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Marine Renewable Energy and Deep-Sea Mining: Environmental trade-offs and their role in the European Clean Energy Transition

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STATUTORY DECLARATION

I hereby declare that I have composed the present thesis autonomously and without use of any other than the cited sources or means. I have indicated parts that were taken out of published or unpublished work correctly and in a verifiable manner through a quotation. I further assure that I have not presented this thesis to any other institute or university for evaluation and that it has not been published before.

Nice, 25.06.2025

Agostini Carolina

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I deliver this thesis admiring the sea and feeling its immensity.

Abstract

The ocean covers more than 70% of the Earth's surface and represents the planet's greatest climate regulator. As Dr. Katherine Richardson emphasises, it is our strongest ally in facing climate change. Not only for its carbon sink capacity, but also through its potential to supply sustainable energy and resources.

Building on this framework, this thesis explores the environmental trade-offs of Marine Renewable Energy (MRE) technologies and deep-sea mining (DSM), focusing both on their ecological implications and their strategic role in the European Union's energy transition.

The core aim is to address a critical gap in current scientific and policy understanding: while these marine-based solutions are increasingly promoted as pathways to decarbonisation, there remains limited empirical knowledge on their long-term impacts on ocean ecosystems.

By examining the complex interplay between environmental risks, regulatory frameworks, and clean energy goals, this research contributes to a more integrated and precautionary approach, one that supports the energy transition without undermining marine biodiversity.

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1. Introduction

The growing urgency of the climate crisis has made the transition to renewable energy a global priority. While solar and wind technologies on land are well developed, there is increasing interest in the untapped potential of harnessing energy from the ocean. Marine Renewable Energy (MRE) sources, indeed, can play an important role in reducing greenhouse gas emissions and diversifying the energy mix. However, their deployment raises important environmental questions, especially regarding their impacts on marine ecosystems.
In parallel, demand for critical minerals needed to build renewable technologies is rising. This has sparked growing interest in Deep-Sea Mining (DSM) as a new source of supply. However, the consequential damage to deep-sea ecosystems is still too unknown and potentially irreversible to sustainably advance this practice. For this reason, the scientific community, together with many experts and policy leaders, is firmly standing against it.

In this context of clean energy transition, the European Union is a key player. It is supporting the development of MRE through ambitious funding and policy goals, while taking a precautionary stance on DSM, calling for more scientific data before any industrial activity begins.

The crucial issue behind this energy framework is, indeed, the dramatic lack of sufficient scientific knowledge and evidence to understand the long-term impacts of these solutions on marine ecosystems, especially regarding DSM. Reducing this gap is the main purpose of this study.

In particular, this thesis aimed to explore the trade-offs between advancing the green transition through MRE and DSM and protecting the marine environment. The study investigates whether developing and exploiting these kinds of energy resources can contribute to a virtuous cycle of decarbonisation and clean energy transition or whether the environmental costs are so high that they create a counterproductive, vicious cycle.

To do so, the research has been driven by the following core research question:

"What are the environmental impacts and trade-offs of deploying marine renewable energy technologies on marine ecosystems, and how are these balanced with the goals of the green energy transition?"

Alongside two main sub-questions:

"What are the environmental impacts of deep-sea mining for materials critical to the green energy transition?"

"What is the European Union's stance on marine renewable energy development and deep-sea mining?"

To analyse these delicate issues, the dissertation was developed by combining an extensive review of the literature with qualitative interviews with three experts in different fields.
Moreover, personally participating in the Third UN Ocean Conference gifted me with extremely enriching insights for this research.

Following this introduction, the discussion will firstly present the analysis of the literature review, as well as explaining the methodology used for the study. Three core chapters will then discuss the research question and sub-questions, including the findings collected from the qualitative interviews at the end of each chapter. The transcriptions of the interviews are integrated into the three final Annexes at the very end of the paper.

Concluding remarks will provide a synthesis of the entire study, summarising possible answers to the pivotal research questions.

2. Literature Review

2.1 INTRODUCTION

This literature review is based on a wide range of sources, including academic papers, scientific reports, publications from institutions, and official documents from the EU. These cover different fields, such as environmental science, marine biology, energy policy and engineering, and international governance, which helps provide a more complete view of the main topics.

Most of the literature on MRE agrees that these technologies are important for reducing greenhouse gas emissions, but also points out the possible risks they pose to marine ecosystems. There is broad support for MRE development, but researchers differ on how serious the environmental impacts might be and how they should be managed. On the other hand, the literature on DSM focuses more on legal, ecological, and governance challenges. There is strong concern about the lack of scientific knowledge and the long-term impacts. Some sources also question whether current laws and institutions, like the ISA or EU policy frameworks, are prepared to manage these impacts responsibly.

This literature review highlights how these two areas raise similar issues, although with a significantly different severity, especially about the need to protect marine ecosystems while also meeting climate and resource needs. By combining scientific and policy perspectives, the review identifies key gaps in current research, such as the lack of data on CEAs, unclear regulations, and limited integration between energy goals and marine conservation. These challenges show the need for more interdisciplinary research.

2.2 DISCUSSION OF THE LITERATURE

2.2.1) Main Research Question on Marine Renewable Energy

"What are the environmental impacts and trade-offs of deploying marine renewable energy technologies on marine ecosystems, and how are these balanced with the goals of the green energy transition?"

MRE technologies are increasingly identified in the literature as key contributors to decarbonisation strategies, due to their capacity to displace fossil fuels and mitigate climate change (Borthwick, 2016; Trifonova et al., 2022). These technologies harness various marine forces to generate electricity, as explained in various specific and technical papers on offshore wind, tidal stream, wave, ocean current, ocean thermal energy conversion (OTEC), salinity gradient, and marine bioenergy (Boehlert & Gill, 2010; Borthwick, 2016; OES-Environmental, 2024).
At the same time, research consistently highlights the need to weigh these climate benefits against potential environmental trade-offs and stressors which may affect the behaviour, physiology, and distribution of marine organisms (Willsteed et al., 2017; Copping et al., 2023). For instance, larger fauna are particularly linked to direct risks of collision and entanglement (Boehlert & Gill, 2010; OES-Environmental, 2024).

Moreover, modelling and observational studies have raised concerns that large-scale MRE arrays may alter local hydrodynamics, sediment transport, and biogeochemical processes, with ecological ripple effects (Chapman et al., 2024; Trifonova et al., 2022).

Regulatory challenges are also widely stressed in the literature, as inconsistencies between national and regional governance frameworks often hinder permitting and assessment processes (Chapman et al., 2024; Wright, 2015).

Nevertheless, a smaller range of authors, including Attrill et alia (2009) and Copping et alia (2020), also identify potential ecological benefits, which will be presented in the first Chapter of the discussion. Some evidence, as in the 2024 State of the Science Report by OES-Environmental, also points to MRE arrays' role as *de facto* MPAs, thanks to restricted human access and reduced fishing pressure (Boehlert & Gill, 2010; OES-Environmental, 2024). Still, the overall ecological balance of MRE remains uncertain, as large-scale empirical data are currently limited and context-specific (Copping et al., 2023).

CEAs are advocated for a holistic understanding of how MRE developments interact with other human activities and climate change pressures (Willsteed et al., 2017).

However, inconsistencies in CEA frameworks and data collection methodologies have resulted in gaps in knowledge on large-scale ecological damages (Chapman et al., 2024; Trifonova et al., 2022). Recent research calls for enhanced international collaboration to develop common assessment protocols and improve data-sharing between scientists, policymakers, and industry stakeholders (Copping et al., 2020; Wright, 2015).
To address these uncertainties, an ecosystem-based approach has been widely supported in the literature, combining environmental and socio-economic considerations to minimise environmental harm while maximising energy production efficiency (Trifonova et al., 2022; OES-Environmental, 2024).

Additionally, the precautionary principle is frequently recommended, ensuring that large-scale MRE deployments strictly follow sufficient scientific evidence on their long-term sustainability (Copping et al., 2023; Willsteed et al., 2017).

In summary, although perspectives vary between promoting the benefits and those more concerned about the risks of MREs, the literature is highly concordant in emphasising the need for further empirical research, improved regulatory coherence, and enhanced stakeholder collaboration to address existing knowledge gaps and develop robust EIA methodologies (Copping et al., 2020; Trifonova et al., 2022; Wright, 2015). As nations accelerate the adoption of offshore renewable energy, prioritising ecosystem-based governance and precautionary management strategies will be crucial to ensure that the contribution to climate change mitigation will not excessively hamper marine biodiversity and ecosystems (Borthwick, 2016; Copping et alia, 2020; Hasselman et al., 2023; Willsteed et al., 2017)

2.2.2 Sub-Questions

1. **Deep-Sea Mining**

"What are the environmental impacts of deep-sea mining for materials critical to the green energy transition?"

DSM has been defined in the literature as a "sustainability conundrum" (Cassotta & Goodsite, 2023; Levin et al., 2020).

It refers to the extraction of valuable mineral resources from the deep sea (Frölicher & Jaccard, 2023), which covers 70% of the Earth's surface and hosts largely unexplored ecosystems. These provide essential services, including, most importantly, carbon storage and climate regulation (Boetius & Haeckel, 2018; Amon et al., 2022). Pivotal for this understanding have been the studies conducted by Dr Diva Amon, especially between 2020-2022 in collaboration with other experts, and aligning with the insights from her interview.

The increasing activity of exploring and exploiting seabed resources in the Area[1], which are considered the common heritage of humankind (Sumaila et al., 2023), has been regulated since 1994 by the International Seabed Authority (ISA), established under the UNCLOS (Cassotta & Goodsite, 2023; Frölicher, T., & Jaccard, S, 2023; Levin et al., 2020). The main legal and policy studies explain its core mandate to "prevent serious harm" and "ensure effective protection" of the marine ecosystems from mining activities (Frölicher, T., & Jaccard, S, 2023), as well as the 31 exploration contracts issued so far and the current development of a new Mining Code for exploitation (EASAC, 2023; Hallgren & Hansson, 2021; Krishnamurthy, 2025). However, there are concerns among academics and scientists that the ISA's regulatory framework is being developed hastily without adequate scientific and environmental considerations (EASAC, 2023; Sumaila et al., 2023).

More scientific papers and reports focus on the specific minerals present in the seabed and needed for the energy transition, which are at the basis of the interest around DSM. (Frölicher & Jaccard, 2023; Levin et al., 2020). These minerals are found in three main deposit types (Toro et al., 2020; EASAC, 2023), which will be explained in the second chapter and in the interviews with Dr Richardson and Amon. The Clarion-Clipperton Zone (CCZ) in the Pacific Ocean is widely mentioned as the richest area for these deposits and a key focus for potential mining activities (Vivoda, 2024).

[1] The Area comprises the seabed, ocean floor and subsoil in the international waters, hence beyond national jurisdiction (EASAC, 2023).

These kinds of minerals have always been extracted from inland ores. However, land-based sources are facing depletion, geopolitical risks, and environmental degradation, making DSM an attractive alternative (Vivoda, 2024).
Accordingly, studies including those by Levin et alia (2020) and Vivoda (2024), are useful to compare the two mining activities, terrestrial and marine, and discuss the trade-offs. In particular, Mikayilov aligns with some other authors in considering the potential advantages of DSM, including no displacement of communities, geopolitical dependence and deforestation (Levin et al., 2020; Toro et al., 2020; Mikayilov, 2021; Vivoda, 2024).

On the other side, mining the deep sea can cause severe and potentially irreversible ecological damage, including ecosystem disturbance, generation of sediment plumes, chemical/noise/light pollution, etc. (Frölicher & Jaccard, 2023; Levin et al., 2020). This is the focus of all the scientific papers analysed, together with the extremely slow recovery rates, with experimental studies showing little to no regeneration even after decades (Simon-Lledó et al., 2019; Vonnahme et al., 2020). The full extent of these impacts remains uncertain, fueling ongoing scientific and policy debates (Amon et al., 2022; Sumaila et al., 2023).

Hallgren & Hansson (2021) categorise these ongoing debates into four narratives: (1) DSM as an essential component of the green economy, (2) equitable distribution of DSM profits, (3) the unknown risks of DSM, and (4) the argument to leave deep-sea minerals untouched. While proponents highlight its potential benefits for global resource security and economic growth, opponents emphasise the lack of sufficient scientific data and the risks of environmental harm (EASAC, 2023; Sumaila et al., 2023).

Opposition to DSM is also evident at the policy level. Several countries, including Chile, Germany, and France, have called for a moratorium on DSM, calling for more research before commercial activities begin (Frölicher & Jaccard, 2023). The European Union, in many official documents and communications, has also advocated for a precautionary pause, aligning with NGOs, scientists, and civil society organisations (Cassotta & Goodsite, 2023; Levin et al., 2020; Sumaila et al., 2023; EJF, 2024).

Concurrently, the literature is widely united in recommending a precautionary approach to DSM (Cassotta & Goodsite, 2023; EASAC, 2023; Levin et al., 2020; Vivoda, 2024)

Finally, some studies suggest possible alternatives to DSM, including improving land-based mining sustainability, investing in mineral recycling, and developing substitution technologies to reduce dependence on critical metals (Frölicher & Jaccard, 2023; Vivoda, 2024). Ultimately, further research and stronger regulatory frameworks are necessary to balance the potential benefits of DSM with the protection of marine ecosystems (Frölicher, T., & Jaccard, S, 2023).

2. The Stance of the European Union

"What is the European Union's stance on marine renewable energy development and deep-sea mining?"

The EU Institutions' official webpages widely summarise and present the significant investments the Union is addressing to offshore wind and ocean energy technologies, in line with its ambitious decarbonisation goals (European Commission, n.d.-a/b/c/d). Furthermore, it has committed €4 billion over the past decade to research and pilot projects, reinforcing its global leadership in ocean energy innovation (European Commission, 2024). However, independent studies highlight that challenges remain, particularly regarding regulatory fragmentation, funding inconsistencies, and spatial conflicts with other maritime activities (Apolonia et al., 2021; Trifonova et al., 2022).

Comparing the EU's ocean energy development to the rest of the world, Europe remains the global leader in tidal stream energy, with 30.5 MW of cumulative installations since 2010, significantly ahead of non-European markets (10.9 MW) (Ocean Energy Europe, 2024). However, the United States and China are rapidly advancing, with the US increasing its ocean energy funding to $120M in 2023, significantly surpassing EU funding levels (Ocean Energy Europe, 2024). In parallel, China is also accelerating investments in large-scale deployment, through its Five-Year Plan (Ocean Energy Europe, 2024).

Despite its commitment to MRE, the EU has taken a firm stance against DSM, emphasising the lack of scientific evidence on its environmental impacts (European

Commission, 2022). The European Parliament has repeatedly called for a moratorium on DSM, aligning with the growing scientific consensus that the risks to marine biodiversity and ecosystem stability are too high (EJF, 2024; EASAC, 2023). Under the Critical Raw Materials Act, DSM is not recognised as a strategic priority, with the EU prioritising alternative solutions such as material recycling and sustainable land-based extraction (European Commission, 2024). The European Commission has also been active in negotiating stricter regulations at the ISA to ensure robust environmental safeguards before any commercial mining operations are considered (Cassotta & Goodsite, 2023).

Looking forward, the EU is expected to reinforce its commitment to sustainable ocean governance through the European Ocean Pact, recently announced to enhance marine protection while supporting a decarbonised blue economy (Pons et al., 2024; European Commission, 2025). The pact emphasises the integration of MRE within a broader ocean sustainability framework, linking climate objectives with biodiversity conservation and marine spatial planning (Van Leeuwen et al., 2025). However, gaps remain in aligning EU policy with implementation at the member-state level, highlighting the need for improved coordination and streamlined regulatory processes (Quero García et al., 2019).

2.3 GAPS IN THE LITERATURE

Despite the growing research on MRE and DSM, significant gaps remain in understanding their long-term environmental impacts and policy implications. As widely recognised by the literature itself, one of the core loopholes regards the lack of empirical data on the cumulative effects of MRE installations on marine ecosystems (Copping et al., 2023; Willsteed et al., 2017). The absence of standardised methodologies for assessing these impacts results in inconsistencies across studies, limiting the ability to draw conclusive findings that can inform robust policy frameworks (Chapman et al., 2024). This is even more true concerning the scientific uncertainty about the potential ecological impacts of DSM and the repercussions for climate change and the entire planet (Sumaila et al., 2023; Levin et al., 2020).

