remains theoretical, however, and of little practical interest. For example, it is considered unrealistic to deploy wind turbines in the Southern Ocean, not only because of the difficult operating conditions, but also because of the distance to users of the electricity. The cost and even the energy expenditure associated with the manufacturing and laying of electric cables, the deployment of floating turbines at great ocean depths and the loss in transmission would prohibit any such project. A more interesting consideration is the technical potential (Figure 5). The technical potential takes into account technical limitations and excludes inaccessible resources. What these technical limitations are will depend on technology developments and trends. Assessments therefore vary depending on the assumptions made.

Bosch et al. (2018) estimate the global and regional offshore wind power potential. They consider three different water depth ranges (0–40 m, 40–60 m and 60–1,000 m) within the EEZ of each country. Various exclusion zones are accounted for. They find that the worldwide technical potential for power production from offshore wind amounts to about 330,000 TWh/year as compared with the world's electric energy production in 2018 of about 26,700 TWh/year (IEA 2018) and the modelled offshore wind contribution in 2050 in Figure 4 which corresponds to 9,000 TWh/year. Bosch et al. (2018) also review resource estimates made by others. The global total estimates range from 157,000 TWh/year to 631,000 TWh/year, depending upon the assumptions made.

Figure 5. Geophysical, Technical, Economic and Social/Political Potential of Wind or other Energy Resources across the Global Ocean

Source: Adapted from Hoegh-Guldberg et al. 2019.

A similar study performed by Eurek et al. (2017) estimated the global potential for offshore wind deployment while including various exclusion zones related to water depth, distance to shore, protected areas and sea ice. They ended up with an estimated potential of 315,000 TWh/year using a capacity factor of 0.285. IEA (2019b) has also made estimates on the technical potential for offshore wind, using somewhat different criteria for exclusion zones. The results are summarised in Table 1. The total global technical resources are found to be about 420,000 TWh/year.

The above estimates for the global potential for offshore wind are 6 to 23 times the present global electricity consumption. Most of the estimates also exceed the present global total primary energy consumption (14,314 million tonnes of oil equivalent (Mtoe) = 166,470 TWh in 2018; IEA (2019b)). The above estimates do not consider limitations due to costs and make some assumptions on technological elements. The economic potential depends on the costs (see next section) of these technologies in relation to competing technologies. The economic potential will be smaller than the technical potential. Figure 4 shows one example of an estimate of economic potential given certain assumptions. Social/political and environmental considerations discussed in Section 5 may limit the potential further (Figure 5).

Status of technology and costs

While there is abundant technical potential for offshore wind energy generation, the economics of deploying energy offshore limit the capacity that might be installed. In future low-carbon scenarios, technologies with similar GHG mitigation potential compete. A conservative approach based on a range of earlier published scenarios was chosen by Hoegh-Guldberg et al. (2019), resulting in an estimate of up to 3,500 TWh/year in 2050 from offshore wind. The 1.6 TW yearly average offshore wind power from Jacobson et al. (2017), corresponding to approximately 14,000 TWh/year, and the 1.0 TW figure (Jacobson et al. 2019) corresponding to approximately 9,000 TWh/year (Figure 4), are estimates of the economic potential for offshore wind in a future low-emission scenario. While the numbers cited in Section 3.1 do take into account areas that would be unavailable for offshore

Table 1. Offshore Wind Potential (TWh/year)

	SHALLOW WATER (DEPTH < 60 M)		DEEPER WATER (DEPTH 60 M – 2,000 M)		TOTAL POTENTIAL
	Near shore	Far shore	Near shore	Far shore	
North America	9,907	13,238	22,819	58,937	104,901
Central and South America	3,847	4,438	6,439	37,144	51,869
Europe	2,629	2,390	14,817	52,009	71,845
Africa	1,123	572	7,699	17,107	26,502
Middle East	478	673	600	1,791	3,543
Eurasia	9,382	17,402	9,943	48,735	85,462
Asia Pacific	8,508	12,451	14,440	41,357	76,757
WORLD	**35,875**	**51,166**	**76,757**	**257,081**	**420,878**

Note: "Near shore" denotes sites less than 60 km from the shore and "far shore" denotes sites at a distance of 60–300 km from the shore.

Source: IEA 2019b.

wind, they are still theoretical and not likely to ever be achieved. However, theoretical estimates are at least an order of magnitude larger than those of Jacobson et al. (2017), indicating that there are no resource constraints on offshore wind installations.

By the end of 2018, the total worldwide installed capacity of wind energy amounted to 564 GW, of which only 23 GW were offshore (IRENA 2019c). The yearly electrical power production from offshore wind amounted to about 77 TWh (IEA 2018). For offshore wind turbines, bottom-fixed turbines in shallow water depth (< 40 m water depth) dominate. Deep-water, floating support structures are used in one wind farm only, a 0.03 GW wind farm on the east coast of Scotland. This wind farm was installed in 2017. Europe presently has the majority of the offshore wind installations, with an installed capacity of 18.5 GW, while Asia has 4.6 GW. It has been anticipated that China will have more installed capacity than Europe by 2021 (Backwell 2019). However, according to IEA (2019a) estimates, China will overtake Europe in the early 2030s. It is expected that North America will be number three after Asia and Europe.

As the wind conditions in general are better offshore – the wind is more stable – the utilisation of the installed generator capacity is generally higher than onshore. In Europe, the capacity factor for offshore wind farms commissioned in 2018 was 43 percent, increasing from 38 percent in 2010. Onshore, the comparable global averages are 34 percent and 27 percent, respectively (IRENA 2018a, 2018b). IEA (2019b) expects that, by 2040, the capacity factors for good offshore sites will move towards 60 percent, while the worldwide average will be close to 50 percent.

In Europe, the capacity factor for offshore wind farms commissioned in 2018 was 43 percent, increasing from 38 percent in 2010.

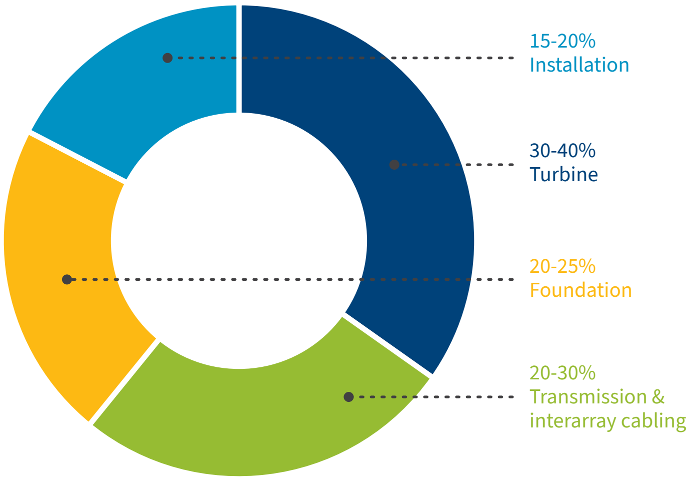
Over the last decade, the cost per MW of installed power has been reduced and the capacity factor for new installations has increased. The operation and maintenance costs per produced megawatt-hour (MWh) are also expected to decline as the turbines are designed to be more robust and fit for the offshore environment. All three factors contribute to a reduced levelised cost of electricity (LCOE; the ratio between the discounted costs over the lifetime of an electricity-generating plant and the sum of actual energy amounts delivered). However, the single most important factor to reduce LCOE is the cost of capital or the discount rate. Reduced project uncertainties and favourable financing terms will contribute to a reduced LCOE. IEA (2019a) shows that using an average discount rate of 4 percent rather than 8 percent may reduce the LCOE for offshore wind projects from US$140/MWh to $100/MWh. As the number of shallow-water, bottom-fixed support structures, mainly monopiles, has increased, the cost reduction due to mass production has been significant. Bottom-fixed offshore wind turbines are thus considered mature and have reached commercial scale. The costs have reached parity with fossil sources of electricity in recent contracts, down towards $50/MWh, without transmission costs. The Dogger Bank Creyke Beck A wind farm won a UK government auction for renewable power in September 2019, with a strike price of $51/MWh (IEA 2019a; Dogger Bank Wind Farms 2019).

IRENA (2019b) shows similar LCOE figures. Stehly et al. (2018) found that the 2017 average in the United States was $124/MWh for bottom-fixed and $146/MWh for floating. In Europe, the LCOE for projects commissioned in the period 2010–15 shows very moderate decline. However, after that, a significant drop in LCOE for new projects is observed. In 2012, the European Union set an ambitious aim of LCOE of $110/MWh in 2020. This aim has already been achieved for several projects. For projects commissioned in 2018, the European average was $134/MWh and for projects in China $105/MWh (IRENA 2019b). However, contracts with record low costs have been signed in the Netherlands ($55/MWh to $73/MWh) and Denmark ($65/MWh) for a near-shore project, excluding grid connection costs. No data are available for floating systems as only one small wind farm has been realised. Ørsted (2019) indicates a cost reduction in offshore wind of 18 percent per doubling of capacity.

Bottom-fixed support structures are designed for site-specific conditions. Worldwide, there are limited large, shallow-water areas suitable for wind-power development. Bosch et al. (2018) estimate the potential wind power production from shallow-water areas (< 40 m) to be less than one-third of the potential production from the deeper areas (60–1,000 m water depth). IEA (2019a) estimates the shallow-water areas (< 60 m water depths) to be about 20 percent of the total areas available (see Table 1). Deep water requires floating support structures. Such solutions are less mature than the bottom-fixed solutions and are presently more expensive than the shallow-water bottom-fixed support structures. Floating support structures are well suited for standardisation and mass production as they do not depend upon site-specific conditions at sea bottom. In a scenario with large-scale deployment of floating offshore wind turbines, it is thus expected that the LCOE will be comparable with that of bottom-fixed support structures.

The increased size of turbines and wind farms, as well as the learning rate of the offshore wind industry, have all contributed to reduced LCOE. However, moving into deeper water and farther from shore has partly outweighed the cost reductions. In Figure 6, an approximate split of the capital costs of offshore wind turbines completed in 2018 is given.

Figure 6. Approximate Split of the Capital Costs of Offshore Wind Turbines Completed in 2018



Source: IEA 2019b; IEA analysis based on IRENA 2019a, IJGlobal 2019 and BNEF 2019.

Future development scenarios

According to IRENA (2019c), the rate of wind energy deployment (2017–18) is 54 GW/year globally. To achieve the required energy transformation (increased electrification, reduced emissions) a significant speed-up in wind energy installations is required. IRENA (2019c) indicate 200 GW/year in 2030, increasing to 240 GW/year in 2050 worldwide. How much of this growth can be taken offshore is uncertain. However, the resources are not a limitation.

According to IEA (2017), offshore wind generation has grown five-fold over the period 2010–15 and is expected to double over the period 2015–20. IEA (2019b) in their SDS has a compound annual growth rate (CAGR) of 16.9 percent for the global offshore wind market in the period 2018–40, while Bloomberg (2019) forecasts growth at a CAGR of over 18 percent over the period 2019–23. Between 2020 and 2025, offshore wind generation needs to triple to be fully on track with the 2°C target. By 2025 about 2,785 TWh/year of electricity should be produced from offshore wind to be in line with the SDS. The corresponding figure for 2040 is 6,950 TWh/year. It is indicated that in 2040 the electric energy produced from other ocean-based renewable energy sources could contribute more than 1,200 TWh/year.

Assuming that it comes from offshore wind alone, this requires an installed capacity of about 326 GW of offshore wind in 2040. To achieve this, 15 GW of offshore wind has to be installed every year for 20 years. Using the Jacobsen et al. (2017) figures, the contribution from offshore wind is larger. To achieve 3,800 GW of installed offshore wind capacity (corresponding to 1,600 GW average power) in 2050, an installation rate of 127 GW/year is required over 30 years. In other words, the 2 scenarios require substantially different installation rates, almost 10 times greater for the Jacobsen et al. (2017) scenario. This difference is mainly due to differences in the assumptions regarding the future contribution of offshore wind to the electricity supply. Both scenarios require an accelerated development of new ocean areas for offshore wind. Development of deep-water areas with floating wind turbines can make a significant contribution to achieve this goal. Even further acceleration would be needed to ensure only a global temperature rise of 1.5°C. It is to be noted that the European Commission (2018) presents a strategic roadmap which would lead to an even larger contribution of offshore wind in their region.

3.2 Other Ocean-Based Renewable Energy

Technical potential

There are several other renewable energy technologies which exploit the available resources of the offshore environment. The technologies that harness energy directly from the ocean itself (i.e. water-based technologies) have particular advantages, such as the power density of moving water (much larger than that of air), the predictability and consistency of the resource (notably tides), and the fact that the resource can typically deliver at times when other renewable energy resources do not. Floating solar photovoltaics and high-altitude wind have different characteristics. The range of other ocean-based renewable energy technologies, summarised in Table 2, include:

- **Tidal range energy:** Tidal range energy technologies include tidal barge energy systems and tidal lagoon energy systems. Tidal range systems represent the bulk of existing installed ocean-based renewable energy, having been in operation for decades. Tidal range technologies act effectively as low-head hydropower systems – in their simplest form, water is constrained on the high tide (by barrage or lagoon) and powers a water turbine on release. The estimated global annual geophysical tidal range potential is around 25,880 TWh (constrained to regions with water depth < 30 m, and a reasonable threshold for energy output). The distribution of this resource, however, is confined to just 0.22 percent of the world ocean. Taking into account the impracticality of ice-covered regions, the global annual potential energy from tidal range technologies is approximately 6,000 TWh, with 90 percent distributed across five countries (O'Neill et al. 2018).
- **Tidal stream energy:** With the rise and fall of tidal water elevation that occurs twice a day, tidal currents are generated. Tidal stream energy converters harvest the energy of these currents and convert it to electrical energy. Many technologies are in development, but convergence towards horizontal axis turbines has occurred. These tidal energy converters are intended to be modular, to be deployed in subsurface arrays. No reasonable estimate for the total global geophysical tidal stream potential is known, but best estimates of the total global technical tidal stream energy potential is approximately 150 TWh/year (with high uncertainty; Yan 2015).
- **Wave energy:** Wave power converts the kinetic and potential energy of the surface wind-waves of the ocean into electrical energy (or some usable commodity, such as desalinated water). Wave energy converters are designed to be deployed in arrays, similar to wind farms. Many concepts are in development, with little to no convergence in technologies. The total geophysical wave energy potential is estimated to be 32,000 TWh/year (Mørk et al. 2010), with estimates of the global technical potential ranging from 1,750 (Sims et al. 2007) to 5,550 (Krewitt et al. 2009) TWh/year.
- **Ocean thermal energy conversion (OTEC):** OTEC exploits the temperature gradient between the cold deep ocean and the warmer surface waters and converts it into electricity or other commodities, such as desalinated water, heating and cooling, or nutrient supply for other marine applications. A temperature gradient in excess of 20 degrees is required, which constrains interest in OTEC to the tropics (+/- 20 degrees latitude). An upper limit of the long-term steady-state global resource has been estimated to about 38,000 TWh/year (Nihous 2018). This is from a theoretical study assuming all OTEC facilities have optimal discharge depth and efficient generators. The technical potential is very uncertain.

> There are several other renewable energy technologies which exploit the available resources of the offshore environment.

- **Salinity gradient energy:** This technology converts energy produced from the chemical pressure that results from the difference in salt concentration between freshwater and saltwater. It can be exploited at river mouths where freshwater and saltwater meet. The technical potential for power generation has been estimated at 1,650 TWh/year (Lewis et al. 2011).
- **Ocean current energy:** These technologies operate along a similar concept to tidal stream energy, harvesting the flow of water in motion. However, the targeted ocean currents for these technologies are the deep-water currents of the thermohaline circulation (e.g., the western boundary currents such as the Kuroshio, the Gulf Stream and the East Australian current). These currents have less variability than the tidal currents but are less accessible. No estimate of technical potential has been made, but it is an area of interest for innovators.
- **Floating solar photovoltaics (PV):** Over the past three years, the installed capacity of floating solar (e.g., PV panels deployed on floating platforms) has increased at a CAGR of 168 percent, to a total capacity of 1.3 GW (World Bank Group, ESMAP and SERIS 2019). This is predominantly on inland waterways (reservoirs, canals, etc.), with the offshore market still nascent. While there are unique challenges for offshore, the available resource presents an opportunity for a growing market. No global estimate of the offshore solar resource is available. However, with the ocean representing 70 percent of the earth's surface, a very rough estimate of the geophysical potential is 70 percent of the almost 1 billion TWh (WEC 2013) of solar radiation reaching the earth's surface each year, which represents an abundant resource.
- **High-altitude wind:** Technologies exploiting wind at high altitudes are under development, notably using kites (Lunney et al. 2017). One advantage of kites compared with conventional turbines is their low demand for materials. Testing in offshore environments has recently begun from a floating platform (Norwegian Offshore Wind Cluster n.d.).

Table 2. Geophysical and Technical Potential Estimates for Ocean-Based Renewable Energy Technologies, with Technology Readiness Levels Estimated

TECHNOLOGY	GEOPHYSICAL ENERGY POTENTIAL (TWH/YEAR)	TECHNICAL POTENTIAL (TWH/YEAR)	TECHNOLOGY READINESS LEVEL
Tidal range	26,000	6,000	9
Tidal stream	–	150	8
Wave	32,000	1,750–5,550	7
OTEC	38,000	–	4
Salinity gradient	–	1,650	3
Ocean current	–	–	3
Floating PV	700,000,000	–	7*
High-altitude wind	–	–	6

Note: The technology readiness level (TRL) scale used here is based on the guidance principles for TRLs for ocean-based energy technologies, as defined by the European Commission (Appendix A in Magagna et al. 2018), ranging from TRL 1 (Basic principles observed), to TRL 9 (Actual system proven in operational environment). The actual assessment of TRLs for each technology is our own. Offshore wind would appear with TRL 9.

** Very recent developments (Oceans of Energy 2020) could justify lifting the TRL of floating PV to 8.*

Since most ocean-based renewable energy technologies are still in early phases without much deployment, few studies have been done on life cycle and material needs assessment (Uihlein 2016). It seems that the major metal requirements of these technologies would be similar to those of offshore wind. Specific requirements for floating solar PV would be similar to those for land-based PV (Arrobas et al. 2017).

Status of technology and costs

At the end of 2018, the total installed capacity of ocean-based energy technologies was 532.1 MW (IRENA 2019a), consisting mainly of tidal barrage technology at two sites. Installed capacity in 2016 was 523.3 MW, which generated 1023.3 GWh electricity (IRENA 2019a), implying a mean capacity factor of 0.23 across the sector. Estimates of the LCOE are subject to a range of parameters, including the local conditions which increase costs. The estimated LCOE for wave energy is in the range of $360–690/MWh (IRENA 2014a). Tidal stream energy LCOE is presently in the range of $275–520/MWh (IRENA 2014b), contingent upon sufficient current speeds. LCOE of OTEC is in the range of $600–940/MWh (IRENA 2014c). Learning rates for ocean-based technologies are typically assumed at around 15 percent (OES 2015), with average LCOEs for wave energy and tidal energy of $165–220/MWh by 2030 (Cascajo et al. 2019; SI Ocean 2013). Due to the capital intensity of OTEC, interest and discount rates have a high impact on LCOE estimates. Economies of scale are anticipated to bring LCOE into a range of $70–190/MWh for installed capacities exceeding 100 MW (IRENA 2014c; OES 2015).

Future development scenarios

Electricity generation from marine technologies increased an estimated 3 percent in 2018 (IEA 2019c). This rate of growth is not on track to meet the IEA SDS target for ocean-based technologies of 15 TWh/year in 2030 (IEA 2019c), which would require an annual growth rate of 24 percent to meet. The IEA SDS corresponds with an emissions target of approximately 25 GT CO_2e by 2030. By 2050, the range of projected power generation from ocean-based technologies for various scenarios (reference technology scenario/two degrees scenario/beyond two degrees scenario) is 108/536/637 TWh/year (2050 emissions 40/13/4.7 GT CO2e), corresponding to annual growth rates from present of 15/21/22 percent (IEA 2019c). The full range of projections currently being put forward for other ocean-based technologies extends up to a max of 1,943 TWh/year (Teske et al. 2010).

4. Motivations for Deep-Seabed Mining

As mentioned above (Section 1.2), there is increased global demand for metals and REEs from emerging technology industries (Table 3). For example, renewable energy production requires significant amounts of a range of metals, generally more than required for production of energy from fossil fuels (IRP 2019; Giurco et al. 2019). Many of the required metals and elements occur together – not only in large amounts but also at higher concentrations than on land – in minerals precipitated in the deep ocean. The higher concentration makes them attractive for mining operations and contributes to their resource potential (Petersen et al. 2016).

