



China Council for International Cooperation on Environment and
Development (CCICED)

**Sustainable Blue Economy
under the Vision of Carbon Neutrality**

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** The co-leaders and members of this special policy study (SPS) serve in their personal capacities. The views and opinions expressed in this SPS report are those of the individual experts participating in the SPS Team and do not represent those of their organizations and CCICED.*

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1. Executive Summary and Recommendations

1.1. Background

The ocean economy, encompassing a broad spectrum of activities tied to oceans, seas, and coasts – from traditional sectors such as fisheries, shipping, and coastal tourism to emerging fields like marine biotechnology and offshore renewable energy – is playing an increasingly vital role in advancing global sustainability and low-carbon development goals.

Recent estimates place the asset value of the ocean’s natural capital at approximately USD 24 trillion. This reflects the cumulative worth of marine ecosystems, coastal habitats, and ocean resources when considered as a global “blue economy balance sheet.” On an annual basis, the ocean contributes around USD 2.5 trillion in economic value through goods and services, positioning it as one of the world’s most significant economic systems. In 2023, ocean-related trade alone reached USD 2.2 trillion, accounting for roughly seven percent of global trade, with ocean-based services and high-tech sectors playing a growing role.

In addition to its economic importance, the ocean offers substantial potential to contribute to climate change mitigation and carbon neutrality. Ocean-based solutions include the protection and restoration of carbon-efficient ecosystems such as mangroves and seagrasses, the development of marine carbon dioxide removal technologies that enhance the ocean’s capacity to absorb carbon, the expansion of offshore renewable energy, the decarbonization of maritime industries, the safeguarding of ocean sediments as natural carbon sinks, and the promotion of aquatic food systems that offer low-carbon protein sources. These solutions underscore the dual function of the ocean as both an economic engine and a climate stabilizer.

Looking to the future, projections from the Organisation for Economic Co-operation and Development (OECD) suggest that the ocean economy will continue to outpace the broader global economy in both value added and employment generation. Under an accelerated low-carbon transition scenario, it is expected to grow to 2.5 times its 1995 size by 2050. However, realizing this potential is contingent upon placing sustainability at the core of ocean economic development. The long-term value of the ocean economy and the effectiveness of ocean-based climate mitigation are deeply interdependent. Unsustainable development practices risk undermining the ecosystem services upon which economic benefits rely.

To ensure the continued prosperity of the ocean economy, a paradigm shift in ocean governance is required—one that regards the ocean as a dynamic living system. This means managing marine environments with a focus on the ecological processes that sustain their productivity and resilience. A healthy ocean is essential not only for economic growth but also for long-term climate stability and social well-being. Future governance frameworks must be comprehensive, adaptive, and inclusive. They must strike a balance between environmental protection, economic advancement, and social equity, while also ensuring that traditionally marginalized groups, including women, have equitable access to opportunities and benefits. Inclusive governance must also ensure that women, Indigenous people, and other marginalized groups are equitably represented in decision-making processes, in line with United Nations’ Sustainable Development Goal (SDG) 5 and international commitments.

In the context of China, the strategic relevance of the ocean economy is particularly pronounced. On July 1, 2025, President Xi Jinping chaired the 6th meeting of the Central Commission for Financial and Economic Affairs (CCFEA) to address key national priorities, including the deepening of a unified national market and the high-quality development of the ocean economy. This meeting underscores the central leadership's dual commitment to market modernization and marine-based economic transformation. It reaffirmed that the high-quality development of the ocean economy is integral to advancing Chinese-style modernization and building maritime strength with distinctive national characteristics. The integration of innovation-driven marine industries with environmental sustainability and carbon neutrality objectives reflects the strategic positioning of the ocean economy within China's broader development agenda. Fully realizing this potential will require coordinated strategies rooted in ecological stewardship, social equity, and a long-term vision for sustainable growth.

1.2. Research Objectives and Activities in 2025

The Ocean SPS on Sustainable Blue Economy Towards Carbon Neutrality, under CCICED Phase VII, continues to explore how governance, blue finance, and green technologies can accelerate the shift to a sustainable blue economy. It examines frameworks and tools to align ocean development with carbon neutrality and explores synergies across marine industries that support both economic growth and climate action. In the remainder of Phase VII, research is focused on seven key topics, with particular attention to marine biodiversity in line with the 30×30 target and the BBNJ Agreement, aiming to strengthen ocean protection and the equitable sharing of marine resources.

In 2025, the SPS advanced four ongoing research areas – ocean economy and blue finance, ocean renewable energy, deep-sea mining, and offshore aquaculture – while launching two new topics on ocean-based carbon solutions and green shipping. The SPS also entered the final stage of a bay-to-bay case study comparing the Guangdong – Hong Kong – Macao Greater Bay Area and the San Francisco Bay Area. Following earlier forums in Hong Kong and Guangdong, a high-level event was held in Macau in January 2025. In May, the SPS conducted a study tour of the San Francisco Bay Area to examine integrated ocean governance and sustainable blue economy practices. The tour included stakeholder workshops, policy discussions, and site visits to leading blue economy initiatives. Insights from this study, together with those from the Greater Bay Area, will inform the comparative bay-to-bay analysis in the next phase of work.

In addition, the SPS organized two side events at the UN Ocean Conference 2025 held in June in Nice – one official Blue Zone event titled “Sustainable Blue Economy in the Vision of Carbon Neutrality” and another in the Green Zone titled “BlueSynergy: Co-Designing a Regenerative Blue Economy Through Cross-Sector Partnerships” – both aimed at advancing dialogue on ocean-based solutions in support of global climate and sustainability goals. At the Blue Zone side event, the SPS, in collaboration with partners – including Xiamen University, WEF, UNGC, the State Key Laboratory of Marine Environmental Science (Xiamen University), Fujian Ocean Innovation Center, UNDP, The Hong Kong University of Science and Technology, AVPN, the China Ocean Development Foundation, and Tara Ocean – issued a statement titled *Call for Action: Shaping the Global Ocean Agenda Beyond 2030* (see Box 1). In addition, the SPS launched a report titled *Advancing China's Sustainable Blue Economy: Building Strong Policy Foundations for Ocean Accounting and Blue Finance*,

containing the full result of one of the work streams implemented under this policy study and which is also summarized in this report.

The report at hand is one in a series of reports from the Ocean SPS and should be seen and read in light of these reports that cover a larger span of ocean related topics for future governance shaping. The Ocean SPS will at the end of CCICED Phase VII deliver an overarching report summarizing the main findings that come out of the study in its entirety.

Box 1. The Blue Zone Side Event Statement

Call for Action: Shaping the Global Ocean Agenda Beyond 2030

As we approach 2030, the target date for the Sustainable Development Goals (SDGs), it is time to look at the full scale and role of the ocean as the foundation of Earth's climate, biodiversity, food security, and future prosperity.

The ocean is vital to life on Earth, as essential to the planet as water is to life itself. We must chart an even more ambitious, science-based, co-designed Global Ocean Agenda for the post-2030 era – placing the ocean at the center of efforts toward a sustainable and just world.

We call upon governments, international organizations, the private sector, financial institutions, scientific communities, civil society, and coastal populations to:

- Integrate ocean priorities into the post-2030 global development framework – recognizing the ocean's critical role in climate regulation, biodiversity, sustainable livelihoods, and food systems.
- Adopt the formula: Thriving Ocean = (Science + Technology + Governance + Finance) × Co-Design ²—uniting science, innovation, policy, and finance through co-design to advance both the protection and sustainable, regenerative use of the ocean.
- Advance a Regenerative Blue Economy – Transforming and accelerating ocean-based production systems to align with global net-zero goals, while enhancing resource efficiency, restoring ecosystem health, and fostering inclusive and equitable economic growth.
- Scale up investment in co-designed, science-based, and proven nature-based and technological solutions – restoring marine ecosystems, enhancing coastal resilience, and accelerating net-zero and carbon neutrality transitions.

The ocean must be at the heart of the global sustainable development agenda beyond 2030. Together, let us forge a future where the ocean is thriving, regenerative, and central to achieving a sustainable, climate-resilient, and equitable world.

1.3. Key Findings

- 1) The development of a China's SBE is a national strategy; however, it remains hindered by a lack of integration with other major domestic priorities, including the carbon neutrality and ecological civilization goals.
- 2) The growth of China's SBE is restricted by a lack of strategic clarity and an underdeveloped support system, including on financing, investor engagement, disclosure mechanisms, and legal frameworks.
- 3) With over 60% of China's GDP generated in coastal regions, strategic hubs, such as the Guangdong – Hong Kong – Macao Greater Bay Area, are well positioned to lead in technological, financial, and policy innovations for advancing SBE and an integrated ocean governance.

1.4. Recommendations

High Level Recommendations

- 1) Enhance strategic coordination to strengthen alignment between sustainable blue economy development and national priorities – such as the 2060 carbon neutrality goal – by integrating SBE into national and regional green development plans, including the 15th Five-Year Plan. Foster a high-quality, green, and low-carbon marine economy, for example by planning and advancing marine infrastructure projects to support technological innovation and industrial upgrading.
- 2) Build a robust regulatory and disclosure framework, introduce innovative insurance mechanisms, and expand diversified financing channels to enhance the financing capacity and efficiency of the marine economy. Develop a comprehensive ocean accounting system and launch a dedicated fund, in order to boost financial support for a blue industry system and its high-quality development.
- 3) Designate key regions such as the Guangdong – Hong Kong – Macao Greater Bay Area as pilot zones for sustainable blue economy development, driving innovation in technology, finance, and policy to advance high-quality growth of China's blue economy.

Specific Recommendations

- 1) To fully harness the ocean's potential for climate action, national carbon neutrality strategies should integrate both marine carbon dioxide removal (mCDR) and the green transition of marine industries through clear targets, cross-ministerial coordination, unified frameworks, and synergistic innovation.
- 2) Establish a national strategy for sustainable ocean energy and zero-emission shipping that integrates ecological impact and ecological carrying capacity, accelerates low-carbon technology innovation and adoption (e.g., offshore PV, green hydrogen, zero-emission vessels), and supports green infrastructure, cross-sector coordination, and international cooperation aligned with carbon neutrality goals.
- 3) Provide policy incentives that will accelerate innovation and optimize development of technologies and operational approaches in the key ocean industries that will ensure sustainability, reduce environmental footprints and concurrently contribute to the national and international carbon neutrality goals.
- 4) Incentivize the adoption of new environmentally sustainable and low-carbon technologies in the ocean industries through a combination of targeted financial incentives (for example subsidies, tax breaks, or

other financial incentives that would make these technologies more economically viable), supportive regulatory frameworks, and investment in skills development.

- 5) Establish frameworks for holistic and comprehensive ocean accounting processes for overarching sustainable blue economy policy planning, and evaluation of the carrying capacity of the marine environment as basis for ocean industry development, considering various factors like water quality, biodiversity, and the environmental and social impact of different industries.
- 6) Encourage expanded and extensive international collaboration through partnerships between governments, industry, and research institutions to support domestic and facilitate global transition toward SBE, through for example regulations, agreements, knowledge sharing and capacity building.

2. Introduction

The Special Policy Study on Sustainable Ocean Management under the vision of carbon neutrality (SPS Ocean Governance) aims in the current CCICED 5-year phase (Phase VII) to study and recommend governance systems, blue finance systems and green technologies which can contribute to accelerating the blue economy, while utilizing the overarching aim of carbon neutrality as an opportunity to ensure a full and equitable transformation of the ocean economy into a sustainable blue economy (SBE). Furthermore, it is its aim to investigate how co-existence and synergies across ocean industries can strengthen both the SBE and the development of ocean-based solutions towards carbon neutrality.

SPS Ocean Governance over the 5-year period will conduct research on seven specific topics, listed below. The first three are overarching topics and the last four are industry-specific topics. These are:

- Ocean economy and blue finance*
- Ocean-based solutions for carbon neutrality*
- Science-based and societal-based ecosystem restoration
- Industry design and transition: Ocean energy*
- Industry design and transition: Green shipping*
- Industry design and transition: Seabed mining*
- Industry design and transition: Offshore aquaculture*
- Industry design and transition: Marine tourism

Topics marked with an asterisk indicate studies that have been initiated and which form the basis for this report. Separate reports have been prepared for each of these policy topics, and while this present report contains a summary of challenges, opportunities and potential policy directions pertaining to these six topics, further supporting details and background information will be found in the stand-alone topical reports.

In considering these topics special attention has been placed on marine biodiversity by e.g., following the agreements reached at the Biodiversity COP15 to protect 30% of land and sea by 2030 (30×30 Agreement), as well as to conserve and sustainably use marine biological diversity of areas beyond national jurisdiction (BBNJ Agreement), in order to promote the protection of the ocean and its biodiversity, and the fair-sharing of its resources and ecosystem services.

Furthermore, it is important to also keep in mind that climate change has had an increasingly dominant impact on global ocean ecosystems. Changes in temperature, pH, dissolved oxygen, salinity, current patterns and other factors are reshaping patterns of growth, reproduction, survival, migration, species interactions and habitat availability in ways that are fraught with uncertainty. Although some marine ecosystems are more affected than others – in particular, coral reefs and other biotic coastal habitats that depend upon a very precise combination of environmental variables – all experience these effects to some degree. Ecosystem changes affect species that are grown through mariculture operations, harvested by fisheries or provide other living marine resource values. Climate change represents a system-scale impact that will affect management of individual sectors and more

comprehensive living marine resource policies; thus, these factors should be considered to ensure that future policies remain effective as environmental conditions evolve^[1].

3. Framing the Issues

3.1. Global Context

The ocean is constantly being explored for new uses of its space and resources, leading to a steady increase in the economic value it provides. Existing and potential new economic activities related to oceans, seas, and coasts – the so-called ocean economy, or blue economy – thus cover a wide range of interlinked established and emerging sectors. The value of the global ocean economy in 2018 was estimated as USD 2.5 trillion annually, with a contribution of 3.3% to the global GDP (USD 86.69 trillion). If considered a country, the ocean economy would be the world’s fifth-largest economy in 2019, according to OECD report of 2025^[2]. In an accelerated transition to low-carbon energy, the ocean economy would continue to grow through 2050 to around 2.5 times the size it was in 1995. Nonetheless, this value is expected to be underestimated due to limitations in valuation methods and data sources, among other factors. According to projections from OECD, by 2030 the blue economy outperforms the growth of the global economy, both in terms of value added and employment. The long-term potential for innovation, employment, and economic growth offered by the ocean economy is promising. The proliferation of the blue economy in political discourse has gained traction in recent years; however, there remains no standardized definition^[3].

In addition to supporting a host of economic opportunities, the ocean also offers a wide array of potential ocean-based climate mitigation options that can contribute to carbon neutrality goals. This includes, but is not limited to, the grooming of carbon-efficient ecosystems (i.e. “blue forests” or “blue carbon”) and approaches that aim to accelerate the ability of the ocean to uptake carbon through biological or geochemical manipulation (i.e., marine carbon dioxide reduction or mCDR), the use of the ocean’s inherent energy potential, minimizing the carbon footprint of ocean-based activities such as shipping, protecting and potentially enhancing the ability of ocean sediments to store carbon (carbon capture and storage, or CCS), as well as reorienting food policy and fisheries management to value aquatic foods from certain types of fisheries and aquaculture production methods as key sources of low-carbon ocean-based protein and micronutrients.

Society, the collective of individuals, communities, and groups that make up the social fabric of a region or nation, encompasses diverse stakeholders, including women, men, girls, boys, and gender-diverse people; workers, employers, civil society organizations, and policymakers, and comprising marginalized and vulnerable populations, as well as future generations who all have different interests relating to the well-being of and opportunities associated with the ocean. The varied needs, rights, and contributions of all these groups is an essential aspect of ocean management and must be taken into consideration.

In recognizing that a healthy ocean environment is a prerequisite to optimally draw on the benefits that the ocean provides, an integrated ocean management approach is required to strike the balance between the environmental, economic, and societal goals, and between short-term economic gains and long-term sustainability of ecosystem services in light of climate change. Therefore, a robust ocean governance framework must take a comprehensive and sustainable approach. The ocean can, if managed carefully, comprehensively, and strategically, play an important role in turning the tide of the current global triple crisis encompassing ongoing climate change, biodiversity loss and pollution.