A further gap lies in the policy and governance dimensions, particularly regarding the European Union's stance on these issues. The majority of available literature on EU policies is derived from official EU reports and documents, limiting independent, critical analyses of its regulatory approach (European Commission, 2024; EJF, 2024). This creates a narrow scope of discussion, as external academic perspectives on the EU's decision-making process, particularly regarding its opposition to DSM, remain relatively underexplored. Moreover, many of the academic sources addressing EU policy frameworks in this field are outdated, with limited recent contributions assessing the evolving legislative landscape and strategic priorities (Cassotta & Goodsite, 2023; Quero García et al., 2019).

To address these gaps, this research will contribute new insights into both the environmental and policy aspects of MRE and DSM. Through qualitative interviews with experts in marine biology and policymaking, this study aims to enhance understanding of the ecological significance of deep-sea ecosystems and how disruptions from DSM could have broader implications for climate regulation and human activities. Additionally, by engaging with members of the European Commission and other stakeholders, this research will gather up-to-date perspectives on the EU's evolving stance.

3. Research Methodology

To address my research question and related sub-questions, my approach will primarily rely on an extensive review of existing literature, and largely on secondary sources. This will help determine the depth of academic and scientific knowledge on the topic, as well as identify the data and evidence currently available to assess the actual environmental impacts of MRE technologies and DSM on marine ecosystems. It will also explore the extent to which these impacts might counteract the benefits these technologies provide to the energy transition.

In addition to the literature review, three semi-structured expert interviews were conducted as primary sources to enrich the analysis. These interviews provided key insights across all three chapters of the thesis.

- Dr. Katherine Richardson, an Earth system scientist, oceanographer, and co-developer of the Planetary Boundaries framework, offered invaluable contributions on the ocean-climate nexus, ocean services, and biodiversity. Her input informed the contextual analysis in Chapter I, the deep-sea mining discussion in Chapter II, and broader geopolitical and EU perspectives in Chapter III.
- Dr. Diva Amon, a marine biologist at the University of California and expert in deep-sea biodiversity and climate impacts, whom I had the pleasure to meet at the Third UN Ocean Conference in Nice. Her expertise supported the scientific and ecological framing of Chapter II on deep-sea mining.
- Xavier Guillou, Team Leader for Maritime Spatial Planning and Marine Renewable Energy at the European Commission's DG MARE, was interviewed alongside legal expert Isabella Hannen. Their contributions focused primarily on the EU's approach to Marine Renewable Energy (MRE) and, briefly, to DSM, informing Chapter III.

All interviews were conducted online using pre-determined questions, later adapted during each discussion. The interviews with Richardson and Amon were recorded and transcribed (Annexes I and II), while a list of questions posed to Guillou and Hannen is provided in Annex III. A synthesis of each interview's findings is included at the end of the relevant chapter, labelled as "Chapter n°.a".

Given the interdisciplinary nature of this topic, my research required the analysis of both qualitative and quantitative data, which were obtained through the interviews and the systematic review of the aforementioned sources. A historical-contextual analysis explored the evolution of MRE technologies and deep-sea mining, the state of the oceans, and climate change. Additionally, through a political and policy-based research, the approaches adopted by the international community and specifically the EU were examined. While this is not a case study-based project, a few projects will be mentioned to contextualise findings from prior research.

Finally, participating in the Third UN Ocean Conference in Nice (June 09–13, 2025), as well as the prior One Ocean Science Congress (June 03-06, 2025), significantly enriched my research, allowing me to gain insights from the panels and side events and to meet relevant experts (including Dr. Amon).

4. Analysis and Discussion

CHAPTER I

Contextual Analysis and Marine Renewable Energy

I.1) CONTEXTUAL FRAMEWORK: The Ocean-Climate Relationship

This research on Marine Renewable Energy is to be placed in the broader urgent climate change crisis, representing one of the most pressing challenges of contemporary times. Science is advocating for a systemic green shift in many sectors of human production and activity. At the core of this necessary clean transition stands the global energy system, still heavily reliant on fossil fuels for more than 80% of the primary energy mix. (Borthwick, 2016; WOR7, 2021). To understand the record levels reached by greenhouse gas emissions linked to this sector, in the 27 years previous to 2016, the cumulative emissions matched those produced in the entire previous human history (Borthwick, 2016). Extreme weather events, including dramatic floods and droughts, are the direct tangible consequence of this accelerating global warming (ETIP Ocean, 2020).

A rapid and massive increase in renewable energies is the best measure to face this crisis (IPCC, 2018; IRENA, 2019). To meet the targets set by the Paris Agreement, in particular to limit global warming to 1.5°C, 70% to 85% of the world's electricity should be generated by renewable sources by 2050 (Soria-Rodríguez, 2022).

But this transition can not be feasible if it does not align more broadly with the UN Sustainable Development Goals, guaranteeing justice and fairness in this process of economic restructuring (IRENA, 2019). From a global perspective, indeed, policy targets are not yet preventing CO2 emissions from rising, at 1.3% annually, with many countries still deeply dependent on fossil fuels and lacking the technological and economic capacity to move away (IRENA, 2019).

It is in this delicate framework that the ocean is gaining growing recognition, not only for the direct impacts related to climate change, but also for its core role in climate mitigation and as a source of new renewable energy solutions (Jacquemont et al., 2022).

Marine scientists and oceanographers have indeed identified the ocean as the Earth's most powerful climate regulator, moderating the planet's energy balance and stabilising atmospheric conditions. Furthermore, anthropogenic global warming has until now been strongly buffered thanks to the ocean heat storage capacity, with more than 90% of the excess heat generated by human activities since the Industrial Revolution being absorbed in the sea and upper water column (Scott-Buechler & Greene, 2019). This has notably slowed down the pace of increasing temperatures, but cannot be taken for granted with the acceleration of the climate crisis (Herr & Galland, 2009).

Indeed, as the ocean waters continue to warm, the so-called "warming in the pipeline", or delayed feedback, risks triggering a vicious cycle, eventually contributing to additional atmospheric heating and consequential sea-level rise and reduced albedo from melting sea ice (Reid et al., 2009; Herr & Galland, 2009; Scott-Buechler & Greene, 2019). The persistence of these processes underscores the long-term and largely irreversible nature of oceanic climate feedback loops, for which the ocean health is not just an ecological concern; it is fundamental to achieve the temperature stabilisation targets (Reid et al., 2009).

Additionally, the ocean's carbon sink ability is equally significant, having absorbed around 40% of human-released CO2 (carbon dioxide) emissions since industrialisation times (Scott-Buechler & Greene, 2019; Reid et al., 2009). To enable carbon sequestration, CO2 dissolves in surface waters and is subsequently transported to the ocean depths for long-term storage, in a physical process known as solubility pumping. Currently, the ocean contains nearly 50 times more carbon than the atmosphere, making it the largest active carbon reservoir on the planet (Scott-Buechler & Greene, 2019).

This is the result of a mix of physical and biological processes. Strong winds cause upwelling and deep mixing, which helps carbon move efficiently between the atmosphere and the ocean. However, this may not continue. Changes in ocean circulation, layering, and temperature, driven by climate change, can reduce the ocean's ability to store carbon as well (Scott-Buechler & Greene, 2019; Reid et al., 2009).

Among the other dramatic impacts of climate change on the oceans, threatening its buffering capacity, ocean acidification is endangering marine biodiversity, particularly calcifying organisms (Reid et al., 2009), and rising water temperatures are altering circulation patterns, increasing stratification, and contributing to oxygen depletion (ETIP Ocean, 2020; Herr & Galland, 2009; Scott-Buechler & Greene, 2019)

It is within this context that MRE emerges as both a necessity and an opportunity, representing low-carbon energy solutions that can directly displace fossil fuel use, contributing to global mitigation efforts and diversifying energy supply, particularly for coastal and island communities (Copping et al., 2020; ETIP Ocean, 2020).

I.2) MARINE RENEWABLE ENERGY

I.2.1) Introduction to MRE

Following what was discussed in the previous section, as the global energy transition accelerates in response to the urgent climate crisis, MRE has emerged as a promising frontier. It includes a those technologies designed to harness the immense power of the ocean and convert it into sustainable electricity. Among the most relevant are offshore wind turbines, wave energy converters, tidal stream and current turbines, OTEC, salinity gradient systems, and marine bioenergy (Borthwick, 2016; Boehlert & Gill, 2010).

Despite the huge technical potential, with wave and tidal stream energy that could generate alone up to 30,700 TWh/year, deployment remains limited, with less than 1 TWh/year produced globally since 2015 (Hasselman et al., 2023).

This gap between potential and production highlights several challenges, including technological underdevelopment, environmental concerns, high costs, and infrastructural limitations (Chapman et al., 2024; Trifonova et al., 2022; Wright, 2015).

In the following subsections, four of the most significant and advancing MRE technologies will be presented in more detail. Namely, offshore wind, wave and current energy, OTEC, and floating photovoltaics.

- Offshore Wind Energy

Offshore wind is currently the most commercially advanced and widely deployed marine renewable energy technology. It involves installing wind turbines in marine environments to harness stronger and more consistent wind resources found at sea,

which allow for efficient, large-scale generation of electricity (IEA-OES, 2023; Seta, 2023).
Offshore wind systems include two main solutions: bottom-fixed turbines, anchored directly to the seabed in shallower waters, and floating wind turbines (FWTs), which are mounted on buoyant platforms suitable for greater depths. Technological innovations are already allowing deployment up to 800 meters of depth, with future designs projected to reach 1250 meters (Herrera Anchustegui & Radovich, 2022).
FWTs open new frontiers for offshore energy generation, especially in ABNJ, with stronger and consistent wind, wider space free from national planning, and minimal interference with coastal activities such as fishing (Seta, 2023). These deep-sea installations also avoid common onshore challenges, such as visual pollution or conflicts over land use (Herrera Anchustegui & Radovich, 2022).

This MRE resource has so far contributed to 0.3% of global electricity (WOR7, 2021), with, however, an accelerating pace. With a total of 69.0 GW, 2024 saw the largest award of offshore wind lease capacity worldwide to date (WFO, 2025). This year, the expansion is expected to reach up to 79.8 GW of lease capacity worldwide. (WFO, 2025). By 2033, the total offshore wind capacity should reach 394.4 GW worldwide, with Europe expected to contribute 45% of that amount (WFO, 2025).

Wrapping up, offshore wind is leading the world's energy transition. It is a key component of climate mitigation strategies thanks to its scalability, access to superior wind resources, and decreased land-use conflict. To achieve its full potential, however, obstacles related to cost, logistics, and regulations need to be addressed, as well as making sure that ecological impacts are appropriately managed through MSP and EIAs (Galparsoro et al., 2022; WFO, 2025).

- Wave and Current Energy

This MRE technology harnesses the mechanical power of ocean surface waves, tides, and deep-sea currents. WECs use devices such as point absorbers, oscillating water columns, and attenuators to convert wave motion into electricity (IEA-OES, 2023). Current-based systems instead, including tidal stream turbines and underwater kites, capture the kinetic energy of predictable water flows (Riefolo et al., 2015; Javadi & Rezaei, 2024).

The global theoretical potential of wave energy is estimated at 29,500 TWh/year, while tidal stream energy could supply an additional 1200 TWh/year. This are numbers that would far exceed current global electricity consumption (Hasselman et al., 2023). However, most of these technologies remain in early pilot or demonstration phases, with deployments largely confined to national waters in Europe and North America (Javadi & Rezaei, 2024).

Nevertheless, future marine energy systems may depend heavily on WECs and existing turbines for their capacity to function in deep-sea environments and possible synergies with other offshore renewable energy sources (SINTEF, 2019).

- Ocean Thermal Energy Conversion (OTEC)

OTEC leverages the temperature difference between warm surface water and cold deep-sea water to generate electricity. The process involves heating a working fluid with surface water until it vaporises and activates a turbine, and then condensing it using cold deep water (IEA-OES, 2023; Rivera et al., 2020). This closed-loop system is best suited for tropical regions where the temperature differential is at least 20°C year-round (Rivera et al., 2020).

Beyond power generation, OTEC systems can desalinate water and support aquaculture, making them highly relevant for island and coastal communities (Copping & Farr, 2023).

OTEC remains in the pilot phase, with projects underway in Hawaii, the Caribbean, and parts of Africa and Asia. Despite the lack of full-scale commercial deployment, it is viewed as a strategic solution for regions with limited terrestrial energy resources (Copping & Farr, 2023; EIA, 2023).

- Floating Photovoltaics

FPVs represent an innovative extension of traditional solar energy systems into marine and coastal environments, with floating structures anchored to water bodies (IEA-OES, 2023). FPV reduces land-use conflicts and benefits from the cooling effect of water, which can enhance panel efficiency (Benjamins et al., 2024).

While most FPV installations are currently located in national waters, growing interest in offshore deployment is opening new possibilities for integration with other marine renewables. This synergy could help maximise the energy potential of offshore sites and provide more consistent power generation. Nonetheless, technical challenges remain, such as anchoring systems, wave resistance, and long-term maintenance, but research to address then is rapidly improving (Benjamins et al., 2024).

As part of broader global decarbonisation strategies, FPV is expected to develop significantly, especially in areas with limited land supply or high population density, thanks to its modular design, scalability, and compatibility with existing offshore infrastructure (Benjamins et al., 2024).

I.2.2) Positive Impacts

As already mentioned, MRE firstly offers huge benefits for the global clean transition in terms of decarbonisation potential. Large-scale deployment of ORE has the capacity to generate hundreds of gigawatts of clean electricity, substantially reducing dependence on fossil fuel imports while fostering energy security and lowering greenhouse gas emissions (Trifonova et al., 2022; IRENA, 2019).

Furthermore, these technologies, adapted to marine conditions, are more reliable compared to other renewables like solar and onshore wind, and typically require less maintenance (Copping et al., 2020).

However, this is not the only reason to make this energy source particularly attractive. From a social perspective, these developments can stimulate coastal and island economies by introducing new jobs, advancing infrastructure, and supporting local supply chains (Trifonova et al., 2022).

In environmental terms, on the other hand, appropriately designed and managed MRE installations can enhance marine ecosystems. Research suggests that these structures can act as artificial reefs and promote fish aggregation, potentially boosting biodiversity in otherwise degraded marine habitats (Attrill et al., 2009; Copping et al., 2020). In some cases, MRE infrastructure may function as *de facto* MPAs, contrasting harmful human activity and supporting ecosystem recovery and fisheries. Finally, MRE can be beneficial also for the blue economy, including offshore aquaculture or ocean

observation systems, and increasing the resilience and subsistence of coastal economies (Copping et al., 2020).
These multi-dimensional benefits create a broader "win–win ecology" model, in which clean energy development supports both climate goals and marine conservation (Attrill et al., 2009; Hasselman et al., 2023)

I.2.3) Negative Impacts

Beyond the benefits linked to MRE technologies, the major environmental pressures they also provoke cannot be ignored. These impacts arise from both the physical presence of these structures and the extraction of kinetic, thermal, or chemical energy from marine systems. Collectively, these activities have the potential to alter ecosystem structure, function, and resilience, particularly in already degraded or biologically sensitive coastal and offshore environments (Trifonova et al., 2022; Wright, 2015).

In brief, MRE infrastructure, such as turbines, cables, platforms, and mooring systems, can lead to habitat loss, changes in benthic and pelagic community composition, and disruption of critical ecological processes like species migration, foraging, and reproduction (Attrill et al., 2009). In some cases, the removal of energy (e.g., from tidal or wave systems) may influence oceanographic dynamics, including sediment transport, stratification, and nutrient cycling, with far-reaching implications for marine productivity and food webs (Trifonova et al., 2022; Hasselman et al., 2023).

To anticipate and manage these negative repercussions, EIAs play a key role, evaluating s the consequences of any single project. However, as the number of MRE installations grows, EIAs must be coupled with Cumulative Effects Assessments to understand the combined and potentially non-linear effects of multiple projects over space and time (Willsteed et al., 2017). These assessments are critical for MSP and sustainable governance, particularly as MRE development overlaps with other maritime sectors (Elliott, 2011; Stelzenmüller et al., 2013).