Mining on land has significant environmental and social impacts (IRP 2019). Among these, displacement of communities, contamination of rivers and groundwater from tailings, damage to communities from tailings slides, violation of land rights, mining community repression and unfavourable child labour/slavery practices (Church and Crawford 2018; Sovacool et al. 2020) have all provided the incentive to look to the ocean as a source of minerals (Batker and Schmidt 2015; IRP 2019). A large fraction of the minerals required for renewable energy technologies are produced in states with corrupt or fragile governance (Church and Crawford 2018). The social impacts of deep-seabed mining is a topic less considered, although concerns have been expressed in the Pacific region about the potential for deep-seabed mining to interfere with local traditional practices, local communities' property, food sources and lifestyle, and that deep-seabed mining could exacerbate social tensions and even lead to political instability (SPC 2012; Aguon and Hunter 2018). Also, the extraction of deep-seabed minerals from offshore sites should not be considered in isolation from the infrastructure development, and the transfer and processing of ore, which would occur on land and could also have impacts similar to mining on land (SPC 2013).

4.1 Will Deep-Seabed Mining Help Address Climate Change?

Deep-seabed mining could lead to an increased global supply of cobalt, copper, nickel, silver, lithium and REEs (Hein et al. 2013), which could make solar energy, wind turbines and electric cars more affordable and/or prevalent, potentially aiding the transition to renewable energy (Dominish et al. 2019). Mining deep-sea polymetallic nodules is calculated to release less CO_2 per kg than mining on land (Van der Voet et al. 2019). A recent report commissioned by a deep-seabed mining company involved with three exploration tenements in the CCZ suggests that extracting half of the CCZ nodules would provide the manganese, nickel, cobalt and copper needed to electrify 1 billion cars, while releasing only 30 percent of the greenhouse gases of land mining (Paulikas et al. 2020).

This conclusion has been questioned under various future global energy scenarios. Teske et al. (2016) conclude that an energy revolution, required to combat climate change, could take place without deep-seabed mining. Increasing mineral production rates in combination with more recycling (e.g., of lithium-ion batteries) and research into alternative technologies that reduce or completely eliminate the use of lithium, silver, neodymium and dysprosium – the critical elements under the greatest resource pressure – would advance

Table 3. Major Uses, Production and Potential Supply in Selected Seabed Deposits Relative to Land-Based Reserves for Metals Targeted for Deep-Seabed Mining

METAL	USES	DEEP-SEA SOURCES	ANNUAL PRODUCTION IN 2017 IN THOUSANDS OF METRIC TONS (TOP 3 LAND PRODUCERS)	ANNUAL PROJECTED DEMAND IN 2050 IN THOUSANDS OF METRIC TONS FROM LOW-CARBON ENERGY TECHNOLOGY	METAL SUPPLY IN THE CLARION-CLIPPERTON ZONE IN THOUSANDS OF METRIC TONS (% OF LAND-BASED RESERVES)#	METAL SUPPLY IN THE PRIME CRUST ZONE IN THOUSANDS OF METRIC TONS** (% OF LAND-BASED RESERVES)#	INFERRED METAL SUPPLY IN SEAFLOOR MASSIVE SULPHIDES IN THOUSANDS OF METRIC TONS*** (% OF LAND-BASED RESERVES)#
Copper (Cu)	Used in electricity production and distribution – wires, telecommunication cables, circuit boards. Non-corrosive Cu-Ni alloys are used as ship hulls	Polymetallic sulphides at hydrothermal vents, polymetallic nodules on abyssal plains	19,700 (Chile, Peru, USA)	1,378	226,000* (23–30% of land-based reserves)	7,400 (0.7% of land-based reserves)	21,600 (2% of land-based reserves)
Cobalt (Co)	Used to produce high-temperature super alloys (for aircraft gas turbo-engines, rechargeable lithium-ion batteries)	Cobalt-rich crusts on seamounts, polymetallic nodules on abyssal plains	110 (Democratic Republic of Congo, Australia, China)	644	44,000 (340–600% of land-based reserves)	50,000 (380% of land-based reserves)	N/A
Zinc (Zn)	Used to galvanise steel or iron to prevent rusting, in the production of brass and bronze, paint, dietary supplements	Polymetallic sulphides at hydrothermal vents	12,800 (China, Peru, Australia)	N/A	N/A	N/A	47,400 (21% of land-based reserves)
Manganese (Mn)	Used in construction for sulphur fixing, deoxidizing, alloying properties	Cobalt-rich crusts on seamounts, polymetallic nodules on abyssal plains	16,000 (China, Australia, South Africa)	694	5,922,000 (114% of land-based reserves)	1,714,000 (33% of land-based reserves)	N/A

Table 3. Major Uses, Production and Potential Supply in Selected Seabed Deposits Relative to Land-Based Reserves for Metals Targeted for Deep-Seabed Mining (Cont.)

METAL	USES	DEEP-SEA SOURCES	ANNUAL PRODUCTION IN 2017 IN THOUSANDS OF METRIC TONS (TOP 3 LAND PRODUCERS)	ANNUAL PROJECTED DEMAND IN 2050 IN THOUSANDS OF METRIC TONS FROM LOW-CARBON ENERGY TECHNOLOGY	METAL SUPPLY IN THE CLARION-CLIPPERTON ZONE IN THOUSANDS OF METRIC TONS (% OF LAND-BASED RESERVES)#	METAL SUPPLY IN THE PRIME CRUST ZONE IN THOUSANDS OF METRIC TONS** (% OF LAND-BASED RESERVES)#	INFERRED METAL SUPPLY IN SEAFLOOR MASSIVE SULPHIDES IN THOUSANDS OF METRIC TONS*** (% OF LAND-BASED RESERVES)#
Silver (Ag)	Used in mobile phones, personal computers, batteries. Also in mirrors, jewellery, cutlery and for antibiotic properties	Polymetallic sulphides at hydrothermal vents	25 (Peru, China, Mexico)	15	N/A	N/A	69 (4.3% of land-based reserves)
Gold (Au)	Used in jewellery, electrical products (metal-gold alloys)	Polymetallic sulphides at hydrothermal vents	2.5–3 (China, Australia, USA)	N/A	N/A	N/A	1.02 (0.002% of land-based reserves)
Lithium (Li)	High-performance alloys for aircraft; electrical, optical, magnetic and catalytic applications for hybrid and electric cars	Cobalt-rich crusts on seamounts, marine sediments	43 (Chile, Australia, China)	415	2,800 (25% of land-based reserves)	20	N/A
Nickel (Ni)	Stainless steel (automobiles, construction), weapons, armour	Cobalt-rich crusts on seamount, polymetallic nodules on abyssal plains	2,100 (Russia, Indonesia, Canada)	2,268	274,000* (180–340% of land-based reserves)	32,000 (21% of land-based reserves)	N/A

Note: The land-based reserves are known with enough certainty that they can be mined economically whereas the seafloor estimates are far from this level of certainty.

** India's 75,000 km^2 nodule claim in the Indian Ocean contains another 7,000 thousand metric tons of Cu and Ni.*

*** Based on 7,533,000 thousand metric tons in the Prime Crust Zone.*

**** Based on 600,000 thousand metric tons in the neovolcanic zone with grades determined as averages of analysis of surface samples.*

Source: Compiled from Hein et al. 2013; Petersen et al. 2016; Miller et al. 2018; Hannington et al. 2010; Fleming et al. 2019; Sovacool et al. 2020.

this option. Recycling costs and thus incidence is a function of energy and raw material costs, which are affected by collection and transportation efficiency; in many cases, where the mass of the desired mineral is small in the waste stream, product redesign would be required for recycling to become effective.

4.2 Can Metal Demand Be Reduced to Avoid Deep-Seabed Mining?

Key to reducing metal demand is the concept of a circular economy, which acts through improved product design, reduced demand, reuse, recycling, reclassification of materials and use of renewable energy for production (Ghisellini et al. 2016). With REEs and metals, it is particularly hard to achieve economies of scale in recycling and reuse, because of the limited quantity of elements contained, the long lifespan of some products using these elements, and metal separation issues requiring complex and energy-intensive processes (Schüler et al. 2011). The materials added to improve product quality and durability can make metal recovery from electronic products even more difficult (Tansel 2017).

Models for increasing metal demand often assume growth in demand based on recent rates of increase, or based on current technology status, which may in fact become obsolete quickly. Commodity price forecasts are notoriously inaccurate. As an example: it is reported that Massachusetts Institute of Technology, commissioned by the ISA to undertake financial modelling for nodule mining in the CCZ, in the space of several months revised its estimate of the likely value of a metric ton of one target metal in nodules (electrolytic manganese metal) from $3,500 to $1,561 (Africa Group 2019). Future demand for resources could be lower than expected, including through saturation in material use as countries move through stages of development (Bleischwitz et al. 2018). This has been documented for copper in the United States, United Kingdom, Japan and Germany, and may be especially relevant for emerging economies, such as China, that are undergoing changing growth patterns that could stabilise demand in the future (Bleischwitz et al. 2018).

5. Sustainability Challenges and Enabling Conditions

5.1 Environment, Vulnerabilities and Costs

Environmental effects of ocean-based renewable energy deployment

The potential benefits of ocean-based renewable energy to contribute to future low-carbon energy generation have been specified in the sections above. However, given the early stages of development of these technologies, there remain environmental risks to the marine environment from their deployment, particularly when considered at the scale required to make a decisive contribution to the future energy system.

As offshore wind is a more mature technology, with greater installed capacity, the risks it poses are slightly better known than for the less mature ocean-based technologies. However, there are still large knowledge gaps in the field of environmental impacts of offshore wind. Considerable lack of baseline data may be a key limitation when evaluating impacts, depending on location and whether there have been any prior studies in the area for other purposes such as oil and gas or fisheries. Baseline data provide information on the state of the marine environment prior to construction, and are used as a basis for comparison over time during the construction and operational phases. Such data may include information on distribution of important and vulnerable species and habitats, and migration routes for marine mammals, fish and birds. Baseline research on species abundance and distribution over annual cycles, population structures and status, and assessment of ecosystem dynamics are necessary.

The literature on the environmental impacts of ocean-based renewable energy was very limited before 2000, but it has increased considerably in the last 20 years (Mendoza et al. 2019; Zydlewski et al. 2015). Boehlert and Gill (2010) provide an early overview of literature with recommendations for needed environmental research on ocean-based renewable energy developments including offshore wind. Impacts range from effects on bird migration, physical habitat change on the seafloor, chemical spills and sound (in air and water) to electromagnetic disturbance from submarine power cables.

The primary environmental concerns of ocean-based renewable energy deployment are typically common to both offshore wind and most of the other ocean-based technologies. Key concerns relate to possible interactions between aspects of the energy conversion systems (turbines, anchors, foundations, mooring lines, etc.) and marine ecosystems. As the installed capacity of these offshore energy systems increases, additional concerns relating to ecosystem processes may arise, such as concerns over changes to atmospheric mixing and climate implications from offshore wind (Wang and Prinn 2011) or concerns around changes in sediment transport and coastal stability implications from other ocean-based technologies (Contardo et al. 2018). OTEC is rather different from the other ocean-based energy technologies. Water discharged in the upper part of the water column would cool and change the environment and may cause concern well before reaching a new steady state consistent with the maximum geophysical potential of OTEC (Nihous 2018).

Regulators and other stakeholders for ocean-based energy projects have identified several possible interactions and potential effects of ocean-based energy devices. These include some that have been evaluated and deemed less critical, such as release of chemicals from coatings or oil spills from devices. As the evidence base grows, there has also been progress towards “retiring” some of the environmental concerns that have been assigned to ocean-based energy developments, such as the effects of electromagnetic fields on marine organisms (Copping et al. 2019). Noise and fauna–device interactions, however, remain key environmental concerns.

Environmental impacts will vary among the technologies. For bottom-fixed offshore wind, noise from piling during construction is of particular concern. Noise associated with pile-driving of foundations can lead to changes in the behaviour of a range of sea animals. For example, porpoise populations have been found to temporarily migrate during construction of offshore wind farms, with population density returning to normal following construction (Carstensen et al. 2006). Based on measurements from wind farms in the German Bight, Brandt et al. (2018) find that harbour porpoises avoid the construction site for up to two days after piling activities, and observable declines in porpoise detections are found up to 17 km away during actual piling activities. Noise mitigation systems have reduced the impacts and such systems are being further developed.

Noise also affects fish. Hammar et al. (2014) studied impacts on cod in an area between Sweden and Denmark addressing impacts from pile-driving, working vessels and cable-trenching during construction, as well as from turbine noise, turbine lubricants and cable electric fields during operation. They found that noise from pile-driving was the most significant stressor and that ecological risks can be significantly reduced by avoiding particular construction events during the cod recruitment period.

Environmental impacts will vary among the technologies.

While sound intensities of noise from shipping and installation of wind turbines, notably pile-driving, will be considerably higher than during operation, noise from operation of wind turbines is also of concern. During the operation phase, the noise from the wind turbines varies with the strength of the wind. Noise arises in the turbine gearbox and generator, and is transmitted through the structure to the water and to the ground. Clearly the noise will depend on the type of gearbox and on the fundament or anchoring.

During the operational phase, the noise from ocean-based energy technologies might be considered comparable with other offshore industries; however, the characteristics of the sound will differ from the sound from other industries (e.g., slower rotational speeds). For subsurface technologies (e.g., wave and tidal devices), marine mammals may be disturbed by certain frequencies of noise and potentially avoid the area.

Wahlberg and Westerberg (2005) review pertinent aspects of underwater sound and hearing abilities of fish, noting that despite decades of increasing anthropogenic noise in the ocean due to maritime traffic and other human activities, the knowledge about fish response to noise is very limited. They conclude that fish can detect offshore wind turbines and that the noise may have a significant impact on the maximum acoustic signalling distances by fish within a range of a few tens of kilometres. The noise level and characteristics are expected to vary between types of wind turbine and fundament, and the hearing abilities at different sound frequencies vary among fish species.

Despite considerable efforts on understanding the impacts of noise from seismic investigations for offshore oil and gas, marine noise management in general is still in its infancy. De Jong et al. (2018) provide experimental evidence for the negative effects of noise on acoustic communication and spawning success for fish. But it remains to be investigated in the field and with noise characteristics from offshore wind activities. Electrification of the service vessels in the wind farm will reduce the noise level and other ship traffic will be minimised in the wind farm area. A risk-based approach integrating noise from different human activities (Faulkner et al. 2018) is proposed as a component of marine spatial planning.

Offshore infrastructure may also create habitats acting as artificial reefs that enhance biodiversity and protect the area against heavy fishing including bottom trawling. Current regulations for the North Sea oil and gas installations require decommissioning at end of life, but complete decommissioning is not favoured by most experts (Fowler et al. 2018), neither for oil and gas nor for offshore wind installations. Both with respect to reef effects and noise, it is worth remembering that the distance between individual turbines in an offshore wind farm is in the order of 6–10 rotor diameters. For state-of-the-art turbines with a rotor diameter of 160–220 m, the distance between the turbines will be in the range of 1–2 km.

Collisions with offshore wind turbines are a notable risk for some seabird species, if turbines are placed such that they disconnect important roosting and feeding sites, or in migratory routes. However, recent research, spanning a two-year monitoring period at the Vattenfall Thanet offshore wind farm (one of the United Kingdom's largest offshore wind farms) has shown the risk of seabirds colliding with offshore wind turbines is lower than previously predicted (Skov et al. 2018), with six strikes recorded during the two-year monitoring period. For other ocean-based energy technologies, collision between devices and marine mammals is a key concern (Copping et al. 2016).

With increasing deployment of offshore wind, the potential environmental risks associated with offshore wind are much more clearly understood and there is growing consensus towards the position that offshore wind farms can be constructed without significantly damaging the environment. However, to achieve this requires proper planning and putting in place mitigation measures (WWF 2014). Other ocean-based technologies, being less mature, with fewer deployments from which to monitor potential risks, have much greater scientific uncertainty surrounding the probability of occurrence, and/or the severity of consequences, specified as the potential risk.

The combination of collecting proper baseline data, careful monitoring of interactions, effective device design and proper marine spatial planning for projects will be required to ensure that potential risks are mitigated. Ecosystem modelling is being used to determine impacts on ecosystem indicators (Raoux et al. 2018). Various approaches and methods for marine spatial planning with specific focus on offshore wind have been proposed (Pinarbasi et al. 2019).

No wind energy projects in the high seas have been proposed up to now. However, the resource is considerable and may be of interest in the future. Elsner and Suarez (2019) make the point that important justice questions remain concerning access and benefits. Even if the UN Convention for the Law of the Sea (UNCLOS; UN 1982) is recognised as the legal basis for any offshore wind deployments in the high seas, there is a danger that flag states may undercut environmental and safety standards for offshore wind energy installations (Elsner and Suarez 2019). Marine spatial planning approaches and the establishment of cooperative mechanisms are needed to safeguard against such developments.

> The combination of collecting proper baseline data, careful monitoring of interactions, effective device design and proper marine spatial planning for projects will be required to ensure that potential risks are mitigated.

Environmental effects of deep-seabed mining

Environmental unknowns, vulnerabilities and costs are some of the most challenging aspects of deep-seabed mining (Thompson et al. 2018). The remoteness of most of the deep ocean combined with the harsh operating conditions (high pressure, low temperatures and darkness), requiring expensive and highly technical equipment, have resulted in limited exploration and scientific research. These constraints, and the vastness of the area in question, mean that the majority of the deep ocean, both within and beyond national jurisdictions, are poorly characterised and understood, or still completely unexplored.

Of the three habitat types vulnerable to mining – abyssal plains with polymetallic nodules, hydrothermal vents with massive sulphides and seamounts with cobalt-rich ferromanganese crusts, the last – especially in the Prime Crust Zone (an area in the West Pacific identified as of the greatest economic interest for mining cobalt-rich crusts)

Environmental unknowns, vulnerabilities and costs are some of the most challenging aspects of deep-seabed mining.

– are the least explored, hence their biodiversity has not yet been characterised (Morgan et al. 2015). Even in polymetallic nodule zones, thought to be bereft of life only 40–50 years ago when UNCLOS Part XI was crafted, four decades of research by contractors and scientific organisations in the nodule-rich CCZ show that environments and associated biodiversity remain largely undiscovered or unidentified. For example, in the eastern CCZ, over 50 percent of species over two centimetres (cm) in size collected by Amon et al. (2016) in 2013, and 34 of the 36 species of xenophyophores (large single-celled organisms) collected by Gooday et al. (2017) in 2015, were new to science. And while hydrothermal vents are the most characterised and understood of the three habitats, many species at vents appear to be rare (comprising < 5 percent of the total abundance in samples), and poorly known (Van Dover et al. 2018). Finally, the connections of these habitats to the wider global functioning is poorly understood, although new studies have begun to shed some light on this (Sweetman et al. 2019; Ardyna et al. 2019).

The impacts of deep-seabed mining remain unknown

Deep-seabed mining is expected to create environmental impacts that involve the following (Van Dover 2014; Levin et al. 2016; Vanreusel et al. 2016; Gollner et al. 2017; Boetius and Haeckel 2018):

- Direct removal of the resources which act as a substrate for specialized faunal communities, including at least half of the species larger than 0.5 millimetres (mm) in size inhabiting these ecosystems – as a result, the animals will be killed or crushed
- Changes to the geochemical and physical properties of the seafloor
- Sediment plumes created from the disturbance on the seafloor as well as from the return water deposited in the water column that may smother or clog feeding apparatus and limit visibility
- Contaminant release and changes to water properties
- Increases in sound, vibration and light

Several large programmes (such as MIDAS and JPI Oceans Mining Impact) have addressed likely mining impacts, but in the absence of disturbance studies on appropriately large scales (across space and time), the intensity, duration and consequences of the impacts of commercial mining remain speculative. Regulators can set rules designed to minimise environmental impacts, such as requiring processed water and sediment to be returned to the ocean at certain depths in order to minimise the creation of a sediment plume in the water column. However, deep-seabed mining poses a risk for biodiversity loss, forced species migrations and loss of connectivity, potentially leading to species extinctions in the deep ocean (Van Dover et al. 2017; Niner et al. 2018). This is of particular concern as many deep-sea species may have genetic compounds that could have biotechnical or pharmaceutical use in the future. There could also be impacts to ecosystem services, such as to fisheries, climate regulation, detoxification and nutrient cycling, but the potential risks have not yet been quantified (Le et al. 2017).

Another poorly understood issue is the length of time that biological communities affected by deep-seabed mining will take to recover. There have been no tests undertaken on a scale that would replicate commercial mining in any of the three habitats, and it is likely that recovery times will differ among ecosystems. However, information gleaned from small-scale experiments, as well as from other industries such as deep-sea trawling, point to lengthy recovery times in each system. Bluhm (2001), Vanreusel et al. (2016), Jones et al. (2017) and Miljutin et al. (2011) have shown that, while there is always some recovery in faunal density and diversity, communities have still not returned to baseline conditions two decades after tests in nodule areas. Simon-Lledó et al. (2019) echoed these findings, showing that, in disturbed areas of the Peru Basin, both the presence of suspension feeders (corals, sponges, etc.)

and diversity generally remained significantly reduced after 26 years. Instead, the community was dominated by deposit feeders and detritivores. They concluded that, if the results of the DISCOL experiment in the Peru Basin could be extrapolated to the CCZ, the impacts of nodule mining (taking into account the area directly impacted, as well as the plume deposition area) may be greater than expected, and could lead to an irreversible loss of some ecosystem functions. As nodule mining will remove the nodules, which take millions of years to form, full-scale recovery will likely take a period of time on that scale. Sites identified as being the most favourable for nodule mining are estimated to span 38 million km^2 (Petersen et al. 2016); individual nodule exploration contracts, of which there are 19 in international waters, each cover 75,000 km^2.