3.2. The Chinese Context

The ocean is a vital source of natural capital, goods and services that supports China's economic growth. It provides spatial resources including an 18,000 km continental coastline, a natural deep-water shoreline spanning over 400 km, more than 60 deep-water port sites, a 38,000 km² intertidal zone, and over 7,300 islands larger than 500 m². With a marine life count exceeding 20,000 species, including over 3,000 fish species, and a variety of marine ecosystems such as mangroves, salt marshes, seagrass meadows, coral reefs, kelp forests, and oyster beds, China's marine biodiversity plays a crucial role in ensuring food security, climate resilience, and a thriving tourism industry. This rich biodiversity supports the world's largest seafood industry in terms of production scale, covering both wild-capture fisheries and aquaculture. The extensive coastal length and favourable conditions have facilitated the development of a substantial marine renewable energy sector, which is the fastest-growing ocean economy sector in the country and the largest in the world, with almost 40% of global offshore wind capacity currently in China. Moreover, emerging ocean economic sectors, such as alternative energy sources and bioprospecting, present opportunities for sustainable exploration and development, if well-researched and governed.

Various marine economic sectors in China including coastal tourism, marine transportation, marine fisheries and aquaculture, and marine biomedicine have been expanding and becoming important parts of the national economy. Furthermore, according to the *Reviving China's Ocean Economy: Empower Sustainable Development* report, the asset value of China's ocean is estimated to be around RMB 54 trillion (USD 7.7 trillion).

Over 50% of China's large cities, more than 40% of its population and 60% of its GDP, are concentrated in the coastal provinces/metropolises. Coastal (mega) cities are, can and should be the engines in developing the synergies between blue economies and carbon neutrality goals. In response to the intense development of the marine industry around the world, marine industrial parks are increasingly being established in coastal areas. The marine industrial park can be an essential part of the Ocean economy (Ocean Province, Ocean City, and Ocean Capital) development plan in China, by integrating and synergizing ocean related industries such as marine fisheries, ocean renewable energy, and maritime operations.

After decades of development and constant adjustment of the industries, China's ocean economy has generally stabilized. However, there is not a full awareness of the great pressure on marine ecosystems caused by the exploitation of the ocean. Climate change, biodiversity loss, pollution, as well as other pressures have all directly or indirectly become challenges to the development of the ocean economy.

As one of the world's leading maritime nations and the second-largest economy, China is actively growing its maritime power. The conservation of ocean health and sustainable development of the ocean economy have been prioritized in China's recent development plans. China's ongoing promotion and implementation of the marine ecological civilization and its efforts to create an "ocean community with a shared future" demonstrate its global ocean governance aspiration and responsibility. The realization of these objectives requires not only government leadership, but also the involvement of businesses, academics, NGOs and the wider public.

With strategic relevance, the Central Financial and Economic Affairs Commission convened its sixth meeting on July 1, 2025, chaired by Xi Jinping, to deliberate on advancing a unified national market and promoting the high-quality development of the marine economy. The meeting underscored that the high-quality marine

economy (or SBE termed in this report) is a vital pillar of Chinese modernization, calling for stronger top-level design, greater policy support, and broader participation from social capital. Key priorities include enhancing independent marine science and technology innovation, fostering leading enterprises and specialized, innovative small and medium-sized enterprises, and advancing industries such as offshore wind power, distant-water fishing, marine biomedicine, cultural tourism, and shipping. The Commission also highlighted the importance of bay-area economic planning, port cluster optimization, ecological protection, layered marine space utilization, and the development of marine carbon sink accounting, while deepening China's engagement in global ocean governance, scientific research, disaster prevention, and blue economy cooperation. This landmark meeting signals that China's marine economy is entering a fast-track phase and is being fully integrated into the Ocean SPS framework.

3.3. Aiming for A Sustainable Blue Economy

Sustainable development is important to maintain long-term economic gains and social well-being globally. The concepts of the blue economy and the green economy, introduced at different times, are both aimed at advancing sustainable development. Under the climate change scenario, which is also exacerbated by pollution and other development activities, both biodiversity and livelihoods are exposed to increasing risks. Ocean economic sectors need to be transformed towards a SBE because they are part of the threat to the ocean if their practices are not well regulated, while on the other hand they can be part of the solution to address climate change. **To achieve a more ambitious transformation, SBE should be included in the top-level policy framing with clear definitions and principles, and well as incorporated into the next 5-year plan to drive the necessary changes.**

The World Bank's definition of the blue economy is the "sustainable use of ocean resources for economic growth, improved livelihoods and jobs, and ocean ecosystem health." But such definitions do not offer principles or guidance for how to ensure and implement multiple bottom line goals including sustainability in economic development, gender and social equity, and environmental conservation. At its core the blue economy refers to socio-economic development through ocean-related sectors and activities with minimal environmental and ecosystem degradation^[4]. The concept of the "blue economy" thus sets new requirements for the sustainable development of the ocean economy.

With the concept of SBE being widely disseminated globally, there is a growing international consensus on the development of an SBE. As the blue economy is being gradually incorporated into regional development strategy frameworks, some organizations have already proposed guidelines for SBE development, including guiding principles, focus and priority areas, initiatives, and recommendations. For example, WWF released the *Principles for a Sustainable Blue Economy* in 2015 and co-developed the *Sustainable Blue Economy Finance Principles* with the European Commission, European Investment Bank and the Prince of Wales' International Sustainability Unit in 2018, hosted by UNEP FI since 2019; and the G20 released the *G20 High-Level Principles on a Sustainable and Climate-Resilient Blue Economy* in 2023.

3.4. Equity

All human beings should have equal rights and opportunities to participate in society regardless of sex, gender, functional ability, sexual orientation, age, ethnicity, and religion. Gender equality is essential for the effective

protection of oceans, the sustainable management of ocean and marine resources, and the accomplishment of the UN SDGs. SDG 5, notes that gender equality requires the fair distribution of power, influence and resources between people of different genders. Policymaking and implementation that adopt a gender-responsive approach – ensuring women and girls have equitable opportunities and the capacity to contribute at all levels of decision-making – are more likely to sustain social welfare and long-term outcomes. Ocean governance, including the transition to SBE therefore demands gender-sensitive and gender-responsive planning, implementation, monitoring and evaluation at project, policy, and grassroots levels.

Most countries, including China, have committed internationally to advancing gender equality and eliminating discrimination, through frameworks such as the United Nations Framework Convention on Climate Change, the UN Convention on Biodiversity, the UN Convention on the Elimination of Discrimination Against Women, the Beijing Platform for Action, and the SDGs.

Yet despite these commitments women remain significantly underrepresented in the blue economy, both in terms of numbers employed and the type of work available to them. Cultural norms and practices continue to favour men in the ocean space, leaving women with less access to resources, decision-making, and rights than men.

Women are more disproportionately concentrated in lower-wage, informal, and subsistence activities such as small-scale fisheries, seafood processing, and coastal tourism, while men dominate higher-wage, formal sectors such as industrial fishing, maritime transport, offshore oil and gas, and marine engineering. These positions offer greater job security, income potential, and access to leadership, meaning that men are more likely to shape the policies and decisions that govern the blue economy. As a result, women's contributions are undervalued, and the needs of their communities are often overlooked.

This imbalance limits women's economic empowerment, widens inequalities, and reduces the resilience of coastal economies. Future ocean governance frameworks must address these inequities directly by ensuring equitable participation, opportunities, and benefits for women and other marginalized groups. Designing any effective action to achieve equality between men and women begins with ensuring the availability of robust sex-disaggregated data to make gender gaps visible in decision-making processes. It also requires targeted measures to ensure women's and girls' access to education, training, finances, and leadership opportunities in SBE-related sectors. In line with this, gender equality dimensions of ocean sustainability were emphasized at the 2024 UN Ocean Decade Conference, which called for reducing gender gaps, providing educational opportunities for young female scientists, and acknowledging the important contributions of women to marine conservation^[5].

Building on such global good practice, effective gender-responsive governance must institutionalize sex-disaggregated data collection, ensure women's equitable representation in leadership positions, and enable their equitable access to finance, capacity-building, and training across all sectors of the blue economy.

4. Sustainable Blue Economy and Ocean-based Solutions towards Carbon Neutrality

4.1. Ocean Economy and Blue Finance¹

Evolution of the Sustainable Blue Economy Narrative in China

Sustainable Blue Economy (SBE) is a concept applied across multiple fields, such as marine industry, blue finance, marine ecosystems, marine management and governance, and marine value accounting. Various organizations have proposed guidelines and principles for SBE development. They include the WWF's *Principles for a Sustainable Blue Economy* (2015) and the *Sustainable Blue Economy Finance Principles* hosted by United Nations Environment Programme Finance Initiative (UNEP FI) since 2019. In 2023, the G20 also released *High-Level Principles on a Sustainable and Climate-Resilient Blue Economy* [6].

a. SBE concept in Chinese policy and governance

The blue economy in China was initially synonymous with the marine economy until the 2000s. A pivotal moment came in April 2009 when the blue economic zone was created on the Shandong Peninsula, then became part of the national strategy, leading to a clearer distinction between the blue economy and the ocean economy. The blue economy began to focus on sustainable development with coordination between ecological and socio-economic systems and integrating development of land and sea. The new narrative of “Sustainable blue economy” which is now gaining more recognition internationally, facilitates the communication of priority actions necessary for promoting sustainability. It is therefore strongly recommended to adopt this term for standardization in China, particularly in the context of policy development and industry engagement.

The SBE in China is currently more of a development concept focused on green growth approaches rather than a concrete policy. This absence of a clear definition, shared goal, accountability and operational framework for the SBE hinders the integration of sustainable practices and resource allocation. Currently, various ministries handle different aspects, leading to potential policy conflicts. For instance, the Ministry of Natural Resources (MNR) oversees overall ocean economy development, the Ministry of Ecology and Environment (MEE) manages ocean protection and pollution control, and the Ministry of Agriculture and Rural Affairs (MARA) handles aquaculture and fisheries. This fragmented governance system lacks a unified approach, which can undermine SBE progress. Establishing a leading ministry could streamline efforts and ensure cohesive policy implementation. A comprehensive governance system that integrates ocean economic sectors and conservation matters is crucial for advancing an SBE and addressing the complex, cross-cutting nature of marine issues.

¹ This section summarizes key findings from the work of Task Team 1 (Ocean economy and blue finance).

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b. Inclusiveness and gender equality in SBE development

The expansion of ocean-based industries can lead to the displacement of local communities, particularly women and marginalized groups, and exacerbate social inequities. Coastal communities often rely on traditional livelihoods, such as fishing and tourism, which may be impacted by industrial activities^[7]. To ensure that the transition to a SBE is equitable, governance models and benefit-sharing mechanisms must explicitly address gender and social inclusion^[8].

Integrating gender metrics into marine economic statistics is essential. The systematic collection and integration of sex-disaggregated data – alongside other inclusion markers such as age, ethnicity, and disability status – into marine labour force statistics^[9] would allow policymakers to track women’s participation across the fisheries, tourism, and blue tech sectors, including their representation in leadership roles^[10]. Mapping these demographic and economic indicators within high-impact sectors in the marine economy will provide an evidence base for policymaking and help identify gaps where targeted interventions are needed within SBE development processes.

Finally, the definition and principles for a SBE developed in the Chinese context should make explicit reference to gender equality and social inclusion, ensuring that women and men, as well as marginalized groups, benefit equitably from ocean-based development opportunities.

Improving Ocean Accounting to Support Sustainable Development

There are four essential accounts that connect ocean assets and governance with sustainable economic practices. These accounts include “ocean asset accounts”, which assess the health of ocean resources; “ocean economy accounts” that track economic activities and revenues; “ocean residue accounts” for waste and emissions entering the ocean; and “ocean governance accounts” that identify management responsibilities and monitor management effectiveness. These four accounts interact dynamically to shape SBE development. By balancing these accounts, stakeholders can promote economic growth while preserving marine ecosystems and ensuring long-term sustainability.

a. Evolvement from ocean economic accounting

In China, the component of the ocean account being mainstreamed for strategic planning and policymaking is the economic account, while the rest are either only partially piloted at the local level or studied in research. Despite Gross Ecosystem Product (GEP) having been piloted and developed in China at various scales, its methodology and application in the ocean space is largely limited, in contrast to the terrestrial side. There is a need for developing a comprehensive ocean accounting approach to advise policies and ensure economic growth does not compromise ocean health. Improving ocean accounting is crucial for informed decision-making in the SBE. For China, besides the sustainable transformation of the ocean industries, a vital next step toward an SBE is the integration of more environmental and natural capital-related information into its existing accounts.

Besides, there needs to be a stronger alignment between China and the other countries on the scope of ocean-related activities and define them and their respective ratios (i.e., direct effects); then analyze input-output reliance (i.e., indirect effects). The scope should capture a wide range of indicators of the induced effects like labor input, disaggregated by sex and other inclusion markers, and scientific and technological innovation.

Regular revisions of the ocean industry statistics accounting system and the digitization of the industry data collection and processing are also necessary.

b. Advancing the valuation of marine ecosystem services in China

The ocean's value extends beyond providing essential resources; it also offers crucial ecosystem services such as climate regulation, coastal protection, water conservation, food supply, livelihoods and cultural value. Recognizing these values is vital for sustainable ocean development. Valuation approaches should be gender-responsive, capturing the differentiated roles and knowledge of women, men, and marginalized groups in managing and benefiting from marine ecosystems. China should develop a national approach to valuing marine ecosystem services and integrate these values into policy and economic development decisions. Comprehensive marine data is essential for formulating sustainable blue economic development plans and improving the marine industry's efficiency. This data should include sex-disaggregated and socially disaggregated information to ensure inclusive evidence for decision-making. Addressing these challenges requires adjusted policies to enhance data collection and analysis, incentivizing public-private partnerships and leveraging technological innovation.

China's ocean observation and data network construction faces two major problems: insufficient ocean observation facilities and incomplete laws and regulations on marine information sharing and service policies. Additionally, China's current marine legal system lacks a relevant legal framework for marine information management, including the ownership, collection rights, attribution and transfer of marine information. This has led to monopolization of marine information and wasted national resources, directly constraining the development of the SBE.

Unlocking Blue Finance to Facilitate the Blue Transformation

In order to direct capital and development policies toward SBE pathways, there is a need for commonly agreed ocean-based principles, accountability frameworks, guidance, criteria and metrics. These must be supported by robust regulation, including the use of incentives and disincentives. While the ocean is not well incorporated within the global finance system, some blue finance frameworks and guidance have been or are being developed and are significant contributions to the emerging blue finance ecosystem.

a. Challenges and policy gaps

Financing sustainable ocean initiatives presents several challenges, including high upfront costs, uncertain returns, lack of precedent deals, poor data and a high-risk governance environment. Market dynamics, such as fluctuating commodity prices, further affect the viability of ocean-based industries^[11]. Additionally, insufficient technical capabilities and data, misalignment between costs and benefits, lack of unified standards and lagging policies hinder financial support for the marine economy, complicating risk identification, capital allocation and product innovation. Data disaggregated by sex and other identity factors is also largely absent, hindering the ability to assess inclusion and distributional impacts.

At the financing policy level, it is essential to create technical standards or a blue finance taxonomy at the national level to define and identify blue industries and activities. China's lack of national guidelines on blue finance leads to assessment bias and restricts large-scale development. While there have been multiple organisations publishing blue finance taxonomies and guidelines, national adoption of these policy tools is

lacking, and thus China can take the initiative to set a national role model. Comprehensive and standardized blue information disclosure, referencing international standards like Taskforce on Nature-related Financial Disclosures (TNFD), is needed to assess and rank the environmental benefits of enterprises, incentivizing financial institutions to invest in blue projects. De-risking mechanisms for blue financing and investment need to be designed to attract the private sector. Lack of understanding of the marine economy leads to underestimating risks of marine ecological degradation, loss of marine biodiversity, and other marine crises on their own finances and overestimating investment risks in blue projects. Standardizing the technical application of methods for accounting for the value of marine ecological products and developing a blue carbon market can incentivize early investments. Issuing blue bonds, like the Bank of China's 2020 issuance, can boost SBE investments. Disclosure and blue bond issuance could also require gender and inclusion metrics to de-risk social outcomes, like incorporating gender-responsive use-of-proceeds and impact reporting.

b. China's blue finance taxonomy development and future applications

China currently lacks incentive policies for financial institutions to support SBE activities. Integrating sustainability considerations into marine protected area assessments and creating local government incentive mechanisms for sustainable projects are necessary. While some standards reference international guidelines, most local policies focus on domestic needs and lack integration with international carbon markets, limiting cross-border cooperation. Additionally, most policies lack dynamic tracking mechanisms and regular evaluations, reducing market confidence in the effectiveness of blue finance initiatives. Over the past two years, local governments in China have carried out a number of explorations and practices of blue finance standards. In 2024 the Yantai government and the Institute of Finance and Sustainability (IFS) jointly compiled and released a blue investment and financing industry support catalogue^[12], which for the first time compiled a qualitative and quantitative system for financial institutions to identify and invest in blue economic activities. Future iterations could embed gender-screening criteria and require sex-disaggregated M&E to track inclusive outcomes.