Among the most relevant environmental stressors associated with MRE systems there are underwater noise, electromagnetic fields, collision risks, habitat modification, and chemical pollution (Copping et al., 2020; Hasselman et al., 2023). These can interact with a wide range of receptors in the marine environment, from marine mammals and seabirds to benthic invertebrates and pelagic fish. The consequential outcomes can be additive, synergistic, or antagonistic depending on the technology, location, and scale of deployment (Hasselman et al., 2023). Moreover, changes to oceanographic conditions such as current velocities or wave regimes can have broader implications for sediment dynamics, water quality, and the ecosystem services (Javadi & Rezaei, 2024; Riefolo et al., 2015).

The spatial and ecological context of each installation is of primary relevance in determining its impacts. As such, effects observed at one site may not be generalisable to others, and careful baseline studies, standardised methodologies, and adaptive management are essential to inform mitigation strategies and ensure long-term ecological sustainability (Copping & Hemery, 2020; Galparsoro et al., 2022).
The next subsections will focus on the impacts derived from the four main MRE technologies previously presented, namely OWE, WECs, OTEC and FPVs.

- Offshore Wind Energy (OWE)

Generates substantial environmental concerns. Firstly, the process of turbine construction, and especially the driving of piles, poses a huge underwater noise, which results in a serious threat to marine mammals. Interfering with communication, it can cause behavioural changes, as well as habitat displacement (WWF-Norway, 2014; Seta, 2023). Operational noise, although less intense, may still have chronic effects. Turbines represent a risk for migration and collision for birds, particularly when situated along migratory paths or in inappropriately positioned installations (Galparsoro et al., 2022).
On the other hand, anchoring on the seabed and laying cables can disrupt benthic habitats, potentially affecting ecosystem integrity and fish populations. While turbine bases may serve as artificial reefs, as discussed in the previous section, they can also attract invasive species or shift local trophic dynamics (WWF-Norway, 2014). The scale of cumulative and transboundary effects cannot be underestimated, especially in heavily developed basins like the North Sea (WOR7, 2021).

- Wave energy converters (WECs) and tidal/current power plants

Although direct collision risk is relatively low, large-scale infrastructures may disturb migration routes for marine mammals or seabirds (ETIP Ocean, 2020; Riefolo et al., 2015). Hydrodynamic changes caused by these devices can modify wave heights, tidal flows, and sediment transport, with implications for coastal morphology and habitat structure (Javadi & Rezaei, 2024). Seabed disturbance during installation may degrade benthic ecosystems, especially those hosting sensitive species like corals. Additional stressors include underwater noise, EMFs, and chemical pollution from potential hydraulic fluid leaks. The combined effects of multiple installations, including altered food webs and spatial displacement of species, remain insufficiently studied and require improved monitoring frameworks (SINTEF, 2019; Copping et al., 2020).

- Ocean Thermal Energy Conversion (OTEC)

Introducing deep-sea water to the surface can disrupt ocean stratification and potentially causing thermal shock to marine life (Copping & Farr, 2023).

Discharge plumes can change the balance of nutrients in the water, which may affect where species live and how food chains function (Rivera et al., 2020). Infrastructure like pipelines and platforms may contribute to habitat fragmentation, invasive species colonisation, and underwater noise pollution, hampering migrations and resilience (Rivera et al., 2020).

- Floating Photovoltaics (FPVs)

Their presence may reduce light penetration, affecting photosynthetic organisms such as phytoplankton, macroalgae, and corals (Benjamins et al., 2024). Anchoring systems can disturb seafloor habitats and resuspend sediments, potentially leading to hypoxic conditions. EMFs from transmission cables may interfere with electro-sensitive species, though effects are still poorly understood (Hooper et al., 2021). Moreover, biofouling and artificial reef effects could attract new species or disrupt existing ecological balances, with uncertain long-term consequences.

I.2.4) Knowledge Gaps

While the environmental implications of MRE are increasingly acknowledged, our current understanding remains fragmented and incomplete. As shown in the previous section, MRE projects can produce a wide range of ecological effects, but quantifying these impacts with precision, especially at scale, remains a persistent challenge. Since only a few full-scale MRE devices and arrays have been deployed so far, there is still a lack of strong, real-world evidence about their impacts (Copping et al., 2020; Hasselman et al., 2023).

This knowledge gap is most acute in post-installation monitoring, where scarcity of consistent, long-term field data undermines our ability to assess the real-world impacts of operational devices. In many cases, it is unclear how risks scale with project size or vary by location (Copping et al., 2020; Hasselman et al., 2023). This higher risk perception caused delays in permits, slowing down project development (Boehlert & Gill, 2010).

To mitigate these challenges, EIAs and CEAs are now key tools. Yet, these assessment methods face key limitations. Current CEAs often rely on disparate data sources, non-standardised methodologies, and uncertain baseline conditions, making it difficult to produce comparable results across sites (Willsteed et al., 2017). The ecological consequences of energy extraction are rarely captured in full because existing models seldom link ecosystem, hydrodynamic, and socio-economic systems (Trifonova et al., 2022). Incorporating ecosystem-based modelling frameworks and natural capital assessments could help decision-makers better balance trade-offs between environmental, energy, and social goals.

To close these gaps, increased investment in multi-disciplinary and standardised research is urgently needed. Several international MRE test centres, such as EMEC in Scotland, Wave Hub in England, and the U.S. DOE-funded marine energy centres, already support prototype testing and environmental monitoring (Borthwick, 2016). These facilities offer valuable opportunities to observe full- and pilot-scale devices in real marine conditions, yet environmental research often lags behind technical innovation and remains underfunded (Boehlert & Gill, 2010).

New survey methods, like using active acoustic tools on both moving and fixed platforms, are starting to improve how we monitor species behaviour and habitat changes directly in their natural environment (Chapman et al., 2024).
However, field studies on key issues, such as animal entanglement with mooring lines, long-term acoustic exposure, or benthic community shifts, remain limited or speculative (Copping et al., 2020).

I.2.5) Recommendations and Way Forward

To make sure MRE is developed with social equity and environmental respect, a coordinated, multidisciplinary approach to governance, research, and development is urgently required. We need to move from separate environmental assessments for each project to a more unified system that looks at the combined effects of multiple projects across important ecological regions (Willsteed et al., 2017).
This would allow marine managers and policymakers to better anticipate and mitigate the compounded impacts of multiple overlapping marine activities, including MRE development, fisheries, and conservation initiatives. International collaboration will be key: nations must work together to establish shared environmental standards, transparent data platforms, and strategic research initiatives that bridge knowledge gaps, particularly around emerging risks like collision, noise pollution, and habitat alteration (Copping et al., 2020).
From a research and innovation point of view, future funding should focus not only on environmental monitoring but also on developing better materials, robotics, data systems, and energy storage to make MRE systems more efficient and sustainable (Borthwick, 2016). More broadly, the technical advances must be coupled with ethics, legislative clarity, regulatory consistency, and marine spatial governance (Wright, 2015). Finally, cross-sectoral cooperation among developers, scientists, policymakers, and funding agencies is essential for clean energy at sea strictly embeds environmental preservation (Copping et al., 2020; Willsteed et al., 2017).

CHAPTER I.a

Insights from the qualitative interview with Katherine Richardson[2]

Following her long and strong expertise in Earth systems and marine biology, Dr. Richardson's reflections reinforced the literature findings on the ocean's pivotal role in climate and ecological dynamics, underlying the uncertain risks deriving from their alteration.

According to Dr. Richardson, just as Charles Darwin's theory of evolution redefined our understanding of life, society is now entering a new paradigm, "a new phase of realisation: not only are we organisms, but we also belong to an ecosystem"; a planetary ecosystem that is tightly interconnected. This understanding became more widespread when people saw satellite images from the Apollo missions, which clearly showed that most of the Earth is covered by water. Covering more than 70% of the planet's surface, the ocean has acted as a dominant moderator of the Earth's climate throughout geological history.

A key driver of this regulatory function is the ocean's vast capacity to store and circulate labile CO_2 (moving and circulating). During past ice ages and interglacial periods, roughly 50 parts per million (ppm) of carbon dioxide moved between the ocean and the atmosphere, reshaping the climate. Yet, while these processes unfolded over 80,000 years, industrial activities have shifted 140 ppm of CO_2 from underground fossil reserves to the atmosphere in less than 300 years, dramatically accelerating the rate of change.

Over 90% of the resulting heat imbalance has already been absorbed by the ocean, on which "we are entirely dependent". Ultimately, "the ocean *is* climate change".

Richardson also emphasised how existing solutions, such as carbon dioxide removal (CDR), often overlook the ocean's response. As she notes, even if atmospheric CO_2 were successfully lowered through new technologies, it would eventually necessitate removing excess CO_2 from the ocean as well, due to the chemical equilibrium between the two systems. This challenge is poorly acknowledged in current policy dialogues.

[2] Full Interview transcript in Annex I

Beyond its role in climate regulation, Richardson discussed how the ocean's biodiversity is also deeply affected by alterations in the climate. Every marine species has a range of environmental conditions in which it can survive. As ocean temperatures rise, many species are migrating towards fresher polar waters, also creating new ecosystems. However, many organisms cannot move and are already facing existential threats. This includes the case of coral reefs, which are undergoing mass bleaching as rising sea temperatures cause them to expel the *zooxanthellae*, symbiotic algae essential to their survival. If heatwaves persist, these algae may not return, resulting in coral death. “Even if we achieve the Paris Agreement targets, which nothing suggests that we will”, she warns, “we are likely to lose coral reefs.” Current estimates indeed suggest that 80–90% of them are already affected by bleaching, and a 2°C rise in temperature would likely eliminate them entirely.

Ocean acidification, driven by CO_2 absorption, presents a further stressor. It particularly affects some organisms, like calcium carbonate producers. However, while “many marine organisms have seen and survived changing Earth conditions”, our knowledge is still too poor and insufficient to predict the long-term ecological consequences of these new dynamics.

In conclusion, “What makes Earth unique is life, and the interaction between biodiversity and the energy system, which has shaped Earth’s conditions for the past three and a half billion years”. And the ocean, as both a regulator of energy and a driver of biological processes, is at the centre of these unique processes. Acknowledging this interaction is essential to preserve its functions and ecosystems and stabilise climate change.

CHAPTER II

Is Deep-Sea Mining necessary for the Clean Transition?

II.1) INTRODUCTION

The deep sea, defined as ocean depths exceeding 200 meters and covering roughly 70% of the planet's surface, enshrines some of the least disturbed and most biologically diverse environments on Earth (Frölicher & Jaccard, 2023; WOR7, 2021). At an average depth of 4,000 meters, it is characterised by high pressure, almost freezing temperatures, and the complete absence of sunlight. Under these conditions, complex ecosystems have evolved, many of which are still poorly understood (Boetius & Haeckel, 2018; Amon et al., 2022). These environments provide crucial services of climate regulation, biodiversity, and potential biopharmaceutical resources, as well as hosting a range of minerals (Boetius & Haeckel, 2018). Although still widely unexplored, the deep-sea is gaining increasing attention from the recently developed industry of deep-seabed mining (DSM).

The latter represents, indeed, the extraction of mineral resources from the deep ocean floor, especially from deposits of polymetallic nodules, cobalt-rich crusts, and hydrothermal vent systems rich in copper, manganese, and cobalt. These are critical raw materials essential for the decarbonisation of energy production (Toro et al., 2020; Cassotta & Goodsite, 2023; Frölicher & Jaccard, 2023).
While interest in these resources has existed for over a century, technological and economic drivers have only recently intensified scientific and commercial attention (Frölicher & Jaccard, 2023). The European Union, for example, projects it will require up to 18 times more lithium and five times more cobalt by 2030 compared to 2020 levels, due to the rise of electric vehicles and energy storage needs (WOR7, 2021). The demand for rare-earth metals used in permanent magnets for wind turbines, digital technology, and EV motors is expected to increase tenfold by 2050 (WOR7, 2021).

Without these materials, building the necessary infrastructure is a utopia (Cassotta & Goodsite, 2023). The pivotal interest now is to secure these metals from less impactful and geopolitically safer sources (Mikayilov, 2021).

DSM presents a fundamental sustainability conundrum (Levin et al., 2020; Toro et al., 2020). As scientific research is not advanced enough, environmental concerns remain substantial, mainly considering the long growth history of these habitats and the uncertain recovery time (WOR7, 2021; Frölicher & Jaccard, 2023; Cassotta & Goodsite, 2023).

II.2) THE INTERNATIONAL SEABED AUTHORITY

Established in 1994 and headquartered in Kingston, Jamaica, the ISA is the primary body responsible for regulating mineral resource activities in the deep seabed areas beyond national jurisdiction, referred to as "the Area" under the UNCLOS (Sumaila et al., 2023; Amon et al., 2022; Hauner, 2024). Currently, 167 states and the European Union are members of the ISA (Frölicher & Jaccard, 2023; WOR7, 2021), whose key core mandate is to manage deep-seabed mineral resources as the "Common Heritage of Humankind," ensuring equitable benefit-sharing while preventing "serious harm" to the marine environment (UNCLOS Article 145; Amon et al., 2022; Smith et al., 2020).

To date, the ISA has issued 31 exploration contracts covering approximately 1.5 million km², particularly in regions like the Clarion-Clipperton Zone (WOR7, 2021; Smith et al., 2020). These contracts allow for environmental baseline studies and resource assessments, but no industrial-scale exploitation has yet begun (Hallgren & Hansson, 2021). Started in 2019, the ISA is now finalising a Mining Code to govern future exploitation, which, however, has been criticised for being rushed and for lacking sufficient scientific evidence (Cassotta & Goodsite, 2023; Blanchard et al., 2024).

The institutional structure mainly comprises a Council, a Legal and Technical Commission (LTC), a Finance Committee, and the Enterprise, which is still inactive (Levin et al., 2020). However, this organisation is also criticised for the internal conflicts of interest, underfunding, and insufficient attention to environmental issues (WOR7, 2021). The balance between the regulatory, promotional, and protective roles is indeed a core concern for environmentalists, together with the liability and ability to ensure fair and equitable benefit-sharing (Frölicher & Jaccard, 2023; Cassotta & Goodsite, 2023; EASAC, 2023).

II.3) CRITICAL MINERALS

This increasing interest in deep-sea mineral exploitation is mainly driven by the urgent global push for decarbonisation, to achieve the Paris Agreement's objectives of limiting global warming to 1.5°C and eliminating CO2 emissions by 2050 (IPCC SR15; Masson-Delmotte et al., 2018; Frölicher & Jaccard, 2023). The seabed hosts a wide range of metals crucial for batteries, electronics, wind turbines, and other components essential to clean energy technologies (Frölicher & Jaccard, 2023; Toro et al., 2020). These metals are recognised as "critical" or "strategic", and include, *inter alia*, rare earth elements (REEs), cobalt, lithium, nickel, and copper (Frölicher & Jaccard, 2023; Wang et al., 2023).

As mentioned before, these minerals are contained in three primary deposits: polymetallic nodules, cobalt-rich ferromanganese crusts, and seafloor massive sulfides (Frölicher & Jaccard, 2023; EASAC, 2023).

The first can be found on abyssal plains at depths of 3,000–6,500 meters, particularly in the Clarion-Clipperton Zone, and are among the most commercially attractive resources. These round concretions, formed through diagenetic and hydrogenetic processes, are rich in manganese, nickel, cobalt, and copper, with some also containing REEs like lanthanum, neodymium, and yttrium (Frölicher & Jaccard, 2023; WOR7, 2021). The CCZ alone spans roughly 5 million km^2 and holds an estimated 25–40 billion tonnes of nodules (WOR7, 2021; Amon et al., 2022). Numerous exploration contracts issued by the ISA are indeed focused on this area for its resource density (Hallgren & Hansson, 2021).

Secondly, Cobalt-rich ferromanganese crusts, present at depths of 800–2,500 meters on seamount slopes, are instead slow-growing formations of iron and manganese oxides rich in cobalt, titanium, molybdenum, and tellurium (WOR7, 2021; EASAC, 2023). Although the total global reserves are estimated at around 40 billion tonnes, geological data for most sites are still lacking (WOR7, 2021; Amon et al., 2022).