On seamounts, where cobalt-rich ferromanganese crusts are located, cold-water corals and other sessile suspension feeders are extremely susceptible to physical disturbances, such as those already caused by bottom-trawling fisheries (Kaiser et al. 2006; Clark and Tittensor 2010; Williams et al. 2010), because they grow extremely slowly (a few mm to ~1 mm per year) and are long-lived (decades to thousands of years) (Roark et al. 2006; Clark et al. 2016). Most seamounts with high trawling impact have coral cover reduced to below 30–50 percent of the coral cover estimated as necessary to maintain habitat viability (Clark and Tittensor 2010). Impact by trawling fisheries is likely to differ from mining, where the entire substrate will be removed. For organisms dependent on cobalt-rich ferromanganese crusts on seamounts, recovery from substrate removal could require thousands to millions of years, given the rate of formation of crusts (Gollner et al. 2017). Sites identified as being the most favourable for crust mining are estimated to cover 1.7 million km^2 (Petersen et al. 2016); each contractor (there are presently five) may have contracts that cover up to 3,000 km^2 consisting of 150 blocks, each no greater than 20 km^2. Polymetallic crusts on seamounts may be the most technically difficult resource to mine and the one most likely to support active fisheries.

At hydrothermal vents, distinct global faunal patterns, vent site distances and natural background disturbance regimes make it currently impossible to predict recovery rates using volcanic eruptions in other regions as an analogy for deep-seabed mining (Gollner et al. 2017). Recent observations of decadal stability and longevity at vents in the Pacific back-arc basins indicate recovery periods may be longer than initially thought (Du Preez and Fisher 2018). Active hydrothermal vents have been proposed by scientists to be set off limits to mining (Van Dover et al. 2018), but no regulations currently limit mining at active hydrothermal vents and many active sites inside exploration contract areas (both within and beyond national jurisdiction) are vulnerable to impacts from mining at nearby inactive vent sites. There is currently little baseline information and no data available for recovery times at inactive vent sites, making predictions there difficult (Gollner et al. 2017). Sites identified as being the most favourable for seafloor massive sulphide mining are estimated to cover 3.2 million km^2 (Petersen et al. 2016); individual contracts may cover up to 10,000 km^2, with up to 100 blocks of 100 km^2.

Deep-seabed mining could result in loss of species and functions before they are understood

The danger of biodiversity loss is of particular concern given the lack of baseline knowledge of the communities in habitats vulnerable to deep-seabed mining (Van Dover et al. 2017; Van Dover 2019; Niner et al. 2018). It is expected that there will be local extinctions, because many of the fauna inhabiting vents, nodule-rich abyssal plains and encrusted seamounts rely on the resources to be extracted as substrate (Vanreusel et al. 2016). For example, Amon et al. (2016) observed that half of the species over 1 cm in size in the eastern CCZ relied on the nodules as an attachment surface. Strong environmental control and prevalence of rare species makes the smallest invertebrates (meiofauna) in the CCZ vulnerable to the risk of extinction from nodule extraction (Macheriotou et al. 2020).

> Another poorly understood issue is the length of time that biological communities affected by deep-seabed mining will take to recover.

If mining was to go ahead with the current state of knowledge, species and functions could be lost before they are known and understood. A consideration of scale, placement and connectivity is key to prevention of biodiversity loss. In vast, contiguous systems such as the CCZ, cumulative impacts from more than one mining operation may threaten species persistence, depending on their location or timing. The same may be true for vents along a mid-ocean ridge or for seamounts in a chain. For this reason, the series of Regional Environmental Management Plans (REMPs), which the ISA has commenced developing as strategic environmental management tools (ISA 2019b), will need clear environmental objectives (Tunnicliffe et al. 2018). The purpose of REMPs, broadly, is to provide region-specific information, measures and procedures in order to ensure the effective protection of the marine environment in accordance with Article 145 of UNCLOS (UN 1982). To this end, REMPs should establish environmental management measures, including the designation of protected areas (in ISA nomenclature, Areas of Particular Environmental Interest or APEIs) prior to or independent of contract placement and periodic reassessment (Wedding et al. 2013; Mengerink et al. 2014; Dunn et al. 2018), and should be used as management tools which feed into regulatory decisions and actions. REMPs should take into account cumulative effects from multiple mine sites, or synergistic effects from different marine uses or stressors, and seek to manage potential conflicts occurring in the same region. Consideration of climate change in REMP development will help to inform spatial management and environmental impact assessment, and ensure that monitoring programmes can differentiate climate from mining impacts (Levin et al. 2020).

> It is difficult to anticipate how best to mitigate the potential impacts of deep-seabed mining because there have been so few studies investigating mining impacts that resemble those actually caused by mining activity, as well as none on the scale on which deep-seabed mining would take place.

The challenges of mitigation and restoration of ecosystems

It is difficult to anticipate how best to mitigate the potential impacts of deep-seabed mining because there have been so few studies investigating mining impacts that resemble those actually caused by mining activity, as well as none on the scale on which deep-seabed mining would take place (Jones et al. 2017; Cuvelier et al. 2018). It is likely that the mitigation hierarchy (avoid, minimise, remediate and offset) used in terrestrial and shallow-water extractive activities is not applicable in the deep ocean (Van Dover et al. 2017). Challenges associated with restoration and recovery include the slow recruitment and growth of deep-sea species, the potentially vast scale of mining impacts, and the limited understanding of the requirements for proper ecosystem functions (Gollner et al. 2017). Additionally, the likely high cost of deploying assisted regeneration techniques, such as the use of artificial substrates, the transplantation or seeding of larvae and the artificial eutrophication of the ocean surface, may also be insurmountable (Van Dover 2014; Niner et al. 2018). Furthermore, no restoration strategies proposed have been tested, and even if benthic remediation were technically feasible, the financial commitment required may be extensive (Niner et al. 2018).

Offsetting is the last stage in the mitigation hierarchy and includes the protection of a similar type and equivalent amount of habitat under threat from other existing or planned activities (e.g. preventing trawling in cobalt-rich ferromanganese crust communities), and the creation or restoration of biodiversity of a similar type in a different location to that lost to ensure no net loss. It also includes compensatory mechanisms – for example, the creation of biodiversity of a different type and/or in a different location, such as in shallow or coastal environments – or additional actions that do not provide biodiversity gains ecologically linked to biodiversity losses, such as capacity-building. All of these options are currently unable to replicate biodiversity and ecosystem services lost through deep-seabed mining, so cannot be considered true offsets (Niner et al. 2018). This is, in part, due to gaps in current ecological knowledge and restoration abilities in the deep sea (Niner et al. 2018).

If deep-seabed mining moves forward, it must be approached in a precautionary and adaptive manner, so as to integrate new knowledge and avoid and minimise harm to habitats, communities and functioning (Jaeckel 2017; Niner et al. 2018). There are a number of ways in which this can be done, with each option informed by goals, standards, indicators and monitoring protocols. Avoiding harm altogether is unlikely to be achievable, given the destructive nature of deep-seabed mining, which will heavily impact the immediate mining sites. The size of mined sites would vary by deposit type, but a single operation might mine polymetallic nodules over about 8,500 km^2 of seafloor over several decades (Ellis 2001; Van Dover 2014; Petersen et al. 2016; Jones et al. 2017; Van Dover et al. 2017; Niner et al. 2018). Some impacts may be avoided at a project level by reducing the footprint of mining within a contracted area and/or by leaving some minerals with associated fauna in place and undisturbed (protected areas or refugia). However, given that the effects of mining will be three-dimensional and diffuse, are poorly understood, and will involve impacts from sediment plumes as well as toxicity and noise, the identification of refugia that are free from impacts will not be straightforward, and biodiversity loss will likely still occur (Ellis 2001; Thiel et al. 2001; Van Dover 2014; Niner et al. 2018).

Minimising losses of biodiversity and other ecosystem damage to the greatest extent possible includes technologies and practices that may be developed and applied to reduce these risks. There is currently limited technological capacity to minimise harm but possible adaptations include instrument optimisation to limit sediment-plume dispersal, longevity and toxicity, to avoid seabed compaction, and to reduce light and noise pollution (Niner et al. 2018). The effectiveness of such measures at reducing biodiversity losses requires testing and will rely upon a strong regulatory framework, with monitoring and enforcement capabilities. Adaptive management has been identified as a useful regulatory approach that could be applied to deep-seabed mining operations once other challenges are addressed (Jaeckel 2016).

5.2 Economic, Societal and Cultural Costs and Benefits

Benefits of ocean-based renewable energy

Ocean-based renewable energy provides several benefits in comparison with other sources of energy. It has very low CO_2 emissions over the life cycle of deployment. Decarbonising the transport and construction in the sector will further reduce its CO_2 footprint. It also has negligible emissions of mercury, SO_2 and NO_2, and no waste generation. Estimating the total social cost of carbon emissions is a widely discussed topic in the literature, and is beyond the scope of the present paper. But it is clear that, if substituting ocean-based renewable energy for coal-fired power, the direct and indirect benefits for human health and well-being would be considerable.

In terms of employment opportunities, offshore wind provides more jobs than fossil fuel electricity. IRENA (2018b) estimates that a total of 2.1 million person-days is needed to develop an offshore wind farm of 500 MW capacity. The largest part of this effort is in manufacturing and procurement (59 percent), but even for countries that do not aim to stimulate production locally, operation and maintenance (24 percent) and installation and grid connection (11 percent) offer considerable local job opportunities. Gender balance is generally better in renewable energy jobs than in fossil fuel. Training and re-skilling of the oil and gas workforce is an attractive opportunity given the relevance of many skills. Much less information is available for other ocean-based renewable energy but a study of tidal stream and wave energy in the United Kingdom suggests that these can deliver similar employment opportunities to offshore wind when being scaled up (Offshore Renewable Energy Catapult 2018). Jobs will mostly be in coastal areas, some of which may currently suffer from a lack of employment opportunities.

Since, in contrast to thermal power plants, there is no water usage associated with ocean-based renewable energy, there will also be significant water savings. This can be important in many areas where water resources are scarce and costly. A brief overview of the impacts of accelerated deployment of ocean-based renewable energy on all the 17 SDGs was given in Hoegh-Guldberg et al. (2019), showing positive impacts on all. Only for the ocean goal SDG 14 was there a potential red flag, associated with negative impacts on marine life and biodiversity.

The deployment of power plants offshore can create conflicts about the use of ocean space for other human activities, such as maritime transport, offshore oil and gas, fisheries and potentially also offshore fish farming, as well as for marine protection (with Marine Protected Areas or MPAs). Baseline ecosystem mapping and marine spatial planning that takes the various interests into account will be required. In some cases, combinations could be fruitful; for example, wind farms with traffic and fisheries restrictions could usefully delineate MPAs. Such considerations will vary from place to place based on local conditions, and ultimately decisions will be based on what is socially and politically acceptable (the social/political potential – see Figure 5).

Benefits of deep-seabed mining

Deep-seabed mining will bring increased metal supply to consumers globally and is likely to benefit the exploitation company, shareholders and members of the supply chain through financial profits (Kirchain and Roth 2019). Deep-seabed mining within a state's national jurisdiction or in the Area under a state's sponsorship has the potential to benefit that state by contributing to government revenues (through taxes and/or royalties). The quantum may be significant. The UK Prime Minister's assessment of the UK sponsorship of an ISA contract as "a 40 billion £ opportunity" has been called "an overly cautious estimate" by one fellow Parliamentarian (House of Commons 2019). The Cook Islands government has valued their national seabed mineral resources at "hundreds of billions of dollars": a significant sum for any nation, let alone one with a population of fewer than 18,000 people (*Cook Islands News* 2018).

Further benefits may include creating jobs and training opportunities, strengthening the domestic private sector, encouraging foreign investment, funding public-service or infrastructure improvements, introducing a new supply of metals, and supporting other economic sectors (SPC 2012; World Bank 2017). Those benefits may not be large, but may nonetheless be significant, as, for example, in the case of small island developing states with limited land resources and economic options (Wakefield and Myers 2018).

Deep-seabed mining in the Area will bring revenue to humankind, collected and managed on humankind's behalf by the ISA. The quantum and form of that revenue will depend on the system of payments for contractors that is currently under negotiation in the ISA. An initial royalty of 2 percent (rising later to 6 percent) has been proposed for the ISA under an economic model based on contractor profits and contractor data. This could lead to the mining company receiving around 70 percent of the total project profits, and the ISA around 6 percent (with the remainder going to the sponsoring state or whichever state is receiving profit taxes from the mining company) (Africa Group 2018b). Some stakeholders have expressed concern with the principles used in that economic model, and the low royalty rate and return to the ISA. Opponents include all of the 47 African countries who are members of the ISA, and who calculated that the proposed payment regime would lead to a return to humankind of less than $100,000 per annum per country, which they did not deem to be fair compensation (African Group 2019). The international seabed regime established by UNCLOS (UN 1982) is predicated on the basis that mining be carried out (only) in such a manner as to "foster healthy development of the world economy and balanced growth of international trade, and to promote international co-operation for the overall development of all countries, especially developing States" (Article 150). So a regime that would see benefits from mining in the Area flow principally to developed states, or to wealthy shareholders of the companies that are conducting the mining should not be permitted (African Group 2018b).

Other benefits may involve technological innovation and the advancement of deep-sea science. Exploration and impact monitoring may expand scientific knowledge that is currently lacking (if levels of data quality and public-sharing are improved) (Pew Charitable Trusts 2017). Similarly, research associated with deep-seabed mining could also increase our understanding of genetic resources, with the potential for use in pharmaceuticals, industrial agents, biomedical products or bioinspired materials (Le et al. 2017).

Economic development is a key driver for most states, but many resource-rich developing states exhibit slow economic growth. The type of windfall income streams that may be generated if successful deep-seabed mining occurs in significant quantities, if not handled carefully, could have negative effects on a state's economic status (Taguchi and Khinsamone 2018). Commentators observe that the risk of this "resource curse" may be combated by sound revenue management, and an integrated resource management approach, grounded in transparent and non-discretionary policy and law, with funds that are generated by deep-seabed mining being used both for long-term investments in infrastructure or socio-economic projects, and also safeguarded for future generations ("intergenerational equity") (SPC 2016). Some Pacific Island countries (Cook Islands, Tonga, Kiribati, Tuvalu) have addressed this challenge by requiring by law the establishment of a ring-fenced sovereign wealth fund in which any proceeds from seabed mining within national waters must be invested.

The ISA has a different revenue management challenge: how to distribute the proceeds from mining in the Area equitably, and for the benefit of all of humankind (Feichtner 2019). This potentially complex aspect of the ISA's regime has received little attention to date, while the more immediately urgent operational rules for mining and the specific payment rate for contractors are under focus. Different models may include: direct distribution of a share of proceeds to individual member states, or some kind of ISA-managed fund to which states can apply for grants (ISA 2013). However, the proceeds available for distribution may not be large amounts, and may also be depleted by the need to cover operational costs of running the ISA (Thiele et al. 2019).

Costs

The economic costs of ocean-based renewable energy has been treated in Section 3 and costs to the environment in Section 5.1. It is clear that, provided that the environmental impact assessment is performed with an integrated ecosystem approach to avoid areas of particular value, ocean-based renewable energy, in particular offshore wind will increasingly become cost-competitive with other sources of electricity. This will be a driving force for expansion in more and more areas around the world, even if none of the indirect benefits to climate, human health and other aspects of sustainable development discussed in Section 5.2 are used as a rationale for policies or incentives for transitioning from fossil fuels to renewables. A cost–benefit analysis incorporating all of these aspects is beyond the scope of this paper but a preliminary assessment was included in the Annex to Hoegh-Guldberg et al. (2019) and further analysis is available in Konar and Ding (forthcoming).

Little cost–benefit analysis has been done for deep-seabed mining projects (SPC and Cardno 2016), although there have been recent calls for such analyses. For example, the UK government has recently committed to analyse the potential economic value to the United Kingdom of the two ISA contracts granted to UK Seabed Resources Ltd under its sponsorship in the CCZ (House of Commons 2019). Pacific Island finance ministers and civil society organisations also agreed at a meeting in May 2019 that an independent regional study on deep-seabed mining and its implication for Pacific economies, the environment and ocean biodiversity, and people's livelihoods would provide a helpful evidence base to inform countries' policy decisions on seabed mining (Pacific Islands Forum Secretariat 2019).

The primary benefits of seabed mining are presumed to be economic, and the primary costs ecological. There may, however, also be economic costs to a state engaging in a deep-seabed mining operation (e.g., DSM Observer 2018), and in regulating it (SPC and Cardno 2016; World Bank 2017). In the Area, if third-party harm or unforeseen damages occur, then either the mining company or the sponsoring state will be liable to cover the costs of compensation or remediation (Craik et al. 2018). UNCLOS (UN 1982)

Little cost–benefit analysis has been done for deep-seabed mining projects, although there have been recent calls for such analyses.

specifically provides that mining in the Area must not adversely affect the economies of developing countries derived from terrestrial mining, or must compensate them (sections 1(5)I and 7(1) of the Annex to the 1994 Agreement). This may mean that proceeds flowing to the ISA from royalties for mining cobalt in the Area, for example, will be used to compensate countries such as the Democratic Republic of Congo (where most cobalt on land originates) for any losses caused by the ISA contract. This has the potential to limit financial benefits flowing to other parties (apart from the contractor and the compensated country). Alternatively, mining in the Area may occur in addition to terrestrial mining for the same metals (which obfuscates arguments about advantages of offshore mining relative to land mining, and adds to overall adverse impacts rather than replacing the existing ones). An increased supply of minerals could drive metal prices down, which again may require ISA proceeds to be used to compensate developing countries whose economies suffer as a result.

Although the mining activities will largely occur at sea, transporting and processing of minerals is likely to occur on land. There are concerns that associated land-based activities will adversely affect local communities' property, food sources and lifestyle (Aguon and Hunter 2018). Equally, local communities may seek to host industrial facilities or support services in the interests of attaining employment or building infrastructure and so on. There may also be concern that coastal communities in countries who permit deep-seabed mining within national waters, or whose national waters lie adjacent to deep-seabed mining sites under international or another state's jurisdiction, and who rely heavily on the sea for their food and income will be affected by deep-seabed mining through the disruption of fragile and diverse ecosystems, through displacement of fisheries, or through failure to respect the rights of indigenous peoples (SPC 2012; Aguon and Hunter 2018). In extreme cases, and particularly in the absence of strong governance systems, other extractive industry activity has been seen to worsen social tensions and even lead to political instability, such as the Bougainville Civil War in Papua New Guinea, which cost thousands of lives. It has also been noted that deep-seabed mining may cause a loss of cultural or spiritual value associated with a pristine ocean, or traditional sense of ownership of or identification with the ocean and its resources (World Bank 2017). Given strong ecological connectivity between waters in areas beyond national jurisdiction (ABNJ) and coastal zones (Popova et al. 2019), concerns have been expressed about transboundary impacts, whereby a mining operation within one jurisdiction causes deleterious effects to the marine environment or coastal communities of a neighbouring country (Singh and Pouponneau 2018). The international legal framework currently contains lacunae with regards to identifying and enforcing liability for compensation, clean-up or remediation (Craik et al. 2018; ITLOS 2011).

Environmental costs, ecosystem services valuation, tradeoffs and intergenerational equity

When the value of the seafloor environment – for example, in terms of ecosystem services – is weighed against the value of the minerals residing on the seafloor, this comparison is almost always made in terms of monetary value. The value of minerals can be estimated based on past, current and predicted future market prices. The living environment can be valued for the services it provides to humans in the form of food, although other provisioning services (such as pharmaceuticals, industrial agents, biomaterials) may be discovered. Regulating services in the form of carbon sequestration or nutrient recycling are modelled rather than measured (e.g., Burdige 2007) and new elements such as dark carbon fixation are being uncovered. In 2015, the Nautilus Solwara 1 project at hydrothermal vents in Papua New Guinea – a very small pilot mine site – was estimated to have $245 million worth of gold and $397 million worth of copper which could be mined over 2.5 years. Earth Economics conducted a social benchmarking study to monetise the impacts of mining at Solwara 1 on ecosystem services and determined that the dollar value of natural capital assets impacted was far lower for Solwara 1 than for a comparable terrestrial mine (Batker and Schmidt 2015). They used the UN Environment Program The Economics of Ecosystems and Biodiversity and Millennium Ecosystem Assessment in utilising a landscape and seascape approach to natural capital valuation based on the land cover type and area disrupted with conservative overestimates. It was determined that the value of ecosystem services of an acre of Solwara 1 hydrothermal vent (valued at $24,724) was either 80 or 1,733 times less than two comparison terrestrial mines. The Earth Economics valuation method has been employed subsequently in social cost–benefit analyses of mining in Papua New Guinea, Cook Islands and the Republic of the Marshall Islands (Wakefield and Myers 2018), while also being criticised for its methodology, given the difficulty of quantifying impacts which have not been or are only just beginning to be studied (World Bank 2017).