Policy Recommendations

- 1) Integration of SBE into ocean governance systems: Investigate and adopt SBE definitions and principles in China in the 15th FYP and develop policy drivers around it, including integrated governance across all levels, SBE transition planning and Marine Spatial Planning (MSP). Form an SBE task force comprising the MNR, the MEE, the Ministry of Science and Technology (MOST), and the National Development and Reform Commission (NDRC). This task force would design collaboration pathways, internally formulate the "Action Plan for Sustainable Blue Economy Development" and coordinate preliminary policy work. Pioneer cities such as Xiamen and Shenzhen can be leveraged to establish "SBE Demonstration Zones." These zones can facilitate pilot cooperation with developed countries on standards and management models related to the SBE, such as adopting SBE principles in strategic policy planning, MSP, ocean accounting and blue finance, as well as including gender lens in the design and financing. Integrating the agendas of SBE, climate actions and biodiversity conservation in partnership with the global community is vital to meet the targets outlined in the Paris Agreement, the Convention on Biological Diversity (CBD) and Agenda 2030.

- 2) Developing robust ocean accounting frameworks for advancing SBE objectives: The foundation of effective ocean accounting lies in the standardization of core definitions and measurement approaches. Developing improved methods that align with concepts and principles of the System of National Accounts (SNA), the System of Environmental-Economic Accounting (SEEA) and guidelines already provided in the technical guidance on ocean accounting for valuing ecosystem services is crucial. Integrating environmental and economic indicators, disaggregated by sex and other identity factors where relevant, helps to create a holistic view of the ocean's contributions to the economy and the impacts of economic activities on marine ecosystems. Additionally, better tools for handling uncertainty and data gaps are needed to ensure that ocean accounting systems can provide reliable information even when data is incomplete or uncertain. Strengthening institutional capacity involves improved coordination between statistical and environmental agencies, enhanced data collection and management, and better technical capacity for integrated environmental-economic analysis. To maximize the impact of ocean accounting, it is essential to enhance the use of accounting information in decision-making processes, ensuring that policymakers have access to relevant and timely data. Developing more sophisticated planning tools based on accounting data allows for more effective and informed policy development.
- 3) Promoting blue finance in national policy and global partnership: Clarifying the definition of blue finance and building it off established frameworks including the Sustainable Blue Economy Finance Principles is essential for its development. National blue standards should follow principles of Do No Significant Harm (DNSH) and "adaptation to latest developments," considering resource endowment, ecological capacity and biodiversity vulnerability. Establish a "Blue Finance Coordination Committee" to oversee policy formulation across coastal provinces and promote mutual recognition of standards. Develop a Blue Finance Project Environmental Benefit Accounting Guide to standardize methods for calculating indicators such as carbon sinks and pollutant reduction. Mandate issuers of blue bonds to disclose the use of funds, environmental impacts of projects, and third-party evaluation reports. Establishing an international marine development bank in Shenzhen could promote the sustainable expansion of the global ocean economy. Cooperative financing methods with global partners should be explored, including merging various forms of capital for conservation, addressing high seas financing obstacles, and collaborating with the OECD Development Assistance Committee (DAC) nations for concessional financing of SBE initiatives. Through the BRI's International Green Development Coalition, China can foster international agreements to advance sustainable development and achieve SDGs.

4.2. Ocean-based Solutions for Carbon Neutrality²

Context Setting

The ocean has played a pivotal role in absorbing a substantial share of anthropogenic carbon emissions and has the potential to sequester and store a larger volume of carbon emissions, offering a diverse range of mitigation opportunities to support global carbon neutrality goals. Ocean-based solutions, which here include approaches in three arenas: 1) marine carbon dioxide removal (mCDR), 2) strategies to decarbonize marine industries, and 3) the development of ocean renewable energy (ORE) – can make critical contributions to emissions reduction, reduction of atmospheric concentrations of carbon dioxide, and the broader energy transition. However, these approaches have thus far been underrepresented in international climate discussions and inadequately integrated into China’s domestic planning.

Marine CDR, which encompasses a set of approaches that seek to enhance the biotic or abiotic pathways by which carbon dioxide is sequestered in the ocean, offers opportunities to potentially reduce atmospheric levels of carbon dioxide. Modeling indicates that several mCDR methods could scale to a billion tonnes annually, but there remains considerable uncertainty in these projections. Added in more complexity is that all CDR methods face a reduced efficiency – termed “CDR tax” – due to negative feedbacks from the Earth System^[13]. For many mCDR approaches there are also questions about their effectiveness and their potential for both desirable and undesirable social-ecological side effects, which are poorly characterized. Additionally, the understanding of how they could be deployed at climate-relevant scales (e.g., the material, energy, and other input costs, as well as the political feasibility of deploying them) has not been thoroughly examined. Exploration is urgently required to determine the effectiveness, socially acceptability, durability, and scalability of mCDR approaches operating within sustainable limits. Moving forward, it is imperative that a comprehensive governance structure for oversight be established for both research and development^[13, 14].

The ocean carbon cycle, a critical part of the global carbon cycle, involves the movement of carbon from the atmosphere into the ocean and the Earth’s interior to maintain equilibrium, a balance in concentration of dissolved CO₂ at the ocean surface with the amount of CO₂ gas in the atmosphere. Due to the large amount of anthropogenic CO₂ released into the atmosphere, the ocean absorbs approximately 10 petagrams of CO₂ annually.

Carbon enters the ocean either through the dissolution of CO₂, which can be used by phytoplankton for photosynthesis, which forms the base of the food web. Carbon may then be respired back into the atmosphere, or transported to the deep ocean via the biological pump (e.g., facilitated by phytoplankton, zooplankton or

² This section summarizes key findings from the work of Task Team 5 (*Ocean-based solutions for carbon neutrality*). Contributors to the work of Task Team 5 are: Kristin Kleisner (EDF), Minhan Dai (Xiamen University), Dabo Guan (Tsinghua University), Xi Liang (University College London), Guanqiong Ye (Zhejiang University), Fei Chai (Xiamen University), Jianghui Li (Xiamen University), Douglas Wallace (Dalhousie University), Wil Burns (Institute for Carbon Removal Law and Policy at American University), Marine Thomas (The Nature Conservancy, Hong Kong), David Keller (Carbon to Sea Initiative), Mark Wells (University of Maine), Diane Hoskins (Carbon to Sea Initiative).

other marine animals and plants) and/or the physical pump, which is facilitated by ocean circulation. Some of the carbon that reaches the deep will eventually form sediments or are subducted into the mantle.

Marine CDR can be grouped into two broad approaches: biotic methods that utilize and bolster natural systems (e.g., nearshore blue carbon habitats or biota) and/or impact the biological carbon pump, and abiotic methods that involve more chemical-based manipulations of the biogeochemical carbon pump (Table 1). Each approach has strengths, limitations, and potential risks. These options also differ in terms of their scalability and the durability of carbon removal (the amount and time frame for which carbon remains removed from the atmosphere). No single approach has the capacity to meet the magnitude of carbon removal needed to help meet the temperature targets of the Paris Agreement^[15]. Thus, a suite of strategies will likely be necessary.

a. Biotic Approaches

- 1) Nutrient fertilization: Adding micronutrients (e.g., iron) or macronutrients (e.g., phosphate or nitrate) to the surface waters of the ocean has been shown to increase phytoplankton production (photosynthesis), which converts inorganic carbon in seawater into organic carbon (mostly as phytoplankton biomass) with the aim that this will increase the biological carbon pump - the movement of this carbon into the deep ocean. At the surface this enhances CO₂ uptake from the atmosphere as the air-sea gas exchange system re-equilibrates to replace the biologically utilized dissolved inorganic carbon. However, the fate of the biologically sequestered carbon, particularly if it is exported to deeper waters, has not been demonstrated. If sequestration of CO₂ in the deep ocean was demonstrated, this approach has the potential to be a major mCDR pathway, with estimates of several gigatons of atmospheric carbon removal for centuries^[16]. While these approaches may amplify the natural removal process of atmospheric CO₂ with comparatively small nutrient inputs, larger-scale chemical and ecological risks exist, including changes in biodiversity and food web dynamics, nutrient depletion in downstream regions, harmful algal blooms, and declining oxygen levels in the deep ocean. However, we currently lack the experimental data needed to quantify these factors. There is also a potential for co-benefits associated with the increased primary production, which could result in enhanced production at higher trophic levels. Some studies suggest increases in net primary production might ultimately result in increases in fish stocks. However, this remains a highly contested proposition that requires additional research.
- 2) Artificial upwelling: Upwelling is a natural process in some regions, bringing nutrients to the surface, stimulating phytoplankton production, which in turn, can result in more uptake of carbon dioxide. Enhancing this process could increase phytoplankton production, but it also returns subsurface CO₂ to the atmosphere. The net result of these opposing outcomes in terms of atmospheric CO₂ concentrations is not well understood, rendering the efficacy of this approach highly uncertain. In addition, upwelling brings cold water to the surface, which modeling studies have suggested can have a larger effect on the carbon cycle through cooling than any fertilization effect. Modeling also suggests that large-scale deployment of upwelling would disrupt ocean circulation, perturb the planet's heat budget, and risks disrupting local ecosystems. This could lead to a situation where deployment of the approach cannot be terminated without causing rapid global warming that could exceed that of business-as-usual projections of climate change.

Table 1: Estimates of aspects of “readiness” based on NASEM, 2022 ^[16] and Doney et al., 2025^[17]

	Biotic Approaches					Abiotic Approaches			
	Nutrient fertilization	Seaweed Cultivation	Terrestrial biomass sinking	Artificial upwelling	Ecosystem restoration	Ocean alkalinity enhancement	Electrochemical approaches	Direct ocean capture	Artificial downwelling
Knowledge Base	Med-High	Med-High	Med	Low-Med	Med-High	Low-Med	Low-Med	Low-Med	Low
Efficacy	Med-High	Low-Med	Med	Low	Low-Med	High	High	High	Low
Durability	Med	Low	Med	Low-Med	Low	Med-High	Med-High	Med	Med
Potential Scale of Carbon Storage	Med-High	Med	Med	Med	Low-Med	Med-High	Med-High	Med-High	Med
Environmental Risk	Med	Med-High	Med-High	Med-High	Low	Med	Med-High	Med	Med-High
Social Considerations	Challenging	Challenging + Positive Impacts	Challenging	Challenging	Less Challenging + Positive Impacts	Challenging	Challenging	Med	Challenging
Co-benefits	Med	Med-High	Low-Med	Med-High	High	Med	Med-High	Med-High	Med-High
Cost of scale-up	Low	Med	Med	Med-High	Low	Med-High	High	Med-High	High
Costs & challenges of carbon accounting	Med	Low-Med	Med	High	Med	Low-Med	Low-Med	Med-High	High
Cost of environmental monitoring	Med-High	Med	Med-High	Med	Med	Med	Med	Med-High	Med-High
Additional resources needed	Low-Med	Med	Med	Med-High	Med	Med-High	Med-High	Med-High	Med-High

Directionality Scale:



Source: NASEM (2022), National Academies of Sciences, Engineering, and Medicine. 2022. A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration. Washington, DC: The National Academies Press; Doney et al. (2025) Principles for Responsible and Effective Marine Carbon Dioxide Removal Development and Governance. Washington, DC: World Resources Institute.

- 3) Seaweed cultivation: Large-scale farming of macroalgae as a mCDR approach accelerates the conversion of CO₂ into biomass, given the very rapid growth of many macroalgal species. Sinking of this biomass in the open ocean then would remove carbon on timescales similar to that of nutrient fertilization methods. However, the sequestration potential of this approach remains uncertain. Moreover, large-scale deployment of this approach could have adverse impacts on benthic communities and potentially reduce phytoplankton net primary production by diversion of nutrients. A comprehensive set of Best Management Practices with on-going monitoring would need to be implemented. There are few co-benefits identified for this approach.
- 4) Production of macroalgae for food, instead of for sinking, does not lead to durable carbon removal, as it is cycled back to the atmosphere over short time scales. However, the conversion of macroalgae into low-GHG products (e.g., biofuels, bioplastics), products that replace more GHG-intensive products (e.g., biostimulants to replace conventional fertilizers) or products that actively sequester GHGs (e.g., supplements for livestock to suppress methane or additives to concrete to sequester CO₂) could be more quantifiable, income-generating and viable pathways. There are also ideas to harvest the biomass and convert it into biofuels with CDR achieved by capturing carbon during fuel combustion (marine bioenergy with carbon capture and storage; BECCS).
- 5) Terrestrial biomass sinking: Carbon fixed via photosynthesis on land can be stored on the deep-sea floor or buried in sediments through the intentional sinking of this biomass. There have also been proposals to sink or bury biochar. Questions remain about how durably the carbon would be stored in well-oxygenated waters where organisms could consume the biomass and respire the carbon. To avoid this some are investigating sinking terrestrial biomass into anoxic oceanic regions where there is some evidence that terrestrial biomass can persist for millennia. Potential side effects include the smothering of benthic ecosystems, disruption of benthic food webs, and oxygen consumption if the biomass is remineralized, which may create anoxic conditions.
- 6) Ecosystem protection and restoration: preserving and restoring blue-carbon habitats can both enhance carbon storage and boost biodiversity – including coastal fisheries species – providing synergies with China's NBSAP (particularly in achieving commitments under Targets 1,2 & 3 of the Kunming-Montreal Global Biodiversity Framework). However, while all efforts should be made to preserve blue carbon habitats and to safeguard the natural pathways by which carbon is sequestered in the ocean, restoration efforts can have mixed success and questions about scalability and permanence remain. Restoration of degraded systems is inherently challenging, can take decades and requires rigorous frameworks for success. As most blue carbon storage is centered around coastal ecosystems (mangroves, tidal and salt marshes, and seagrasses), climate projections and sea-level rise also need to be taken into account to predict the durability of restoration efforts and the adaptive capacity of these systems (for e.g. buffer areas to avoid coastal squeezing). Additionally, coastal blue carbon ecosystems are highly productive with increasing competing anthropogenic activities. While ecological restoration is generally well-accepted (non-controversial), there is a need to understand socio-economic trade-offs.

b. Abiotic approaches

- 1) Ocean alkalinity enhancement (OAE): The addition of alkaline minerals to seawater shifts seawater carbon chemistry to enhance the transformation of dissolved CO₂ into bicarbonate and carbonate ions and thereby reduce the partial pressure of CO₂ in the uppermost layer of the ocean. This will result in an enhanced uptake of CO₂ by the ocean without an acidifying effect as normally happens with the oceanic uptake of anthropogenic CO₂ – since the alkalinity increase counters this effect. The approach is a magnified version of the natural process of rock weathering during the hydrologic cycle, and is a potentially major mCDR pathway. A particular advantage of the approach is that the durability of carbon removal is on multi-millennial time scales, in comparison to most other biotic methods which may only effectuate storage for decades or centuries. Although OAE has high theoretical potential as alkaline minerals are very abundant and ocean chemistry would allow for gigaton scale removal, the logistical challenges of scaling are high given the larger mass of material that must be distributed, and the long time frames needed for the alkalinity-enhanced surface waters to remain in contact with the atmosphere. Additionally, the ecological risks of deployments are only beginning to be examined and potential co-benefits to deployments are not well defined.
- 2) Electrochemical approaches: A subset of OAE is electrochemical alkalization, which involves using electrochemistry to remove acid from seawater thereby increasing its alkalinity. The effect of this increased alkalinity is functionally the same as described above for mineral OAE. This approach is in very early stages of evaluation for both efficacy and risks, some of which will be the same as associated with mineral-derived OAE.
- 3) Direct ocean capture (DOC): Like ocean alkalinity enhancement, DOC seeks to leverage seawater chemistry to facilitate atmospheric carbon dioxide removal. However, while OAE seeks to enhance the ability of ocean waters to hold carbon dioxide, DOC approaches entail the direct removal of carbon dioxide from the ocean. The vast majority of carbon stored in the ocean is in the form of dissolved inorganic carbon (DIC). DOC approaches utilize electrochemical or other methods to extract DIC from seawater. The electrochemical approach employs electrolysis to divide seawater drawn into a facility into separate streams, enriched in hydrogen (H⁺) and hydroxide (OH⁻) ions, respectively. The reintroduction of the acid (H⁺) stream into seawater can substantially lower pH and convert 100% of DIC into carbon dioxide. The carbon dioxide can then be stripped from the water as a gas using a vacuum pump. The alkalinity of the seawater can then be restored by adding the electrochemically disassociated base (OH⁻) to the seawater^[18]. As is the case with other mCDR approaches, drawdown of carbon dioxide from the atmosphere occurs via equilibration of seawater with air, resulting in the carbon dioxide being stored in the seawater as DIC. The exact duration of CO₂ storage in the ocean can vary, with some methods offering the potential for storage for thousands of years, while others may be shorter-lived. While DOC can reverse ocean acidification in specific areas, potential environmental risks to marine ecosystems, such as marine food webs, need further study. The process requires significant energy, and some methods may depend on specific materials. Overall, there is uncertainty around whether this approach can be scaled safely to be cost-effective.
- 4) Artificial downwelling: These approaches entail the transfer of surface water into the subsurface region, carrying atmospherically equilibrated CO₂. The potential efficacy of this approach has not been well

quantified, and it likely would be feasible only at smaller scales. A potential co-benefit of the method would be to subduct anthropogenically eutrophied surface waters, improving local coastal ecosystems. However, the potential for environmental impacts including the risk of increased ocean acidification, hypoxia, the production of other greenhouse gases like nitrous oxide or methane and the disturbance of marine ecosystems are of concern. The durability of artificial downwelling systems varies, but most current technologies would not work for long-term, large-scale applications due to high costs, complex maintenance, and potential for mechanical failure, although some systems have operated successfully for years in contained environments like bays.