Finally, Seafloor massive sulfides (SMS) form in hydrothermal vent systems where superheated, metal-rich seawater comes into contact with cold ocean water, causing copper, zinc, gold and silver sulfides to precipitate (WOR7, 2021; Smith et al., 2020). These deposits also contain tech-critical elements such as cobalt, indium, and tellurium (Frölicher & Jaccard, 2023). Found at depths ranging from 1,000 to 4,000 meters, SMS systems lie along mid-ocean ridges and are estimated to cover 3.2 million km² globally, much of it in ABNJs (Amon et al., 2022).

The value of these deposits is not to be linked only to economic interests. They represent a fundamental source of ecosystems. More specifically, polymetallic nodules provide habitat for a wide range of benthic life, including microbes, foraminifera, and megafauna such as deep-sea octopuses and corals (Smith et al., 2020; Amon et al., 2022). Cobalt-rich crusts on seamounts are recognised as vulnerable marine ecosystems and are home to species like sponges and corals (Smith et al., 2020). SMS deposits host unique microbial communities adapted to extreme environments (Smith et al., 2020). Their ecological significance further complicates discussions around their extraction.

II.4) ADVANTAGES AND COMPARISON WITH LAND MINING

DSM is appealing even when considering the accelerating depletion of land-based ores and the delicate questions this is arising (Frölicher & Jaccard, 2023; Mikayilov, 2021). While terrestrial mineral reserves may, in principle, be sufficient to support the global transition to renewable technologies (Frölicher & Jaccard, 2023), their extraction carries significant environmental, social, and geopolitical issues. Land-based mining causes severe ecological degradation, including deforestation, biodiversity loss, water pollution, and massive greenhouse gas emissions (Mikayilov, 2021; Vivoda, 2024). From a social perspective, local communities are often threatened through displacement and human rights violations. For instance, child labour is a major concern in cobalt mining sites in the Democratic Republic of Congo, which supplies around 60% of the global cobalt market (Levin et al., 2020; Toro et al., 2020; Vivoda, 2024). Furthermore, the global supply chain for many critical minerals is overly reliant on single exporters, with over 80% of rare earth elements supplied by China. This creates deep geopolitical and market dependencies (Vivoda, 2024; Toro et al., 2020).

Conversely, DSM is considered a potentially lower-impact alternative. It does not require environmental destruction for infrastructure like roads or tunnels and avoids direct human displacement, with potentially safer jobs (Mikayilov, 2021; WOR7, 2021). From an economic point of view, extracting several metals simultaneously from single deep-sea deposits would be more efficient than targeting individual land-based sources (WOR7, 2021; Mikayilov, 2021).
Furthermore, if DSM were able to increase the supply of minerals and consequently lower their prices, renewable energy would become more accessible to everyone, accelerating the global adoption of clean solutions (Vivoda, 2024).

In conclusion, according to the supporters of this practice, if managed with robust regulation and environmental safeguards, DSM could provide a more ethical and sustainable pathway to securing the raw materials needed for a low-carbon future (Mikayilov, 2021; Vivoda, 2024).

II.5) ENVIRONMENTAL IMPACTS

Despite all these promises to support the green transition, the environmental risks that DSM would cause are extremely delicate and still too poorly known. These operations would threaten some of the most remote, biodiverse, and fragile ecosystems on Earth, with consequences that could be long-lasting or even irreversible (Frölicher & Jaccard, 2023; Amon et al., 2022; Levin et al., 2020).

The recognised environmental impacts of DSM can be broadly categorised into five main areas: 1) direct removal of biologically active resources and destruction of benthic habitats; 2) generation of sediment plumes; 3) chemical contamination and release of toxic substances; 4) increased noise, vibration, and light pollution; 5) cumulative and synergistic effects with other stressors such as climate change and overfishing (Frölicher & Jaccard, 2023; EASAC, 2023; Amon et al., 2022).

1. Habitat Destruction and Biodiversity Loss:

Mining activities involve the removal of key habitat structures like the deposits of polymetallic nodules, cobalt-rich crusts, or hydrothermal vent chimneys, that serve as foundational substrates for deep-sea biodiversity, as previously discussed (Amon et al., 2022; Smith et al., 2020). Destroying these systems, which took millions of years to develop, leads to the potentially permanent loss of highly specialised and often endemic organisms, or even to species extinctions (Levin et al., 2020; Frölicher & Jaccard, 2023). For instance, in nodule-rich regions such as the CCZ, mining is projected to affect over 500,000 km² through direct removal and sediment burial (Smith et al., 2020).

2. Sediment Plumes:

The sediment plume that would be generated through mining is double: one at the seafloor (collector plume) and another in the water column from waste discharge (dewatering plume) (Amon et al., 2022). These plumes could affect filter feeders like corals and sponges, decrease the food for benthic fauna, and alter the morphology of the seabed. For instance, in the CCZ, a single operation might discharge up to 80,000 m³ of sediment daily, affecting up to 24,000 km² over time (Sumaila et al., 2023). These plume impacts could extend 10–30 km from the mining site (WOR7, 2021; Smith et al., 2020).

3. Chemical Pollution and Toxicity:

DSM risks releasing harmful substances, especially metals like copper, cobalt, and zinc. This is particularly critical in mining sulfide-rich hydrothermal vents, where metal-rich plumes may disrupt ocean chemistry, deplete oxygen, and lead to toxic accumulation in marine organisms (Amon et al., 2022; Frölicher & Jaccard, 2023). These effects are difficult to quantify, as conducting toxicity experiments in deep waters remains very complex and expensive (EASAC, 2023).

4. Noise, Light, and Vibration Pollution:

Mining machines would introduce artificial light, sound, and mechanical vibrations into environments that are naturally dark and quiet (Amon et al., 2022; WOR7, 2021). These disturbances may alter animal behaviour, navigation and communication, although specific impacts remain uncertain (Levin et al., 2020; EASAC, 2023).

5. Long-Term and Cumulative Effects:

The limited scientific evidence and understanding of the deep-sea ecosystems and resilience further exacerbate the full scale of DSM's environmental impacts (Frölicher & Jaccard, 2023).

Recovery from disturbance is expected to be exceptionally slow, spanning centuries or millennia (Frölicher & Jaccard, 2023; Levin et al., 2020). In the Peru Basin, the DISCOL experiment simulated mining and revealed that even after 26 years, visible seafloor scars and reduced biodiversity persisted, with microbial recovery estimated to take over 50 additional years (Vonnahme et al., 2020; WOR7, 2021). Furthermore, large-scale restoration artificially replacing polymetallic nodules would cost around US$ 5.3–5.7 million per km^2, and applying it to even just 30% of mining concessions would exceed the global defence budget (Sumaila et al., 2023).

DSM could also interfere with deep-sea carbon cycling. While the global effects on atmospheric CO_2 are likely limited in the near term, the alteration of sediment structures and processes may eventually reduce carbon burial capacity (Levin et al., 2020). The particles and chemicals released can also affect the vertical flow of organic material and greenhouse gas production (Orcutt et al., 2020; Passow & De La Rocha, 2006).

Finally, it should not be forgotten that the impacts of DSM would add to other existing stressors, including climate change, unsustainable fishing and marine pollution (Frölicher & Jaccard, 2023; Levin et al., 2020). Without rigorous environmental assessments, greater scientific knowledge and legally binding regulations, the DSM could amplify rather than reduce humanity's ecological footprint (Cassotta & Goodsite, 2023; Amon et al., 2022; Mikayilov, 2021).

II.6) DEBATE AND NARRATIVES

The advantages and negative impacts of DSM just discussed are currently at the centre of a global debate, reflecting a profound tension between the need for critical minerals to support the transition to clean energy and the ethical, environmental and geopolitical risks associated with opening up a new frontier in resource extraction (Levin et al., 2020). What was presented in the last sections can be wrapped up in the contrasting narratives that outline this debate.

On the one hand, supporters of DSM often consider it as part of a “green economy in a blue world” (Hallgren & Hansson, 2021), arguing that exploiting seabed mineral reserves can alleviate supply constraints and reduce dependence on environmentally and socially damaging terrestrial mining (Hallgren & Hansson, 2021). DSM is portrayed as less intrusive, avoiding deforestation, displacement of communities, and the high infrastructure demands of land-based mining (Vivoda, 2024; Mikayilov, 2021). According to a second, supportive argument, the economic potential of diversifying supply chains and enhancing energy security could improve fair sharing of resources through the International Seabed Authority under the Common Heritage of Mankind principle (Hallgren & Hansson, 2021).

However, these positive arguments are contrasted by a broad coalition of states, scientists, NGOs, and international bodies that are voicing strong opposition to DSM. Over 700 international scientists and experts have signed a petition urging a ban on DSM until its environmental impacts are sufficiently assessed by reliable scientific knowledge (Frölicher & Jaccard, 2023). Countries including Chile, Costa Rica, Ecuador, Germany, Spain, Panama, and Vanuatu advocate for a precautionary pause, while France has taken a more decisive stance by banning DSM in its jurisdiction (Frölicher & Jaccard, 2023). European Union institutions, the European Parliament, and several Member States support a moratorium, as it is still too uncertain what constitutes “serious harm” and enforceable environmental thresholds are still lacking (EASAC, 2023).
This growing resistance reflects the third main narrative of the debate, that of the “depths of the unknown,” which underscores the fragile, understudied nature of deep-sea ecosystems and the potentially irreversible damage DSM could inflict. Scientific studies consistently show that recovery from mining in the deep ocean, where life grows and regenerates over millennia, is slow or even impossible (Amon et al., 2022; Levin et al., 2020). Added to this, the concerns are exacerbated by the risks linked to sediment plumes, chemical pollution, noise, and light disruptions that could harm marine species and biogeochemical cycles (Frölicher & Jaccard, 2023; EASAC, 2023).

Furthermore, critics reject the argument that DSM is indispensable for decarbonisation. Invoking the green transition to justify DSM underestimates the potential of, and shifts the focus and investments from, recycling, improved resource efficiency and circular economy models, which could reduce demand for critical minerals by up to 58% (Sumaila et al., 2023). These alternatives, combined with responsible terrestrial mining and battery innovation, could eliminate the need for DSM outright. According to this analysis, promoting DSM now risks undermining the very sustainability goals it claims to support (Sumaila et al., 2023).
Finally, a fourth narrative, claiming to "let the minerals be", is even harsher in considering DSM an unjustifiable assault on ecosystems for uncertain short-term profits. It also raises concerns about the governance of the ISA, which is accused of favouring state and corporate actors, as well as lacking transparency and sufficient environmental oversight (Hallgren & Hansson, 2021; Sumaila et al., 2023).

In synthesis, the current debate around DSM remains polarised, with proponents emphasising strategic opportunity and the need for resources, and opponents highlighting irreversible environmental harm, weak institutional safeguards, and advocating for more sustainable alternatives already existing. More than the feasibility, the core question is whether DSM is justifiable when seeking long-term, sustainable and fair development.

II.7) LACK OF SCIENTIFIC EVIDENCE

As mentioned many times already, the main obstacle to a possibly responsible development of DSM lies in the profound lack of scientific knowledge and evidence about the deep-sea ecosystems and the potentially irreversible impacts (Frölicher & Jaccard, 2023).
The shortage of reliable environmental baseline data is one of the most important gaps. Due to difficulties in conducting ongoing, long-term observation, it is very complex to understand how deep-sea ecosystems work, how resilient they are to disturbance, and what vital ecosystem services they offer. And it is equally challenging to monitor ecological changes between sampling campaigns because timeseries data are frequently irregular and poor (Radziejewska et al., 2022). This severely limits our capacity to

assess whether DSM operations comply with the ISA's mandate to prevent "serious harm" to the marine environment (Frölicher & Jaccard, 2023).

The scientific knowledge deficits can be summarised in two main categories: on the one hand, the lack of baseline data and detailed mining operation assessments; on the other, insufficient understanding of cumulative and indirect impacts, such as sediment plume behavior, chemical toxicity, and noise-related disturbances (Frölicher & Jaccard, 2023). The majority of deep-sea species lack even basic biological information, such as growth rates, reproductive cycles, stress tolerances, and connectivity (Smith et al., 2020).
Even in areas like the Clarion-Clipperton Zone, where research is comparatively more advanced, 70–90% of collected species are new to science, and it is estimated that an additional 25–75% remain undiscovered (Amon et al., 2022). Other resource zones, such as cobalt-rich crusts and inactive sulfides, are even less understood or entirely unexplored.
When considering, for instance, sediment plumes generated by mining operations, both from collectors on the seafloor and reinjection of waste close to the surface, their impacts are still highly vague. Even slight increases in sediment levels can disturb filter feeders and affect the overall functioning of the ecosystem, especially in ultra-sensitive areas with low background turbidity, such as the CCZ. Furthermore, mining technologies are still being developed, which makes impact assessment even more difficult (Smith et al., 2020).

As a result, developing specific environmental regulations remains complex, without generally recognised sediment sensitivity thresholds or forecasting instruments to evaluate stressor reactions from mining-related operations (Smith et al., 2020).
Because of this profound uncertainty, there is growing international support, backed by over 700 scientists and experts, for a DSM moratorium until we gain sufficient scientific knowledge. Without further research, evidence-based environmental management and effective regulation are impossible (Frölicher & Jaccard, 2023).

II.8) RECOMMENDATIONS AND PRECAUTIONARY PRINCIPLE

At the basis of this widespread call for a moratorium on DSM lies a strong consensus among scientists and some policymakers to promote a precautionary approach. Given that industrial-scale DSM has yet to be tested and its long-term impacts remain poorly understood, any alternative is considered to be premature and irresponsible at present (Cassotta & Goodsite, 2023; Vivoda, 2024).

According to this precautionary principle, each stage of DSM, from exploration to experimental testing and eventual exploitation, must follow environmental criteria, legally binding standards, and be rigorously monitored (EASAC, 2023; Levin et al., 2020).

Experts recommend slowing the transition from exploration to exploitation and adopting a comprehensive scientific roadmap. Before any project is authorised, basic research should be expanded and contractor data should be openly accessible (Amon et al, 2022).

Furthermore, DSM governance must also take into account climate change, which exacerbates mining-related stressors and can amplify long-term impacts on marine biodiversity and ecosystem services (Levin et al, 2020).

Ultimately, aligning DSM with sustainability requires not only tighter environmental oversight, but also investment in low-impact technologies, circular economy models, and global cooperation. Until these systems are in place, the precautionary pause cannot be avoided (Frölicher & Jaccard, 2023; Sumaila et al., 2023).

CHAPTER II.a

Insights from Qualitative Interviews on DSM

The qualitative interviews with Dr. Diva Amon and Dr. Katherine Richardson presented invaluable insights concerning the question of deep-sea mining. This chapter will provide a synthesis of these discussions, which broadly reflect and strengthen some of the findings from the literature, while contrasting some others.

1) Interview with Diva Amon[3]

From her profound expertise in deep-sea ecosystems and functions, Dr. Amon's stance on DSM is one of strong opposition and criticism.

She emphasised that although the ocean depths hold mineral resources currently essential for electric batteries and green technologies, primarily cobalt and nickel, they also "harbour incredible biodiversity and unique ecosystems that we are only just beginning to understand". The three main resources containing these minerals are polymetallic nodules, scattered across the seabed with metals accumulating around a small nucleus; hydrothermal vents, rich in polymetallic sulfides; and cobalt-rich crusts on seamounts. These have been mainly explored in the eastern-central Pacific Ocean area of the CCZ, "although access to these resources at depths of 4-6 kilometres is extremely complex and costly".

What we are seeing now, she explained, is an acceleration in activity compared to past decades, with a shift from state interest to private companies' activity, although often still backed by national governments. "This marks a new phase, more commercially driven and much faster".

Dr. Amon also stressed the vital role played by the ocean in climate regulation through carbon and heat storage, "buffering some of the worst impacts of climate change". The long-lasting environmental impacts of DSM, including sediment plumes (which can carry toxic metals for long distances), habitat destruction, and light-noise pollution, "could have ripple effects we can't fully predict". She notes that the damage to seabed

[3] Full transcript in Annex II

ecosystems caused by the scraping machinery, estimated to remove up to 20 cm of surface, may be irreversible on human timescales, with recovery potentially taking millennia.