The use of terrestrial metrics to quantify deep-sea services overlooks functions not found on land and fails to recognise that deep-sea vent ecosystems are small and among the rarest on the planet (active vents are estimated to cover a total area of less than 50 km^2 globally). Each hydrothermal vent is different from others, and the biodiversity and vent functions remain poorly known (Van Dover et al. 2018). For example, it was only recently found that skates lay their egg cases at vents (Salinas-de-León et al. 2018). In general, the ecosystem services of the deep sea are poorly known (Armstrong et al. 2012; Thurber et al. 2014), so are under-considered in cost–benefit analyses and are rarely addressed in the development of mining regulations (Le et al. 2017). Particularly under-represented are the non-monetary social, cultural and livelihood values of seabed ecosystems or possible downsteam impacts where the minerals are landed. A greater focus is needed on how to value non-monetary assets linked to the existence and aesthetic and educational uses of biodiversity, as well as the functions and services not yet discovered.

Disruptions caused by deep-seabed mining at the seafloor, in the overlying water column and where ore is brought to land can cause conflict with other economic sectors and threaten loss of non-market ecosystem services (Thompson et al. 2018). Noise, light, sediment plumes with contaminants, and oil leakages can threaten both commercial and subsistence fisheries (Miller et al. 2018). In the case of phosphorites, there is often direct spatial overlap between fisheries and the mineral resource, as well as potential disruption in the overlying waters caused by extraction (Levin et al. 2016). It is also possible that mining activity could prevent future use of the mining site for other purposes. Seafloor substrates targeted for mining may hold genetic resources that could be lost (Le et al. 2017; Van Dover et al. 2018). These are subject to the Nagoya Protocol within national waters, and are the subject of negotiations in international waters (UN General Assembly 2018), but are not currently regulated in the Area (Vierros et al. 2016). Deep-seabed mining could disrupt carbon cycling linked to iron flux from hydrothermal vents, which plays a role in stimulating primary production and carbon drawdown from the atmosphere (German et al. 2015; Ardyna et al. 2019), and by removal of autotrophic microbes that fix carbon, and fauna that bury carbon in sediments (Sweetman et al. 2019). Loss of tourism from the threat of mining is feared in diverse settings such as Papua New Guinea, Fiji, Portugal and Spain (Thompson et al. 2018). Since no full-scale mining impacts have occurred, the nature and extent of these tradeoffs cannot be studied and thus remain speculative.

The value of lost ecosystem services due to mining impacts could appear in the financial code as a form of monetary compensation (e.g., to the common heritage of humankind) or be factored into the amount of the royalty payable by the miner. Built into the concept of the common heritage of humankind is the principle of intergenerational equity, in which, in addition to sharing the benefits of resources, the resources in the natural environment are preserved for generations to come (Jaeckel et al. 2017). The idea of partitioning resources among current and future generations is an important component of sustainability (and intergenerational equity) for non-renewable resources.

> The value of lost ecosystem services due to mining impacts could appear in the financial code as a form of monetary compensation or be factored into the amount of the royalty payable by the miner.

Decisions to mine

Most discussions of deep-seabed mining address where, when and how to conduct deep-seabed mining, as well as what the impacts might be, but not

BOX 1. Scenarios for Deep-Seabed Mining

Scenario 1. Full steam ahead on current knowledge

Accept environmental and economic risks, social and equitability concerns and proceed with mining the seabed within and beyond national jurisdiction as soon as legally possible. Biodiversity and its ecological functions in the areas impacted could be lost, possibly irreparably. The scale and ramifications of those impacts – as well as the extent to which the mining will lead to overall benefit for humankind – are hard to predict on current knowledge.

Scenario 2. Slow the transition from exploration to exploitation – precautionary pause

Allow more time to fully assess and understand the environmental risks, including through additional scientific study prior to issuing exploitation contracts; design spatial protections carefully (including the identification of regions to set aside from mining) and develop additional methods to promote resilience; further clarify the need for deep-seabed metals; develop mining regulations in a careful, thorough and transparent manner, with independent expert input and engagement of all stakeholders. Stop issuing new exploration contracts, and do not grant any mining contracts, unless and until the above has been undertaken.

Scenario 3. Indefinite moratorium on deep-seabed mining

Deep-seabed mining does not move forward. Refocus on initiatives that enable transition to circular economies with emphasis on metal demand reduction through reuse, recycling, alternative materials, extended product lifetimes and behavioural change.

whether to mine (Kim 2017). The distribution of metal resources and their production creates geopolitical uncertainties that were to be solved by designating minerals in the Area as the “Common Heritage of Mankind” (UN 1982). In 2012, most cobalt (68 percent) was mined in the Democratic Republic of the Congo, Chile produced 32 percent of copper, China 90 percent of REEs and almost 78 percent of terrestrial manganese resources were found in South Africa (Brown et al. 2014). Extraction of these minerals creates social and environmental problems on land (Kim 2017; IRP 2019), which proponents of deep-seabed mining have argued are mostly absent in the ocean (Lodge and Verlaan 2018).

Currently, opinions on whether deep-seabed mining should proceed span a broad spectrum (Box 1). At one end, there is the adamant opposition to any deep-seabed mining, with the claim that adverse effects on the environment will outweigh the benefit of additional metals (Kim 2017). This perspective argues that seabed minerals are not needed (Teske et al. 2016) and suggests that “we should do more with less” via a circular economy that advances recycling, reuse and extended product lifetimes.

In the middle, there are calls for pilot testing and further scrutiny of the issue, as well as for a moratorium or precautionary pause to allow more scientific study and to see the highest environmental standards and the precautionary approach embodied in deep-seabed mining regulations and guidelines. A pause may in practice prevent the issue of additional mining contracts unless and until there is scientifically supported evidence – not currently available – that the impacts will be outweighed by the benefits. Concerns have been voiced that the process has gone too fast relative to the state of knowledge and the ISA’s capacity for environmental management. Various bodies have proposed different forms of such a precautionary pause or moratorium on deep-seabed mining in international waters, namely the European Parliament, the UK House of Commons Environment Audit Committee, the Long Distance Fleet Advisory Council (LDAC) of the European Union (LDAC 2019), and the UN Secretary General’s

Special Envoy for the Ocean. A major aim of such a pause is to allow scientific research to advance, possibly in conjunction with the Decade of Ocean Science for Sustainable Development (Johnson 2019). Additionally, Fiji has proposed, and Papua New Guinea and Vanuatu may be considering, a similar moratorium within their national jurisdictions.

At the other end, there is the stance that deep-seabed mineral projects should be facilitated and incentivised (essentially the current position of the ISA). To date, no requests for exploration contracts have been denied by the ISA and there is a current push to develop the Mining Code (regulations, guidelines and procedures) by 2020 so that exploitation may commence (ISA 2017, n.d.).

The complexity of the stakeholder input to decisions about deep-seabed mining cannot be underestimated (Box 2). The most vocal are states with exploitation contracts (Figure 3), and the mining companies that partner with them. Those states with mines on land, and those with a history of ocean conservation have also weighed in, while civil society and the public in general have had a limited voice to date (Fleming et al. 2019).

BOX 2. Stakeholders for Deep-Seabed Mining

At this time, those expressing the greatest interest in deep-seabed mining, both actively and passively (and not necessarily always to propel the industry forward) include the following groups:

- Nations that have ISA exploration contracts (e.g., China, India, Japan, Russia, South Korea and various EU countries)
- Countries that have deep-sea mineral deposits of commercial interest within national jurisdictions (e.g., Papua New Guinea, Tonga, Cook Islands, Namibia, Japan, Kiribati)
- Countries that actively mine the same minerals on land (e.g., Democratic Republic of Congo, Chile, South Africa)
- Mining companies that have claims within EEZs or have partnered with states on international exploration claims (e.g. Nautilus Minerals, UK Seabed Resources Ltd, Global Sea Mineral Resources, Deep Green)
- Research institutions and scientific networks (e.g. JPI Oceans, the Deep-Ocean Stewardship Initiative, InterRidge, and the Deep Ocean Observing Strategy) interested in bringing science to decision-making and the development of regulations, and in providing sustained observations that can help to address outstanding scientific questions
- States, environmental advocacy groups, intergovernmental organisations (IGOs) and non-governmental organisations (NGOs) focused on conservation and biodiversity maintenance (e.g. International Union for Conservation of Nature, Deep-Sea Conservation Coalition, Greenpeace, WWF, The Pew Charitable Trusts)
- Other components of the blue economy, such as the deep-sea fishing industry and underwater cabling companies, with potential conflict or spatial overlap
- Civil society and religious groups that are largely active within EEZs and wary of exploitation of local and indigenous peoples and threats to their local environment and culture (e.g. the Holy See, Deep Sea Mining Campaign, the Pacific Conference of Churches, Alliance of Solwara Warriors, Fair Ocean, Misereor, Brot für die Welt)

It is possible, as has been shown with other habitats, that with time and education, civil society may be willing to pay to forgo blue industrial growth for conservation of the deep sea in order to preserve ecosystem services (Aanesen and Armstrong 2019). Deep-sea scientists are a growing constituency that is increasingly engaged as part of baseline surveys for contractors or discussions with the ISA via organisations such as the Deep-Ocean Stewardship Initiative and InterRidge.

Regulatory sectors overlap in areas targeted for or potentially impacted by deep-seabed mining. Water-column impacts in international waters falling under ISA jurisdiction will intersect with management by regional fisheries management organisations under the Food and Agriculture Organization of the United Nations or the regime overseen by the International Maritime Organization which regulates contaminants and dumping (and which is implemented via individual "flag states" to whom vessels are registered). Current negotiations on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction (BBNJ), with its focus on spatial protections, environmental impact assessment, marine genetic resources and technology transfer and capacity-building, has large potential overlap with the ISA for the Area (which includes the entire seafloor). The designation and nature of spatial protections, applications of ecosystem-based management, the disposition and accessibility of data, and the development of shared goals and objectives to achieve sustainability are all areas where the ISA will need to work across sectors both within the United Nations, and with industry, academia and civil society.

6. Governance and Regulatory Framework for Deep-Seabed Mining

6.1 State Level

A state should adopt appropriate measures to exercise control over any seabed mineral activities under its jurisdiction and to secure compliance with international standards. State laws relating to the management of seabed mineral activities must be "no less effective than international rules, regulations and procedures" (UNCLOS; UN 1982) – such as the Mining Code of the ISA, currently under negotiation (ISA n.d., 2019d). Direct obligations under international law in respect of seabed mining include: applying the precautionary approach, employing best environmental practice, and conducting prior environmental impact assessment (ITLOS 2011). These obligations apply to states regardless of their individual wealth or capacity (ITLOS 2011). A number of states, particularly in the Pacific region, have implemented national legislation to govern seabed mineral activities (both within national and international jurisdiction) (e.g. Fiji, Tonga, Tuvalu, Kiribati, Cook Islands, Federated States of Micronesia, Nauru, United Kingdom, Belgium, United States, Japan, Germany, China) (Lily 2018; World Bank 2017). It is notable, however, that several states actively engaged in exploration activities as yet have no detailed legal regime in place (e.g. India, France, South Korea, Brazil, Russia, Poland) (Lily 2018; ISA 2019a).

The creation of adequate legislative frameworks by states, while essential, is not sufficient in itself: implementation and enforcement of the rules created are also crucial (ITLOS 2011). This point is supported by international law (e.g., UNCLOS, Articles 214 and 215; UN 1982), which requires appropriate environmental standards not only to be governed by domestic legislation, but also to be implemented through monitoring and enforcement. Strong institutions are particularly important to the oversight of seabed mining; legal, fiscal and environmental matters will all require dedicated public administration capacity. This may be particularly challenging for small developing states with limited administrative and technical capabilities. Provision should also be made for independent oversight and public notification of, and participation in, decision-making (SPC 2012; United Nations Conference on Environment and Development 1992).

To date, little scrutiny has been applied to the states who sponsor ISA activities, including the extent to which relevant measures are in place to ensure ISA contractor compliance (and compensation for third-party damages) via domestic regulation (Lily 2018), and the nature of the arrangements between the state and the ISA contract-holder (Rojas and Phillips 2019). There is little information in the public domain as to the extent to which the sponsoring state, or another state, stands to benefit financially from the contract – which may be deemed of particular importance where the sponsoring state is a developing state.

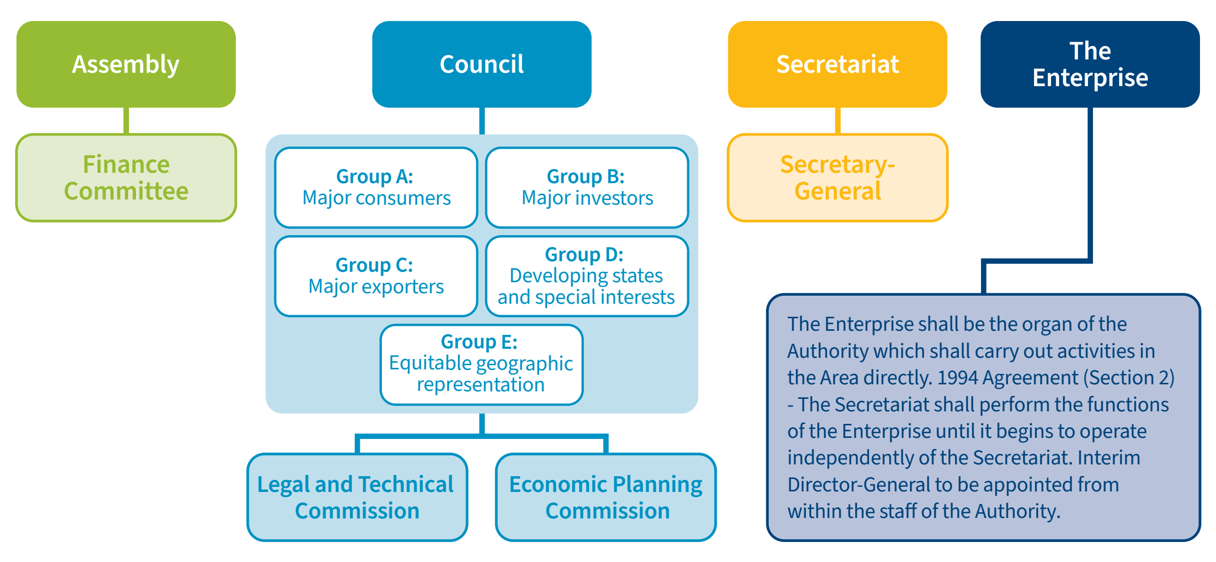
6.2 International Level

The ISA is tasked to "organise and control" contractors to "secure compliance" with ISA rules, including those rules designed to deliver on the ISA's mandate to "protect and preserve the marine environment" (UNCLOS; UN 1982). Much of the oversight authority within the ISA rests with the Council and the Legal and Technical Commission (LTC) which provides initial recommendations regarding rules, regulations and procedures, as well as recommendations on applications for mining contracts (Box 3). In some instances, it is difficult for the Council to take a decision contrary to an LTC recommendation. For example, in order to decide not to approve an application for a mining contract where the LTC recommends approval, a two-thirds majority of the 36 Council member states would be required. Even then, any one of four chambers within the Council could veto that disapproval decision (UN 1994, Annex, section 3, para. 11(a)). For this reason, the potential for a mining "approval bias" at the ISA has been noted (Greenpeace 2019; Pew Charitable Trusts 2019), and the composition, election, expertise and capacity of the LTC are often under scrutiny. The fact that only 3 of the 30 commissioners currently in post appear to have

BOX 3. The International Seabed Authority (ISA)

The ISA is an intergovernmental agency created by the UN Convention on the Law of the Sea (UNCLOS; UN 1982), with a structure that includes the following organs: the Assembly, the Council, the Legal and Technical Commission, the Finance Committee, the Economic Planning Commission, The Enterprise and the Secretariat (Figure B3.1).

Figure B3.1. The International Seabed Authority Governance Structure



The Enterprise shall be the organ of the Authority which shall carry out activities in the Area directly. 1994 Agreement (Section 2) - The Secretariat shall perform the functions of the Enterprise until it begins to operate independently of the Secretariat. Interim Director-General to be appointed from within the staff of the Authority.

Source: Adapted from Grid Arendal (https://www.grida.no/resources/6311).

The executive body of the ISA is its "Council", comprising 36 member states. These states are elected in a number of different groups, designed to ensure a diversity of nations, representing different interests. These groups include major consumers or importers of the relevant metals, the largest investors in deep-seabed mining in the Area, major exporters of the relevant metals from land-based sources, developing countries with special interests (e.g. land-locked, geographically disadvantaged, islands), and five regional geographic groupings (Africa, Asia-Pacific, Eastern Europe, Latin America and Caribbean, and Western Europe and Others). The groups are then organised into four chambers, for decision-making purposes (UN 1994, Annex, section 3, para. 15).

BOX 3. The International Seabed Authority (ISA) (Cont.)

The Council reports to the Assembly, which comprises all 168 ISA member states. Both organs meet at least annually at the ISA's headquarters in Kingston, Jamaica.

The ISA is supported by a Secretariat, also based in Jamaica, headed by a Secretary-General who is the chief administrative officer of the ISA, and required to support all ISA meetings and to perform such other administrative functions as may be instructed (UNCLOS, Article 166).

Another key organ within the ISA is the Legal and Technical Commission (LTC). This is a group of, currently, 30 experts, serving in their individual capacities, who meet bi-annually with responsibility to prepare recommendations and advisory inputs to the Council. The LTC's mandate includes the provision of recommendations on applications for ISA contracts, and preparing drafts of rules, regulations and procedures of the ISA, for Council consideration or adoption (UNCLOS, Article 165).

The Finance Committee oversees the ISA's administrative budget. The Economic Planning Commission is tasked with examining the impacts of mining in the Area on land-based mining economies; its function is currently being covered by the LTC. The Enterprise is envisaged to be an in-house mining arm of the ISA, who will commence operations via joint ventures with other contractors. The Enterprise has not yet been operationalised.

ecological science backgrounds has been remarked upon as a particular challenge, given the ISA's environmental protection mandate, and the LTC's immediate task to review environmental impact assessment reports, to develop environmental management plans, and to draft regulations, standards and guidelines pertaining to environmental management and thresholds. Criticisms of the LTC have also extended to a lack of transparency and potential conflict of interests (Greenpeace 2019; Ardron et al. 2018; Seascape 2016).

There is no other precedent of an international intergovernmental treaty body (with 168 members, each with their own political priorities and interests) attempting to act as a minerals licensing, monitoring and enforcement, and revenue collection agency – as is required of the ISA (French and Collins 2019). UNCLOS even envisages an in-house mining wing of the ISA called "The Enterprise" (Article 170). When The Enterprise comes into existence, the ISA will be required to issue exploration or mining contracts to, and regulate, itself. These are functions that within national jurisdictions are usually performed by a raft of different government agencies operating under separate mandates. The ISA also faces constraints from the infrequency of meeting, a lack of funding and the fact that the same governments may be represented simultaneously in the ISA's advisory body, decision-making organ and as mining contractors. The challenges of conflict management and capacity constraint will be exacerbated if and when the ISA operates as a mining company itself ("The Enterprise"), as envisioned by UNCLOS (African Group 2018a). Different stakeholders have previously raised concerns with regards to the ISA due process and governance practice (Seascape 2016; Ardron et al. 2018; Belgium Government 2018; German Government 2018). Noting the capacity limitations and other constraints of the existing ISA structures, several parties have called for better incorporation of science and external, independent expertise in the ISA's development of regulations, rules and procedures, and in its regulatory oversight of contracts (Pew Charitable Trusts 2019).

The regulations for mining within the Area are under negotiation at the ISA currently. While there is a political push for these to be finalised by 2020 (ISA 2017), there appears to be a large amount of work still required to reach agreement on all necessary elements of the regime

(ISA 2019c; Pew Charitable Trusts 2019), and at the ISA Annual Sessions in July 2019 and February 2020, several member states called for "quality over haste".