Knowledge Gaps

a. Measuring efficiency and durability of carbon removal

It will be critical to quantify the reliability and effectiveness of mCDR approaches in removing CO₂ from the atmosphere, particularly in cases where monetary credits will be claimed. Monitoring, reporting and verification (MRV) is the complex process for measuring and modeling the amount of carbon (and other greenhouse gases, GHGs) removed by a CDR approach, and each approach faces different challenges for this goal. Across all mCDR approaches there are areas where improvement will need to be made, particularly: 1) lack of standardized protocols for MRV, 2) incomplete understanding of the carbon cycle, 3) incomplete understanding of how mCDR may impact other climate relevant processes, 4) difficulties in establishing a baseline for evaluating perturbations due to natural variability, and 5) technical challenges in measuring and modeling many variables. Addressing these challenges will require a combination of well-designed observation programs and improved skills of existing biogeochemical and ecological models as well as the development of standardized MRV protocols. Additionally, policy makers and scientists need to come to a consensus on what adequate timescales for durability of stored carbon are, which may differ by approach.

b. Measuring ecological benefits and impacts

Any human intervention to accelerate mCDR, whether biotic or abiotic, will alter ecosystems in desirable and undesirable ways. Social acceptance of specific mCDR methods will depend on the balance of perceived needs against these environmental changes, so quantifying these changes will be essential. This is sometimes referred to as ecological MRV (eMRV) or environmental impact monitoring. Developing the tools (observations/modelling) and frameworks for adequately quantifying and interpreting shifts in ecological systems is in many ways more complex than that of MRV, and research on this aspect is at best in its infancy, and non-existent at worst. Progress beyond conceptualization of these issues will depend first on rigorous lab and bench studies, followed by mesocosm experiments and field trials at scales that allow for adequate detection of impacts, i.e., a stage-gating approach where the pace of technological development and deployment is constrained by environmental safety considerations.

Given that the record of successful human interventions in ecological processes has at best a tattered record, effective eMRV will need to build in thresholds for sensitive sentinels (biotic and abiotic) so that when passed the mCDR implementation can be adjusted or halted if needed to mitigate the impacts. Identifying the sentinel parameters and their thresholds in itself will be a major undertaking, and little research has been devoted so far

to this aspect. However, there are reasonable strategies for addressing some of these aspects, and progress is underway.

c. Social and Cultural benefits and impacts

Decision-makers responsible for facilitating the implementation of mCDR approaches will need to balance the efficacy and ecological effects as well as the perspectives of the local and regional stakeholders and communities that will be affected. Research is needed then to identify any social and cultural obstacles to the adoption of mCDR technologies. This should include gender-responsive consultations with women and men from diverse backgrounds, or organizations representing their interests, to understand their perspectives and differentiated impacts. For the more controversial approaches (e.g., large scale, more intense levels of manipulation, potential for more substantial harms), there will also need to be broader consideration of national and international perspectives. Regardless of scope, these perspectives will need to be guided by an open exchange of scientific strategies along with respectful consideration of the concerns and fears of potential outcomes. Strong linkages should be developed with local and regional leaders very early in the process both to inform but also to help shape the design of MRV and eMRV protocols (e.g., by identifying socially important sentinel species or parameters). Fostering trust in the evaluation process will go a long way to enable early testing and later implementation of mCDR approaches. Efforts in this direction currently are only in their very early stages, but will need to proceed in conjunction evaluation of mCDR approaches if communities affected by mCDR projects are to be engaged and supportive.

d. Assessing mCDR feasibility and desirability³

Determining the viability of mCDR techniques will require assessing a variety of factors, including its logistical practicality, the target scale of carbon removal (i.e., implementation scale), the financial investments needed for implementation, and life cycle analyses for carbon removal (net carbon release/removal). These assessments will require sophisticated analyses for climate-scale implementations with estimation of century-scale changing economic environments (e.g., techno-economic, cost-benefit and lifecycle assessments that consider efficacy and the financial investments needed for implementation, MRV, and eMRV).

A first step is to assess what is feasible, i.e., What can we do?. Here the assessment should focus on: environmental and technological constraints, e.g., Is suitable infrastructure and technology available? Does the environment allow the option?, as well as political and legal feasibility, i.e., Is the option politically possible? Is the option legally allowed?.

Then the desirability of the option can be assessed, i.e., What do we want? Here the assessment should focus on:

- Effectiveness (How effective in reducing climate change is the option?)
- Economic efficiency (What are the costs and benefits of the option?)
- Justice (How fair is the governance and the distribution of benefits and burdens among humans?)
- Environmental ethics (How good or bad are the effects on nature?)

³ <https://iopscience.iop.org/article/10.1088/1748-9326/adc93f>

These considerations should be integral to the development and testing of mCDR approaches to maximize the potential cost/benefits of each method. Additionally, it will be essential during the assessment to account for how mCDR approaches may in the future interact with the built and natural environment over extended periods of time and at climate-relevant scales.

Assessing the desirability of any given mCDR approach will lean heavily on how well the social and cultural considerations have been incorporated^[19]. While there will never be complete agreement, moving forward will require a balancing of the desirability for action against the fears of intended and unintended outcomes, which makes early engagement of research and activities towards social and cultural perspectives so vital. Communities, stakeholders and interested parties must be generally supportive of the mCDR action.

Policy Gaps

It is clear from the 2024 – 2025 *Energy Conservation and Carbon Reduction Action Plan* issued by the State Council that China's current focus in responding to climate change remains on reducing carbon dioxide emissions. However, to achieve its carbon neutrality target by 2060, substantial magnitudes of CDR will be required to offset emissions from hard-to-abate industries^[20]. For land-based CDR, policy incentives and regulatory frameworks for the forestry sector have been established, including its inclusion in the nationally determined contributions (NDCs)^[21] and in the voluntary carbon emissions trading system^[22, 23]. Similar frameworks for mCDR exist in a limited way for some nearshore nature-based CDR approaches (e.g., mangrove and seagrass restoration), but technical mCDR are still experimental, and frameworks for including them in NDCs do not yet exist. On the national front, China currently lacks a comprehensive policy framework for implementing and regulating nature-based and technical mCDR. This hinders large-scale restoration efforts and limits coordination, public engagement, and private sector participation of research and development of technical mCDR approaches. Clear guidelines, incentives, and institutional support are essential to scale and sustain these initiatives.

The lack of a comprehensive policy framework also limits regulatory oversight for both biotic and abiotic mCDR approaches. The absence of frameworks for research, deployment, monitoring, and risk management raises concerns about environmental impacts and unchecked field trials and deployment. Policies on intellectual property, technology transfer, and international collaboration must be strengthened to support innovation and ensure responsible, equitable growth.

In addition, the development of robust measurement, reporting, and verification (MRV and eMRV) systems is critical for mCDR pathways. Without standardized protocols, it will be difficult to assess the real climate benefits of mCDR projects, ensure environmental integrity, and build the confidence needed to attract investment and foster international cooperation. Furthermore, greater alignment is needed between national ocean strategies, climate policies, and blue economy plans to integrate mCDR into broader sustainable development goals. Advancing effective, safe and scalable mCDR approaches in China will require a coordinated approach both nationally and internationally that combines scientific research, pilot projects, finance support, capacity building, inclusive stakeholder engagement, and gender-sensitive social impact assessments, alongside supportive governance structures and market mechanisms.

Policy Recommendations⁴

Integrate both marine carbon dioxide removal and the broader green transition of the marine industry into national carbon neutrality strategies.

To fully leverage the ocean's potential in achieving climate goals, it is essential to embed both mCDR approaches and the decarbonization of marine sectors – such as shipping, ports, offshore energy, and coastal industries – into national carbon neutrality roadmaps. This requires:

- Setting clear, measurable targets for ocean-based mitigation alongside terrestrial strategies;
- Ensuring cross-ministerial coordination (e.g., between environment, energy, transportation, and ocean affairs agencies);
- Establishing a unified framework that aligns research, infrastructure investment, and regulatory oversight;
- Promoting synergies between mCDR approaches and other new ocean industries to maximize climate, biodiversity, and socio-economic co-benefits.

To address the critical issue of mCDR, several policy recommendations can be implemented to ensure effective and sustainable practices.

- 1) **R&D:** Ensure research is comprehensive so as to evaluate the effectiveness, environmental and social safety, feasibility and desirability of any mCDR approach and conducted according to best practices and robust guardrails. Specifically:
 - a. Define the RD&D Portfolio: Establish a comprehensive research, development, and demonstration (RD&D) strategy for mCDR pathways. This includes technology development, optimization, scalability, and foresight into emerging approaches, along with associated risks and co-benefits.
 - b. Developing methodologies and Tools: Support (via long-term funding and through policies) the improvement of methodologies (models and direct observations) for measuring, reporting and verifying CDR outcomes, including ecosystem impacts and full life-cycle assessments under projected future climate conditions, and for facilitating optimal siting and operational planning of mCDR initiatives.
- 2) **Regulatory framework:** Establish and support robust national and international governance structures and financing mechanisms to support the development, regulation, and deployment of mCDR. Key measures include:
 - a. Government-led standards and guidelines: Governments should take the lead in formulating standards and protocols to guide research and deployment.
 - b. Financial Incentive: Formulate policy incentives such as concessional loan, tax credit, grant and subsidies to support mCDR related project development and investment activities.

⁴ This theme is still under active consideration in the SPS and the policy recommendations are preliminary.

- c. Governance and Finance Frameworks: Establish robust national and international governance structures and financing mechanisms to support the development, regulation, and deployment of mCDR.
 - d. International collaboration: Marine CDR efforts transcend national boundaries, necessitating global cooperation to share knowledge, resources, and best practices. Governments should engage in international agreements and partnerships aimed at accelerating the research, development, and deployment of marine CDR technologies.
 - e. Social safeguards and inclusion: Require gender-responsive social impact assessment, sex-disaggregated indicators in MRV/eMRV, and inclusive consent and consultation processes to ensure just and equitable outcomes.
- 3) **Market Development:** Work to develop robust standards that must underpin voluntary and compliance markets for CDR and support integration of mCDR into carbon markets.
- a. Market Development: Enable markets for mCDR co-products and support integration into carbon markets, particularly for nature-based solutions where carbon benefits are uncertain or undervalued in high-quality credit systems.

5. Marine Industry Design

5.1. Marine Industry Low-carbon Transition⁵

Context Setting

The marine industry refers to economic activities involving the development and utilization of marine resources. The imperative for decarbonization has recently extended to the marine domain, making the low-carbon transition of the marine industry a strategic priority. The low-carbon transition of the marine industry consists of two dimensions:

- 1) **The decarbonization of traditional marine industries**, such as marine transportation, fishing and aquaculture etc., through technological upgrading, energy restructuring, and process optimization. For instance, 38% of the total potential reduction in maritime CO₂ emissions can be achieved through optimizing international trade patterns.
- 2) **The expansion of emerging marine renewable industries**. The emerging marine industry holds significant potential for contributing to global climate mitigation efforts, particularly by providing alternatives to fossil fuel-based energy through offshore renewables, and by enhancing carbon sequestration via offshore Carbon Capture, Utilization and Storage (CCUS).

Minimizing the carbon footprint of ocean-based activities (e.g., shipping) is essential for global carbon-neutrality goals, yet the marine industry's "blue transition" is hampered by major knowledge and policy gaps. Progress requires robust baseline data on emissions and ecosystem conditions, integrated research that couples technological advances with measurement of ecological impacts, and coherent policy frameworks that align incentives, finance, and governance with national and international climate objectives. Because most existing tools were designed for land-based systems, they frequently do not account for the unique dynamics of marine ecosystems—underscoring the need for sector-specific methodologies and standards.

Knowledge Gaps

The primary knowledge gaps hampering efforts to minimize the carbon footprint of ocean-based activities involve methodologies and metrics, long-term data and research, empirical uncertainties, and social impacts.

a. Measuring efficacy and durability of carbon removal in the industrial sector

- 1) **Methodology and metrics**: Significant knowledge gaps hinder the green transition of the marine industry. Firstly, while carbon footprint accounting exists for specific sectors like marine transport and offshore energy (often using approaches similar to land-based industries), systematic methodologies are lacking for other marine industries and the sector as a whole. Secondly, there is a critical absence of localized carbon life cycle inventory data (carbon storage/removal vs. carbon released) specific to marine processes, limiting accurate assessments. Finally, inconsistent system boundaries applied across studies make carbon footprint results incomparable and obscure the true climate impact of marine activities.

⁵ This section summarizes key findings from the work of Task Team 5 (*Ocean-based solutions for carbon neutrality*). See footnote 2.

2) Long-term data: Despite ongoing efforts to decarbonize, the marine industry still faces three fundamental data and technical shortfalls that must be addressed to enable a credible low carbon transition:

- Opaque and incomplete emission monitoring data: Although a variety of carbon emission accounting frameworks exist, their application across shipping, fishery, renewable energy and tourism remains sporadic and inconsistent. In shipping, for example, the long-term, ship-type-specific emission factors are hard to establish. Likewise, catch records for different fishing gears and site aquaculture statistics are fragmentary or nonexistent, preventing the accurate calculation of carbon footprints for those sub-sectors^[24].
- Engineering Challenges for Alternative Fuels and Propulsion: Alternative fuels (LNG, methanol, hydrogen, ammonia) promise steep CO₂ reductions, but each introduces its own set of hurdles. Engine retrofits and burner designs must accommodate very different combustion characteristics, while incomplete combustion in LNG systems (methane slip) and unburned ammonia emissions are unsolved technical risks. Onshore and onboard storage and bunkering infrastructure for these fuels are sparse. Measuring fugitive emissions of methane or ammonia with reliable accuracy is still an unsolved instrumentation challenge, leading to wide modeling uncertainties.
- Unclear Pathways from R&D to Commercial Deployment: Many promising low carbon solutions have been proven in the lab or at pilot scale but have not made the leap to full commercial operation. For instance, floating offshore wind opens up vast deep-water resources yet still depends on a slow, labor intensive process of assembling turbines onshore, towing them into position, and securing their moorings^[25].

3) Empirical gaps: It is essential for evaluating the marine industry transition through quantitative analysis of cost structures, policy incentives, and demand-response analysis. However, existing studies fall short in three key areas.