Critically, Amon challenges the argument of DSM as a solution to terrestrial mining issues as misleading, since it may simply add to global competition rather than resolve environmental or humanitarian concerns. In line with this view, mining companies have begun lobbying for access to these resources in the name of national security, shifting the narrative from energy needs to defense and geopolitical matters.
Similarly, she rejects the idea that DSM is necessary for the green transition, pointing out that technological advances, like cobalt-free batteries, are reducing the need for seabed minerals.
The answer to the core question of this research, being it whether DSM would support or undermine efforts to address the climate crisis, lies strongly on the second option: "DSM as a strategy to combat climate change is incredibly short-sighted. The ocean is one of our best defences against global warming, and damaging it would be counterproductive".

Regarding regulation, Amon aligns with the concern that, without deeper scientific knowledge, advancing exploitation would not respect the ISA's mandate of "effective protection" and prevention of "serious harm." Highlighting the lack of large-scale research, she advocates independent studies "over much longer timescales and in a variety of locations" for informed decision-making to be possible.

Ultimately, Dr Amon acknowledges and supports the growing international movement against DSM, bolstered by global summits such as the UN Ocean Conferences. Since the 2022 second UNOC in Lisbon, where the first three national moratoriums were announced, 33 countries and several stakeholders have joined the call for a pause, with France leading the outright ban, and this is essential until further knowledge is gained.

2) Interview with Katherine Richardson

Although being more convinced that DSM will be part of our future, Dr Richardson aligned with Amon's idea that there cannot be such a thing as "sustainable DSM", as there are no truly "sustainable" technologies in general. Rather, sustainability is fundamentally about societal trade-offs: whether the environmental and social costs are justified by the value a given activity delivers. These are ethical questions, "that we, as a society, need to confront".

Historically, since Aristotle's and, later, Von Linné's (Carl Linnaeus) idea that "Nature's there for us to use", the value of nature was considered to be null until it was integrated in our economic system. However, Richardson highlighted how this is changing nowadays. "We are beginning to give nature a value in its own right", as reflected in the UN's target to protect a third of both land and ocean. What is urgent now is "to accept that we are a part of a system, that everything is interconnected" and that our interconnections with nature cannot be considered as "externalities".

If DSM is to proceed, "and I suspect we probably will, as it is seen as the most socially and environmentally acceptable option for meeting our needs right now", it must not repeat the same extractive mistakes made on land. She advocates reserving, firstly, fully protected marine areas, and only then determining what level of exploitation, be it DSM, fisheries, or aquaculture, might be permissible elsewhere. This would mark a shift from the current sector-by-sector regulation to a holistic legal and spatial governance system, "integrating DSM into a broader framework that ensures space for nature first, and then carefully balances the other uses of the ocean that we value".

Operating as a circular economy system, "nature has managed to survive for over 3 billion years without running out of resources". Now DSM is attractive because we want more, there are limits. In line with Amon's stance, Richardson advocates for a change in our approach and use of resources "so that, hopefully, in the future, there won't be as much demand for new minerals".

Finally, the interview confirmed a major theme in the DSM literature: the persistent and critical lack of scientific knowledge. Dr. Richardson highlighted the limitations of current ocean science, noting that data collection in the deep sea is not only technically difficult but also underfunded and late. Just as in the case of the Atlantic Meridional Overturning Circulation (AMOC), where consistent records only began in 2004, the lack of historical data severely constrains our ability to evaluate trends and risks. These gaps are especially problematic given the urgency of decisions being made today. Instead of informed governance, scientific understanding is playing catch-up with commercial interest.

This cautionary view echoed the reflections that were widely shared at the third UN Ocean Conference. Both scientists, including Dr Sylvia Earle, state leaders, like the President of French Polynesia, and representatives of indigenous communities stressed the conflicting pressures between the drive for mineral access and the relational, often spiritual, ocean ethics. As discussed with Richardson, the key difference lies only in proximity: Indigenous communities are closely connected to their ecosystems and must accommodate nature's limits, whereas industrial societies have abstracted these interactions, reducing nature to a set of external commodities.

Together, these insights make clear that any path forward on DSM must balance more than mineral demand; it must reconcile science, ethics, long-term planetary health, and economic redesign.

CHAPTER III

The EU's Stance on MRE and DSM for its Clean Energy Transition

III.1) MARINE RENEWABLES IN THE EU

The EU has taken a decisive leadership role in the transition to a climate-neutral economy, with a central focus on the deployment of renewable energy. This commitment is supported by the EU's climate goals, which include a legally binding target to reach net-zero greenhouse gas emissions by 2050 and to cut emissions by 55% by 2030, compared to 1990 levels (European Commission, 2020). Renewable energy is therefore not only a cornerstone of the European Green Deal, but a central component of the EU's broader strategy for energy security, economic growth, and environmental sustainability (European Commission, 2020).

III.1.1) MRE in the EU Energy Policy

Acknowledging the great potential in its seas and waters, the EU has made offshore renewable energy a key part of its climate strategy. The 2020 Offshore Renewable Energy Strategy (COM(2020)741) aims to scale offshore wind capacity from 12 GW to at least 60 GW by 2030 and 300 GW by 2050, alongside 1 GW and 40 GW of ocean energy over the same period (European Commission, 2020). These targets necessitate investments of up to €800 billion and a 30-fold increase in current capacity (European Commission, 2020).

In its most recent updates, Member States collectively set even higher targets: 111 GW by 2030 and 317 GW by 2050, surpassing the Commission's original estimates (European Commission, n.d.-b). To achieve this, the EU is promoting cross-border cooperation, enhancing Maritime Spatial Planning, and reinforcing funding instruments like the Innovation Fund and the Strategic Energy Technology (SET) Plan (European Commission, n.d.-b).

More specifically, the EU is currently leading in offshore wind technology, responsible for 42% of global installed capacity as of 2019, with 93% of the technology produced in Europe. Floating offshore wind is being increasingly explored, with 150 MW projected by 2024. However, further clarity and policy ambition are required to bring down costs to below €100/MWh by 2030 (European Commission, 2020).

Beyond offshore wind, the EU has also been a leader in developing ocean energy, especially tidal and wave technologies. By 2023, Europe had installed 30.5 MW of tidal stream energy and 13.3 MW of wave energy since 2010. EU companies hold most of the patents in these areas (Ocean Energy Europe, 2024). France and the UK have strongly supported the sector, with the UK allocating 53 MW and France investing €65 million in the FloWatt project (Ocean Energy Europe, 2024).
However, only 1 MW of wave energy remains operational, reflecting challenges in long-term project viability. Despite this, ocean energy has the advantage of being predictable and stable, making it a valuable particularly in remote and island regions (Ocean Energy Europe, 2024).

Globally, the EU faces growing competition from the US and China. The US invested $520M in ocean energy over the past five years, deploying 1.6 MW of tidal stream energy in 2023 alone (Ocean Energy Europe, 2024). China's Five-Year Plan also prioritises ocean energy, backed by subsidies and revenue guarantees. These trends underscore the need for more consistent and targeted EU funding and market signals, especially in the 2024 revision of National Energy and Climate Plans (NECPs) (Ocean Energy Europe, 2024).

III.1.2) The Regulatory Framework

After the first Renewable Energy Directives in 2009 and 2018, the EU further strengthened the measures for the uptake of renewables in 2023 through Directive (EU) 2023/2413. These frameworks aim to increase the share of RE in all sector, from transport, to heating and cooling, buildings, and industry, promoting electrification, the use of hydrogen, and smart infrastructure (European Commission, n.d.-d).

From 1990 to 2017, RE's contribution to the EU's total primary energy supply rose from 5.1% to 14.6%, thanks to long-term strategic planning and cross-sectoral policies (Apolonia et al., 2021).

In the framework of these efforts and objectives, MRE plays an increasingly significant role.

In addition to the Renewable Energy Directives, several other policies support the development of MRE. These include the Blue Growth Strategy, the Marine Strategy Framework Directive (MSFD), and the Maritime Spatial Planning Directive (MSPD). At the same time, the Environmental Impact Assessment Directive and the Birds and Habitats Directives under Natura 2000 ensure that MRE projects take biodiversity impacts into account (ETIP Ocean, 2020).
Marine Spatial Planning has proven crucial in managing sea space conflicts and project approvals. Countries like Germany, the Netherlands, and the UK have used MSP to align energy, environmental, and economic objectives (Quero García et al., 2019). Integrated, ecosystem-based planning facilitates stakeholder involvement and simplifies norms, while reducing the time to market for new technologies (Quero García et al., 2019).

Nonetheless, challenges persist, including fragmented governance, inconsistent funding, and complex permitting. Furthermore, deployment is hampered by the absence of dedicated legislation and fit-for-purpose financial mechanisms (Apolonia et al., 2021). Developers of early-stage technologies often struggle to access feed-in tariffs and R&D grants, unlike the offshore wind sector, which benefits from well-established support schemes. Moreover, environmental uncertainties, including habitat disruption, collision risks, and acoustic impacts, require further research and better data. The Copernicus Marine Service and EMODnet are crucial tools, but enhanced data-sharing and coordination are needed (Apolonia et al., 2021).

III.1.3) The International Framework

International agreements such as the UNCLOS the Convention on Biological Diversity (CBD), and various regional sea conventions (e.g., OSPAR, Barcelona, Helsinki) shape the EU's marine environmental obligations. Although these frameworks offer broad targets, they do not provide specific guidance for marine MRE, leaving specific clarifications on the EU legislation (Soria-Rodríguez, 2020).

In particular, UNCLOS Articles 192 and 206 obligate states to protect the marine environment and conduct impact assessments (United Nations, 1982). The CBD similarly mandates EIAs for activities likely to affect biodiversity. These provisions are operationalised in EU law through directives like the MSFD and EIA Directive, which set stricter environmental standards for MRE projects (Soria-Rodríguez, 2020).

Although Europe still leads in MRE technology and deployment, the US and China are increasingly challenging its position with more coordinated strategies in the US and China. These countries offer higher and more stable levels of public funding, simplified permitting, and strong market incentives. Europe's lack of coordination and uneven support across countries could weaken its competitive edge in MRE (Ocean Energy Europe, 2024).

Still, the EU has set a global benchmark in integrating environmental, industrial, and climate policy objectives. If the current momentum is sustained and funding mechanisms improved, Europe can retain its leadership while ensuring a just and ecologically sound energy transition (Ocean Energy Europe, 2024).

III.2) DEEP-SEA MINING IN THE EU

III.2.1) From Blue Growth to Precautionary Approach

Over the past decade, the EU has undergone a profound transformation in its approach to DSM. Once seen as a promising frontier for economic growth and strategic autonomy in raw materials, DSM is now increasingly perceived as a high-risk venture fraught with environmental uncertainties. The EU's changing stance highlights a broader internal tension between driving the green transition and protecting marine ecosystems. This shift is shaped by updated regulations, growing scientific concerns, and political debate within its institutions (Evans Pim, 2024.

In the early 2010s, DSM was firmly embedded within the EU's "Blue Growth" strategy. In 2012, the European Commission estimated that by 2020, up to 5% of the world's minerals could come from the ocean floor, and that this amount could double by 2030 (Evans Pim, 2024). This enthusiasm led the EU to invest over €100 million in

DSM-related research and development, primarily through Horizon 2020, with a peak investment of €84 million (Evans Pim, 2024).

However, support for DSM began to decline as environmental and governance concerns grew. In 2018, the European Parliament passed a key resolution calling for the EU to stop supporting DSM in Areas Beyond National Jurisdiction. It also urged Member States to stop promoting seabed mining. The resolution clearly called for an international moratorium on commercial DSM until we gain enough scientific evidence to show it will not seriously harm marine ecosystems (EJF, 2024; EASAC, 2023; Cassotta & Goodsite, 2023). This moment marked a pivotal turn in institutional discourse and policy direction.

The 2020 EU Biodiversity Strategy confirmed this shift, stating that marine minerals should not be exploited "before the effects of deep-sea mining on the marine environment, biodiversity and human activities have been sufficiently researched" and only if it can be demonstrated that the technology "causes no serious harm" (European Commission, 2022). This commitment was reinforced in the Commission's 2022 Joint Communication on International Ocean Governance, which stated that DSM should be banned until "scientific gaps are properly filled" and strong environmental protections are in place, in line with UNCLOS obligations (European Commission, 2022; Seas at Risk, 2024).

The European Commission further clarified its stance in response to concerns about Mario Draghi's 2023 competitiveness report, which had suggested DSM could be environmentally sustainable. The Commission strongly rejected this recommendation, making clear that these projects would not be classified as "Strategic Projects" under the newly adopted Critical Raw Materials Act (EJF, 2024).

III.2.2) Scientific Research and the ERDEM Project

While distancing itself from commercial DSM, the EU has continued to support scientific research and technology development to better understand deep-sea ecosystems and the potential impacts of extraction. A notable initiative in this context is the ERDEM project, which aims to create a Framework for Sustainable Deep-Sea

Mining through collaborative research involving scientists, policymakers, and industry actors (European Commission, n.d.-c).

The objectives of ERDEM include developing a governance framework (GFORSE); integrating legal instruments, impact assessments, and policy recommendations; Advancing robotic and sensor-based mining technologies for low-impact telemining; Establishing real-time environmental monitoring systems using mobile, geo-referenced sensors; Enhancing ecological knowledge of deep-sea biodiversity, resilience, and geological dynamics (European Commission, n.d.-c).

Although ERDEM explores DSM technologies, its primary focus is environmental precaution, governance innovation, and cross-border cooperation rather than exploitation. The initiative illustrates a more cautious and knowledge-driven approach that aligns with the broader precautionary stance in EU policy.

III.2.3) Growing Political Consensus, but Fragmented Legal Unity

As of 2024, fourteen European countries now support a moratorium, precautionary pause, or full ban on DSM, an increase from zero just three years earlier (Evans Pim, 2024). The European Parliament has echoed this stance through successive resolutions (2021, 2022, 2024), while the European Investment Bank has excluded DSM from its funding portfolio for the environmental risks (Evans Pim, 2024).

However, despite this growing political consensus, the EU still lacks a formal, unified negotiating position at the ISA. Indeed, in 2021 the Commission issued a proposal to establish a common EU position, which was hindered due to internal divergences among Member States (Evans Pim, 2024).

This fragmentation is also reflected in the legislative framework, as the 2023 Critical Raw Materials Act (CRMA), which aims to strengthen the EU's strategic autonomy in securing key resources for the green transition. Notably, the CRMA initially identified underwater minerals as potential targets for extraction (Pelaudeix, 2018). This designation could have allowed DSM projects to be recognised as *EU Strategic Projects*, opening pathways for both funding and implementation. However, due to sustained pressure from environmental NGOs and the Parliament, the final version of the CRMA stopped short of granting such strategic status to DSM (EJF, 2024).

Meanwhile, the EU continues to advocate within the ISA for robust environmental regulations, including the development of threshold values and science-based standards to ensure effective protection of the marine environment (European Commission, 2022).

III.2.4) Conclusion

Europe's move away from DSM enshrines the important questions about the balance between strategic independence and environmental sustainability. The EU depends heavily on external sources for the critical minerals needed for the green transition, unlike more self-sufficient regions such as China or the US (Cassotta & Goodsite, 2023). Despite this reliance, the EU has chosen to prioritise environmental caution over pursuing deep-sea mineral extraction.

The current EU's stance on DSM can be summarised as one of precaution. Although not all Member States legally banned it, current policy discussions increasingly support a moratorium and prioritise protecting marine ecosystems over industrial development.

III.3) THE EU OCEAN PACT

At the Third United Nations Ocean Conference (UNOC3) in Nice, at the beginning of June 2025, EU Commission President Ursula von der Leyen announced the European Ocean Pact, a major initiative that brings all EU ocean-related efforts into one strategic plan.

Building on the foundation set by the Manifesto for a European Ocean Pact (Pons et al., 2024), the Pact highlights the vital importance of healthy oceans for ecological resilience, social wellbeing, and economic strength across the EU.