6.3 Mining in the Context of the UN Sustainable Development Goals

Several SDGs that affect materials use and natural resources (presumably designed for land use) are relevant to the ocean, including SDG 8.4, which addresses decoupling of materials use and environmental degradation, and SDG 12.2, which considers efficient use and sustainable management of natural resources (OECD 2018). Deep-seabed mining could contribute positively to several SDGs. Financial and economic benefits could help to relieve poverty (SDG 1), in the least developed countries such as Kiribati as an ISA-sponsoring state, or Solomon Islands as a state with sovereign rights over minerals within national jurisdiction, for example. But the benefit-sharing mechanisms have yet to be determined and are likely to be modest for non-mining countries (Kim 2017). Benefits from a greater availability of metals will almost certainly accrue to the most industrialised (or industrialising) nations, but could contribute to clean energy (SDG 7), which would counter climate change (SDG 13). These benefits all come with tradeoffs for the ocean environment under SDG 14, "Conserve and sustainably use the oceans, seas and marine resources for sustainable development", along with questions over the extent to which seabed mining can meet SDG 12.2, the target to "achieve the sustainable management and efficient use of natural resources" by 2030.

A recent report on mining governance on land introduces the concept of a Sustainable Development Licence to Operate (SDLO). The SDLO adopts principles, standards of behaviour and best practices compatible with SDGs and their targets (IRP 2019). However, many struggle to understand what sustainability looks like in the context of deep-seabed mining. Obtaining maximum economic benefit in return for the extraction of minerals, and applying this to the long-term development goals of the poorest populations would seem to be a prerequisite.

Within SDG 14 targets, sustainability seems to encompass protecting ecosystems, conservation, economic benefits, scientific knowledge, and governance. When defined in relation to the extraction of living resources, sustainability often involves eco-certification, harvesting low on the food chain, avoiding government subsidies, technology innovation to avoid bycatch, and management to achieve maximum sustainable yield (Carr 2019). Could there be parallels for deep-seabed minerals? Could mining practices undergo review for a certification of limited damage to the environment? This is already effectively the mandate of the ISA. Could metal-containing end-products, such as mobile phones, come with source information about the metals in order to enable consumers to base their purchase choices on informed and ethical grounds? Could miners select mineral substrates of lesser value to biota or leave a significant fraction of the hard substrate on the seabed? What technologies can minimise the intensity, area or duration of impact on the environment? Given that most of the targeted minerals precipitate very slowly (e.g., 1–10 mm/million years for polymetallic crusts and nodules (Hein et al. 2013)), would there be an equivalent of maximum sustainable yield?

The drafters of UNCLOS appeared to pre-empt some of these issues, by stipulating that the ISA's production policy should be based on the principle that "there shall be no discrimination between minerals derived from the Area and from other sources. There shall be no preferential access to markets for such minerals or for imports of commodities produced from such minerals", while also requiring that state subsidies be avoided (UN 1994, Annex, section 6). These principles may be difficult to implement and police in practice.

Just as vulnerable marine ecosystems (VMEs) (e.g., dense corals and sponges) are protected from bottom fishing in international waters (UN General Assembly 2006), it has been proposed that active hydrothermal vents, which function as VMEs, should be protected from deep-seabed mining (Van Dover et al. 2018). There is a wholesale ban on bottom trawling in deep water (> 800 m) in the European Union and elsewhere to prevent major habitat destruction. Although there are mineral resources of value in the EEZs of many countries, especially island nations in the West Pacific, none have permanently banned seabed mining. Notably, a precautionary pause/moratorium has recently been proposed by Fiji (Fiji Sun 2019) and mining licences for phosphorites have been denied in Mexico and New Zealand (Miller et al. 2018).

7. Opportunities for Action

Considering the above analyses, some high-level opportunities for action regarding ocean-based renewable energy (Section 7.1) and deep-seabed mining (Section 7.2) are presented here. The development of the global energy system referred to in Section 7.1 is intimately linked to both renewable energy and the use of minerals, Section 7.2. The Appendix provides further elaboration of challenges, detailed opportunities for action and associated benefits and some alternative or additional options. These are designed to ensure that ocean-based renewable energy is harvested in a manner that exploits its potential to contribute to sustainable development, and to ensure that the ocean, particularly in the context of deep-seabed mining, remains healthy and resilient for future generations.

7.1 Ocean-Based Renewable Energy and the Global Energy System

As discussed in Section 2.1, ocean-based renewable energy plays a significant role in cost-optimised models for transitioning the global energy system to a global temperature increase of 1.5°C, in line with the Paris Agreement. In particular, offshore wind has the potential for further cost reductions and for the upscaling of implementation over the coming decade (see Section 3.1). The actual development path will depend upon several factors, including access to areas, grid connections, financing models, ownership and, in some cases, regulation of cross-border electric cables and legal conditions. While the expansion of offshore wind is well under way, the speed of development and implementation of further cost-reducing technologies, such as floating large turbines in deeper waters with bigger wind resources, depends on government incentives.

WindEurope has listed several challenges to be addressed to scale up offshore wind (WindEurope 2019). They also state six policy recommendations for Europe (WindEurope 2019, 66–67):

- Governments should set ambitious maritime spatial planning policies to deliver 450 GW by 2050.
- Governments should ensure that permitting and other relevant authorities have the necessary expertise and resources to consent enough sites.
- Governments should accelerate the expansion of the necessary on- and offshore grid infrastructure.
- The EU should elaborate a regulatory framework for offshore hybrid projects (e.g., hydrogen).
- Governments should accelerate the electrification of transport, heating and industrial processes.
- Governments should ensure visibility and confidence in volumes and revenue schemes.

ETIP Ocean (2019) describes a set of challenges and actions that would help lift ocean-based renewable energy in Europe towards delivering 100 GW by 2050.

Offshore wind and other ocean-based renewable energy does use metals, including some REEs, but it is not a major driver for deep-seabed mining exploration and exploitation. New technological solutions for components of offshore wind installations change the specific demands from one resource to another, showing the adaptability of the industry. The environmental impact of ocean-based renewable energy can slow down or limit its expansion. Baseline surveys and marine spatial planning exercises involving all stakeholders are required. Noise remains a concern but floating structures are expected to be more environmentally benign.

> The significant environmental and social impacts of mining on land could be improved with focused effort, yet presently add incentive to look to the ocean as a source of minerals.

Other ocean-based renewable energy technologies should be developed to provide a wider range of energy sources in the future, particularly in areas with more limited wind resources. The low-carbon future energy system, as well as human activities in general, have to be developed and operated within given resource limitations. Minerals must be used in a way that is compatible with sustainable development in all its dimensions. In particular, the use of deep-seabed mining implies many potentially negative side effects and uncertainties and should be avoided at least until more knowledge has been gathered.

Opportunities for action are:

- **STRENGTHEN RESEARCH, DEVELOPMENT AND DEMONSTRATION PROGRAMMES** to scale up offshore wind, in particular to make floating offshore wind cost-competitive more quickly.
- **SUPPORT MARINE SPATIAL PLANNING AND SUSTAINABLE OCEAN ECONOMY PLANS** with taxation schemes and regulations that stimulate investments in variable renewable energy supply from the ocean to the shore.
- **STRENGTHEN RESEARCH AND DEVELOPMENT FOR OTHER OCEAN-BASED RENEWABLE ENERGY TECHNOLOGIES** to make them more mature and available to contribute significantly in later decades.
- **STRENGTHEN RESEARCH AND DEVELOPMENT AND ECONOMIC INCENTIVES TO FAVOUR A LESS MINERAL-INTENSIVE GLOBAL ENERGY SYSTEM**, including ocean-based renewable energy.

7.2 Deep-Seabed mining

Deep-seabed mining represents a sustainability conundrum. The significant environmental and social impacts of mining on land (IRP 2019; Church and Crawford 2018) could be improved with focused effort, yet presently provide incentives to look to the ocean as a source of minerals (Batker and Schmidt 2015; IRP 2019). But extreme knowledge gaps remain, particularly in understanding how deep-ocean ecosystems will respond to industrial-scale mining disturbance. There is an inherent conflict between a duty to protect the marine environment, and a call to mine the deep sea for metals. The remote nature of the deep ocean and its unfamiliarity to most people raise the challenge of ensuring the participation of all relevant stakeholders to inform decisions taken at the international and state level that relate to areas out of sight. How society moves past these crossroads, and the decisions taken on behalf of humankind by governments at the ISA, will likely have a lasting impact on our ocean.

Because no deep-seabed mining has occurred yet, but substantial policy-making is in progress, four opportunities for additional action are proposed:

- **DEVELOP AND EXECUTE A ROAD MAP TO BUILD THE REGULATORY CAPACITY OF THE ISA TO ENSURE EFFECTIVE PROTECTION FOR THE MARINE ENVIRONMENT** from harmful effects of mining in a transparent and inclusive manner. This would include the creation of environmental consents, evidence, inspectorate and enforcement functions, and would involve a slower process of transitioning from exploration to exploitation.

- **ESTABLISH AN INTERNATIONAL RESEARCH AGENDA AND TIMELINE, IN CONJUNCTION WITH THE UN DECADE OF OCEAN SCIENCE FOR SUSTAINABLE DEVELOPMENT,** to collect and synthesise high-quality deep-sea scientific data to fill identified gaps in knowledge required for decision-making and environmental management, before any deep-seabed mining takes place.

- **PROMOTE THE IDENTIFICATION, DECLARATION AND ENFORCEMENT OF SPATIAL PROTECTIONS** (including large, biologically representative, fully protected no-mining zones established in perpetuity prior to any award of exploitation contracts), **ACROSS ALL OCEAN REGIONS UNDER ISA JURISDICTION**. This would enable states to demonstrate efforts towards their international duties to ensure effective protection for the marine environment from mining's harmful effects (UNCLOS; UN 1982), to achieve in-situ conservation (Convention on Biological Diversity; UN 1992) and to conserve a percentage of marine areas (SDG 14.5 and Aichi Biodiversity Target 11). More time could also allow new opportunities to emerge for industry and scientists to partner on testing technological and conceptual innovations for mineral recovery that minimise harm to the marine environment.

- **CREATE INCENTIVES AND REMOVE BARRIERS TO IMPLEMENT A CIRCULAR ECONOMY**, which acts through improved product design, reduced demand, reuse, recycling, reclassification of materials and use of renewable energy for production (Ghisellini et al. 2016). For metals targeted by deep-seabed mining, this would require independent research and long-term planning with attention focused on Life Cycle Sustainability Analysis (Van der Voet et al. 2019). Alternative energy technologies are already under investigation which reduce the use of lithium, silver, neodymium and dysprosium. New solid-state battery designs avoid the use of cobalt and nickel and have great durability and longevity. Redesign of existing batteries is required to avoid additives that improve product quality and durability but make metal recovery from electronic products even more difficult (Tansel 2017). More government policy focus, consumer awareness and behaviour change to favour a less mineral-intensive renewable energy system will also be crucial.

Appendix: Detailed Opportunities for Action

The *Opportunities for Action* in the main document are expanded upon below.

- To ensure that ocean-based renewable energy is harvested in a manner that exploits its potential to contribute to sustainable development.
- To ensure that the ocean, particularly in the way it is considered for deep-seabed mining, remains healthy and resilient for future generations.

Each recommendation is prefaced by a specific challenge to be addressed, the recommendation itself, what following the recommendation would imply and the benefits to be achieved. In some cases, alternative or additional options are also described.

I. Detailed Opportunities for Action for Ocean-Based Renewable Energy

Detailed Opportunity for Action 1

CHALLENGE 1: OCEAN-BASED RENEWABLE ENERGY COULD CONTRIBUTE SIGNIFICANTLY TO SUSTAINABLE GLOBAL ENERGY SUPPLY, BUT THE DEVELOPMENT IS TOO SLOW FOR TIMELY PHASE-OUT OF FOSSIL FUEL.

DETAILED OPPORTUNITY FOR ACTION 1: Strengthen research, development and demonstration programmes and financing, taxation and legal regimes to scale up ocean-based renewable energy, in particular market incentives to make floating offshore wind cost-competitive faster, but also research and development to make other ocean-based renewable energy technologies more mature.

BY DOING THIS: The harmful effects of CO_2 emissions on the climate and on the ocean will be reduced. The urgent transformation of the global energy system will accelerate.

ASSOCIATED BENEFITS: A new sector of the ocean economy will develop including new jobs. Less mineral-intensive options will reduce pressure on mining.

ALTERNATIVE (OR ADDITIONAL) OPTION: Create regional national or international programmes focusing on different energy technologies, recognising that the various ocean-based renewable energy sources are unequally distributed because of varying wind resources, wave climate, tidal range and so on. Create floating or remote plants converting renewable electricity to hydrogen to supply fuel for shipping and transport to shore.

Detailed Opportunity for Action 2

CHALLENGE 2: RAPID TRANSFORMATION OF THE ENERGY SYSTEM HELPS TO SAVE THE CLIMATE, BUT CONTRIBUTES TO THE DEMAND FOR RARE MINERALS AND THE PRESSURE TO ACCELERATE DEEP-SEABED MINING DURING THE DECARBONISATION PHASE, BEFORE RE-USE AND THE CIRCULAR ECONOMY CAN BE DEPLOYED.

DETAILED OPPORTUNITY FOR ACTION 2: Strengthen research and development and economic incentives to favour a less mineral-intensive renewable energy system.

BY DOING THIS: The transformation of the global energy system can take place without risking harmful effects on the deep-sea environment, its ecosystem services or other potential resources.

ASSOCIATED BENEFITS: The global energy system will develop in a more sustainable way with less material use overall. Note that the recommendation has system-wide implications beyond the choice of renewable energy source. For example, the need for batteries as well as the curtailment of electricity from renewable energy can be reduced in an energy system with well-developed demand management and other types of energy storage than batteries.

II. Detailed Opportunities for Action Specifically for Deep-Seabed Mining

A rapidly growing literature on deep-seabed mining has generated many ideas for the development of protection and management schemes for the marine environment, on governance options, ways to approach initial mining operations, and on alternatives to deep-seabed mining. The series of recommendations below emerge from the synthesis presented here, informed in part by the information gaps and scientific uncertainties associated with deep-seabed mining.

Detailed Opportunity for Action 3A and 3B

CHALLENGE 3: UNCLOS WAS WRITTEN IN A TIME OF LIMITED KNOWLEDGE ABOUT DEEP-SEA ECOSYSTEMS, THEIR VULNERABILITIES AND THE SERVICES THEY PROVIDE (E.G., HYDROTHERMAL VENTS HAD NOT YET BEEN DISCOVERED). EXTREME KNOWLEDGE GAPS REMAIN, PARTICULARLY IN UNDERSTANDING HOW DEEP-OCEAN ECOSYSTEMS WILL RESPOND TO INDUSTRIAL-SCALE MINING DISTURBANCE.

DETAILED OPPORTUNITY FOR ACTION 3A: Slow the process of transitioning from exploration to exploitation, and take the time necessary to fully develop – in a transparent and inclusive manner – the ISA rules, regulations and procedures for mining (possibly extending the ISA-imposed deadline from 2020 to 2030), and institute a precautionary pause in the issuance of new contracts by the ISA during this period.

BY DOING THIS: The (legally required) precautionary approach is applied. More time is allowed for scientific study, and appropriate scientific input into regulations and decision-making, including the development of environmental goals and objectives, and identification of science-based indicators and thresholds.

ASSOCIATED BENEFITS: More time would also allow for broader stakeholder input, and building of ISA capacity, to include data access and management mechanisms, access to relevant independent expertise, and regulatory capacity.

ALTERNATIVE (OR ADDITIONAL) OPTION: Develop rules, regulations and procedures at the ISA that set highly stringent and prescriptive environmental standards, and give ISA decision-makers appropriate agility and powers to reject applications to mine, and to amend required conduct from contractors where there is a threat of serious, irreversible or otherwise unacceptable harm to the marine environment, including through cumulative impact. This should include the adoption by the ISA of a conscious policy of a controlled, staged development approach to exploitation: initially cautious about the number and size of sites licensed for mining activities – with new projects not authorised until existing ones are completed and the impacts measured.

DETAILED OPPORTUNITY FOR ACTION 3B: Create as soon as possible an international research agenda to collect and synthesise high-quality scientific data (during the Decade of Ocean Science for Sustainable Development, 2021–2030), which answers strategic questions about deep-sea ecosystems required for decision-making and environmental management related to deep-seabed mining.

BY DOING THIS: The deep-sea environment can be better understood before taking decisions that could irreparably affect it. Current knowledge of species distributions, connectivity, habitat requirements, ecological functions and ecosystem services, vulnerability to mining impacts (including cumulative impacts, sediment plumes, noise and light), resilience, recovery and mitigation potential, and the influence of cumulative impacts from climate stressors can be expanded. The agenda should also support and engage existing sustained observing programmes to enhance relevant deep-sea data acquisition, improve understanding of natural variability, and develop standards around the acceptable level of statistical power for monitoring impacts of seabed mineral activities. New opportunities can emerge for industry and scientists to partner on testing technological and conceptual innovations for mineral extraction techniques that minimise harm to the marine environment. The agenda should promote FAIR data principles (findable, accessible, interoperable, reusable) and facilitate data portals that create compatibility across networks and agencies (e.g., the ISA, Intergovernmental Oceanographic Commission clearinghouse, regional fisheries management organisations).

ASSOCIATED BENEFITS: Greater understanding of deep-sea environments, and improved data quality and sharing will also assist with governance decisions beyond those relevant to seabed mining, including the negotiations at the Intergovernmental Conference on Marine Biodiversity of Areas Beyond National Jurisdiction (BBNJ), climate change talks at the United Nations Framework Convention on Climate Change (UNFCCC) and conservation initiatives, and will constitute important work towards SDG 14, including Target 14.A (“increase scientific knowledge, develop research capacity and transfer marine technology”).

ALTERNATIVE (OR ADDITIONAL) OPTION: ISA marine scientific research, data management and strategic environmental assessment functions should be strengthened, and additional requirements or incentives be exerted by the ISA upon contractors and member states, encouraging multilateral cooperation, so that more science across wider biogeographic areas is collected, analysed, published and used to inform ISA policy and regulation.

Detailed Opportunities for Action 4A and 4B

CHALLENGE 4: THERE IS AN INHERENT CONFLICT BETWEEN A DUTY TO PROTECT THE MARINE ENVIRONMENT, AND A CALL TO MINE THE DEEP SEABED FOR METALS.

DETAILED OPPORTUNITY FOR ACTION 4A:
Enable as soon as possible an expert and independent environmental and scientific committee to handle ISA environmental regulations and decision-making, to assess monitoring and impact assessment and to identify triggers for regulatory action or cessation of mining.

BY DOING THIS: The ISA can bolster its capacity and expertise to manage its mandated environmental stewardship function. This should be run separately from other ISA functions (such as contract award and management, revenue collection and distribution, and direct engagement in mining, through The Enterprise).

ASSOCIATED BENEFITS: A science-driven, expert-led, transparent, independent, consistent and consultative regulatory agency will garner greater public and investor trust and confidence, which should enhance the ISA’s ability to meet its bifurcated duty both to develop the mineral resources of the Area and to protect and preserve the marine environment. Any steps taken to strengthen the ISA’s regulatory capacity will contribute towards the goal of preventing serious harm to the marine environment, and minimising other harmful effects from mining.

DETAILED OPPORTUNITY FOR ACTION 4B: Ensure the declaration (by 2022) and enforcement of a network of large, biologically representative, fully protected no-mining zones established in perpetuity prior to any award of exploitation contracts, across all ocean regions under ISA jurisdiction. These should be designed according to scientific principles, and placed on the basis of physical, geochemical, ecological and social analyses. Ideally, they should cover at least 30 percent of the Area, ensure connectivity, be representative of habitats that will be lost to mining and protect particularly vulnerable habitats.

BY DOING THIS: The precautionary approach to environmental management of deep-seabed mining is enacted by ensuring that representative benthic habitats and associated ecosystems are protected from harm on regional scales. This is particularly important given uncertainties regarding the severity, frequency and spatial extent of mining impacts.

ASSOCIATED BENEFITS: Protected areas can serve as refugia for marine species, offer climate resilience and preserve ecosystem functions. Their declaration would enable states to demonstrate efforts towards their international duties to ensure that the marine environment is effectively protected from mining's harmful effects (UNCLOS; UN 1982), to achieve in-situ conservation (Convention on Biological Diversity; UN 1992) and to conserve a percentage of marine areas (SDG 14.5 and Aichi Biodiversity Target 11).

Detailed Opportunity for Action 5

CHALLENGE 5: THE REMOTE NATURE OF THE DEEP OCEAN AND ITS UNFAMILIARITY TO MOST PEOPLE RAISE THE CHALLENGE OF ENSURING THE PARTICIPATION OF ALL RELEVANT STAKEHOLDERS TO INFORM DECISIONS TAKEN AT THE INTERNATIONAL AND STATE LEVEL THAT RELATE TO AREAS OUT OF SIGHT.