- Lack of full spectrum cost accounting: Although laboratory experiments and theoretical models have extensively explored alternative fuels and CCS technologies, there remains a dearth of techno-economic data covering the carbon life cycle. In particular, there are few sea trial case studies across different vessel types (container ships, tankers, bulk carriers, fishing vessels) or route profiles (deep sea, coastal, feeder), leaving policymakers and investors unable to accurately gauge costs at each link of the value chain, or to tailor infrastructure investments and subsidy schemes.
- Insufficient quantification of policy incentives and investment returns: There is a notable absence of studies that draw on firms' actual financial records or project level accounting to isolate the marginal impacts of government subsidies, carbon pricing, tax credits, or carbon border adjustment measures (CBAM) on internal rates of return (IRR) and net present value (NPV). For example, within the shipping sector, the financial impacts of EU Emission Trading Standards (ETS) allowances, the Fuel EU Maritime regulation and CBAM on shipowners' investment returns have

not been empirically isolated. Without such analysis, it remains difficult to optimize or coordinate policy tools in ways that effectively stimulate low carbon investment.

- Gaps in cost-pass-through and demand-response analysis: Most existing work relies on marginal abatement cost curves (MACC) to model the cost effectiveness of alternative fuels under various greenhouse gas regimes^[26]. However, there is almost no empirical measurement of how much different market actors – shippers, travelers, mining concessionaires – are actually willing to pay for a “green premium,” nor of the price and demand elasticities that govern how increased costs translate into higher freight rates, ticket prices, or resource rental fees. Without these real-world estimates, projections of market uptake and the design of demand-side policies remain speculative.
- 4) Social impact: There is a limited understanding of the social implications associated with the transition of the marine industry towards ocean-based solutions for carbon neutrality. This includes the potential changes in employment patterns, community structures, and the overall well-being of coastal populations. Communities dependent on traditional marine-based livelihoods may face disruptions, while new opportunities for employment and economic growth may arise. Understanding how these transitions affect local livelihoods, social cohesion, and public health is vital for ensuring equitable and inclusive development pathways. There is a need to understand the environmental and social implications of these solutions, including potential impacts on marine ecosystems and coastal communities. As such, studies should use sex-disaggregated labour data and track the distribution of costs and benefits across people of different genders and groups in vulnerable situations.

b. Measuring ecological benefits and impacts of marine industry transition

There is a need for standardized methodologies for assessing ecological benefits and impacts related to transitioning the marine industry to low-carbon alternatives. The marine environment encompasses diverse ecosystems, each with unique sensitivities and resilience to change. Therefore, developing metrics that can accurately quantify improvements in biodiversity, habitat restoration, and ecosystem services is crucial yet challenging.

c. Measuring social and Cultural benefits and impacts of marine industry transition

Understanding the social and cultural benefits and impacts of the marine industry’s low-carbon transition is essential for fostering public support and ensuring the sustainability of such initiatives. These benefits may include enhanced community well-being, improved health outcomes due to cleaner air and water, and increased economic opportunities associated with the development of new low-carbon technologies. Conversely, potential impacts could include disruptions to traditional industries, changes in community dynamics, and the need for workforce retraining. These effects are often experienced differently by women and men, with gender roles shaping access to new opportunities and exposure to risks. Understanding how these transitions affect the balance and distribution of benefits and costs and the impacts to local livelihoods, social cohesion, and public health is vital for ensuring equitable and inclusive development pathways. By recognizing both the benefits and challenges, policymakers can develop strategies to mitigate negative impacts and enhance positive outcomes.

Currently, knowledge gaps of social and cultural benefits and impacts of the marine industry low low-carbon transition pertain to the understanding of how these changes affect local communities, social structures, and

cultural practices. Very little evidence exists of how women, youth, Indigenous peoples, and other marginalized groups are specifically affected, limiting the design of inclusive policies. While there is growing recognition of the need to transition towards a low-carbon marine industry, there is limited research on the specific social and cultural dimensions of this transition, such as:

- The extent to which low-carbon technologies can create new economic opportunities and jobs within marine communities is not fully understood.
- The potential impacts on traditional industries and the need for workforce retraining have not been thoroughly explored.

This lack of understanding can hinder the development of effective gender-sensitive and inclusive policies and strategies that account for the diverse needs and perspectives of affected communities. Therefore, there is an urgent need for more empirical research to fill these knowledge gaps and inform policymaking processes

d. Assessing feasibility and desirability

One critical area is the lack of data on the feasibility and potential impact of various ocean-based solutions. For instance, the technical and economic viability of large-scale marine renewable energy projects, such as offshore wind farms and wave energy converters, requires further investigation. Additionally, there is a need to understand the environmental and social implications of these solutions, including potential impacts on marine ecosystems and coastal communities. Furthermore, the integration of marine-based carbon sequestration technologies, such as ocean alkalinity enhancement and enhanced weathering, into existing industrial practices presents unique challenges that require in-depth research.

Policy Gaps

Under the current international legal framework governing the ocean, the United Nations Convention on the Law of the Sea (UNCLOS) provides only general obligations for marine environmental protection under Articles 192-195 and requires environmental impact assessments (EIAs) for activities likely to cause significant harm to the marine environment under Article 206. However, it offers no specific legal definitions, permitting procedures, or regulatory standards for mCDR technologies.

- 1) **Clear timelines and milestones for measuring progress are lacking:** Currently, there is no comprehensive roadmap outlining the stages and deadlines for the adoption of these solutions within the marine industry. Additionally, there is a notable absence of specific milestones to measure progress and ensure that the transition is occurring at the necessary pace. This lack of clarity can hinder effective planning and implementation, potentially delaying the industry's contribution to achieving carbon neutrality.
- 2) **Absence of policies that specifically target the social and environmental impacts:** Currently, there is limited guidance and regulation concerning how the transition within the marine industry should address these impacts. Social and environmental impact policies are rarely required to be gender-sensitive and inclusive, overlooking differentiated risks and benefits for women, youth, and marginalized groups. This absence can lead to unforeseen consequences, such as negative social and environmental externalities, which could undermine the overall effectiveness of carbon neutrality efforts. Furthermore, the lack of

specific policies creates uncertainty for stakeholders, making it challenging to navigate the transition process and align their activities with broader carbon neutrality goals.

- 3) **Lack of comprehensive and standardized frameworks for assessing the feasibility of such transitions:** Currently, there is a significant variability in how different stakeholders perceive and evaluate the feasibility of ocean-based solutions. This lack of standardization leads to fragmented efforts and potentially misaligned priorities, which could hinder the overall progress towards carbon neutrality. Additionally, the absence of comprehensive frameworks limits the ability to compare and contrast different ocean-based solutions, making it difficult to identify the most promising avenues for further research and investment. This results in inconsistent methodologies and criteria being used, making it difficult to compare and benchmark progress across different regions and countries.
- 4) **The existing policies often focus on individual aspects of marine industry transition:** The focus is often on technology development or economic incentives without addressing the broader systemic changes required. This fragmented approach limits the effectiveness of policies in driving meaningful and sustained transformation.
- 5) **Overlapping jurisdictional oversight from coastal states:** Industries and projects operating within exclusive economic zones (EEZs) are subject to overlapping jurisdictional oversight from coastal states, the International Maritime Organization (IMO), the London Protocol, and regional organizations such as the European Union. For projects located on the high seas, governance relies almost entirely on flag state regulation and the IMO/Protocol framework. These fragmented and poorly coordinated regulatory regimes lack vertical integration, clear delineation of responsibility, and mechanisms for risk allocation. As a result, compliance pathways remain unclear, permitting timelines are extended, investment costs increase, and the absence of standardized protocols for long-term monitoring and disclosure leads to overlapping accountability, hindering efforts to quantify environmental risks and economic losses across institutional settings.
- 6) **Transparent reporting.** Currently, there is a lack of standardized reporting frameworks for the marine industry to disclose its progress and impact in transitioning towards ocean-based solutions for carbon neutrality. This lack of transparency makes it difficult for stakeholders to assess the effectiveness of these solutions and hold industries accountable for their commitments. Furthermore, without clear reporting guidelines, there is a risk of greenwashing, where companies may claim to be taking action without providing substantial evidence to support these claims. Reporting mechanisms also lack requirements for sex-disaggregated data and gender-sensitive indicators, reducing accountability for equitable outcomes.

Policy Recommendations

To address the critical issue of marine industry transition and its carbon footprint, several policy recommendations can be proposed.

- 1) **Incentivize the adoption of low-carbon technologies and practices:** This can be achieved through subsidies, tax breaks, or other financial incentives that make these technologies more economically viable.

- 2) Stringent regulations to limit emissions from marine vessels and operations: This includes setting clear emission standards and enforcing penalties for non-compliance. Governments should support research and development into new, innovative technologies that can further reduce the carbon footprint of the marine industry.

5.2. Renewable Energy⁶

Context Setting

Marine Energy is an exceptionally broad concept that encompasses various forms of energy existing in or derived from the ocean, as well as their utilization methods. In a narrow sense, marine energy refers specifically to the vast natural energy contained directly within the ocean, including wave, tidal and current energy, ocean thermal energy conversion (OTEC), and salinity gradient energy – all of which can be harnessed to generate electricity and serve as stable, sustainable, and cost-competitive energy sources. However, from a broader perspective, marine energy should not be confined solely to these renewable sources. Resources such as oil and gas trapped in subsea geological formations, naturally occurring gas hydrates in solid form on the seabed, and even hydrogen energy extracted via seawater electrolysis should also be defined as marine energy. Under this definition, marine energy and its industrial framework constitute a far more complex and diversified system.

The industrial models for marine energy vary significantly depending on the specific energy type and its stage of development. Offshore oil and gas, as a conventional form of marine energy exploitation, closely resemble the industrial models of onshore hydrocarbon development. However, they require advanced technologies and equipment in marine engineering, such as offshore structure design, deepwater drilling, and operational support systems – precisely the areas that formed the initial core of marine engineering R&D and industrialization. The utilization of distributed offshore renewable energy, including offshore wind, offshore photovoltaics (PV), and other marine renewables, has given rise to a novel industrial model: offshore renewable energy development. While this model inherits the industrial framework of onshore renewable energy projects, it demands even greater breakthroughs in marine-specific technologies and innovative equipment. Seawater electrolysis for hydrogen production has yet to achieve large-scale commercial application. Although critical advancements have been made in core technologies, a significant gap remains in establishing a technically and economically competitive industrial system for cost-effective seawater-derived hydrogen. Marine carbon capture (including ocean-based carbon removal projects) currently struggles to achieve net economic benefits, with its value lying more in addressing climate change through socio-environmental contributions. Its industrial model remains exploratory.

Against this backdrop, advancing industrial design and transformation in the marine energy sector requires addressing highly synergistic and complex challenges. It must fully integrate conventional and new energy

⁶ This section summarizes key findings from the work of Task Team 2-1 (*Ocean Renewable Energy*). Contributors to the work of Task Team 2-1 are: Lars Johanning (University of Plymouth), Chong Ng (ORE Catapult, UK), Deborah Greaves (UK Supergen ORE Hub), Matthew Finn (EMEC, UK), Carlos Guedes Soares (The Centre for Marine Technology and Ocean Engineering (CENTEC), Portugal), Karl Henning Halse (NTNU, Norway), Zhen Gao (Shanghai Jiaotong University), Xiaoming Sun (Beijing University of Chemical Technology), Chunli Bao (Energy Economics Institute, China), Yingru Zhao (Xiamen University), Qing'an Li (Chinese Academy of Science), Tao Zhang (China Geological Survey), Jia He (China International Engineering Consulting Corporation), Siming Zheng (Zhejiang University), Ye Yao (Tianjin University), Xi Xie (WEF).

systems, even necessitating marine spatial planning (MSP) for coordinated development. Only through such holistic approaches can industrial growth be effectively harmonized. Under the goal of achieving carbon neutrality by 2060, green and low-carbon transformation stands as the central direction for the future of the marine energy industry.

Knowledge Gaps

An electrified energy system is more efficient than a fossil-fuelled energy system in today's energy industry. The demand for clean and sustainable energy supply continues to increase globally. Hence, the predicted shift towards electricity will be the key future energy transition target and it will de-couple the energy needs with the fossil fuel supply, which can clearly claim the contribution to carbon neutrality. Ocean energy industry varies from offshore oil and gas, offshore wind, marine renewables to the green hydrogen generation. Even deep marine energy extraction has shown the features of novel energy industries and high consistency with the energy transition trends. However, as a high-tech, high-risk strategic emerging sector, the development of the ocean energy industry faces dual challenges: on one hand, it must address natural risks arising from complex marine environments; on the other, it urgently needs to resolve systemic difficulties arising from industrial transformation. Currently, certain critical shortcomings still exist.

- 1) The fundamental understanding and monitoring data for marine environment interaction with the ocean energy industry has been seriously neglected, so it caused the unawareness of the long-term environmental effect and potential risk or threat caused by ocean energy industry
- 2) There is a lack of systematic assessment of environmental interactions, necessitating an integrated value assessment system covering economic feasibility, social benefits, and ecological sustainability to scientifically justify its development necessity.
- 3) There exists a deficiency in systematic assessment, including insufficient research on the environmental impacts of wind, solar, wave, and tidal energy development. In particular, comprehensive evaluation of wind farm disturbance effects on marine flow fields and wind fields, as well as changes in chemical dynamics fields and cumulative ecological impacts, urgently requires improvement.
- 4) It is imperative to establish a systematic assessment framework targeting both the intrinsic development of the industry and its coupling effects with the environment, encompassing a comprehensive consideration of engineering entity performance and eco-environmental interactions.
- 5) Now we are lacking the methodology to assess the contribution of the ocean energy industry, especially the marine renewable energy, to Carbon Neutrality and Sustainable Blue Economy effectively and accurately, which could help us to understand the contribution clearly and support the issuing of more positive policy to accelerate industry development for ocean energy.

Policy Gaps

The marine energy industry currently faces systemic governance challenges including a fragmented policy framework, tiered coordination failures in implementation, and a lack of evidence-based clarity in decision-making, necessitating an urgent establishment of a coordinated policy framework driven by scientific assessment.

- 1) For the marine renewable energy industry, as it is still in its early stage, cost-effectiveness has been the most obvious obstacle to advancing the industry development. However, renewable subsidy policies have been eliminated with other mature renewable energy industries simultaneously, ie. making scaling of marine renewables more difficult.
- 2) Within the ocean renewable energy industry research has been insufficient advanced towards marine spatial planning, regulation and consent level and procedures. Such research is needed to enable the ocean industry to accelerate grow and become a dominant source in our energy mix in the future.
- 3) The research, innovation and demonstration investment in ocean energy industries, especially in marine renewable energy has not been sufficient to underpin the needs of the rapid industry development.

Policy Recommendations

The large-scale deployment of the ocean energy industry significantly amplifies biological-environmental impacts on marine ecosystems, making related issues and potential threats imperative to address. In offshore oil and gas development, underwater drilling and exploitation cause seabed damage, with oil spills posing the most severe hazards to marine environments. For large-scale offshore wind farms (exceeding 10GW), construction and operational noise emerge as the primary environmental disturbance. Offshore photovoltaic projects introduce shielding effects, water obstruction, seabed erosion, and silt accumulation, creating complex ecological consequences. Additionally, tidal current units disrupt flow fields, sound fields, and electromagnetic fields, generating multi-physical field coupling effects. These cumulative impacts underscore the urgent need for sustainable mitigation strategies in marine energy expansion.

The research and evaluation of marine (ecological) environmental carrying capacity for large-scale ocean energy deployment is extremely limited and lacks effective interaction mechanisms and evaluation models to support. Based on the latest research and conclusive summary, the following policy recommendations can act as research finding and guidance support to promote the SBE towards carbon neutrality:

- Strengthen research in the field pertaining to the interaction between marine energy development and marine ecology, clarify the marine environmental impact mechanism of the marine energy system, accurately evaluate the benefits and balance points between the scale of marine energy development and ecosystem functions.
- Constructing a monitoring and evaluation system for the ocean ecological environment in future large-scale ocean energy development, developing multi-factor ocean ecological environment monitoring technology and equipment suitable for large-scale ocean energy development, and forming a collaborative development theory and verification strategy for evaluating the ocean environmental carrying capacity to the ocean energy system.
- Establish an assessment and evaluation system for the carrying capacity of the marine ecological environment in the marine energy system and promote the establishment of an eco-friendly marine energy development industry model that covers the entire chain of planning, construction and operation based on new-developed theories and evaluation frameworks.