The Pact is based on six main pillars: restoring marine ecosystems, building a resilient and low-carbon blue economy, supporting coastal and island communities, improving maritime security, boosting ocean knowledge and innovation, and strengthening the EU's role in global ocean diplomacy and governance (Torbidoni, 2025, Scholaert, 2025). It brings together and expands existing tools, such as the European Green Deal and the EU Biodiversity Strategy, to create a more coordinated approach that tackles the connected problems of climate change, pollution, and biodiversity loss (Van Leeuwen et al., 2025).

Of particular relevance to this chapter, the Pact explicitly reaffirms the EU Commission's precautionary approach to DSM, maintaining its call for a moratorium on exploitation until scientific evidence can demonstrate no harm to marine ecosystems (European Commission, 2025).
In parallel, the Pact recognises the strategic importance of scaling up offshore renewable energy, including wind and ocean energy technologies, as key enablers of the EU's climate neutrality, energy security, and industrial competitiveness objectives. To that end, it calls for enhanced regional cooperation, better spatial planning, and investment in infrastructure to support the responsible rollout of MRE, with an emphasis on co-existence with other marine uses and environmental conservation (European Commission, 2025).

To ensure the Pact's long-term impact, the Commission plans to table a binding *Ocean Act* by 2027. This legislative proposal, requested by many stakeholders, aims to update and combine existing maritime laws, especially the MSPD, into a modern legal framework that can better coordinate EU marine policies and ensure consistency across actions (Scholaert, 2025). Together, the Pact and the upcoming Ocean Act mark an important shift toward integrated, strategic, and sustainability-focused ocean governance, reinforcing the EU's leadership in protecting ocean health while supporting innovation and resilience in the blue economy (Scholaert, 2025).

CHAPTER III.a

Insights from Qualitative Interviews on the EU's Stance

1) Interview with Katherine Richardson

In the broader context of EU efforts to lead a just and green transition, the insights shared by Dr. Katherine Richardson helped placing the EU's current debates within a global, systemic framework.

Firstly, she highlighted how the EU is facing a dual pressure. On the western side, the United States, under the Trump administration, are increasingly keen on intensifying drilling and mining, "with little regard for environmental limits".

On the Eastern side, China is emerging as a global leader in both renewable energy and biodiversity investment. Notably, China has significantly outpaced the EU and U.S. in its commitment to green technologies, boasting the world's largest wind turbine manufacturers, the highest penetration of solar and wind energy, and growing dominance in electric vehicles.

For Europe, maintaining competitiveness in this global arena requires accelerating its own green transition, especially in the renewable energy sector.

However, when talking about biodiversity, "there is still a long way to go". The broader public in the EU does not fully value biodiversity in its own right, but that mindset is slowly shifting.

This evolving awareness is particularly relevant to DSM. The latter exemplifies the deep tension between two paradigms: the traditional resource-extractive model, which treats nature as a commodity, and the emerging recognition of nature's intrinsic value.

DSM must not be treated in isolation. Instead, it should be understood as one component within a larger systemic shift in global sustainability governance.

The debate over DSM mirrors broader societal questions about how to guarantee fair share of limited resources, not only among human populations, but also with other living organisms.

Internationally, The SDGs embody this effort by integrating diverse social, economic, and environmental objectives into a single global framework.
In this light, DSM becomes a test case for the EU's ability to design ocean governance holistically. Ultimately, it challenges traditional legal and institutional models and calls for integrated, long-term strategies that prioritise both planetary limits and interactions between species.

2) Interview with Xavier Guillou[4]

In this interview Mr Guillou, team leader for Maritime Spatial Planning and MRE at the DG MARE of the European Commission, an important distinction has been pointed out since the beginning. That between MRE and DSM, both in policy and practice, with firm EU's support for the first, and precaution or opposition towards the second. According to Guillou, there is no direct technological or material dependency linking offshore renewables to DSM. The need for critical raw materials in this sector is comparatively minor and largely addressable through existing supply chains and alternative sources.
Indeed, most of the critical materials challenges in the energy sector stem from other areas, such as IT and battery production, rather than from MRE technologies. For instance, the structural components of offshore wind infrastructure, primarily steel, concrete, and polymers, can mostly be sourced within Europe.
Accordingly, while some global actors are pursuing DSM more actively, particularly in the Pacific, the EU is not currently funding or prioritising research in this area, nor has it identified concrete resource zones within its waters that would warrant such exploration.

On the marine renewable energy front, Guillou highlighted the relatively low but rapidly growing contribution of offshore wind to EU energy production.
The interview also highlighted the importance of regional cooperation and maritime spatial planning as essential tools for the expansion of offshore energy. Currently, coordination is stronger in the North and Baltic Seas, where geographic proximity necessitates integrated planning among member states. These areas serve as models for

[4] Interview questions in Annex III

cross-border governance, not only in terms of energy but also concerning environmental protection and marine space management. Initiatives such as the North Seas Energy Cooperation Declaration and the Greater North Sea Basin Initiative as key examples of this approach.

Finally, Guillou stressed how regional coordination represents a real strategic necessity, especially in light of recent geopolitical events and infrastructure vulnerabilities in the maritime domain.
In summary, Guillou's perspective reflects the EU's strategic adoption of MRE as a cornerstone of decarbonisation and the call for science-based policy, integrated planning, and transnational cooperation for Europe's marine spaces.

5. Conclusion

This thesis set out to examine the environmental trade-offs of Marine Renewable Energy technologies and deep-sea mining, with a specific focus on their role in the European Union's green energy transition and their implications for ocean ecosystems. At the core of the research lies a fundamental question: do these marine-based activities support climate mitigation efforts, or do they risk deepening environmental degradation by attempting to solve one crisis at the expense of another?

While definitive conclusions are limited by a lack of empirical data, particularly in the case of DSM, the research suggested that MRE and DSM lead to very different answers. MRE technologies show strong potential to contribute meaningfully to decarbonisation goals, and although they introduce localised ecological impacts, these can be mitigated through improved regulatory tools, such as more robust Environmental Impact Assessments and Cumulative Impact Assessments. Their benefits to the energy system, especially under an ecosystem-based management approach, are widely recognised in both the literature and expert interviews.

In contrast, DSM emerges as an activity that cannot currently be pursued sustainably. The deep-sea remains one of the least understood environments on Earth, and the limited data available suggests that damage from mining activities could be long-lasting or even irreversible. Moreover, as highlighted by both the literature and expert voices, and particularly Dr Diva Amon, the time, costs, and uncertainties associated with industrialising DSM make it a less viable solution compared to alternatives such as mineral recycling, improved land-based practices, and technological advancements. Notably, insights from Xavier Guillou also clarify that the link between MRE and DSM is weaker than often assumed, as most critical mineral demand stems from other sectors.

These findings align closely with the European Union's current stance: supporting the development of MRE through innovation and investment, while calling for a precautionary pause on DSM until sufficient scientific knowledge and regulatory safeguards are in place. This approach is increasingly shared by other international actors and strongly supported by the scientific community.

Interviews with experts were key to informing and enriching this analysis. Dr Katherine Richardson provided essential context on the ocean's role as a climate regulator and emphasised the interconnectedness of ecosystems and global systems. Dr Amon's expertise on the deep sea brought valuable scientific insight into the risks associated with DSM. Dr Guillou's perspective shed light on EU policy dynamics and regulatory implementation, bridging science and governance.

Finally, participating in the 2025 United Nations Ocean Conference offered not only an extraordinary personal opportunity but also tangible proof of the urgency and relevance of my research. The topics explored in this thesis are at the heart of today's discussions among leaders in science, diplomacy, and policy. As the world moves forward with climate action, ensuring that marine-based solutions do not compromise the ocean's health is critical to a truly sustainable transition.

6. Acronyms

ABNJ: Areas Beyond National Jurisdiction

AMOC: Atlantic Meridional Overturning Circulation

BBNJ: Biodiversity Beyond National Jurisdiction

CBD: Convention on Biological Diversity

CCZ: Clarion Clipperton Zone

CHH: Common Heritage of Humankind

CIA/CEA: Cumulative Impact/Environmental Assessment

CRMs: Critical Raw Materials

DSM: Deep-Sea Mining

EIA: Environmental Impact Assessment

EMFs: Electromagnetic Fields

FPVs: Floating Photovoltaics

ISA: International Seabed Authority

MPA: Marine Protected Areas

MRE: Marine Renewable Energy

MSP: Maritime Spatial Planning

ORE: Offshore Renewable Energy

OTEC: Ocean Thermal Energy Conversion

SDGs: Sustainable Development Goals

OWE: Offshore Wind Energy

RE: Renewable Energy

REEs: Rare Earth Elements

SMS: Seafloor Massive Sulfides

UNCLOS: UN Convention on the Law of the Sea

UNOC: UN Ocean Conference

WECs: Wave Energy Converters

References

Amon, D. J., Gollner, S., Morato, T., Smith, C. R., Chen, C., Christiansen, S., Currie, B., Drazen, J. C., Fukushima, T., Gianni, M., Gjerde, K. M., Gooday, A. J., Grillo, G. G., Haeckel, M., Joyini, T., Ju, S.-J., Levin, L. A., Metaxas, A., Mianowicz, K., Molodtsova, T. N., & Pickens, C. (2022). Assessment of scientific gaps related to the effective environmental management of deep-seabed mining. *Marine Policy, 138*, 105006. https://doi.org/10.1016/j.marpol.2022.105006

Apolonia, M., Fofack-Garcia, R., Noble, D. R., Hodges, J., & Correia da Fonseca, F. X. (2021, August 10). Legal and Political Barriers and Enablers to the Deployment of Marine Renewable Energy. In *Energies* (Vol. 14(16)). https://doi.org/10.3390/en14164896

Attrill, M., Inger, R., Bearhop, S., & Broderick, A. C. (2009, December). Marine renewable energy: Potential benefits to biodiversity? An urgent call for research Wiley. In *Journal of Applied Ecology* (Vol. 46(6), pp. 1145 - 1153). 10.1111/j.1365-2664.2009.01697.x

Benjamins, S. et al., 2024, 'Potential environmental impacts of floating solar photovoltaic systems', Renewable and Sustainable Energy Reviews, vol. 199 https://www.sciencedirect.com/science/article/pii/S1364032124001862

Blanchard, C., Harrould-Kolieb, E., Jones, E., & Taylor, M. L. (2024, January). The current status of deep-sea mining governance at the International Seabed Authority. In *Marine Policy* (Vol. 147). https://doi.org/10.1016/j.marpol.2022.105396

Boehlert, G. W., & Gill, A. B. (2015, October 2). Environmental and Ecological Effects of Ocean Renewable Energy Development: A Current Synthesis. In *Oceanography* (Vol. 23(2), pp. 68–81). https://doi.org/10.5670/oceanog.2010.46

Borthwick, A. G.L. (2016, March). Marine Renewable Energy Seascape. In *Engineering* (Vol. 2(1), pp. 69-78). ScienceDirect. https://www.sciencedirect.com/science/article/pii/S2095809916301503

Cassotta, S., & Goodsite, M. (2023). Sustainable and Just Deep-Sea Mining for the Energy Green Transition: A Conundrum Without Legal, Governance or

Technological Solutions. The Case of the EU. In *European Energy and Environmental Law Review* (Vol. 32, Issue 6, pp. 268 – 282). https://doi.org/10.54648/eelr2023017

Chapman, J., Williamson, B. J., Couto, A., Zampollo, A., Davies, I. M., & Scott, B. E. (2024, June). Integrated survey methodologies provide process-driven framework for marine renewable energy environmental impact assessment. In *Marine Environmental Research* (Vol. 198). https://doi.org/10.1016/j.marenvres.2024.106532

Copping, A. E., Hemery, L. G., Overhus, D., & Garavelli, L. (2020, November). Potential Environmental Effects of Marine Renewable Energy Development-The State of the Science. In *Journal of Marine Science and Engineering*. 10.3390/jmse8110879

Copping, A. & Farr, H., 2023, 'Feasibility, Environmental Effects, and Social Acceptance of Ocean Thermal Energy Conversion', Pacific Northwest National Laboratory https://tethys.pnnl.gov/publications/feasibility-environmental-effects-social-acceptance-ocean-thermal-energy-conversion

EASAC. (2023, June). *Deep-Sea Mining: assessing evidence on future needs and environmental impacts*. https://easac.eu/fileadmin/user_upload/EASAC_Deep_Sea_Mining_Web_publication_.pdf

EIA, 2023, Ocean thermal energy conversion produces energy from temperature differences in ocean waters, viewed 06 May 2025

Environmental Justice Foundation (EJF). (2024, January 09). CRITICAL MINERALS AND THE GREEN TRANSITION DO WE NEED TO MINE THE DEEP SEAS? In *EJF*. file:///Users/carolinaagostini/Downloads/EJF_critical-minerals-and-the-green-transition.pdf

Environmental Justice Foundation (EJF). (2024, October 10). EU Commission reaffirms stance against deep-sea mining in favour of marine protection. In *EJF*. https://ejfoundation.org/news-media/eu-commission-reaffirms-stance-against-de ep-sea-mining-in-favour-of-marine-protection#:~:text=It%20proves%20that%20the%20European,the%20ocean%20for%20our%20batteries.

ETIP Ocean, 2020, 'Ocean Energy and the Environment: Research and Strategic Actions', *European Technology & Innovation Platform for Ocean Energy* *https://www.etipocean.eu/knowledge_hub/ocean-energy-and-the-environment-research-and-strategic-actions/*

European Commission. (n.d.-a). *Environmentally Responsible Deep Sea Mining commitment*. European Commission. Retrieved January 13, 2025, from https://single-market-economy.ec.europa.eu/sectors/raw-materials/eip/raw-materials-commitment/environmentally-responsible-deep-sea-mining_en

European Commission. (n.d.-b). *EU funding for offshore renewables*. European Commission. https://energy.ec.europa.eu/topics/renewable-energy/financing/eu-funding-offshore-renewables_en

European Commission. (n.d.-c). *Offshore renewable energy*. European Commission. https://energy.ec.europa.eu/topics/renewable-energy/offshore-renewable-energy_en

European Commission. (2022, June 24). *JOINT COMMUNICATION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS*. Brussels. https://oceans-and-fisheries.ec.europa.eu/system/files/2022-06/join-2022-28_en.pdf

European Commission. (n.d.-d). Renewable Energy Directive. *Energy - European Commission*, https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en. Accessed 22 June 2025.