DETAILED OPPORTUNITY FOR ACTION 5: The ISA, member governments and non-governmental bodies should cooperate immediately to enhance societal awareness of the choices associated with deep-seabed mining (through social media, traditional media, formal educational programmes and other forms of outreach) and diverse and inclusive opportunities for interested parties to have their views heard and considered in deep-seabed mining decision-making processes. The ISA regime, and states with mining interests, should maximise opportunities for public and expert consultation, including during the contract application, approval and review process. Non-governmental observers should be facilitated to attend ISA and state meetings. Such meetings should be supported by technical advisory inputs that are comprehensive and fully explained (with dissenting views noted) and produced in a timely fashion. Meeting documents, contracts, financial information, compliance information and environmental data should all be made publicly available immediately.

BY DOING THIS: Better and more durable decisions will be taken. It will enable the collection of comprehensive relevant information by decision-makers and will enhance public understanding, consent and commitment to implementation. Trust and confidence in the ISA's decisions will be improved.

ASSOCIATED BENEFITS: Consultation with as wide a group of experts and stakeholders as possible will assist national and international policy-makers to take the complex and momentous judgement calls that are inherent in deciding what degree of environmental harm is deemed acceptable in order to facilitate access to metals. It will also be a means for governments to operationalise commitments made at the international level (various regional environmental treaties, the Rio Declaration (UN Conference on Environment and Development 1992) and Rio+20), as well as the ISA's duty to act on behalf of all of humankind (UNCLOS; UN 1982).

ALTERNATIVE (OR ADDITIONAL) OPTION: Member governments should:

- attend ISA meetings at which crucial decisions are taken (for example, approval of the ISA's Exploitation Regulations currently under negotiation, or a decision whether or not (and on what terms) to approve or disapprove the first mining application made to the ISA);
- hold meaningful prior national consultations on the relevant issues, before attending; and
- reflect the results of those national consultations in their positions at the ISA.

Detailed Opportunity for Action 6

CHALLENGE 6: THE GROWING GLOBAL DEMAND FOR METALS IS THREATENING TO PUSH EXTRACTIVE PRACTICES BEYOND PLANETARY BOUNDARIES.

DETAILED OPPORTUNITY FOR ACTION 6: Engage urgently in independent research and long-term planning to facilitate a circular economy for targeted rare metals and rare earth elements, initially with a five-year programme (2020–25). Focus attention on Life Cycle Sustainability Analysis (Van der Voet et al. 2019) and developing alternative methods to address the metal demand. Create incentives and reduce barriers to promote the following:

- Recycle, reduce, re-use opportunities
- Product redesign that enables improved metal recycling or extended product lifetime
- Demand reduction via use of alternatives and consumer behaviour change
- Improved sustainability of on-land mining practices
- More sustainable metal waste disposal practices and less resulting pollution

BY DOING THIS: The negative environmental impacts of land-based mining can be minimised and the need for deep-seabed mining is reduced, while human development is supported, in line with the SDGs. Social, economic, behavioural and technical issues can be addressed together.

ASSOCIATED BENEFITS: More government policy focus, and consumer awareness and demand about metal sourcing and use, should stimulate innovation and lead to better environmental and human rights practices by extractive industries. The circular economy and enhanced secondary production of metals will reduce energy use and carbon emissions. It should also enhance competitiveness and economic growth, and new employment opportunities. This can also identify possible less harmful alternatives to deep-seabed mining.

Endnote and References

Endnote

1. Brazil has more recently indicated that the site in question falls within national jurisdiction (not the ISA's jurisdiction), according to an extended continental shelf claim, lodged by Brazil subsequent to the award of their ISA contract.

References

Aanesen, Margrethe and Claire W. Armstrong. 2019. "Trading Off Co-Produced Marine Ecosystem Services: Natural Resource Industries Versus Other Use and Non-Use Ecosystem Service Values." *Frontiers in Marine Science* 6. https://doi.org/10.3389/fmars.2019.00102.

African Group. 2018a. "Statement by Algeria on Behalf of the African Group to the International Seabed Authority 6 July 2018." https://www.isa.org.jm/document/statement-algeria-obo-african-group-1.

African Group. 2018b. "Statement by Algeria on Behalf of the African Group to the International Seabed Authority 9 July 2018." https://www.isa.org.jm/document/statement-algeria-obo-african-group-2.

African Group. 2019. "Statement by Algeria on Behalf of the African Group to the International Seabed Authority 25 February 2019." https://www.isa.org.jm/document/algeria-obo-african-group.

Aguon, Julian and Julie Hunter. 2018. "Second Wave Due Diligence: The Case for Incorporating Free, Prior, and Informed Consent into the Deep Sea Mining Regulatory Regime." *Stanford Environmental Law Journal* 38: 3–56.

Ali, Saleem H., Damien Giurco, Nicholas Arndt, Edmund Nickless, Graham Brown, Alecos Demetriades, Ray Durrheim et al. 2017. "Mineral Supply for Sustainable Development Requires Resource Governance." *Nature* 543 (7645): 367–72.

Amon, Diva J., Amanda F. Ziegler, Thomas G. Dahlgren, Adrian G. Glover, Aurélie Goineau, Andrew J. Gooday, Helena Wiklund and Craig R. Smith. 2016. "Insights into the Abundance and Diversity of Abyssal Megafauna in a Polymetallic-Nodule Region in the Eastern Clarion-Clipperton Zone." *Scientific Reports* 6 (July): 30492. https://doi.org/10.1038/srep30492.

Anderson, K. and G. Peters. 2016. "The trouble with negative emissions." *Science* 354 (6309): 182–83. https://doi.org/10.1126/science.aah4567.

Ardron, Jeff A., Henry A. Ruhl and Daniel O. B. Jones. 2018. "Incorporating Transparency into the Governance of Deep-Seabed Mining in the Area beyond National Jurisdiction." *Marine Policy* 89 (February): 58–66. https://doi.org/10.1016/j.marpol.2017.11.021.

Ardyna, Mathieu, Léo Lacour, Sara Sergi, Francesco d'Ovidio, Jean-Baptiste Sallée, Mathieu Rembauville, Stéphane Blain et al. 2019. "Hydrothermal Vents Trigger Massive Phytoplankton Blooms in the Southern Ocean." *Nature Communications* 10 (1): 2451. https://doi.org/10.1038/s41467-019-09973-6.

Armstrong, Claire W., Naomi S. Foley, Rob Tinch and Sybille van den Hove. 2012. "Services from the Deep: Steps towards Valuation of Deep Sea Goods and Services." *Ecosystem Services* 2 (December): 2–13. https://doi.org/10.1016/j.ecoser.2012.07.001.

Arrobas, Daniele La Porta, Kirsten Lori Hund, Michael Stephen Mccormick, Jagabanta Ningthoujam and John Richard Drexhage. 2017. *The Growing Role of Minerals and Metals for a Low Carbon Future (English)*. Washington, DC: World Bank Group. http://documents.worldbank.org/curated/en/207371500386458722/The-Growing-Role-of-Minerals-and-Metals-for-a-Low-Carbon-Future.

Backwell, Ben. 2019. "Globalization of Offshore Wind." Paper presented at GWEC, Tokyo, 8 March 2019. Brussels: Global Wind Energy Council.

Batker, David and Rowan Schmidt. 2015. "Environmental and Social Benchmarking Analysis of Nautilus Minerals Inc: Solwara 1 Project." Earth Economics. https://mining.com/wp-content/uploads/2015/06/Earth-Economics-Environmental-Social-Benchmarking-Solwara-1-2015.pdf.

Baturin, Gleb Nikolaevich. 1982. *Phosphorites on the Sea Floor Origin, Composition and Distribution*. Vol. 33 of *Developments in Sedimentology.* Elsevier Scientific. https://www.sciencedirect.com/bookseries/developments-in-sedimentology/vol/33/suppl/C.

Belgian Government. 2018. "Strengthening Environmental Scientific Capacity of the ISA." Submission by Belgium to the International Seabed Authority, 22 June 2018. https://ran-s3.s3.amazonaws.com/isa.org.jm/s3fs-public/files/documents/belgium-capacity.pdf.

Bleischwitz, Raimund, Victor Nechifor, Matthew Winning, Beijia Huang and Yong Geng. 2018. "Extrapolation or Saturation – Revisiting Growth Patterns, Development Stages and Decoupling." *Global Environmental Change* 48 (January): 86–96. https://doi.org/10.1016/j.gloenvcha.2017.11.008.

Bloomberg. 2019. "Global Offshore Wind Power Market Will Grow at a CAGR of 18% During 2019-2023 | Technavio." Press release, 28 May. https://www.bloomberg.com/press-releases/2019-05-28/global-offshore-wind-power-market-will-grow-at-a-cagr-of-18-during-2019-2023-technavio.

Bluhm, Hartmut. 2001. "Re-Establishment of an Abyssal Megabenthic Community after Experimental Physical Disturbance of the Seafloor." *Deep Sea Research Part II: Topical Studies in Oceanography*, Environmental Impact Studies for the Mining of Polymetallic Nodules from the Deep Sea 48 (17): 3841–68. https://doi.org/10.1016/S0967-0645(01)00070-4.

BNEF (Bloomberg New Energy Finance). 2019. *Offshore Wind Projects June 2019.* London: BNEF.

Boehlert, G. and Gill, A. 2010. "Environmental and Ecological Effects of Ocean Renewable Energy Development: A Current Synthesis." *Oceanography* 23 (2): 68–81.

Boetius A. and M. Haeckel. 2018. “Mind the Seafloor.” *Science* 359 (6371): 34–36.

Bosch, J., I. Stafell and A. Hawkes. 2018. “Temporally Explicit and Spatially Resolved Global Offshore Wind Energy Potentials.” *Energy* 163: 766–81.

Boubault, A. and N. Maizi. 2019. “Devising Mineral Resource Supply Pathways to a Low-Carbon Electricity Generation by 2100.” *Resources* 8 (1): 33. https://doi.org/10.3390/resources8010033.

Brandt, M., A. Dragon, A. Diederichs, M. Bellmann, V. Wahl, W. Piper, J. Nabe-Nielsen, G. Nehls. 2018. “Disturbance of Harbour Porpoises During Construction of the First Seven Offshore Wind Farms in Germany.” *Marine Ecology Progress Series* 596, 213–32. https://doi.org/10.3354/meps12560.

Brown, Chris G. 2018. “Mining at 2,500 Fathoms under the Sea: Thoughts on an Emerging Regulatory Framework.” *Ocean Science Journal* 53 (2): 287–300. https://doi.org/10.1007/s12601-018-0033-z.

Brown, T.J., N.E. Idoine, E.R. Raycraft, R.A. Shaw, E.A. Deady, J. Rippingale, T. Bide, C.E. Wrighton, J. Rodley. 2014. *World Mineral Production 2008–2012*. Keyworth: British Geological Survey.

Burdige, D. 2007. “Preservation of Organic Matter in Marine Sediments: Controls, Mechanisms, and an Imbalance in Sediment Organic Carbon Budgets?”. *Chemical Reviews* 107 (2): 467–85.

Carr, Sarah. 2019. “All Things to All People: What Different Groups Mean When They Talk about the Blue Economy.” The Skimmer on Marine Ecosystems and Management. 18 March. https://meam.openchannels.org/news/skimmer-marine-ecosystems-and-management/all-things-all-people-what-different-groups-mean-when.

Carstensen, J., O.D. Henriksen and J. Teilmann. 2006. “Impacts of Offshore Wind Farm Construction on Harbour Porpoises: Acoustic Monitoring of Echolocation Activity Using Porpoise Detectors (T-PODs).” *Marine Ecology Progress Series* (MEPS) 321: 295–308. https://doi.org/10.3354/meps321295.

Cascajo, R., Emilio García, Eduardo Quiles, Antonio Correcher and Francisco Morant. 2019. “Integration of Marine Wave Energy Converters into Seaports: A Case Study in the Port of Valencia.” *Energies* 12 (5): 787. https://doi.org/10.3390/en12050787.

Church, C. and Crawford, A. 2018. *Green Conflict Minerals.* Winnipeg: International Institute for Sustainable Development.

Clack, C.T.M., Staffan A. Qvist, Jay Apt, Morgan Bazilian, Adam R. Brandt, Ken Caldeira, Steven J. Davis et al. 2017. “Evaluation of a Proposal for Reliable Low-Cost Grid Power with 100% Wind, Water, and Solar.” *Proceedings of the National Academy of Sciences*, 114 (26): 6722–27. https://doi.org/10.1073/pnas.1610381114.

Clark, Malcolm R. and Derek P. Tittensor. 2010. “An Index to Assess the Risk to Stony Corals from Bottom Trawling on Seamounts.” *Marine Ecology* 31 (S1): 200–11. https://doi.org/10.1111/j.1439-0485.2010.00392.x.

Clark, Malcolm R., Franziska Althaus, Thomas A. Schlacher, Alan Williams, David A. Bowden and Ashley A. Rowden. 2016. “The Impacts of Deep-Sea Fisheries on Benthic Communities: A Review.” *ICES Journal of Marine Science* 73 (S1): i51–69. https://doi.org/10.1093/icesjms/fsv123.

Collins, Patrick Colman, Peter Croot, Jens Carlsson, Ana Colaço, Anthony Grehan, Kiseong Hyeong, Robert Kennedy et al. 2013. “A Primer for the Environmental Impact Assessment of Mining at Seafloor Massive Sulfide Deposits.” *Marine Policy* 42 (November): 198–209. https://doi.org/10.1016/j.marpol.2013.01.020.

Contardo, S., R. Hoeke, M. Hemer, G. Symonds, K. McInnes and J. O’Grady. 2018. “In Situ Observations and Simulations of Coastal Wave Field Transformation by Wave Energy Converters.” *Coastal Engineering*, 17 July. https://doi.org/10.1016/j.coastaleng.2018.07.008.

Cook Islands News. 2018. “Ocean floor holds rich future.” 21 October. http://www.cookislandsnews.com/item/71099-ocean-floor-holds-rich-future.

Copping, A., N. Sather, L. Hanna, J. Whiting, G. Zydlewski, G. Staines, A. Gill, I. Hutchison et al. 2016. *Annex IV 2016 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Pacific Northwest National Laboratory.* https://tethys.pnnl.gov/publications/state-of-the-science-2016.

Copping, A. et al., 2019. *European Wave and Tidal Energy Conference Proceedings.* https://ewtec.org/proceedings/.

Craik, A. Neil, Alfonso Ascencio-Herrera, Andres Rojas, Christopher Brown, Dire Tladi, Eden Charles, Elie Jarmache et al. 2018. *Legal Liability for Environmental Harm: Synthesis and Overview*. Liability Issues for Deep Seabed Mining Series, Paper No. 1, July. Centre for International Governance Innovation. https://www.cigionline.org/publications/legal-liability-environmental-harm-synthesis-and-overview.

Cuvelier, Daphne, Sabine Gollner, Daniel O.B. Jones, Stefanie Kaiser, Pedro Martínez Arbizu, Lena Menzel, Nélia C. Mestre et al. 2018. “Potential Mitigation and Restoration Actions in Ecosystems Impacted by Seabed Mining.” *Frontiers in Marine Science* 5.

De Jong, K., M.C.P. Amorim, P.J. Fonseca, C.J. Fox and K.U. Heubel. 2018. “Noise Can Affect Acoustic Communication and Subsequent Spawning Success in Fish.” *Environmental Pollution* 237: 814–23.

Deetman, Sebastiaan, Stefan Pauliuk, Detlef P. van Vuuren, Ester van der Voet and Arnold Tukker. 2018. “Scenarios for Demand Growth of Metals in Electricity Generation Technologies, Cars, and Electronic Appliances.” *Environmental Science and Technology* 52: 4950−59. https://doi.org/10.1021/acs.est.7b05549.

Dogger Bank Wind Farms. 2019. “World’s Largest Wind Farm Successful in CfD Auction.” Press release, 20 September. https://doggerbank.com/downloads/CfD-results-press-release-FINAL.pdf.

Dominish, E., N. Florin and S. Teske. 2019. *Responsible Minerals Sourcing for Renewable Energy.* Report prepared for Earthworks by the Institute for Sustainable Futures, University of Technology Sydney.

DSM Observer. 2018. “The Writing is on the Wall for Solwara 1 – PNG Should Withdraw.” January. http://dsmobserver.com/2018/01/solwara-1-png-withdraw.

Du Preez, Cherisse and Charles R. Fisher. 2018. “Long-Term Stability of Back-Arc Basin Hydrothermal Vents.” *Frontiers in Marine Science* 5. https://doi.org/10.3389/fmars.2018.00054.

Dunn, Daniel C., Cindy L. Van Dover, Ron J. Etter, Craig R. Smith, Lisa A. Levin, Telmo Morato, Ana Colaço et al. 2018. “A Strategy for the Conservation of Biodiversity on Mid-Ocean Ridges from Deep-Sea Mining.” *Science Advances* 4 (7). https://doi.org/10.1126/sciadv.aar4313.

Ellis, Derek V. 2001. “A Review of Some Environmental Issues Affecting Marine Mining.” *Marine Georesources & Geotechnology* 19 (1): 51–63. https://doi.org/10.1080/10641190109353804.

Elsner, P. and S. Suarez. 2019. “Renewable Energy from the High Seas: Geo-Spatial Modelling of Resource Potential and Legal Implications for Developing Offshore Wind Projects Beyond the National Jurisdiction of Coastal States.” *Energy Policy* 128: 918–29. https://doi.org/10.1016/j.enpol.2019.01.064.

ETIP Ocean. 2019. *Powering Homes Today, Powering Nations Tomorrow.* https://www.etipocean.eu/resources/powering-homes-today-powering-nations-tomorrow.

Eurek, Kelly, Patrick Sullivan, Michael Gleason, Dylan Hettinger, Donna Heimiller and Anthony Lopez. 2017. “An Improved Global Wind Resource Estimate for Integrated Assessment Models.” Preprint. Golden, CO: National Renewable Energy Laboratory.

European Commission. 2018. *A Clean Planet for All. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy.* Brussels: European Commission.

Faulkner, R., N. Merchant and R. Martinez. 2018. “Marine Noise Budgets in Practice.” *Conservation Letters* 11 (3): 1–8. https://doi.org/10.1111/conl.12420.

Feichtner, Isabel. 2019. “Mining for Humanity in the Deep Sea and Outer Space: The Role of Small States and International Law in the Extraterritorial Expansion of Extraction.” *Leiden Journal of International Law* 32 (2): 255–74. https://doi.org/10.1017/S0922156519000013.

Fiji Sun. 2019. “Fiji Budget 2019: A Budget That Is Securing Our Nation A Sustainable Future.” 10 June. https://fijisun.com.fj/2019/06/10/fiji-budget-2019-a-budget-that-is-securing-our-nation-a-sustainable-future.

Fleming, Jory, Lucinda Ford and Edward Hornsby. 2019. *Facing the Abyss: The Future of Deep Sea Mining*. Environmental Change Institute, Oxford University. https://doi.org/10.6084/m9.figshare.7564976.v1.

Fowler, A., A. Jørgensen, J. Svendsen, P. Macreadie, D. Jones, A. Boon, D. Booth. et al. 2018. “Environmental Benefits of Leaving Offshore Infrastructure in the Ocean.” *Frontiers in Ecology and Environment* 16(10): 571–78. https://doi.org/10.1002/fee.1827.

French, Duncan and Richard Collins. 2019. “A Guardian of Universal Interest or Increasingly Out of Its Depth? The International Seabed Authority Turns 25.” *International Organizations Law Review*, April. http://eprints.lincoln.ac.uk/34948/.

Furre, A.-K., O. Eiken, H. Alnæs, J.N. Vevatne and A.F. Kiær. 2017. “20 Years of Monitoring CO_2-Injection at Sleipner.” *Energy Procedia* 114: 3916–26. https://doi.org/10.1016/j.egypro.2017.03.1523.

German, C.R., L.L. Legendre, S.G. Sander, N. Niquil, G.W. Luther, L. Bharati, X. Han and N. Le Bris. 2015. “Hydrothermal Fe Cycling and Deep Ocean Organic Carbon Scavenging: Model-Based Evidence for Significant POC Supply to Seafloor Sediments.” *Earth and Planetary Science Letters* C (419): 143–53. https://doi.org/10.1016/j.epsl.2015.03.012.

German Government. 2018. “Statement by Germany to the International Seabed Authority 27 June 2018.” https://www.isa.org.jm/document/isba24c18.

Ghisellini, Patrizia, Catia Cialani and Sergio Ulgiati. 2016. “A Review on Circular Economy: The Expected Transition to a Balanced Interplay of Environmental and Economic Systems.” *Journal of Cleaner Production, Towards Post Fossil Carbon Societies: Regenerative and Preventative Eco-Industrial Development* 114 (February): 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007.

Giurco, Damien, Elsa Dominish, Nick Florin, Takuma Watari and Benjamin McLellan. 2019. “Requirements for Minerals and Metals for 100% Renewable Scenarios.” In *Achieving the Paris Climate Agreement Goals*, edited by S. Teske, 437–57. https://doi.org/10.1007/978-3-030-05843-2_11.