- Strengthen the top-level design of ocean energy industry, including a national strategic plan, comprehensive/integrating resources mapping, industry promotion action plan and financial support policy, to construct the infrastructure of ocean energy industry design/transition.
- Enable the multiple-scenario utilization or demonstration of ocean energy, especially focus on the new promising industry like offshore photovoltaic, wave/tidal energy and offshore green hydrogen, to apparently make the contribution to SBE easily calculated from the ocean energy industry.
- Enhance the leading effects of research, innovation and integrated ocean management in the process of making ocean energy the future major contributor to the domestic and global low carbon neutrality goals.
- Enlarge the collaboration scope with the international academic or industrial partners to integrate the global knowledge and research outputs.

5.3. Green Shipping⁷

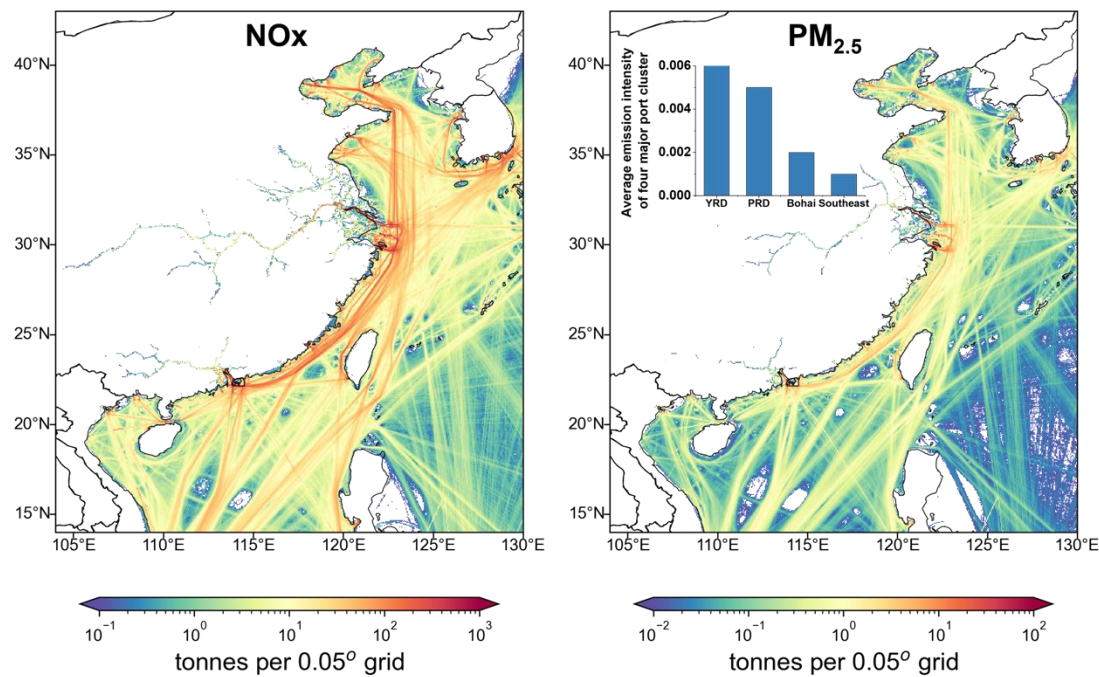
Emerging Trends in Global Shipping Emissions

Over the past three decades, international maritime trade has increased by more than 2 folds, reaching about 12.3 billion tonnes in 2023^[27]. In 2021, CO₂ emissions from global international shipping reached 805 million tonnes, a 1.7-time increase compared to 1970 and accounts for 2.21% of global anthropogenic CO₂ emission. Shipping emissions peaked at 887 million tonnes in 2017 – 2.4 times the low level of 366 million tonnes in 1983. Latest studies suggested GHG emissions from global shipping were on the rise again after COVID, and are projected to grow with continued growth in global maritime trade volume^[28]. Container ships, due to their high energy consumption and rapid growth, have been a key driver of emissions growth. Future mitigation efforts should prioritize high-carbon-emission vessel types, especially container ships, and focus on technological upgrades to cap their total carbon emissions. Spatially, shipping emissions have risen across the world between 1970 and 2021, with marked increases along Europe-Far East trade routes—especially East Asia—and around the Cape of Good Hope.

⁷ This section summarizes key findings from the work of Task Team 2-2 (*Green Shipping*). Contributors to the work of Task Team 2-2 are: Qingyan Fu (Shanghai Academy of Environmental Sciences), Dandan Huang (Shanghai Academy of Environmental Sciences), Xin Wang (Shanghai Academy of Environmental Sciences), Jason Anderson (ClimateWorks Foundation), Freda Fung (ClimateWorks Foundation), Qiuxia Wang (ClimateWorks Foundation), Wei Xu (ClimateWorks Foundation), Jun Ma (Institute of Finance and Sustainability), Lin Cui (Yangtze Delta Marine Technology Innovation Center), Huan LIU (Tsinghua University), Yang Zhang (Fudan University), Yue Li (Transportation Planning and Research Institute), Songbing DING (Shanghai International Port Group), Guodong Wu (Shanghai Marine Equipment Research Institute), Huihui CHENG (Clean Air Asia), Hang Yin (Vehicle Emission Control Center), Yan Xin (Energy Foundation China), Shuang Zhang (Dalian University), Chun Chang Zhang (Shanghai Maritime University), Guiyang Ling (Commission Office of Shanghai Combined Ports), Zhiyong Xu (Shanghai Municipal Port & Shipping Development Center), Guanghao Wu (Shanghai Jinsinan Institute of Finance), Christine Loh (Hong Kong University of Science and Technology), Pernille Dahlgaard (Maersk McKinney Moller Center for Zero Carbon Shipping), Christian F. Ørby (Maersk McKinney Moller Center for Zero Carbon Shipping), Faig Abbasov (Transport & Environment), Hyoun Sook Lee (Transport & Environment), Felix Khann (Transport & Environment), Elena Talalasova (Global Maritime Forum), Xiaoli Mao (International Council on Clean Transportation), Zhihang Meng (International Council on Clean Transportation), Ping Deng (Pacific Environment), Ted Zhang (Pacific Environment).

The Sulfur Emission Control Area (SECA) policy of the International Maritime Organization (IMO) [29] effectively decoupled SO₂ and CO₂ emissions between 2006 and 2012 along the “Baltic – North American – global” corridor. In China, intensity of shipping emissions showed significant regional differences (Figure 1). The Yangtze River Delta (YRD) is home to an internationally important port and trade cluster, and ship emission intensity ranks the highest in the country based on 2022 data. Average emission intensity of NO_x, SO₂, CO, PM_{2.5}, HC, and VOCs were 0.183 tonnes/(yr•km²), 0.080 tonnes/(yr•km²), 0.020 tonnes/(yr•km²), 0.006 tonnes/(yr•km²), 0.010 tonnes/(yr•km²), and 0.009 tonnes/(yr•km²), respectively. All pollutant levels in YRD were significantly higher than other port clusters. Comparison across all port clusters shows that the Pearl River Delta ranks second in ship emission intensity, and its PM_{2.5} emission intensity (0.005 tonnes/(yr•km²)) is about 83.3% of that in the YRD; the PM_{2.5} emission intensity of ships in the southeast coastal port cluster and the Bohai Rim region is 0.001 tonnes/(yr•km²) and 0.002 tonnes/(yr•km²), respectively, which were only 16.7% and 33.3% of the base value of YRD (Figure 1, bar chart in right panel). Regional differences are highly correlated with shipping density of each port region[30].

Figure 1. Intensity of NO_x and PM_{2.5} emissions from shipping in China[30]



Data source: Zhang X, Cheng S, Wu F, et al. (2025) Characterization of pollutant discharges from ships within 100 nautical miles of China’s coastline and certain inland river ports, 2022. Marine Pollution Bulletin, 215: 117876.

Shipping emissions also pose significant threats to air quality and public health of China’s port cities. With China’s domestic shipping emission control area (DECA) policies gradually upgraded between 2016 and 2020, average concentration of primary PM_{2.5} emissions from ships in Chinese port cities decreased from 3.58 µg/m³ to 2.73 µg/m³, and their share of total anthropogenic PM_{2.5} emissions decreased from 10.3% to 8.83%. However, ships remain a major source of air pollution in China’s coastal cities. With the introduction of a series of national policies since 2018, including DECA, SO₂ and PM pollution from ships saw significant reduction. However, NO_x and VOCs emissions continued to rise, with total VOC emissions from Chinese vessels

increasing by 90%^[31]. Between 2016 and 2020, the contribution rate of PM2.5 from inland river vessels in Chinese waters increased from 17% to 41%, while that from ocean-going vessels decreased from 43% to 32%, forming a tripartite pattern of emissions among inland river ships, ocean-going ships, and coastal ships. Combating air pollution from domestic shipping (river and coastal) and oceangoing shipping is therefore equally important for improving air quality of port cities and reaching the goal of building a “Beautiful China”.

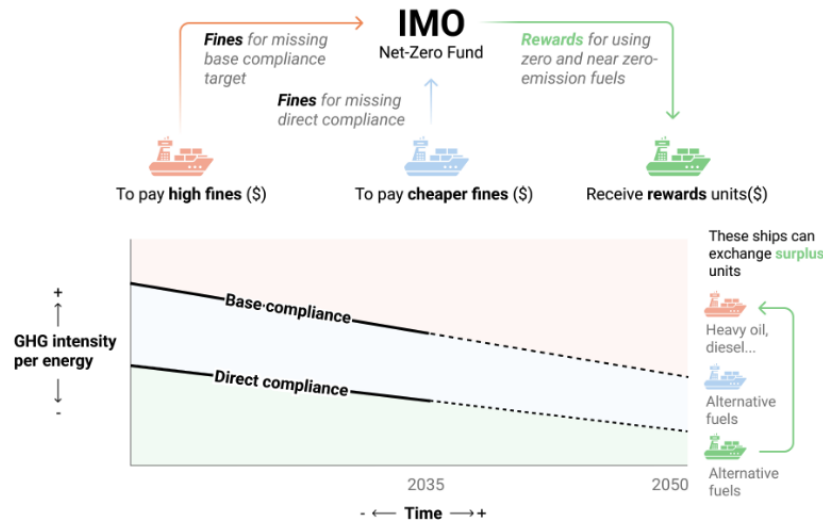
Policies and Actions Led by Ports and First Movers

a. IMO’s Climate Actions

The IMO established a regulatory framework to enhance energy efficiency by introducing the Energy Efficiency Design Index (EEDI) for new ships in 2013, and subsequently the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII) targeting in-use vessels. These measures aim to promote energy efficiency improvements, thereby reducing greenhouse gas (GHG) emissions and air pollution. They contributed to the widespread use of slow steaming to reduce fuel consumption and operational costs, but due to continuous growth of global shipping volume, absolute impacts of these energy efficiency regulations, and other commercially driven measures, on overall GHG reduction are limited^[32]. Analysis suggested that the EEXI could only reduce CO₂ emissions by 1.3% by 2030^[33]. To accelerate GHG reduction in shipping, the IMO adopted the 2023 GHG Reduction Strategy for Ships, which aims for net-zero GHG emissions from international shipping by or around 2050, a reduction of GHG emissions from international shipping by at least 20% (striving for 30%) by 2030 and 70% (striving for 80%) by 2040, and by 2030 zero or near-zero (ZNZ) fuels and energy (including wind energy) accounting for 5% (striving for 10%) of global international shipping energy consumption^[34]. These goals are set on a lifecycle basis to avoid shifting emission responsibilities upstream, and GHG assessments will consider CO₂, nitrous oxide (N₂O), and methane.

To achieve these goals, in 2023 IMO approved a legally binding Net Zero Framework (NZF), introducing a set of increasingly stringent tiered fuel GHG intensity (GFI) standards and a GFI-linked carbon pricing mechanism. Ships not meeting the GFI standards can pay to comply, by contributing to an IMO Net-Zero Fund, which generates revenue that will be used to reward ships that use ZNZ fuels and technologies, and support just and equitable transition efforts (Figure 2). NZF defines that the GHG intensity of ZNZ fuel eligible for rewards should not exceed 19.0 g CO₂eq/MJ before 2035, and from 2035 onwards the GHG intensity threshold for ZNZ fuels will be tightened to 14.0 g CO₂eq/MJ^[35]. The CII regulation is also currently being updated.

Figure 2. Functioning of the IMO Net-Zero Framework^[36]



Source: T&E (2025c). IMO Net-Zero Framework Assessing the impact of the IMO's draft Net-Zero Framework, Briefing – April 2025.

However, the implementation of NZF faces several challenges. Analysis suggested that absolute GHG reduction is projected to be only 5%-10% by 2030, which does not align with the 1.5 °C climate target and falls far short of IMO's 20-30% reduction goal for 2030^[36, 37]. In addition, the success of the NZF in realizing the expected reduction effects hinges on whether the ZNZ fuel reward system can accelerate the supply and uptake of scalable ZNZ fuels, such as hydrogen-based electrolytic ammonia and methanol (e-ammonia and e-methanol). While analysis suggests that e-ammonia will be the most cost competitive compliant fuel option in the long term^[38], IMO's reward system for ZNZ fuels, including the reward amounts and eligibility (e.g., sustainability standards, indirect land use change consideration), are yet to be decided. These factors will only be clarified upon completion of the relevant technical guidelines in the next year or two. These uncertainties increase the investment uncertainty and risks for ZNZ fuel capable vessels and production of electrolytic fuels (e-fuels) in the short term.

At the same time, it is expected that NZF's GFI non-compliance contributions and carbon pricing mechanisms will not bridge the price gap between scalable ZNZ fuels (such as electrolytic green ammonia and green methanol), and fossil methane and biofuels (the cheapest compliant fuels in the near-term). This may result in shipping companies adopting a wait-and-see approach, opting to use biofuels or fossil methane on existing vessels, or pay fines to meet NZF requirements, and postponing orders for ships that can run on ZNZ fuels. This will risk further delaying the development of a global ZNZ fuel industry chain^[39].

b. EU Fit for 55 Low-Carbon Development Policy

In 2024, the European Union began subjecting shipping to its emission trading system (ETS) and in 2025 started implementing the Fuel EU Maritime Regulation. These policies limit the GHG intensity of energy used by vessels calling at EU ports, imposing penalties on high-GHG-emitting ships, and encouraging ships to increase the use of low/zero GHG-emitting fuels by setting e-fuel multiplier and quota. Besides, shore power usage and supply are mandated from 2030 through the Renewable Energy Directive and Alternative Fuel Infrastructure

Regulation, respectively. Additionally, part of the ETS revenue has been used to subsidize the production of marine e-fuels and construction of shore power facilities.

As the first globally binding regulatory framework promoting the production and uptake of low/zero-emission marine fuels, EU's policies set the example for defining, mandating, and supporting green fuels, with fuel producers worldwide now producing and certifying fuels in accordance with EU's sustainable green fuel standards, and EU's ETS market being considered for expansion, possibly in Turkey and the UK.

c. Actions led by Ports and Industry First Movers

Major ports have actively taken steps to promote shipping's low-carbon transition. For example, Rotterdam, Singapore, Gothenburg and Gangavaram have implemented port fee reductions for zero-emission vessels to incentivize the use of green fuels. Antwerp is strongly promoting hydrogen energy projects. Leveraging its unique position as the world's top bunkering hub and largest transshipment port, Singapore created a green fuel supply model built upon a global energy network. It also cooperates with multiple ports to establish green and digital shipping corridors to coordinate development across the ZNZ fuel value chain that enables deployment of ZNZ-fuel capable vessels. These measures aim to secure Singapore's competitive edge during the shipping industry's transition to zero-emission.