European Commission. (2020, November 19). An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future. In *Communication from the Commission to the EU Parliament, the Council, the EU Economic and Social Committee and the Committee of the Regions*.

https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A741%3AFIN&qid=1605792629666

European Commission. (2024). The EU blue economy report 2024. In *Publications Office of the European Union*. https://medblueconomyplatform.org/wp-content/uploads/2024/05/the-eu-blue-economy-report-2024.pdf

European Commission. (2025, June 05). The European Ocean Pact - Communication to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. In *European Commission*. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=comnat:COM_2025_0281_FIN

European Parliament, & Council of the European Union (2018). Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. *Official Journal of the European Union, L 328*, 82–209. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32018L2001

European Parliament & Council of the European Union. (2023). Directive (EU) 2023/2413 of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652. *Official Journal of the European Union*, L 263, 31 October 2023, 211–280. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023L2413

European Parliament. (2025, May 21). EU Strategy for Offshore Renewable Energy Sources. In *A EU green Deal - Legislative Train*. https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/file-offshore-wind

Evans Pim, J. (2024, September). The changing seascape of deep-sea mining in Europe. In *Seas at Risk*. https://seas-at-risk.org/wp-content/uploads/2024/09/EU-DSM-Report_September-digital-w-appendix.pdf

Frölicher, T., & Jaccard, S. (2023, April). The state of knowledge on the environmental impacts of deep-sea mining. In *University of Bern*.

https://boris.unibe.ch/183008/10/report_deepsea_mining_froelicher_jaccard_final_published.pdf

Galparsoro, I. et al., 2022, 'Reviewing the ecological impacts of offshore wind farms', npj Ocean Sustainability, vol. 1, no.1 https://www.nature.com/articles/s44183-022-00003-5

Gleckler, P. J., Durack, P. J., Stouffer, R. J., & Johnson, G. C. (2016). Industrial-era global ocean heat uptake doubles in recent decades. *Nature Climate Change, 6*(4), 394–398. https://doi.org/10.1038/nclimate2915

Hallgren, A., & Hansson, A. (2021, May 08). Conflicting Narratives of Deep Sea Mining. In *Sustainability* (Vol. 13(9)). https://doi.org/10.3390/su13095261

Hasselman, D. J., Hemery, L. G., Copping, A. E., Fulton, E. A., Fox, J., Gill, A. B., & Polagye, B. (2023, December 15). Scaling up' our understanding of environmental effects of marine renewable energy development from single devices to large-scale commercial arrays. In *Science of The Total Environment* (Vol. 904). https://doi.org/10.1016/j.scitotenv.2023.166801

Haugan, P. M., & Levin, L. A. (2020, June 24). Blue Print: What Role for Ocean Renewable Energy and Deep-Seabed Minerals in a Sustainable Future? In *High Level Panel for A Sustainable Ocean Economy*. https://oceanpanel.org/publication/what-role-for-ocean-based-renewable-energy-and-deep-seabed-minerals-in-a-sustainable-future/

Hauner, S. (2024). Deep-sea mining: Exploration rights under ISA regulation. *Mining Technology.* https://www.mining-technology.com/features/deep-sea-exploration-rights-under-international-seabed-authority-regulations/

Herr, D., & Galland, G. R. (2009). *The ocean and climate change*. In *Tools and guidelines for action* (72 pp.). IUCN. https://www.researchgate.net/publication/237410901_The_Ocean_and_Climate_Change_Tools_and_Guidelines_for_Action

Herrera Anchustegui, I. & Radovich, V.S., 2022, 'Wind Energy on the High Seas: Regulatory Challenges for a Science Fiction Future', Energies, vol. 15, no. 23 https://www.mdpi.com/1996-1073/15/23/9157

Hooper, T., Armstrong, A. & Vlaswinkel, B., 2021, 'Environmental impacts and benefits of marine floating solar'. Solar Energy, vol. 219, pp. 11-14, https://doi.org/10.1016/j.solener.2020.10.010

IEA Ocean Energy Systems (2024). OES Annual Report 2023 - An Overview of Ocean Energy Activities in 2023. Access on 05 May 2025 https://www.ocean-energy-systems.org/publications/oes-annual-reports/document/oes-annual-report-2023/

IRENA (2019), Global energy transformation: A roadmap to 2050 (2019 edition), International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/-/media/Irena/Files/Macroeconomic-benefits/IRENA_Global_Energy_Transformation_2019.pdf

Jacquemont, J., Blasiak, R., Le Cam, C., Le Gouellec, M., & Claudet, J. (2022). Ocean conservation boosts climate change mitigation and adaptation. *One Earth, 5*(10), 1126–1138. https://doi.org/10.1016/j.oneear.2022.09.002

Krishnamurthy, R. (2025, March 18). Negotiations on mining code for deep-sea mining begin in Jamaica amid mounting pressure from industries. In *DownToEarth*. https://www.downtoearth.org.in/mining/negotiations-on-mining-code-for-deep-sea-mining-begin-in-jamaica-amid-mounting-pressure-from-industries

Levin, L. A., Amon, D. J., & Lily, H. (2020, October 01). Challenges to the sustainability of deep-seabed mining. In *Nature Sustainability* (Vol. 3(10)). 10.1038/s41893-020-0558-x

Li, H., Sun, X. & Zhou, H., 2022, 'Wave energy: history, implementations, environmental impacts, and economics', 2nd International Conference on Materials Chemistry and Environmental Engineering, 10.1117/12.2646119. https://tethys.pnnl.gov/sites/default/files/publications/Li-et-al-2022_0.pdf

Mikayilov, E. (2021). The Environmental Impacts of the World Energy Transition: the Role of Raw Materials Mining. In *Master's Thesis Politecnico di Torino*. https://webthesis.biblio.polito.it/secure/18772/1/tesi.pdf

Ocean Energy Europe. (2024, April). Ocean Energy. Stats & Trends 2023. In *Ocean Energy Europe*. Rémi Gruet and Victor Kempf. https://www.oceanenergy-europe.eu/wp-content/uploads/2024/05/Ocean-Energy-Stats-and-Trends-2023.pdf

OES-Environmental. (2024, September 17). OES-Environmental 2024 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. In . *Report for Ocean Energy Systems (OES)*. 10.2172/2438585

Pelaudeix, C. (2018). Deep Seabed Mining of Critical Metals. Strategic and Governance Challenges. *Éditoriaux de l'Ifri.* https://www.researchgate.net/publication/329801489_Deep_Seabed_Mining_of_Critical_Metals_Strategic_and_Governance_Challenges

Pons, G., Lamy, P. L., & Valverde, E. (2024, May). Manifesto for a European Ocean Pact. In *Europe Jacque Delors and Oceano Azul Foundation*. https://europejacquesdelors.cdn.prismic.io/europejacquesdelors/ZlhQ4KWtHYXtT7X9_ManifestoforaEuropeanOceanPact_digital_MAY2024.pdf

Quero García, P., García Sanabria, J., & Chica Ruiz, J. A. (2019, January). The role of maritime spatial planning on the advance of blue energy in the European Union. In *Marine Policy* (Vol. 99, pp. 123-131). https://doi.org/10.1016/j.marpol.2018.10.015

Reid, P. C., Fischer, A. C., Lewis-Brown, E., Meredith, M. P., Sparrow, M., Andersson, A. J., Antia, A., Bates, N. R., Bathmann, U., Beaugrand, G., Brix, H., Dye, S., Edwards, M., Furevik, T., Gangstø, R., Hátún, H., Hopcroft, R. R., Kendall, M., Kasten, S., Keeling, R., & Washington, R. (2009). Impacts of the oceans on climate change. In Advances in Marine Biology (Vol. 56, pp. 1–150). Academic Press. https://doi.org/10.1016/S0065-2881(09)56001-4

Rezaei, T. & Javadi, A., 2024, 'Environmental impact assessment of ocean energy converters using quantum machine learning'. Journal of Environmental Management, vol. 362. https://pubmed.ncbi.nlm.nih.gov/38833932/

Riefolo, L. et al., 2015, 'Environmental Impact Assessment Of Wave Energy Converters: A Review', International Conference on Applied Coastal Research SCACR https://www.researchgate.net/publication/285579453_Environmental_Impact_Assessment_Of_Wave_Energy_Converters_A_Review

Rivera, G., Felix, A. & Mendoza, E., 2020, 'A Review on Environmental and Social Impacts of Thermal Gradient and Tidal Currents Energy Conversion and Application to the Case of Chiapas, Mexico', International journal of environmental research and public health, vol. 17, no. 21 https://www.mdpi.com/1660-4601/17/21/7791

Scholaert, F. (2025, June 17). The European Ocean Pact: And an Ocean Act by 2027. In *Epthinktank*. https://epthinktank.eu/2025/06/17/the-european-ocean-pact-and-an-ocean-act-by-2027/

Scott-Buechler, C. M., & Greene, C. H. (2019). Chapter 6 – Role of the ocean in climate stabilisation. In M. Bui & N. Mac Dowell (Eds.), *Bioenergy with carbon capture and storage: Using natural resources for sustainable development* (pp. 109–130). Academic Press. https://doi.org/10.1016/B978-0-12-816229-3.00006-5

Seas at Risk. (2024, October 10). *European Commission rejects Draghi report's call for deep-sea mining*. Seas At Risk. https://seas-at-risk.org/general-news/european-commission-rejects-draghi-reports-call-for-deep-sea-mining/

Seta, M., 2024, 'Environmental Impact Assessment of Offshore Windfarms in Areas Beyond National Jurisdiction: Who Should Have Obligations? ' *Australian Year Book of International Law*, vol 41, no. 1, pp. 74–101 https://brill.com/view/journals/auso/41/1/article-p74_4.xml?srsltid=AfmBOopojkJjZDi_ZtkQiXccISYWRQ5_pU0WuxUDr1kow_1B1gwEADvA

Shi, W. et al., 2023, 'Review on the development of marine floating photovoltaic systems', Ocean Engineering, vol. 286, no.1. https://doi.org/10.1016/j.oceaneng.2023.115560

SINTEF, 2019, Identifying key environmental effects of wave energy deployments, viewed 06 May 2025 https://blog.sintef.com/energy/identifying-key-environmental-effects-of-wave-energy-deployments/

Smith, C. R., Tunnicliffe, V., Colaço, A., Sweetman, A. K., Washburn, T., & Amon, D.

J. (2020). Deep-sea misconceptions cause underestimation of seabed-mining impacts. *Trends in Ecology & Evolution, 35*(10), 853–857. https://doi.org/10.1016/j.tree.2020.07.002

Soria-Rodríguez, C. (2020, May 18). The international regulation for the protection of the environment in the development of marine renewable energy in the EU. In *RECIEL*. https://doi.org/10.1111/reel.12337

Soria-Rodríguez, C., 2022, 'Marine renewable energy technologies on the high seas: challenges and opportunities to strengthen international environmental and renewable energy governance'. *Cambridge International Law Journal,* vol 11, no. 2, pp. 202–219 https://investigacion.ujaen.es/documentos/63cc8e95ab05b07b6665adf1?lang=eu

Sumaila, U. R., Alam, L., Pradhoshini, K., Onifade, T. T., Karuaihe, S. T., Karuaihe, P., Levin, L. A., & Flint, R. (2023, November 08). To engage in deep-sea mining or not to engage: what do full net cost analyses tell us? In *NPJ Ocean Sustainability* (Vol. 2(19)). https://www.nature.com/articles/s44183-023-00030-w.pdf

Torbidoni, G. (2025, June 05). Brussels proposes the Pact for the Oceans: more protected areas, a fleet of drones and a network of ambassadors. In *eunews*. https://www.eunews.it/en/2025/06/05/brussels-proposes-the-pact-for-the-oceans-more-protected-areas-a-fleet-of-drones-and-a-network-of-ambassadors/

Toro, N., Robles, P., & Jeldres, R. I. (2020, November). Seabed mineral resources, an alternative for the future of renewable energy: A critical review. In *Ore Geology Reviews* (Vol. 126). https://doi.org/10.1016/j.oregeorev.2020.103699

Trifonova, N., Scott, B., Griffin, R., Pennock, S., & Jeffrey, H. (2022, June 7). An ecosystem-based natural capital evaluation framework that combines environmental and socio-economic implications of offshore renewable energy developments. In *Progress in Energy* (Vol. 4(3)). IOPScience. https://iopscience.iop.org/article/10.1088/2516-1083/ac702a/meta

United Nations Framework Convention on Climate Change. (2015). *Adoption of the Paris Agreement* (Report No. FCCC/CP/2015/L.9/Rev.1). https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

Vivoda, V. (2024, October). Uncharted depths: Navigating the energy security potential of deep-sea mining. In *Journal of Environmental Management*, Vol. 369. https://doi.org/10.1016/j.jenvman.2024.122343

Van Leeuwen, J., van Noort, C., Flannery, W., & Varjopuro, R. (2025, February 17). A European Oceans Pact to Enhance Ocean Governance. In *CrossGov*. https://crossgov.eu/a-european-oceans-pact-to-enhance-ocean-governance/

Willsteed, E., Gill, A. B., Birchenough, S. N.R., & Jude, S. (2017, January 15). Assessing the cumulative environmental effects of marine renewable energy developments: Establishing common ground. In *Science of The Total Environment*. Vol. 577, pp. 19-32. https://www.sciencedirect.com/science/article/pii/S0048969716323403

World Forum Offshore Wind (2025, April). *Global offshore wind report 2024*. https://wfo-global.org/wp-content/uploads/2025/04/WFO_Global-Offshore-Wind-Report-2024_final.pdf

Wright, G. (2015, February). Marine governance in an industrialised ocean: A case study of the emerging marine renewable energy industry. In *Marine Policy* Vol. 52, pp. 77-84. https://www.sciencedirect.com/science/article/pii/S0308597X14002838?casa_token=zkBjhpiwTdMAAAAA:6Jyq3MpTuc3CSNZ9gqdRdMh_ggoCE8dHhNdttCG1xv14bVNU_etdPo27yHx_HZdse10PAFculw

WWF-Norway, 2014, Environmental impacts of offshore wind power production in the North Sea: A literature overview. World Wide Fund for Nature (WWF). Access on 05 May 2025. https://media.wwf.no/assets/attachments/84-wwf_a4_report___havvindrapport.pdf

ANNEX I

Interview with Katherine Richardson

Nice, 11.06.2025

1) The Ocean's Role in Climate Regulation

The ocean plays a fundamental role in regulating the Earth's climate. Could you briefly explain why it is so crucial to preserve it and what risks arise when its balance is disrupted by human impacts arising from resource exploitation?
Moreover, given that the ocean stores much of the planet's excess heat, it is warming at an alarming rate. What are the main consequences of this process, for which the clean energy transition is urgently needed?

Richardson:
Well, I think we're in a moment similar to when Darwin shocked society in 1859, an event that ultimately led us to understand that we are organisms just like all others, not God's finest creation. We are products of evolution. Now, we're entering a new phase of realisation: not only are we organisms, but we also belong to an ecosystem.
I think this awareness began when we started seeing images of Earth from space in the late '60s and early '70s, during the Apollo missions. When you look at Earth from space, it becomes clear that our ecosystem is overwhelmingly dominated by the ocean. It covers over 70% of the Earth's surface and, over geological time, has acted as the main conductor of climate conditions.
Of course, the sun is the ultimate driver of energy, but internally, the ocean has been the great regulator, because it's the only place on Earth with such a vast amount of *labile* CO_2 (that is, CO_2 that moves and circulates). When the Earth transitioned from Ice Ages to interglacial periods, about 50 parts per million (ppm) of CO_2 shifted between the ocean and the atmosphere. So the ocean has played a crucial role in changing atmospheric CO_2 levels, and, therefore, the climate.
These are long-term processes, which makes them less noticeable than more immediate changes like deforestation, where we can directly observe carbon no longer being stored. Because of this, we tend to overlook the ocean's role. But if we think about it,

we can intuitively understand that a change of 80 ppm of atmospheric CO_2 is hugely significant for the climate. It took 80,000 years to make that change naturally, between Ice Ages and non-Ice Ages. Yet in just the last 300 years, we've increased atmospheric CO_2 by 140 ppm, moving it from underground fossil reserves into the atmosphere.

This shift affects the entire Earth system, especially the ocean, on which we are entirely dependent. The ocean *is* climate change, because climate change is essentially a shift in the Earth's energy balance, and over 90% of the excess heat from that imbalance is being stored in the ocean.

Something we tend to forget is this: we talk about removing CO_2 from the atmosphere, but we don't yet have technology capable of doing that effectively at scale. And even if we did, no one seems to acknowledge that once atmospheric CO_2 drops below oceanic concentrations, we'll also need to remove CO_2 from the ocean. That's an even bigger challenge.

2) Biodiversity and Climate Interconnections

How does it relate to biodiversity? How does climate change interact with biodiversity in the ocean?

Richardson:

Well, first of all, every organism has a window in which they can survive up temperature and other kinds of conditions as well. And so many marine organisms are moving at the moment, and they're moving further, towards the poles, where it gets colder.

We are getting new ecosystems out of it, which may be fine, but they're different ones than the ones we are used to exploiting. Now, of course, there are some ecos. There is also a group of organisms that can't move themselves, such as corals.

We are relatively certain that, even if we achieve the goals of the Paris Agreement, which nothing suggests that we will, then we will likely lose Coral Reefs because of the heat. They are bleaching. When it gets warm, they spit out their *zooxanthellae*, the little organisms that live inside of them, and they are dependent. If the heat is only for a short period, the *zooxanthellae* can go back to their normal status. But if it stays too long, and if they don't come back, that's what we call coral bleaching. And at this point, about 80 or 90% of the coral reefs in the world are suffering from bleaching. And if we get up to 2°C, we'll lose them all.

And then, on top of that, you have the acidification, because you put more CO_2 in the water. Is our organism going to go extinct? We honestly don't know. I mean, life has been in the ocean for a very, very long time, and Earth conditions have been much different from what they are today. So many of the organisms there have seen and survived other conditions. So we really don't know. We can see the rearrangement of existing organisms. We can see some groups, especially the calcium carbonate producers, that get affected by acidification and ones that can't move away from areas that are too warm, that may be threatened. But otherwise, we really don't know what the effects are going to be.