Gollner, Sabine, Stefanie Kaiser, Lena Menzel, Daniel O.B. Jones, Alastair Brown, Nelia C. Mestre, Dick van Oevelen et al. 2017. “Resilience of Benthic Deep-Sea Fauna to Mining Activities.” *Marine Environmental Research* 129 (August): 76–101. https://doi.org/10.1016/j.marenvres.2017.04.010.

Gooday, Andrew J., Maria Holzmann, Clémence Caulle, Aurélie Goineau, Olga Kamenskaya, Alexandra A.-T. Weber and Jan Pawlowski. 2017. “Giant Protists (Xenophyophores, Foraminifera) Are Exceptionally Diverse in Parts of the Abyssal Eastern Pacific Licensed for Polymetallic Nodule Exploration.” *Biological Conservation* 207 (March): 106–16. https://doi.org/10.1016/j.biocon.2017.01.006.

Goodenough, Kathryn M., Frances Wall and David Merriman. 2018. “The Rare Earth Elements: Demand, Global Resources, and Challenges for Resourcing Future Generations.” *Natural Resources Research* 27 (2), April. https://doi.org/10.1007/s11053-017-9336-5.

Graedel, T.E., E.M. Harper, N.T. Nassar and B.K. Reck. 2015. “On the Materials Basis of Modern Society.” *Proceedings of the National Academy of Sciences* 112: 6295. https://doi.org/10.1073/pnas.1312752110.

Greenpeace. 2019. *In Deep Water: The Emerging Threat Of Deep Sea Mining.* https://storage.googleapis.com/planet4-international-stateless/2019/06/f223a588-in-deep-water-greenpeace-deep-sea-mining-2019.pdf.

Grubler, A., C. Wilson, N. Bento, B. Boza-Kiss, V. Krey, D.L. McCollum, N.D. Rao et al. 2018. “A Low Energy Demand Scenario for Meeting the 1.5 Degrees C Target and Sustainable Development Goals without Negative Emission Technologies.” *Nature Energy* 3: 515–27. https://dx.doi.org/10.1038/s41560-018-0172-6.

Hammar, L., A. Wikström and S. Molander. 2014. Assessing Ecological Risks of Offshore Wind Power on Kattegat Cod. *Renewable Energy* 66: 414–24.

Hannington, M., J. Jamieson, T. Monecke and S. Petersen. 2010. “Modern Sea-Floor Massive Sulfides and Base Metal Resources: Toward an Estimate of Global Sea-Floor Massive Sulfide Potential.” *Society of Economic Geologists, Inc.* Special Publication 15, pp. 317–38.

Hein, J.R. and A. Koschinsky. 2014. “Deep-ocean Ferromanganese Crusts and Nodules.” In *Treatise on Geochemistry*, 2nd edition, edited by Heinrich D. Holland and Karl K. Turekian, 273–91. Elsevier.

Hein, J.R., K. Mizell, A. Koschinsky and T.A. Conrad. 2013. “Deep-Ocean Mineral Deposits as a Source of Critical Metals for High- and Green-Technology Applications: Comparison with Land-Based Resources.” *Ore Geology Reviews* 51: 1–14.

Hertwich, E.G., T. Gibon, E.A. Bouman, A. Arvesen, S. Suh, G.A. Heath et al. 2015. “Integrated Life-Cycle Assessment of Electricity-Supply Scenarios Confirms Global Environmental Benefit of Low-Carbon Technologies.” *Proceedings of the National Academy of Sciences* 112 (20): 6277e82.

Hoegh-Guldberg. O. et al. 2019. *The Ocean as a Solution to Climate Change: Five Opportunities for Action*. Washington, DC: World Resources Institute. http://www.oceanpanel.org/climate.

House of Commons. 2019. *Hansard*, 20 February, vol. 654, col. 572WH. https://hansard.parliament.uk/Commons/2019-02-20/debates/19022027000002/UKDeepSeaMiningIndustry.

IEA (International Energy Agency). 2017. *Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations.* Paris: International Energy Agency. www.iea.org/etp2017.

IEA. 2018. *Offshore Energy Outlook. World Energy Outlook Series.* Paris: International Energy Agency.

IEA. 2019a. *World Energy Outlook 2019*. www.iea.org/reports/world-energy-outlook-2019.

IEA. 2019b. *Offshore Wind Outlook 2019. World Energy Outlook Special Report*. https://www.iea.org/reports/offshore-wind-outlook-2019.

IEA. 2019c. *Global Energy & CO2 Status Report (GECO): The Latest Trends in Energy and Emissions in 2018*. https://www.iea.org/reports/global-energy-co2-status-report-2019.

IJGlobal. 2019. *Asset Data. http://ijglobal.com.*

IPCC (Intergovernmental Panel on Climate Change). 2005. *IPCC Special Report on Carbon Dioxide Capture and Storage.* Prepared by Working Group III of the Intergovernmental Panel on Climate Change, edited by B. Metz, O. Davidson, H.C. de Coninck, M. Loos and L.A. Meyer. Cambridge, UK and New York: Cambridge University Press.

IPCC. 2018. *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.* Edited by V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield. Cambridge, UK and New York: Cambridge University Press.

IRENA (International Renewable Energy Agency). 2014a. *Ocean Thermal Energy Conversion: Technology Brief.* Abu Dhabi: IRENA. www.irena.org/DocumentDownloads/Publications/Ocean_Thermal_Energy_V4_web.pdf.

IRENA. 2014b. *Tidal Energy: Technology Brief.* Abu Dhabi: IRENA. www.irena.org/documentdownloads/publications/tidal_energy_v4_web.pdf.

IRENA. 2014c. *Wave Energy: Technology Brief.* Abu Dhabi: IRENA. www.irena.org/documentdownloads/publications/wave-energy_v4_web.pdf.

IRENA. 2018a. *Offshore Wind Investment, Policies and Job Creation: Review of Key Findings for G7 Ministerial Meetings, Halifax, Canada*. Abu Dhabi: IRENA. www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_offshore_wind_note_G7_2018.pdf?la=en&hash=B186614D923AB1F0A07D7285612C4B037057A0C0.

IRENA. 2018b. *Renewable Energy Benefits Leveraging Local Capacity for Offshore Wind.* Abu Dhabi: IRENA. www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/May/IRENA_Leveraging_for_Offshore_Wind_2018.pdf.

IRENA. 2019a. *Global Energy Transformation. A Roadmap to 2050.* 2019 Edition. Abu Dhabi: IRENA. www.irena.org/publications/2019/Apr/Global-energy-transformation-A-roadmap-to-2050-2019Edition.

IRENA. 2019b. *Renewable Energy: A Gender Perspective.* Abu Dhabi: IRENA. https://irena.org/-/media/Files/IRENA/Agency/Publication/2019/Jan/IRENA_Gender_perspective_2019.pdf.

IRENA. 2019c. *Renewable Capacity Statistics 2019.* Abu Dhabi: IRENA. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Mar/IRENA_RE_Capacity_Statistics_2019.pdf.

IRP (International Resource Panel). 2019. *Mineral Resource Governance in the 21st Century: Gearing Extractive Industries Towards Sustainable Development*, edited by Elias T. Ayuk, Antonio M. Pedro, Paul Ekins, Bruno Oberle, Julius Gatune, Ben Milligan et al. Nairobi: United Nations Environment Programme. https://www.resourcepanel.org/reports/mineral-resource-governance-21st-century.

ISA (International Seabed Authority). 2013. *Implementation of Article 82 of the United Nations Convention on the Law of the Sea*. Kingston, Jamaica: ISA.

ISA. 2017. *Report of the Chair of the Legal and Technical Commission on the Work of the Commission at Its Session in 2017*. Document ISBA/23/C/13. Kingston, Jamaica: ISA. https://www.isa.org.jm/document/isba23c13.

ISA. 2019a. *Comparative Study of the Existing National Legislation on Deep Seabed Mining*. Kingston, Jamaica: ISA. https://www.isa.org.jm/document/comparative-study-existing-national-legislation-deep-seabed-mining-0.

ISA. 2019b. *Implementation of the Authority's Strategy for the Development of Regional Environmental Management Plans for the Area*. Document ISBA/25/C/13. Kingston, Jamaica: ISA. https://www.isa.org.jm/document/isba25c13.

ISA. 2019c. *Draft Regulations on Exploitation of Mineral Resources in the Area*. Document ISBA/25/C/18. Kingston, Jamaica: ISA. https://www.isa.org.jm/document/isba25c18.

ISA. 2019d. *Draft Regulations on Exploitation of Mineral Resources in the Area*. ISBA/25/C/WP.1. Kingston, Jamaica: ISA. https://www.isa.org.jm/document/isba25cwp1-0.

ISA. n.d. "The Mining Code." Kingston, Jamaica: ISA. https://www.isa.org.jm/mining-code.

ITLOS (International Tribunal for the Law of the Sea). 2011. "Responsibilities and Obligations of States Sponsoring Persons and Entities with Respect to Activities in the Area - List of Cases: No. 17." Advisory Opinion, 1 February. International Tribunal for the Law of the Sea. https://www.itlos.org/en/cases/list-of-cases/case-no-17/#c587.

Jacobson, M.Z., Mark A. Delucchi, Zack A.F. Bauer, Savannah C. Goodman, William E. Chapman, Mary A. Cameron, Cedric Bozonnat et al. 2017. "100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World." *Joule* 1, 108–121. http://dx.doi.org/10.1016/j.joule.2017.07.005.

Jacobson, M.Z., M.A. Delucchi, M.A. Cameron and B.V. Mathiesen. 2018. "Matching Demand with Supply at Low Cost in 139 Countries Among 20 World Regions with 100% Intermittent Wind, Water, and Sunlight (WWS) for all Purposes." *Renewable Energy* 123: 236–48. https://doi.org/10.1016/j.renene.2018.02.009.

Jacobson, Mark Z., Mark A. Delucchi, Mary A. Cameron, Indu Priya Manogaran, Yanbo Shu, Anna-Katharina von Krauland. 2019. "Impacts of Green New Deal Energy Plans on Grid Stability, Costs, Jobs, Health, and Climate in 143 Countries." *One Earth* 1 (4): 449–63.

Jaeckel, A. 2016. "Deep Seabed Mining and Adaptive Management: The Procedural Challenges for the International Seabed Authority." *Marine Policy* 70: 205–11.

Jaeckel, Aline L. 2017. *The International Seabed Authority and the Precautionary Principle: Balancing Deep Seabed Mineral Mining and Marine Environmental Protection*. Publications on Ocean Development. Vol. 83. Nijhoff: Brill. https://brill.com/view/title/33967.

Jaeckel, Aline, Kristina M. Gjerde and Jeff A. Ardron. 2017. "Conserving the Common Heritage of Humankind – Options for the Deep-Seabed Mining Regime." *Marine Policy* 78 (April): 150–57. https://doi.org/10.1016/j.marpol.2017.01.019.

Johnson, David Edward. 2019. "Protecting the Lost City Hydrothermal Vent System: All Is Not Lost, or Is It?" *Marine Policy* 107 (September): 103593. https://doi.org/10.1016/j.marpol.2019.103593.

Jones, Daniel O.B., Stefanie Kaiser, Andrew K. Sweetman, Craig R. Smith, Lenaick Menot, Annemiek Vink, Dwight Trueblood et al. 2017. "Biological Responses to Disturbance from Simulated Deep-Sea Polymetallic Nodule Mining." *PLOS ONE* 12 (2): e0171750. https://doi.org/10.1371/journal.pone.0171750.

Kaiser, M., K. Clarke, H. Hinz, M. Austen, P. Somerfield and I. Karakassis. 2006. "Global Analysis and Recovery of Benthic Biota to Fishing." *Marine Ecology Progress Series* 311 (March): 1–14. https://doi.org/10.3354/meps311001.

Kim, Rakhyun. 2017. "Should Deep Seabed Mining Be Allowed?" *Marine Policy* 82 (August): 134–37. https://doi.org/10.1016/j.marpol.2017.05.010.

Kirchain, Randolph and Richard Roth. 2019. "MIT Presentation: Decision Analysis Framework & Review of Cash Flow Approach." Paper presented at the Financial Payment System Working Group Meeting, February. https://www.isa.org.jm/document/mit-presentation-decision-analysis-framework-review-cash-flow-approach.

Konar, Manaswita and Helen Ding. Forthcoming. *A Sustainable Ocean Economy for 2050: Approximating Its Benefits and Costs.* Washington, DC: World Resources Institute.

Krewitt, W., K. Nienhaus, C. Kleßmann, C. Capone, E. Stricker, W. Graus, M. Hoogwijk, N. Supersberger, U. von Winterfeld and S. Samadi. 2009. "Role and Potential of Renewable Energy and Energy Efficiency for Global Energy Supply." *Climate Change* 18: 336.

LDAC (Long Distance Advisory Council). 2019. "LDAC Advice on Deepsea Mining R.04.19.WG5." Madrid: Long Distance Advisory Council. https://ldac.eu/en/publications/706-ldac-advice-on-deepsea-mining-r-04-19-wg5.

Le, Jennifer T., Lisa A. Levin and Richard T. Carson. 2017. "Incorporating Ecosystem Services into Environmental Management of Deep-Seabed Mining." *Deep Sea Research Part II: Topical Studies in Oceanography*, Advances in Deep-Sea Biology: Biodiversity, Ecosystem Functioning and Conservation 137 (March): 486–503. https://doi.org/10.1016/j.dsr2.2016.08.007.

Levin, Lisa A., Kathryn Mengerink, Kristina M. Gjerde, Ashley A. Rowden, Cindy Lee Van Dover, Malcolm R. Clark, Eva Ramirez-Llodra et al. 2016. "Defining 'Serious Harm' to the Marine Environment in the Context of Deep-Seabed Mining." *Marine Policy* 74 (December): 245–59. https://doi.org/10.1016/j.marpol.2016.09.032.

Levin, Lisa A., Chih-Lin Wei, Daniel C. Dunn, Diva J. Amon, Oliver S. Ashford, William Cheung, Ana Colaço et al. 2020. "Climate Change Considerations are Fundamental to Management of Deep-Sea Resource Extraction." *Global Change Biology (in press).*

Lewis, A., S. Estefen, J. Huckerby, W. Musial, T. Pontes and J. Torres-Martinez. 2011. "Ocean Energy." In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, edited by O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, et al. Cambridge, UK, and New York: Cambridge University Press.

Lily, Hannah. 2018. *Sponsoring State Approaches to Liability Regimes for Environmental Damage Caused by Seabed Mining*. Liability Issues for Deep Seabed Mining Series, Paper No. 3, December. Centre for International Governance Innovation. https://www.cigionline.org/publications/sponsoring-state-approaches-liability-regimes-environmental-damage-caused-seabed.

Lodge, Michael W. and Philomène A. Verlaan. 2018. "Deep-Sea Mining: International Regulatory Challenges and Responses." *Elements* 14 (5): 331–36. https://doi.org/10.2138/gselements.14.5.331.

Lunney, E., M. Ban, N. Duic and A. Foley. 2017. "A State-of-the-Art Review and Feasibility Analysis of High Altitude Wind Power in Northern Ireland." *Renewable and Sustainable Energy Reviews* 68, 899–911. http://dx.doi.org/10.1016/j.rser.2016.08.014.

Macheriotou, L., A. Rigaux, S. Derycke, A. Vanreusel. 2020. "Phylogenetic Clustering and Rarity Imply Risk of Local Species Extinction in Prospective Deep-Sea Mining Areas of the Clarion–Clipperton Fracture Zone." *Proceedings of the Royal Society B* 287, 20192666. http://dx.doi.org/10.1098/rspb.2019.2666.

Magagna, D., L. Margheritini, A. Alessi, E. Bannon, E. Boelman, D. Bould et al. 2018. "Workshop on identification of future emerging technologies in the ocean energy sector." 27 March 2018, Ispra, Italy. Luxembourg: European Union. https://doi.org/10.2760/23207.

Marques, S. and T.C.M. de Araújo. 2019. "Survey and Assessment of Seabed Resources from the Brazilian Continental Shelf by the Law of the Sea: From National to International Jurisdictions." *Ocean & Coastal Management* 178: 104858.

Mendoza, E., D. Lithgow, P. Flores, A. Felix, T. Simas, R. Silva. 2019. "A Framework to Evaluate the Environmental Impact of OCEAN Energy Devices." *Renewable and Sustainability Reviews* 112: 440–49.

Mengerink, K.J., Cindy L. Van Dover, Jeff Ardron, Maria Baker, Elva Escobar-Briones, Kristina Gjerde, J. Anthony Koslow et al. 2014. "A call for Deep-Ocean Stewardship." *Science* 344, 696–98.

Miljutin, Dmitry M., Maria A. Miljutina, Pedro Martínez Arbizu and Joëlle Galéron. 2011. "Deep-Sea Nematode Assemblage Has Not Recovered 26 Years after Experimental Mining of Polymetallic Nodules (Clarion-Clipperton Fracture Zone, Tropical Eastern Pacific)." *Deep Sea Research Part I: Oceanographic Research Papers* 58 (8): 885–97. https://doi.org/10.1016/j.dsr.2011.06.003.

Miller, Kathryn A., Kirsten F. Thompson, Paul Johnston and David Santillo. 2018. "An Overview of Seabed Mining Including the Current State of Development, Environmental Impacts, and Knowledge Gaps." *Frontiers in Marine Science* 4. https://doi.org/10.3389/fmars.2017.00418.

Morgan, Nicole B., Stephen Cairns, Henry Reiswig and Amy R. Baco. 2015. "Benthic Megafaunal Community Structure of Cobalt-Rich Manganese Crusts on Necker Ridge." *Deep Sea Research Part I: Oceanographic Research Papers* 104 (October): 92–105. https://doi.org/10.1016/j.dsr.2015.07.003.

Mørk, G., S. Barstow, A. Kabuthand, M.T. Pontes. 2010. "Assessing the Global Wave Energy Potential." Paper presented at OMAE2010 29th International Conference on Ocean, Offshore Mechanics and Arctic Engineering, Shanghai, China, 6–11 June.

Nihous, G.C. 2018. “A Preliminary Investigation of the Effect of Ocean Thermal Energy Conversion (OTEC) Effluent Discharge Options on Global OTEC Resources.” *Journal of Marine Science and Engineering* 6 (1): 25. https://doi.org/10.3390/jmse6010025.

Niner, Holly J., Jeff A. Ardron, Elva G. Escobar, Matthew Gianni, Aline Jaeckel, Daniel O. B. Jones, Lisa A. Levin et al. 2018. “Deep-Sea Mining With No Net Loss of Biodiversity—An Impossible Aim.” *Frontiers in Marine Science* 5. https://doi.org/10.3389/fmars.2018.00053.

NMP (Namibian Marine Phosphate). n.d. “About NMP.” http://www.namphos.com (accessed 13 May 2020).

Norwegian Offshore Wind Cluster. n.d. “Makani’s First Offshore Flight Last Week.” https://offshore-wind.no/news/makanis-first-offshore-flight-last-week (accessed 14 May 2020).

Oceans of Energy. 2020. “Offshore Floating Solar Farm Installed and Operational at the Dutch North Sea.” February. https://oceansofenergy.blue/north-sea-1-offshore-solar-project.

OECD (Organisation for Economic Co-operation and Development). 2018. *Global Material Resources Outlook to 2060 – Economic drivers and environmental consequences*. Paris: OECD Publishing. oe.cd/materials-outlook.

OES (Ocean Energy Systems). 2015. *International Levelised Cost of Energy for Ocean Energy Technologies*. Ocean Energy Systems. https://www.ocean-energy-systems.org/oes-projects/levelised-cost-of-energy-assessment-for-wave-tidal-and-otec-at-an-international-level/.

Offshore Renewable Energy Catapult. 2018. *Tidal Stream and Wave Energy Cost Reduction and Industrial Benefit.* https://ore.catapult.org.uk/?orecatapultreports=tidal-stream-and-wave-energy-cost-reduction-and-industrial-benefit.

O’Neill, S.P., Athanasios Angeloudis, Peter E. Robins, Ian Walkington, Sophie L. WardaIan Masters, Matt J. Lewis et al. 2018. “Tidal Range Energy Resource and Optimization: Past Perspectives and Future Challenges.” *Renewable Energy* 127: 763–78. https://doi.org/10.1016/j.renene.2018.05.007.

Ørsted. 2019. *Making Green Energy Affordable*. Whitepaper. Gentofte, Denmark: Ørsted. https://orsted.com/en/Explore/Making-green-energy-affordable.

Pacific Islands Forum Secretariat. 2019. “2019 Femm Action Plan.” 2019 Forum Economic Ministers Meeting, Pacific Islands Forum Secretariat Conference Centre, Suva, Fiji, 8–9 May.

Paulikas, D., S. Katona, E. Ilves, G. Stone and A. O’Sullivan. 2020. *Where Should Metals for the Green Transition Come From? Comparing Environmental, Social, and Economic Impacts of Supplying Base Metals from Land Ores and Seafloor Polymetallic Nodules.* https://www.autoevolution.com/pdf/news_attachements/ocean-floor-could-be-the-next-el-dorado-for-ev-battery-raw-materials-142915.pdf.