Furthermore, shipping companies have started ordering ZNZ-fuel vessels and partnering with fuel producers to secure long-term fuel supply (e.g., A.P. Moller-Maersk with Goldwind and LONGi for green methanol). H2Global, a foundation set up by Germany, is pioneering a mechanism to link off-takers of green hydrogen with producers, providing price – and investment certainties to both sides.⁸ Upstream cargo owners such as Amazon and IKEA participate in the Zero – Emission Shipping Buyers Alliance (ZEMBA), supporting the application of hydrogen-based green ammonia and green methanol by paying a premium. Leading financial institutions are also stepping up to assess climate alignment of their portfolio. These pioneering practices demonstrate that port policies and leading companies play a key guiding role in promoting green fuel adoption.

d. China's Regulations and Initiatives to Promote Zero-Emission Shipping Transition

China is also actively advancing a green and low-carbon transition of its shipping industry, focusing on eight strategies that include the deployment of new energy ships, upgrading and renewal of older vessels, and use of shore power in ports. The country is working to build a comprehensive policy framework from top-level deployment to specific measures. Key documents such as the Outline for the Construction of Nation with Strong Transportation System explicitly call for the promotion of various green power ships. The "1+N" policy system for carbon peak and carbon neutrality emphasizes accelerating the development of new energy vessels. Documents such as the *Plan of Action to Launch a Large-scale Renewal of Transportation Equipment* provides policy and financial support for the shipping industry's green and low-carbon transition, and industrial and green fuel policies assist in the development of related industries.

Local policies in cities like Shanghai and Dalian are advancing the creation of green marine fuel hubs. China's largest port, and the world's busiest container port, Shanghai, has made significant progress in green and low-

⁸ More information about the H2Global mechanism can be found at <https://www.h2-global.org/the-h2global-instrument>.

carbon transition. Its container terminals are all shore power capable, port vehicles are all electrified, and photovoltaic and wind energy systems are widely deployed. LNG bunkering volume at Shanghai Port ranked the top globally in 2024, and it has completed China's first bunkering operation of green methanol. Through building the supply chains for hydrogen, ammonia, and methanol, Shanghai strives to become the green bunkering hub for the Asia-Pacific region. Policies and measures adopted in Shanghai to facilitate port operation and ships to switch to ZNZ fuels and technologies exemplify the important role of port cities in enabling shipping's ZNZ transition and attainment of local clean air targets⁹, and set a good example for other China ports to follow.

New Energy Ship Technology and Fuels

The global shipping industry is accelerating its low-carbon transition, and new energy ship technologies have become a focal point of competition. On a global scale, South Korea, as a major shipbuilding country, dominates in building LNG-fueled ships (secured 75% of LNG carrier newbuild orders in 2022)^[40] and is actively improving its shipbuilding capabilities for methanol, ammonia, and battery-powered vessels^[41-43]. Europe is focusing on LNG dual-fuel ships and methanol-powered ships, while Japan has launched its first commercial ammonia-powered tugboat, with Germany and Norway leading the way in ammonia fuel cell technology. The U.S. and Japan have commercialized hydrogen fuel cell ships, and Norway and the Netherlands are respectively leading on technology innovation in pure electric ferries and vessels using swappable batteries. While China got off a slow start, it saw a ramp up of demonstration projects in recent years. For instance, the "Three Gorges Hydrogen Ship No.1" hydrogen fuel cell ship and the 5500HP ammonia-powered workboat were launched. China also developed and built the world's largest and China's first 740TEU pure electric open-top container ship, along with LNG retrofitted ships such as "Suihang 906" and methanol-powered ships like "Jianglong", which demonstrated significant breakthroughs in various new energy propulsion technologies.

In terms of advancing adoption, electric ships show significant advantages in serving short-distance transportation and port operations and have become one of the primary technology options for low-carbon transition. Norway, through implementing strong public procurement policies for ferries, and Singapore through mandating all new harbor crafts be zero-emission by 2030 combined with incentives offered under Green Craft Program, created domestic demand for zero-emission ships. These regulations foster commercial deployment of battery electric ships in both countries, and hydrogen-powered ferries in Norway, and catalyzed the building of refueling infrastructure. In China, provinces such as Hubei and Fujian have implemented incentive programs, like free passage of river/canal locks, and launched the "Electrified Yangtze River" initiative. The Yangtze River Delta plans to operate 1,800 electric ships by 2030, underscoring the significant potential for electrifying inland waterway ships. But further promotion and deployment of electric vessels faces two main hurdles in China: high initial capital costs of building electric ships, and insufficient infrastructure for battery charging and swapping.

⁹ See an earlier CCICED publication for more discussion on the roles of port cities and various approaches adopted to balance economic and environmental development in major river basins and deltas ([link](#); accessed September 19, 2025).

Regarding ZNZ fuel development, which is essential for decarbonizing ocean-going vessels and a core element of IMO's NZF, it is still at the nascent stage. There has been remarkable growth in announced green ammonia and methanol production projects since 2023, and the projection of these green fuel supplies would, in theory, be sufficient to meet IMO's 5 – 10% ZNZ fuel goal by 2030. But most of the announced projects have not reached a final investment decision, with only a small fraction starting construction^[44].

Based on shipbuilding orders, alternative fuel-capable ships account for 16%. By 2030, it is estimated that there will be around 1360 LNG-powered ships, 430 methanol-powered ships, and about 40 ammonia-powered ships and 41 hydrogen-powered ships in operation¹⁰. However, most of these ships are dual-fuel vessels – they can run on traditional and alternative fuels-their demand for new fuels therefore hinges on the price difference between conventional and alternative fuels, which in turn depends on IMO's ZNZ fuel rewards and non-compliance contributions for using conventional fuels.

Challenges in Shipping Decarbonization

In contrast to the aviation industry, which has limited zero-emission transition fuel options, the shipping industry's transition to zero emissions will involve a variety of green fuels. Inland waterway and short-distance coastal shipping will primarily focus on battery propulsion, while long-distance coastal and ocean-going shipping can achieve net-zero emissions using multiple ZNZ fuels, including hydrogen-based e-fuels (green methanol, green ammonia) and sustainable biofuels. The multiple fuel options, combined with the fact that the IMO NZF technical guidelines are still being developed, presents significant challenges for first-mover shipowners, fuel logistics companies, and ports. They face the challenge of preparing for multiple fuels during the early stage of transition, which spreads the available funding and resources thin and increases stranded asset risks. At the same time, the high capital costs of building or retrofitting new energy ships, the lack of infrastructure for refueling, storage, and transportation of ZNZ fuels, and the lack of comprehensive refueling, storage, and safety guidelines may result in most shipowners delaying their transition decisions. This could hinder financing of green fuel production projects as final investment decisions typically require long-term fuel offtake contracts and may slow the development of the entire fuel supply chain.

Fuel producers also face multiple challenges in advancing and scaling development and uptake of ZNZ fuels: First, while alkaline and proton exchange membrane (PEM) electrolyzers for producing e-fuels are commercially available, capital costs remain high¹¹, resulting in much higher current price of hydrogen-based ZNZ e-fuels (3 to 4 times) over conventional fuels^[45, 46]. Second, green methanol production currently relies heavily on biogenic carbon feedstock, whose cost is high due to limited availability and collection difficulties, and increased demand from shipping and competition with other sectors would further drive cost up^[47]. Third, the locations of production and demand for hydrogen-based e-fuels are misaligned, cross-regional coordination is required to create the fuel supply chain. Fourth, a lack of unified ZNZ fuel standards, fragmented international

¹⁰ DNV (2025) Alternative Fuels Insight (<https://www.dnv.com/services/alternative-fuels-insights-afi--128171>, accessed June 10, 2025).

¹¹ IEA (2025) Electrolysers – Overview (<https://www.iea.org/energy-system/low-emission-fuels/electrolysers>, accessed June 26, 2025).

rules, and a lack of accurate emissions-accounting methodologies and certification schemes for measuring, tracking and reporting emissions to assure fuel quality also hinder investment in ZNZ fuel production^[48].

Policy Recommendations

Despite the formidable challenges, accelerating the transition of the shipping industry to zero emissions has become a global consensus. Decarbonizing global shipping presents significant opportunities for shipbuilding, green fuel production, port, and shipping sectors. China possesses a full industry chain that can facilitate the development of zero-emission shipping: a leading shipbuilding industry (China accounted for half of the global new shipbuilding orders in 2023), major ports are highly-connected to world shipping networks, abundant renewable energy resources, and a strong manufacturing base of green energy production and storage equipment^[49, 50]. Because of its abundant renewable energy resources and low-cost renewable energy equipment and electrolyzer production capacity, China is regarded as the world's most cost-effective country for producing green methanol and green ammonia^[51, 52]. China is therefore well positioned to contribute to the global transition to zero-emission shipping, thereby strengthening the competitive position of its shipping, port, and green energy sectors, through:

- 1) Continuing to encourage research and development of zero-emission ships and key components (such as alternative fuel engines, fuel cells, and batteries), promote the expansion of the zero-carbon ship market in order to take the lead in green ship building.
- 2) Accelerating technology innovation in and expanding capacity of ZNZ fuel production (such as electrolyzers and biomass gasifiers) to reduce fuel production costs and expand the production and supply capacity of green marine fuels; the global shipping demand for green fuel can put not yet connected renewable energy capacity to use, and help de-risk the continued buildout of renewable energy capacity required for the country's energy transition.
- 3) Establishing port infrastructure to provide ZNZ fuel refueling services, along with shore-side power and battery charging capabilities, creating global energy hubs, through adopting domestic policies and safety guidelines to de-risk and support deployment of green hydrogen-based fuels in Chinese ports.
- 4) Promoting learning and knowledge exchange by drawing on Chinese domestic and international shipping best practices, building on existing industry alliances and green shipping corridor initiatives to develop international green fuel supply chains, accelerate the scaling of ZNZ fuel adoption offer training to seafarers and key shore-based personnel to support upskilling of maritime workforce and ensure safe transition to ZNZ fuels, and actively participate in the formulation of IMO fuel sustainability standards, and robust fuel certification and tracing schemes.

The application of new energy ships and green fuels urgently requires the improvement of relevant regulations and incentive policies at the national and subnational levels. At the technology level, it is essential to promote sustainable fuel production, standardize and enhance the adaptability of ship propulsion systems to ZNZ fuels, and create a multi-dimensional policy support system driven by the state, supported by regional leadership and international cooperation. Moreover, it is crucial to increase infrastructure investment and establish technology standards. Policies and programs adopted in other countries/regions that induce demand for ZNZ fuels and technology, such as those adopted in Norway, Singapore and the EU, could offer valuable insights to inform

China's green shipping strategy. In-depth case studies of international experiences should be conducted to shed light on the more diverse set of policy tools, implementation models, and innovation pathways that China could consider to address key barriers for shipping's ZNZ transition discussed above.

In the near future, it is recommended to focus on the large-scale equipment renewal initiative as a key lever to accelerate the promotion of new energy and clean energy ships, and continuously refine and implement the scrappage and renewal subsidy program for old ships. Furthermore, the construction of green shipping corridors should be explored. These subsidy policies and green shipping corridor programs could integrate more clear eligibility criteria, innovation-focused fuel/technology uptake targets and environmental standards, with policy support and subsidy levels commensurate with GHG benefits of eligible fuels and technologies to maximize environmental outcomes. Robust monitoring mechanisms should also be put in place to strengthen credibility, increase transparency, and ensure long-term sustainability of these programs.

The integration of transportation and energy should also be a key measure, speeding up the construction of clean fuel refueling networks for inland waterways and coastal ports, forming a certain scale of green fuel supply capacity. With a focus on controlling carbon emissions, the management mechanism should be enhanced (including exploring full life-cycle emissions accounting for ships and setting mandatory reduction targets for domestic ships, and clean fuel supply targets) and comprehensive supporting policies should be refined.

Future Outlook

The global shipping industry has entered a critical phase of systemic decarbonization. Currently, the sector still faces multiple challenges in reducing air pollution and GHG emissions, including multiple energy technology pathways, high costs of ZNZ fuels and vessels, and insufficient supporting policies. However, the IMO NZF provided a clear direction of the zero-emission transition regulatory framework, and member states will be developing global guidelines and standards that drive zero-emission transition of the global shipping industry. Against the backdrop of China's "dual carbon" goals and high-quality development vision, green transition of China's shipping industry presents multiple opportunities:

- 1) The development of hydrogen-based green energy supply chains to meet growing global demand for ZNZ fuels and participating in the formulation of IMO fuel sustainability standards to ensure global recognition;
- 2) Building of new energy bunkering ports that facilitate creation of global green energy hubs;
- 3) Expanding the zero-carbon ship market to capture the leadership in green ship building.

In the future, policy incentives, technology breakthroughs, standards development, and green finance support are imperative to drive the shipping industry's zero-emission transition. China should leverage its policy advantages, rapidly expanding renewable electricity supply and industry base, building on green corridor initiatives, to catalyze the transformation of green ports, boost construction of new energy ships, and promote the creation of a diversified ZNZ fuel "production, supply, and sales" system that take into account long-term fuel viability. At the subnational levels, major port cities could lead by introducing supporting policies and other enabling programs, as evidenced by Shanghai's comprehensive efforts to advance the supply and uptake of electrification and ZNZ fuels, like green methanol. These port city policies, if proven successful, could be replicated in peer port cities in China and other regions. Through integrated policies and measures, China can

lead the zero-emission transformation of its shipping sector and make substantial contributions to its carbon peaking and carbon neutrality goals, while setting a new example in shipping decarbonization, advancing development of green marine energy and equipment, and contributing to global climate goals that benefit people and the planet.

5.4. Deepsea Mining¹²

Context Setting

Like those found on land, the deep seabed is also known to contain mineral deposits. The promise by some of the potential economic value attached to these mineral deposits has led to increased extractive attention. However, unlike its terrestrial counterpart, commercial extraction of mineral deposits from the deep seabed is yet to take place. The recent surge of interest in deep-sea mining (DSM) is largely driven by rising global desire for critical minerals such as cobalt, nickel, copper, and rare earth elements – resources considered essential for electric vehicles, renewable energy storage, and clean technologies. Consequently, some industry actors and governments have proposed the consideration of DSM as a solution to reduce dependency on terrestrial mining and geopolitical bottlenecks.

Notwithstanding, it is important for this narrative to not obscure the profound risks and uncertainties associated with mining in one of Earth's most sensitive and least understood ecosystems. DSM remains a nascent and untested industry with no demonstrable commercial viability to date. However, it is noted that test projects are currently being undertaken by several operators (including China Minmetals) to assess means of advancing technological maturity.

While some investors and states anticipate high economic gain, there have been suggestions that these promises may be overstated. The costs – technological, environmental, legal, and reputational – may ultimately outweigh potential returns. Some studies suggest that models indicate that DSM presently makes little financial sense, while others suggest through technological iteration and scientific innovation, deep-sea mineral resource commercial extraction may become economically viable.

Meanwhile, the necessity of deep-sea mining for the green transition remains subject to debate. Technological innovation, material substitution, mineral recycling, and shifts to battery chemistries that do not rely on seabed minerals have significantly reduced demand forecasts, and alternative pathways to meet clean-energy goals may exist. China is leading such innovations with great success

Policy pathways for DSM should be developed against this backdrop. This chapter underlines the most pressing knowledge and policy gaps that must be addressed before any further consideration of DSM exploitation.

¹² This section summarizes key findings from the work of Task Team 3 (*Deepsea Mining*). Contributors to the work of Task Team 3 are: Jiabiao Li (Second Institute of Oceanography), Pradeep Singh (Oceano Azul Foundation), Eva Ramirez-Llodra (REV Ocean), Rashid Sumaila (University of British Columbia), Kaja Lønne Fjærtøft (WWF International), Rong Wang (Second Institute of Oceanography), Rui Bao (Ocean University of China), Yejian Wang (Second Institute of Oceanography), Xuewei Xu (National Deep Centre, China), Xiaojun Zhuo (Changsha Research Institute of Mining and Metallurgy Co., Ltd.), Nengyou Wu (Laoshan Laboratory), Xuan Zeng (Changsha Research Institute of Mining and Metallurgy Co., Ltd.), Dabo Guan (Tsinghua University), Chengjun Liu (Changsha Research Institute of Mining and Metallurgy Co., Ltd.).