3) ***Deep-Sea Mining:***

This also aligns with the question of deep-sea mining and its human-driven direct impacts on marine ecosystems. Do you see a future where DSM can be developed sustainably, or is it something that we should not develop at all?

Richardson:

First of all, all living organisms survive by using the resources on Earth. So there's nothing bad about that, and there's no such thing as sustainable deep-sea mining. There's also no such thing as a sustainable technology. All sustainability is a question of compromise. It is about the overall societal value we get out of using the Earth's resources. Is that done with minimum environmental and social costs? And are those environmental and social costs relevant in terms of the value that society gets out of doing all of this?

For example, in Iceland, some land is used to grow genetically modified wheat to produce a serum that helps reduce wrinkles, something marketed for cosmetic use, like anti-ageing creams. But land is a limited and valuable resource. So we have to ask: does the benefit of fewer wrinkles for a small group of people outweigh the cost of using that land? These are ultimately ethical decisions that we, as a society, need to confront.

So you ask me if I see a future for sustainable deep-sea mining, I see a future for it. But I think we have to make sure that we don't make the same mistakes in the ocean that we have made on land.

If you go back to Aristotle, he basically said that nature's there for humans to use. And then Von Linné came in the 1700s and said, "Nature's there for us to use." And that sort of feeling has for over 2,000 years been dominant: that nature didn't have a value until we started to use it in our economic system. That's changing. We now have the UN as a convention where people signed on to have a third of all ocean or land area under some kind of protection. So in our society, we're beginning to give nature a value in its own right.

If we're going to pursue deep-sea mining, and I suspect we probably will, we'll need to make compromises with other societal values. So I think the first step should be to reserve certain areas from any industrial activity. Instead of looking at deep-sea mining in isolation, we should start by identifying zones that represent the full range of deep-sea ecosystems and protect them from all forms of exploitation.

Once we've safeguarded those areas, we can look at what remains and ask: what do we want to do there? Do we want to allow deep-sea mining? Fishing? Aquaculture? There's a long list of activities we want to carry out, and we'll need to make decisions about how much of each and where they should happen.

I don't think our current legal system is equipped to handle this. It's too focused on sector-specific activities like deep-sea mining. Instead, we need to rethink the system holistically, integrating deep-sea mining into a broader framework that ensures space for nature first, and then carefully balances the other uses of the ocean that we value.

I can see deep-sea mining happening in our future, but I don't believe it will ever truly be sustainable. I think we might pursue it because it's seen as the most socially and environmentally acceptable option for meeting our needs right now. But we need to keep in mind that everything life needs to survive is already on this planet, and Earth doesn't have an umbilical cord. Aside from energy, all our mineral resources are here.

Nature has managed to survive for over 3 billion years without running out of resources, and it's done that by operating as a 100% circular economy. Right now, we're going after deep-sea mining because we want more, but there are limits. Even if we don't hit those limits in the next ten years, we must change our approach. We need to shift how we use resources so that, hopefully, in the future, there won't be as much demand for new minerals.

Interviewer comment:

That's exactly what I was discussing a few days ago with others at the UNOC. It's fascinating how everything is so deeply interconnected and delicate. What struck me most is the range of perspectives present here at the conference, from representatives of island states and Indigenous peoples to private sector actors. These groups often have opposing views. Indigenous communities, especially those from island nations, tend to have a very different, more relational connection to the ocean, one that contrasts sharply with the resource-driven, competitive approach of private companies seeking access to seabed minerals.

Richardson:

The Indigenous people don't have a different relationship with nature than we do. They use it to meet all of their needs. But because they're so close to the interactions that they're having with nature, they accommodate them, and they try to limit their impacts. Whereas we, in a global economy, have removed ourselves from those interactions, we call them "externalities".

If you begin to accept that we're a part of an ecosystem or a system, that everything is interconnected, then nothing can be external. This is really all about a confrontation with our economic system.

4) ***The Knowledge Gap:***

A recurring concern in the literature regards the lack of sufficient scientific data on DSM's long-term impacts and implications. This has led the European Union and several countries to impose a moratorium until sufficient evidence is gained. From your experience in the scientific community, have you seen meaningful progress in addressing this knowledge gap? What steps are most urgently needed to inform better policy decisions?

Richardson:
Oh yes, absolutely, but it's been very difficult. The problem is that working in the deep sea is expensive. Now that the deep sea has become interesting, people expect to gather all the necessary information in just one year. But these studies should have started 20 years ago.
This is similar to the issue we've had with the AMOC (Atlantic Meridional Overturning Circulation), for example. The data we have on the AMOC only begins in 2004, and you can't draw firm conclusions from just 21 years of observation. We've seen that it has weakened by about 15% in that time, but we don't know whether that decline started earlier. Maybe such a fluctuation (plus or minus 15%) is completely normal. We simply don't know, because we don't have the data from before.

Interviewer's comment:
Dr. Sylvia Earle, who spoke at the opening ceremony of the UNOC, shared how much has changed over the course of her research career, from interests and capabilities to technologies. She reminded us that only 50 years ago, we didn't even have the ability to view the ocean from space. Before space exploration, we couldn't grasp just how vital the ocean is when seen from a planetary perspective. So, our understanding of the ocean has evolved drastically in a relatively short time.
But this process of gaining knowledge is still ongoing, and it's moving in different directions. The challenge is that we now face an urgent need for a green transition, while the knowledge gaps remain significant and will take years to close. For example, even if deep-sea mining were to proceed, it would take years to become industrialised. That's one of the arguments against it; it's a huge investment in something highly uncertain. We don't yet know how it will develop or whether, by the time it's operational, we'll still need the same minerals for the same technologies, as you pointed out earlier.

5) The European Union's Approach to Marine Resource Exploitation

In line with its ambitious Green Deal and decarbonisation goals, the EU has significantly invested in offshore wind and ocean energy technologies, recognising them as essential components of the energy transition. On the other hand, as mentioned, it *has taken a firm stance against DSM, emphasising the lack of scientific evidence on its environmental impacts. Do you agree with this strategy? Is the EU doing enough to maximise the potential of MRE while maintaining its environmental commitments?*

Richardson:

In the European Union, we've been used to looking westward for decades. But now, we see the direction the U.S. is heading under leadership like Trump's "drill, baby, drill", with little regard for environmental limits. At the same time, if we look eastward toward China, something very interesting is happening.

China has been investing in its military and securing resources globally, but it has also made massive investments in biodiversity and renewable energy, about three times more than what the U.S. or the EU has spent. China is clearly leading in many areas: it has the highest penetration of wind and solar energy, the largest wind turbine manufacturer, and it's poised to flood global markets with electric vehicles.

If Europe wants to remain competitive, it must double down on the green transition, particularly on renewables.

I think Europe is making progress on energy, but when it comes to biodiversity, there's still a long way to go, and that's where deep-sea mining becomes particularly relevant. The broader public still doesn't fully value biodiversity in its own right, but that mindset is slowly shifting.

It's remarkable. Who would've imagined, 20 years ago, that we'd now be trying to secure international agreements to protect 30% of the ocean and land for biodiversity? That we'd begin to assign value to biodiversity not just for its economic utility, but for its intrinsic worth? This is exactly the tension at the heart of the deep-sea mining debate: on one hand, the old view that natural resources are simply there to be extracted; on the other, the emerging view that nature itself has rights and that our actions carry long-term consequences.

I believe this kind of confrontation will only grow in importance. Thirty years from now, people will likely be shocked by some of the things we're considering today, things we currently think are progressive or "green."

That’s why it's so important not to treat deep-sea mining in isolation. When we zoom out just a little, it becomes clear that DSM is part of a much broader societal discussion. Even the Sustainable Development Goals (SDGs) reflect this shift, they are a systemic attempt to rethink our relationship with the planet.
There was nothing particularly new in the SDGs themselves; we already knew we had challenges in all of those 17 areas before 2015. What was new was bringing them together in one unified framework. It’s not just the individual goals that matter, but the interactions between them. That’s what makes the SDGs important: they reflect a global vision of how to share Earth’s limited resources among people and with all other living organisms.

Your research fits into this framework. Deep-sea mining is one "box" on that list, but the real value lies in examining how it connects with others. What are the interactions, the trade-offs, the systems-level implications? These are the questions we need to ask.
I think we’re living in an incredibly exciting time, because these big questions are finally starting to be asked.

Interviewer’s comment:
It's really exciting to be here at the UNOC right now. I can see firsthand how everything is interconnected and how the different actors are asserting their views. At the same time, it’s clear that what people say publicly at events like this doesn’t always align with the policies they pursue at home. Still, I sense a genuine desire for collaboration.
The conference itself seems to have triggered some momentum: many countries rushed to ratify the BBNJ Agreement, which shows a bit of acceleration in the process. That makes me feel a bit hopeful.
All of this reinforces my belief in multilateralism, especially in fields like this. I really hope we continue building political decisions on the foundation of scientific research and evidence, because that’s the only way we can avoid making long-term mistakes for short-term gains.

Thank you very much for your time and invaluable insights.

ANNEX II

Interview with Diva Amon

Nice, 18.06.2025

Introduction

My research mainly explores whether the exploitation of ocean resources, both for marine renewable energy (MRE) and deep-sea mining (DSM), can contribute to a virtuous cycle of decarbonisation and clean energy transition or whether the environmental costs are so high that they create a counterproductive, vicious cycle.

Given your expertise in the deep sea, I would like to focus with you on my first sub-question, discussing the broader role of the ocean and deep-sea ecosystems in climate regulation and the delicate question of deep-sea mining and its environmental trade-offs.

Questions for the Interview:

1) *Why has deep-sea mining gained so much attention recently? What kinds of deep-sea resources are so attractive?*

Amon: The ocean depths harbour incredible biodiversity and unique ecosystems that we are only just beginning to understand. There are three main types of mineral resources that are drawing attention: polymetallic nodules, scattered across the seabed with metals accumulating around a small nucleus; hydrothermal vents, rich in polymetallic sulfides; and cobalt-rich crusts on seamounts. These formations contain currently essential metals for electric batteries and green technologies, primarily cobalt and nickel.

One of the most active regions for deep-sea mineral exploration is the Clarion-Clipperton Zone, an area in the high seas of the eastern-central Pacific Ocean, roughly the size of the contiguous United States. This region has attracted particular interest for its abundance of polymetallic nodules, although access to these resources, which lie mostly at depths of 4-6 kilometres, is extremely complex and costly.

What we are seeing now is an acceleration in activity compared to past decades. Initially, mostly national governments were discussing potential exploration, but now private companies, many backed by state interests, are increasingly interested. This marks a new phase, more commercially driven and much faster.

2) How is the deep ocean connected to climate change, and why is it important to preserve it?

Amon: The deep ocean is the largest ecosystem on Earth, and it plays a crucial role in regulating our climate. It stores vast amounts of heat and carbon, effectively buffering some of the worst impacts of climate change. It's also home to a wealth of genetic resources we barely understand yet. Disrupting it through mining could have ripple effects we can't fully predict.

3) What kind of impacts could deep-sea mining have on these ecosystems?

Amon: The potential impacts are vast and long-lasting. The extraction process involves the use of large machinery that scrapes the seabed, destroying habitats, creating plumes of sediment and generating significant noise and light. These plumes not only affect the surrounding area, but can carry fine particles and toxic metals for long distances, impacting marine life far beyond the extraction site. Even worse, there is a second sediment plume generated when the mining vehicle returns sediment-rich water to the ocean after extracting the metals.

Although scientific knowledge of the deep sea has evolved considerably since the UNCLOS negotiations in the 1960s and 1970s, we are still far from knowing how these systems respond to such disturbances. What we do know is that these are stable environments, unaccustomed to change, which have developed over a very long period of time. It is estimated that the extraction process removes and disturbs between 10 and 20 cm of the seabed and that recovery is unlikely on a human timescale. Even the removal of minerals, which form part of the seafloor and attachment surface for lots of animals, could make the recovery of these ecosystems impossible except on geological timescales.

4) What do you think of the main arguments being made in favour of DSM?

Amon: What began as a discussion about climate change has now turned into a matter of defence and geopolitics. Mining companies have begun lobbying for access to these resources in the name of national security. This is worrying because it shifts the debate from environmental protection to extractive competition. Regardless of the scenario, DSM will not replace terrestrial mining and reduce all the environmental and humanitarian problems associated with it. Rather, it will create more competition.

5) To conclude, in your view, does deep-sea mining support or undermine efforts to address the climate crisis?

Amon: Deep-sea mining as a strategy to combat climate change is incredibly short-sighted. The ocean is one of our best defences against climate change, and damaging it would be counterproductive. Furthermore, technological innovation is already moving away from some of the minerals that are the target of deep-sea mining. Cobalt-free batteries are advancing rapidly, and by the time deep-sea mining reaches industrial scale, which will take at least a decade, the demand for these particular metals will likely have changed. It is false to claim that we need to extract minerals from the seabed for sustainable development.
Furthermore, we need a much deeper scientific understanding. Approximately 70-90% of the species found in places such as the Clarion-Clipperton Zone are completely new to science. There are simply too many things we do not know. If we proceed now, we risk losing ecosystems and services that we may never be able to recover.

6. Considering the international regulatory framework, the ISA is in charge of "preventing serious harm" and "ensuring effective protection" of the marine ecosystems from mining activities. Indeed, it is currently developing a new Mining Code for exploitation. Do you think it will be sufficient, or is it being developed too hastily without adequate scientific and environmental considerations?

Amon: Time will tell. We know for certain that far more science is needed to make informed decisions about preventing harm to the marine environment from DSM. It will take decades to gain this scientific knowledge. Advancing exploitation without it is irresponsible and not in line with the precautionary approach or the mandate of the ISA.

7. *You have often emphasised the lack of scientific evidence on the long-term impacts of DSM, a concern widely echoed in the academic literature. This is also a key reason for many countries to call for a moratorium on this activity. From your experience in the scientific community, have there been meaningful advances in closing this knowledge gap? And what steps do you believe are most urgently needed to guide informed and precautionary policy decisions, especially as commercial interest in DSM rapidly accelerates?*

Amon: There have been a handful of limited studies on the long-term impacts of DSM on the ocean, and none of these have been on the scale or duration of commercial mining. Far more independent studies over much longer timescales and in a variety of locations are needed if informed decision-making is to be possible.

8. *(personal question) During the UN Ocean Conference and the previous One Ocean Scientific Congress, the deep-sea and DSM have been discussed by many actors, often aligning with the precautionary approach and calls for a moratorium that you advocate. What do you think will be the legacy of these international summits? Do you foresee any meaningful shifts or strengthened cooperation?*

Amon: There have absolutely been meaningful shifts wrt to DSM through the UNOCs. In 2022, at UNOC2, the first three countries committed to a moratorium on DSM in ABNJ. Also at that conference, France went even further calling for an outright ban on the activity. Since then (3 years), there have been 33 more countries calling for a pause, moratorium or ban on DSM (total = 37), as well as numerous other stakeholders.

Thank you.

ANNEX III

Interview with Xavier Guillou and Isabella Hannen[5]

Nice, 24.04.2025

1) **The Relationship between Marine Renewables and Deep-Sea Mining:**

Could you clarify whether there is a connection between the development of marine renewable energy technologies and the need for deep-sea mining, especially in terms of sourcing critical raw materials for the clean energy transition?"

2) **Offshore Wind and Other MRE Technologies:**

Offshore wind appears to be the most developed MRE source in Europe. Could you briefly explain how it is leveraged? And to what extent are other MRE sources being explored as part of the EU's clean energy transition strategy?

3) **The EU's stance on DSM :**

Due to the lack of scientific data on DSM's long-term impacts and implications. The European Union and several countries imposed a moratorium until sufficient evidence is gained. From your experience in the EU Commission, have you seen meaningful progress in addressing this knowledge gap? Is the EU committed to financing research in this field?

4) **Maritime Spatial Planning and cross-border coordination:**

Given your role in implementing the Maritime Spatial Planning Directive, how effectively is it being applied at the national level across member states? Is there sufficient coordination, particularly since marine environments are cross-border in nature and impacts from renewable energy developments often extend beyond national jurisdictions?

[5] For this discussion, the interviewees allowed me to record exclusively for taking notes. Hence, this annex includes only the questions that I posed during the interview.