Pavel, Claudiu C., Roberto Lacal-Arántegui, Alain Marmier, Doris Schüler, Evangelos Tzimas, Matthias Buchert, Wolfgang Jenseit and Darina Blagoeva. 2017. “Substitution Strategies for Reducing the Use of Rare Earths in Wind Turbines.” *Resources Policy* 52: 349–57. http://dx.doi.org/10.1016/j.resourpol.2017.04.010.

Petersen, S., A. Krätschell, N. Augustin, J. Jamieson, J.R. Hein and M.D. Hannington. 2016. “News from the Seabed – Geological Characteristics and Resource Potential of Deep-Sea Mineral Resources.” *Marine Policy* 70 (August): 175–87. https://doi.org/10.1016/j.marpol.2016.03.012.

Pew Charitable Trusts. 2017. *First Report of the Code Project: Developing International Seabed Authority Environmental Regulations.* Philadelphia: Pew Charitable Trusts. http://pew.org/2wiPnNk.

Pew Charitable Trusts. 2019. *Fourth Report of the Code Project: Summary of Stakeholder Comments on the 2018 ISA Draft Regulations*. Philadelphia: Pew Charitable Trusts. https://pew.org/2GqmMyN.

Pinarbaşi, K., I. Galparsoro, D. Depellegrin, J. Bald, G. Pérez-Morán and A. Borja. 2019. “A Modelling Approach for Offshore Wind Farm Feasibility with Respect to Ecosystem-Based Marine Spatial Planning.” *Science of the Total Environment*, 667: 306–17. https://doi.org/10.1016/j.scitotenv.2019.02.268.

Popova, Ekaterina, David Vousden, Warwick H.H. Sauer, Essam Y. Mohammed, Valerie Allain, Nicola Downey-Breedt, Ruth Fletcher et al. 2019. “Ecological Connectivity Between the Areas Beyond National Jurisdiction and Coastal Waters: Safeguarding Interests of Coastal Communities in Developing Countries.” *Marine Policy* 104: 90–102. https://doi.org/10.1016/j.marpol.2019.02.050.

Ramirez-Llodra, E., Hilde C. Trannum, Anita Evenset, Lisa A. Levin, Malin Andersson, Tor Erik Finne, Ana Hilario et al. 2015. “Submarine and Deep-Sea Mine Tailing Placements: A Review of Current Practices, Environmental Issues, Natural Analogs and Knowledge Gaps in Norway and Internationally.” *Marine Pollution Bulletin 97, 13–35. https://doi.org/10.1016/j.marpolbul.2015.05.062.*

Raoux, A., G. Lassalle, J. Pezy, S. Tecchio, G. Safi, B. Ernande et al. 2018. “Measuring Sensitivity of Two OSPAR Indicators for a Coastal Food Web Model under Offshore Wind Farm Construction.” *Ecological Indicators* 96 (1): 728–38. https://doi.org/10.1016/j.ecolind.2018.07.014.

Reid, W.V., M.K. Ali and C.B. Field. 2019. “The Future of Bioenergy.” *Global Change Biology* 23 October, 1–13. https://doi.org/10.1111/gcb.14883.

Roark, E. Brendan, Thomas P. Guilderson, Robert B. Dunbar and B. Lynn Ingram. 2006. “Radiocarbon-Based Ages and Growth Rates of Hawaiian Deep-Sea Corals.” *Marine Ecology Progress Series* 327 (December): 1–14. https://doi.org/10.3354/meps327001.

Rojas, Andres and Freedom-Kai Phillips. 2019. *Effective Control and Deep Seabed Mining: Toward a Definition*. Liability Issues for Deep Seabed Mining Series, Paper No. 7, February. Centre for International Governance Innovation. https://www.cigionline.org/publications/effective-control-and-deep-seabed-mining-toward-definition-1.

Salinas-de-León, Pelayo, Brennan Phillips, David Ebert, Mahmood Shivji, Florencia Cerutti-Pereyra, Cassandra Ruck, Charles R. Fisher and Leigh Marsh. 2018. “Deep-Sea Hydrothermal Vents as Natural Egg-Case Incubators at the Galapagos Rift.” *Scientific Reports* 8 (1): 1788. https://doi.org/10.1038/s41598-018-20046-4.

Schüler, D., M. Buchert, R. Liu, S. Dittrich and C. Merz. 2011. *Study on Rare Earths and Their Recycling*. Freiburg, Germany: Öko-Institut. http://www.ressourcenfieber.eu/publications/reports/Rare%20earths%20study_Oeko-Institut_Jan%202011.pdf.

Seascape Consultants. 2016. “Periodic Review of the International Seabed Authority pursuant to UNCLOS Article 154.” ISBA/22/A/CRP.3 (1)

Simon-Lledó, Erik, Brian J. Bett, Veerle A.I. Huvenne, Kevin Köser, Timm Schoening, Jens Greinert and Daniel O.B. Jones. 2019. “Biological Effects 26 Years after Simulated Deep-Sea Mining.” *Scientific Reports* 9 (1): 8040. https://doi.org/10.1038/s41598-019-44492-w.

Sims, R.E.H., R.N. Schock, A. Adegbululgbe, J. Fenhann, I. Konstantinaviciute, W. Moomaw, H.B. Nimir et al. 2007. "Energy Supply." In *Climate Change 2007: Mitigation of Climate Change.* Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by B. Metz, O.R. Davidson, P.R. Bosch, R. Dave and L.A. Meyer, 251–322. Cambridge, UK: Cambridge University Press.

Singh, P. and Pouponneau, A 2018. "Comments to the Draft Regulations on Exploitation of Mineral Resources in the Area: Transboundary harm and the rights of Coastal States adjacent to the Area." Kingston, Jamaica: International Seabed Authority. 28 September. https://webcache.googleusercontent.com/search?q=cache:PDmK51pCqlwJ:https://ran-s3.s3.amazonaws.com/isa.org.jm/s3fs-public/files/documents/comments_0.pdf+&cd=1&hl=en&ct=clnk&gl=uk.

SI Ocean. 2013. *Ocean Energy: Cost of Energy and Cost Reduction Opportunities.* SI Ocean Project.

Skov, H., S. Heinanen, T. Norman, R. Ward, S. Mendez-Rondan and I. Ellis. 2018. *ORJIP Bird Collision and Avoidance Study – Final Report April 2018*. The Carbon Trust.

Sovacool, Benjamin K., Saleem H. Ali, Morgan Bazilian, Ben Radley, Benoit Nemery, Julia Okatz and Dustin Mulvaney. 2020. "Sustainable Minerals and Metals for a Low-Carbon Future." *Science* 367 (6473): 30–33. https://doi.org/10.1126/science.aaz6003.

SPC (Secretariat of the Pacific Community). 2012. "Pacific-ACP states regional legislative and regulatory framework for deep sea minerals exploration and exploitation." Prepared under the SPC-EU EDF10 Deep Sea Minerals Project.

SPC. 2013. *Deep Sea Minerals: Deep Sea Minerals and the Green Economy*. Edited by E. Baker and Y. Beaudoin. Vol. 2. https://nicholasinstitute.duke.edu/sites/default/files/publications/chapter_4_-_sustainable_economic_development_and_deep_sea_mining.pdf.

SPC. 2016. "Pacific-ACP states regional financial framework for deep sea minerals exploration and exploitation." Prepared under the SPC-EU EDF10 Deep Sea Minerals Project.

SPC and Cardno. 2016. *An Assessment of the Costs and Benefits of Mining Deep-sea Minerals in the Pacific Island Region: Deep-sea Mining Cost-Benefit Analysis*. https://www.sprep.org/attachments/VirLib/Regional/deep-sea-mining-cba-PICs-2016.pdf.

Stegen, K.S. 2015. "Heavy Rare Earths, Permanent Magnets, and Renewable Energies: An Imminent Crisis." *Energy Policy* 79: 1–8. http://dx.doi.org/10.1016/j.enpol.2014.12.015.

Stehly, T., P. Beiter, D. Heimiller and G. Scott. 2018. *2017 Cost of Wind Energy Review*. Golden, CO: National Renewable Energy Laboratory.

Sweetman, Andrew K., Craig R. Smith, Christine N. Shulse, Brianne Maillot, Markus Lindh, Matthew J. Church, Kirstin S. Meyer, Dick van Oevelen, Tanja Stratmann and Andrew J. Gooday. 2019. "Key Role of Bacteria in the Short-Term Cycling of Carbon at the Abyssal Seafloor in a Low Particulate Organic Carbon Flux Region of the Eastern Pacific Ocean." *Limnology and Oceanography* 64 (2): 694–713. https://doi.org/10.1002/lno.11069.

Taguchi, Hiroyuki, and Soukvisan Khinsamone. 2018. "Analysis of the 'Dutch Disease' Effect on the Selected Resource-Rich ASEAN Economies." *Asia & the Pacific Policy Studies* 5 (2): 249–63. https://doi.org/10.1002/app5.233.

Takaya, Y., K. Yasukawa, T. Kawasaki et al. 2018. "The Tremendous Potential of Deep-Sea Mud as a Source of Rare-Earth Elements." *Scientific Reports* 8, 5763. https://doi.org/10.1038/s41598-018-23948-5.

Tansel, Berrin. 2017. "From Electronic Consumer Products to E-Wastes: Global Outlook, Waste Quantities, Recycling Challenges." *Environment International* 98 (January): 35–45. https://doi.org/10.1016/j.envint.2016.10.002.

Teske, S., T. Pregger, S. Simon, T. Naegler, W. Graus and C. Lins. 2010. "Energy [R]evolution: A sustainable world energy outlook." *Energy Efficiency* 4: 409. https://doi.org/10.1007/s12053-010-9098-y.

Teske, S., S. Sawyer and O. Schafer. 2015. *Energy [r]evolution: A sustainable world energy outlook 2015*. Greenpeace International, Global Wind Energy Council, Solar Power Europe. 5th Edition 2015 World Energy Scenario. https://www.greenpeace.org/archive-international/Global/international/publications/climate/2015/Energy-Revolution-2015-Full.pdf.

Teske, Sven, Nick Florin, Elsa Dominish and Damien Giurco. 2016. *Renewable Energy and Deep Sea Mining: Supply, Demand and Scenarios*. Report Prepared by ISF for J.M.Kaplan Fund, Oceans 5 and Synchronicity Earth. Sydney: Institute for Sustainable Futures. https://opus.lib.uts.edu.au/bitstream/10453/67336/1/DSM%20-%20RE%20resource%20Report_9_FINAL%20DRAFT-NEWTITLE-ANDNAME.pdf.

Thiel, Hjalmar, Gerd Schriever, Ahmed Ahnert, Hartmut Bluhm, Christian Borowski and Kay Vopel. 2001. "The Large-Scale Environmental Impact Experiment DISCOL—Reflection and Foresight." *Deep Sea Research Part II: Topical Studies in Oceanography*, Environmental Impact Studies for the Mining of Polymetallic Nodules from the Deep Sea 48 (17): 3869–82. https://doi.org/10.1016/S0967-0645(01)00071-6.

Thiele, Torsten, Harald Ginzjy, Sabine Christiansen and Hans-Peter Damian. 2019. "A Benefit Sharing Mechanism Appropriate for the Common Heritage of Mankind, UBA/IASS Workshop Summary, Potsdam." Project No. (FKZ) 3717 25 227 0. Institute for Advanced Sustainability Studies e.V.

Thompson, Kirsten F., Kathryn A. Miller, Duncan Currie, Paul Johnston and David Santillo. 2018. "Seabed Mining and Approaches to Governance of the Deep Seabed." *Frontiers in Marine Science* 5. https://doi.org/10.3389/fmars.2018.00480.

Thurber, A.R., A.K. Sweetman, B.E. Narayanaswamy, D.O.B. Jones, J. Ingels and R.L. Hansman. 2014. "Ecosystem Function and Services Provided by the Deep Sea." *Biogeosciences* 11 (14): 3941–63. https://doi.org/10.5194/bg-11-3941-2014.

Torres, Aurora, Jodi Brandt, Kristen Lear and Jianguo Liu. 2017. "A Looming Tragedy of the Sand Commons." *Science* 357*:* 970–971. https://doi.org/10.1126/science.aao0503.

Tunnicliffe, Verena, Anna Metaxas, Jennifer Le, Eva Ramirez-Llodra and Lisa A. Levin. 2018. "Strategic Environmental Goals and Objectives: Setting the Basis for Environmental Regulation of Deep Seabed Mining." *Marine Policy* 114, April. https://doi.org/10.1016/j.marpol.2018.11.010.

Uihlein, A. 2016. "Life Cycle Assessment of Ocean Energy Technologies." *International Journal of Life Cycle Assessment* 21: 1425–37.

United Nations. 1982. "Convention on the Law of the Sea." https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf.

United Nations. 1992. "Convention on Biological Diversity." https://www.cbd.int/doc/legal/cbd-en.pdf.

United Nations. 1994. “Agreement Relating to the Implementation of Part XI of the Convention.” https://www.un.org/Depts/los/convention_agreements/texts/unclos/closindxAgree.htm.

United Nations Conference on Environment and Development. 1992. “Rio Declaration on Environment and Development.” https://www.cbd.int/doc/ref/rio-declaration.shtml.

United Nations General Assembly. 2006. “Resolution 61/105, 8 December. Sustainable fisheries, including through the 1995 Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks, and related instruments.” United Nations document A/RES/61/105.

United Nations General Assembly. 2018. “Resolution 72/279, 31 May. Repositioning of the United Nations development system in the context of the quadrennial comprehensive policy review of operational activities for development of the United Nations system.” United Nations document A/RES/72/279.

Van der Voet, Ester, Lauran van Oers, Miranda Verboon and Koen Kuipers. 2019. “Environmental Implications of Future Demand Scenarios for Metals: Methodology and Application to the Case of Seven Major Metals.” *Journal of Industrial Ecology* 23 (1): 141–55. https://doi.org/10.1111/jiec.12722.

Van Dover, C.L. 2014. “Impacts of Anthropogenic Disturbances at Deep-Sea Hydrothermal Vent Ecosystems: A Review.” *Marine Environmental Research*, Special Issue: Managing Biodiversity in a Changing Ocean, 102 (December): 59–72. https://doi.org/10.1016/j.marenvres.2014.03.008.

Van Dover, C.L. 2019. “Inactive Sulfide Ecosystems in the Deep Sea: A Review.” *Frontiers in Marine Science* 6: 461. https://doi.org10.3389/fmars.2019.00461.

Van Dover, C.L., J.A. Ardron, E. Escobar, M. Gianni, K.M. Gjerde, A. Jaeckel, D.O.B. Jones et al. 2017. “Biodiversity Loss from Deep-Sea Mining.” *Nature Geoscience* 10 (7): 464–65. https://doi.org/10.1038/ngeo2983.

Van Dover, C.L., S. Arnaud-Haond, M. Gianni, S. Helmreich, J.A. Huber, A.L. Jaeckel, A. Metaxas et al. 2018. “Scientific Rationale and International Obligations for Protection of Active Hydrothermal Vent Ecosystems from Deep-Sea Mining.” *Marine Policy* 90 (April): 20–28. https://doi.org/10.1016/j.marpol.2018.01.020.

Vanreusel, Ann, Ana Hilario, Pedro A. Ribeiro, Lenaick Menot and Pedro Martínez Arbizu. 2016. “Threatened by Mining, Polymetallic Nodules Are Required to Preserve Abyssal Epifauna.” *Scientific Reports* 6 (June): 26808. https://doi.org/10.1038/srep26808.

Vare, L.L., M.C. Baker, J.A. Howe, L.A. Levin, C. Neira, E.Z. Ramirez-Llodra, A. Reichelt-Brushett et al. 2018. “Scientific Considerations for the Assessment and Management of Mine Tailings Disposal in the Deep Sea.” *Frontiers in Marine Science* 5, 17. https://doi.org/10.3389/fmars.2018.00017.

Vierros, Marjo, Curtis A. Suttle, Harriet Harden-Davies and Geoff Burton. 2016. “Who Owns the Ocean? Policy Issues Surrounding Marine Genetic Resources.” *Limnology and Oceanography Bulletin* 25 (2): 29–35. https://doi.org/10.1002/lob.10108.

Wahlberg, M. and Westerberg, H. 2005. “Hearing in Fish and Their Reactions to Sounds from Offshore Wind Farms.” *Marine Ecology Progress Series* 288, 295–309.

Wakefield, Jeffrey R. and Kelley Myers. 2018. “Social Cost Benefit Analysis for Deep Sea Minerals Mining.” *Marine Policy* 95 (September): 346–55. https://doi.org/10.1016/j.marpol.2016.06.018.

Wang, C. and R.G. Prinn. 2011. “Potential Climatic Impacts and Reliability of Large-Scale Offshore Wind Farms.” *Environmental Research Letters* 6 (2). http://dx.doi.org/10.1088/1748-9326/6/2/025101.

WEC (World Energy Council). 2013. Chapter 8: Solar. In *World Energy Resources: 2013 Survey*. London: World Energy Council. https://www.worldenergy.org/assets/images/imported/2013/09/Complete_WER_2013_Survey.pdf.

Wedding, L.M., A.M. Friedlander, J.N. Kittinger, L. Watling, S.D. Gaines, M. Bennett, S.M. Hardy and C.R. Smith. 2013. “From Principles to Practice: A Spatial Approach to Systematic Conservation Planning in the Deep Sea.” *Proceedings of the Royal Society B: Biological Sciences* 280 (1773): 20131684. https://doi.org/10.1098/rspb.2013.1684.

Wilburn, D.R. 2011. *Wind Energy in the United States and Materials Required for the Land-Based Wind Turbine Industry From 2010 Through 2030*. Scientific Investigations Report 2011–5036. US Department of the Interior and US Geological Survey.

Williams, Alan, Thomas A. Schlacher, Ashley A. Rowden, Franziska Althaus, Malcolm R. Clark, David A. Bowden, Robert Stewart, Nicholas J. Bax, Mireille Consalvey and Rudy J. Kloser. 2010. “Seamount Megabenthic Assemblages Fail to Recover from Trawling Impacts.” *Marine Ecology* 31 (S1): 183–99. https://doi.org/10.1111/j.1439-0485.2010.00385.x.

WindEurope. 2019. *Our Energy, Our Future: How Offshore Wind Will Help Europe Go Carbon-Neutral*. WindEurope and BVG Associates. https://windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-Our-Energy-Our-Future.pdf.

World Bank. 2017. *Precautionary Management of Deep Sea Minerals.* Washington, DC: World Bank. http://documents.worldbank.org/curated/en/349631503675168052/Precautionary-management-of-deep-sea-minerals.

World Bank Group, ESMAP and SERIS. 2019. *Where Sun Meets Water: Floating Solar Market Report.* Washington, DC: World Bank. http://www.seris.sg/doc/publications/ESMAP_FloatingSolar_TEXT-A4-WEB.pdf.

WWF. 2014. *Environmental Impacts of Offshore Wind in the North Sea – A Literature Review*. Oslo: WWF. https://www.wwf.no/assets/attachments/84-wwf_a4_report___havvindrapport.pdf.

Yan, J., ed. 2015. *Handbook of Clean Energy Systems.* Vol. 5. John Wiley and Sons.

Zydlewski, G., A. Copping and A. Redden. 2015. “Special Issue: Renewable Ocean Energy Development and the Environment.” *Estuaries and Coasts* 38 (1), 156–58. https://doi.org/10.1007/s12237-014-9922-2.

Abbreviations

APEI	Area of Particular Environmental Interest
BBNJ	biodiversity beyond national jurisdiction
BECCS	bioenergy with carbon capture and storage
CAGR	compound annual growth rate
CCS	carbon capture and storage
CCZ	Clarion-Clipperton Zone
CDR	carbon dioxide removal
EEZ	exclusive economic zone
FAIR	findable, accessible, interoperable, reusable
GW	gigawatt (10^9 watt)
GWh	gigawatt-hours
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISA	International Seabed Authority
ITLOS	International Tribunal for the Law of the Sea
LCOE	levelised cost of electricity
LDAC	Long Distance Fleet Advisory Council
LED	low energy demand
LTC	Legal and Technical Commission, International Seabed Authority
MPA	Marine Protected Area
Mtoe	million tonnes of oil equivalent
MW	megawatt (10^6 watt)
MWh	megawatt-hours
OTEC	ocean thermal energy conversion
PV	photovoltaic
REE	rare earth element
REMP	Regional Environmental Management Plan
REY	rare earths and yttrium
SDG	Sustainable Development Goals (United Nations)
SDLO	Sustainable Development Licence to Operate
TIMES	The Integrated MARKAL-EFOM System model generator
TW	terawatt (10^{12} watt)
TWh	terawatt-hours
UNCLOS	United Nations Convention on the Law of the Sea
UNFCCC	United Nations Framework Convention on Climate Change
VME	vulnerable marine ecosystem

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