Knowledge Gaps

a. Environmental Baseline Deficiency

There remains a significant lack of scientific understanding of deep-sea ecosystems. In the Clarion-Clipperton Zone (CCZ), one of the main mining targets, up to 92% of species remain unclassified. Most areas proposed for mining have not undergone comprehensive ecological surveys. Without this data, it is difficult, if not impossible, to predict or mitigate environmental impacts.

b. Lack of Knowledge on Ecosystem Recovery and Resilience

Deep-sea organisms grow and recover extremely slowly. Historic disturbance experiments have shown minimal recovery even after decades. The absence of meaningful data on ecosystem resilience renders any mitigation or restoration plan speculative at best.

c. Incomplete Understanding of Cumulative Impacts

Most environmental assessments focus on individual project-level impacts. Yet, sediment plumes, noise, and chemical pollution may combine across operations and regions. These cumulative effects could have broad, cascading consequences for biodiversity and food webs – including commercially important fisheries.

d. Data Gaps on Carbon and Climate Functions

Deep-sea sediments play a role in carbon sequestration and nutrient cycling. DSM could disrupt these functions, releasing stored carbon and weakening the ocean's role in climate regulation. Current carbon models do not adequately incorporate these risks.

e. Gaps in Socio-Cultural Knowledge

Impacts on Indigenous and coastal communities are under-researched. Cultural ties to ocean territories, spiritual heritage, and livelihood dependencies are inadequately understood and not fully considered in DSM governance processes.

f. Dependence on Contractor-Generated Data

Much of the data collected under the International Seabed Authority (ISA) exploration contracts is proprietary or designed to facilitate resource extraction. Independent scientific research is needed to ensure objectivity and inform precautionary governance, though ISA should conduct independent reviews given the operational challenges of third-party data collection.

g. Lack of Knowledge to Set Environmental Thresholds

The scientific data necessary to set environmental thresholds, baselines, and mitigation criteria is currently lacking, making it premature to finalize regulations that will allow the commencement of exploitation activities. Scientific literature suggests that acquiring this knowledge will take decades of dedicated research. In any case, the ISA should lead collaborative efforts with international deep-sea research institutions to accelerate data accumulation through shared observations and experiments.

Policy Gap

a. Economic Viability Assumptions Remain Unproven

While DSM has been portrayed as a lucrative frontier, most financial models put forward by private actors are speculative. Real-world data points to volatile mineral prices, high capital expenditures (USD 1 – 4 billion), and limited demand. Once environmental liabilities, regulatory compliance, and insurance premiums are accounted for, many scenarios suggest DSM would be economically nonviable. However, some views have been expressed that through technological iteration and scientific innovation, deep-sea mining may become economically viable.

b. Debate Over The Role of Deep-Sea Mining In Driving the Green Transition

While the role of DSM as a prerequisite to solve the climate crisis remains a subject of debate, some studies have concluded that the green transition can be achieved without deep-sea mining. Technologies such as lithium-iron-phosphate (LFP) and sodium-ion batteries are rapidly gaining market share, reducing demand for metals like cobalt and nickel. While some projections still anticipate an overall increase in demand for certain metals like copper and nickel in the short to mid-term, circular economy strategies, including mineral recycling and urban mining, are expected to supply a significant portion of future mineral needs by 2050 as compared to present day. It remains to be seen what role deep-sea minerals can play in supply chain resilience strategy, taking into account global factors and variabilities, though any development must be premised on sufficient ecological protection.

c. Absence of Precautionary Operationalization

Although the precautionary principle is cited in ISA negotiations, it lacks defined criteria or mechanisms for enforcement. Without this, the principle remains rhetorical rather than functional. Policy frameworks must clearly define thresholds for scientific uncertainty, unacceptable risk, and safeguards to halt activities.

d. Missing Integration with Global Commitments

DSM threatens progress on the Global Biodiversity Framework (GBF), the SDGs, and the Paris Agreement. GBF Goals A – D and 18 of 23 targets are incompatible with DSM. Likewise, SDG 14 (Life Below Water) would be undermined by the destruction of seafloor habitats.

e. Lack of Economic Safeguards and Liability Mechanisms

There is no insurance mechanism or liability fund to compensate states or communities for environmental or economic damages caused by DSM. Given the potential for transboundary impacts and ecosystem collapse, the absence of financial safety nets represents a serious governance failure. Following its mandate, the ISA should prioritize the establishment of an equitable benefit-sharing mechanism that delivers for the benefit of humankind as a whole.

f. Inadequate Public Participation and FPIC

ISA negotiations lack mechanisms for the Free, Prior and Informed Consent (FPIC) of Indigenous peoples. Public consultations are limited and often inaccessible, particularly for women, which limits consideration of differentiated perspectives and impacts. This undermines procedural justice and risks legal and reputational challenges.

g. Overlooking UNCLOS Mandates

The United Nations Convention on the Law of the Sea (UNCLOS) mandates not only the equitable sharing of benefits from DSM but also the effective protection of the marine environment. The deep sea is recognized under UNCLOS as the “common heritage of humankind,” and any use of its resources must serve both current and future generations. Advancing DSM without fulfilling this obligation jeopardizes intergenerational equity and the foundational legal principles of ocean governance.

Policy Recommendations

Promote scientific leadership and support structured and precautionary approach to deep seabed mining:

- 1) In line with China’s commitment to ecological civilization and the precautionary principle, the government should support a structured and precautionary approach to deep seabed mining which should remain in effect until sufficient scientific evidence – generated through independent, comprehensive, and peer-reviewed research – demonstrates that such activities can be conducted without harm to marine ecosystems or biodiversity and within agreed thresholds. Any unilateral action by actors or governments in the absence of regulations outside the ISA should be collectively resisted by member states. At the same time, China is encouraged to take a leading role in advancing deep-sea scientific research, particularly in areas such as baseline ecological data, cumulative impacts, environmental mapping, environmental monitoring, and the possibility of remediation, with the aim to actively close knowledge gaps that will allow for informed decision-making. More concretely, China should, in collaboration with entities such as the ISA, UNEP, IOC-UNESCO, as well as with other states, international organizations and partners, seek to initiate and actively promote ecological mapping exercises in deep sea hotspots with the view to feed such information into publicly-available baseline databases and repositories. In this respect, China should provide support through the deployment of research vessels and capacity sharing efforts with the meaningful participation of developing states. At the same time, China is encouraged to promote the development of standardized survey protocols and data-sharing arrangements.
- 2) Strengthen strategic resource security through circular economy and innovation. To reduce reliance on primary mineral extraction and align with China’s dual-carbon goals and green development strategy, the government should increase investments in the circular economy, including high-efficiency recycling systems, material recovery, and urban mining. At the same time, China should accelerate innovation in new battery chemistries and other technologies that reduce or eliminate the need for critical minerals sourced from high-risk environments, including the deep sea.
- 3) Finally, China is encouraged to champion the establishment of science-based governance frameworks that align with the UNCLOS and uphold the Common Heritage of Humankind. China should ensure that any future decisions regarding deep-sea mining are fully compatible with the objectives of the Global Biodiversity Framework, the Sustainable Development Goals, the Paris Agreement, and other efforts aimed at protecting nature and advancing global sustainability. Supporting a consensus-based approach would reinforce China’s international leadership in ocean governance and contribute to the long-term protection of the deep-sea environment for future generations.

5.5. Offshore Aquaculture¹³

Context Setting

Over the past half-century, mariculture has been one of the fastest-growing sectors in global food production, playing a significant role in ensuring food security, promoting coastal economic prosperity, and improving dietary structures. However, intensive mariculture in certain regions has led to negative impacts, including frequent disease outbreaks, excessive nutrient discharges, damage to natural habitats, and spatial competition with other marine industries. Expanding mariculture from nearshore to offshore areas has thus become an urgent necessity. Offshore aquaculture can produce high-quality aquatic animal protein without being constrained by land or freshwater resources while minimizing ecological impacts on coastal zones (e.g., nutrient discharges and sea lice transmission). It has long been favored by scholars and policymakers, with its core technical challenge lying in ensuring the safe operation of aquaculture facilities under offshore wind and wave conditions. In recent years, advancements in marine engineering technology have provided favorable conditions for the rise of offshore aquaculture.

China is the world's largest mariculture producer and a leader in offshore aquaculture development. Currently, China's deep-sea cage farming (defined by an operational water depth > 20 m) yields approximately 470,000 tons annually. Given that finfish species constitute most of the deep-water cage production, this output already represents one-fifth of China's total marine finfish aquaculture yield. Offshore aquaculture exhibits considerable diversity in production models. Commercialized farming facilities currently include: 1) Gravity-based cages, which are structurally simple and low-cost but have moderate storm resistance, typically deployed in partly sheltered areas with gentle currents; 2) Truss-frame cages or platforms, featuring rigid metal truss structures with excellent storm resistance, capable of integrating modular functions such as automated operation, renewable energy, and recreational tourism; and 3) Closed containments, which incur high construction and operational costs, with self-navigating ones called "aquaculture vessels". Each facility type brings distinct ecological, economic, and social performances.

The offshore aquaculture industry remains in its nascent stage globally. In fact, neither academia nor industry has established a robust consensus on the definition of offshore aquaculture, and substantial knowledge gaps persist regarding its expansion potential, technological trajectories, and primary risks. Therefore, more comprehensive scientific data and inclusive stakeholder engagement in decision-making processes are needed to chart a clearer strategic pathway for the future of offshore aquaculture.

Knowledge Gaps

While numerous innovative practices have emerged in offshore aquaculture, the pathway to large-scale development remains far from clear. Although China's central government has explicitly endorsed it, a comprehensive industrial policy framework at more detailed and concrete governance levels has yet to be established. Decision-makers exhibit significant knowledge gaps regarding the ecological, economic, and social risks of offshore aquaculture, which this section briefly indicates.

¹³ This section summarizes key findings from the work of Task Team 4 (*Offshore Aquaculture*). Contributors to the work of Task Team 4 are: Rod Fujita (EDF), Ling Cao (Xiamen University), Shuanglin Dong (OUC), Hui Liu (Yellow Sea Fisheries Research Institute), Fang Sun (EDF)

a. Ecological Risks

Offshore aquaculture primarily focuses on high-trophic-level finfish species, which not only require substantial inputs of external feeds but also risk disrupting surrounding ecosystems. On the input side, the expansion of offshore aquaculture may exacerbate the overexploitation of wild forage fish – a critical intermediate component of marine food webs. On the output side, while offshore areas theoretically benefit from strong hydrodynamic exchange, the environmental impacts of accumulated feed residues and metabolic waste on water columns and benthic sediments require further empirical validation. Additionally, site selection must account for habitats and migratory corridors of threatened wildlife and other ecologically critical species – an area demanding deeper research.

b. Economic Risks

Compared to conventional aquaculture, offshore systems entail higher initial investments, more expensive stocked species, and greater vulnerability to extreme weather events, resulting in pronounced economic uncertainty. The underdeveloped insurance market for offshore aquaculture further limits private-sector participation, necessitating measured government intervention. Moreover, products of offshore aquaculture rely on premium pricing to offset costs, yet current value-added processing and distribution channels remain inadequate. It remains unclear whether consumer markets can absorb sufficient high-end demand, especially given intensified competition as production scales up.

c. Social Risks

The most pressing social concern is the limited capacity to integrate small-scale producers from ocean-reliant communities into employment opportunities. Advanced automation and the technical demands of farming management – requiring expertise in engineering or aquaculture – reduce demand for unskilled labor. These characteristics marginalize livelihood fishers/culturists, with disproportionately adverse effects on women already occupying vulnerable positions within communities. On the consumption side, expansion of offshore aquaculture may reduce the supply of affordable seafood for low-income groups, potentially undermining local food and nutrition security. However, these risks rarely receive adequate attention in policy deliberations.

Policy Gaps

a. Insufficient attention to intrinsic differences among offshore aquaculture models in high-level strategic planning

Currently, the majority of China's offshore aquaculture output comes from gravity-based cages, which require relatively low investment, construction, and operational demands, enabling rapid adoption. They represent only incremental innovation compared to traditional nearshore cages and are more transitional in nature, yet they sometimes receive disproportionately positive media coverage. In contrast, equipped offshore aquaculture (truss-frame cages/platforms and closed containments) faces high barriers to entry, with distinct practices from traditional models in species selection, feeding, and maintenance that lack domestic and international precedents. Small and medium enterprises are generally reluctant to bear the trial-and-error costs. This approach also requires interdisciplinary expertise spanning aquaculture, marine engineering, ecology, and automation – a need that currently remains unmet due to mismatches between university training programs and industry demands.

The fundamental issue is that policymakers often treat offshore aquaculture as a homogeneous concept while overlooking its internal diversity, resulting in incomplete industrial policies.

b. Widespread absence of specialized spatial plans for offshore aquaculture at local government levels

Some decision-makers still fail to recognize that offshore aquaculture's purpose extends beyond simply creating new production space – it must shoulder the critical responsibility of transitioning nearshore farming capacity, requiring clear guidance pathways. Despite central government support, only a few concentrated development areas like Changdao (Shandong) and Lianjiang (Fujian) have established dedicated spatial plans, while most coastal regions lag behind. Compounding this issue is the insufficient scientific basis for informed decision-making. Globally, empirical assessments of ecological pressures from offshore aquaculture remain scarce, and dedicated carrying capacity assessment frameworks for offshore environments await development. Particularly concerning is that current equipped aquaculture technologies now enable operations in previously unexploited marine areas, potentially causing unprecedented ecosystem disturbances that demand rigorous validation.

c. Underdeveloped upstream and downstream supporting industries for offshore aquaculture

While respecting market-driven resource allocation principles, offshore aquaculture must simultaneously maintain product competitiveness to justify premium pricing and explore cross-sector synergies to distribute costs. Significant mismatches exist between its industrialized model and existing supply chains built for traditional aquatic food production. Value-adding initiatives lag notably, including sustainable certification, premium retail/restaurant distribution channels, and deep processing for high-end ready-to-cook foods. Offshore wind-aquaculture integration presents a viable pathway to reduce carbon footprints and share infrastructure costs, yet China's pilot projects remain predominantly driven by wind power enterprises with insufficient government promotion. Furthermore, policymakers at all levels have inadequately addressed how to enhance welfare for indigenous ocean-reliant communities, particularly women in them, during this transition.

Policy Recommendations

- 1) National ministries should develop a more detailed industrial support strategy building upon the Opinions on Accelerating the Development of Offshore Aquaculture (June 2023). This new document must clearly define the scope and subcategories of offshore aquaculture, recognizing the distinct characteristics of gravity-based cages, truss-frame cages/platforms of various scales, and closed containments. Policy frameworks should address bottleneck challenges faced by operators of different scales, establishing tiered support systems to enhance industrial diversity.
- 2) A comprehensive upstream-downstream industrial ecosystem requires systematic development. Demonstration clusters integrating production, processing, certification, and marketing should be established, with prioritized participation opportunities for groups in vulnerable situations including small-scale producers and women in ocean-reliant communities. Streamlined access to sustainable seafood certification programs should be created to enhance market recognition and competitiveness. Financial instruments tailored for offshore aquaculture, including insurance, credit, and bonds, require accelerated deployment.
- 3) Scientific frameworks for carrying capacity and ecological risk assessment of offshore aquaculture should be developed to guide spatial planning that balances conservation and productivity. Targeted research

should further elucidate biological mechanisms of candidate species/varieties, optimize breeding selection, and accelerate development of low-ecological-footprint aquafeed ingredients. Research projects addressing these critical bottlenecks warrant prioritized funding from science and technology authorities.

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List of Abbreviations

AVPN: Asian Venture Philanthropy Network
BBNJ: Biodiversity Beyond National Jurisdiction
BRI: Belt and Road Initiative
CCS: carbon capture and storage
CDR: Carbon Dioxide Removal (mCDR: marine Carbon Dioxide Removal)
ETS: Emission Trading Standards
GDP: Gross Domestic Product
GHG: Greenhouse Gases
IOC: Intergovernmental Oceanographic Commission
ISA: International Seabed Authority
MSP: marine spatial planning
MEE: Ministry of Ecology and Environment
MNR: Ministry of Natural Resources
MRV: Monitoring, reporting and verification (eMRV: ecological MRV)
NBSAP: National Biodiversity Strategy and Biodiversity Plan
NDC: National Determined Contributions
NZF: Net Zero Framework
OAE: Ocean alkalinity enhancement
OECD: Organisation for Economic Co-operation and Development
SECA: Sulfur Emission Control Area
SBE: Sustainable Blue Economy
SDG: Sustainable Development Goals
UNCTAD: United Nations Conference on Trade and Development
UNDP: United Nations Development Program
UNEP: United Nations Environment Programme
UNGC: United Nations Global Compact
WEF: World Economic Forum
WWF: World Wildlife Fund
YRD: Yangtze River Delta