Chapter 3
Ecosystem-Based Integrated Oceans Management Under the Vision of Carbon Neutrality

1 Introduction

1.1 *The Ocean and Climate Change*

Over the last century, human activities around the globe have contributed substantially to unprecedented changes in climate and biodiversity. Changes in the climate mean increased risk of natural disasters, changing habitats, biodiversity loss, and food safety jeopardized by fluctuating productivity. Climate change and biodiversity loss combined increasingly threaten nature, as well as human lives, livelihoods, and well-being around the world. Strong, impactful and consolidated efforts to tackle and meet the climate and biodiversity crises are required to achieve and enable societal equality on all levels. The ocean-based solutions do, can, and should play a fundamental role in this regard.

As it is, the world's oceans play a critical role in capturing carbon dioxide (CO_2) from the atmosphere. Around 25% of all anthropogenic CO_2 emissions are absorbed by the ocean, thereby making it one of the world's largest "carbon sinks." Ocean-based mitigation options to remove/sequester and store greenhouse gases (GHGs) offer significant potential to contribute to global efforts to limit global warming and for achieving the goals of the Paris Agreement. The High Level Panel for a Sustainable Ocean Economy estimates that by 2050 ocean-based climate mitigation and carbon storage options could make up 21% of the emission reductions needed to limit global warming to 1.5 °C [1]. However, the penetration of CO_2 into the ocean causes ocean acidification which has diverse impacts on biological, biogeochemical, and ecological components of the ocean, and consequential impacts are of concern as the ocean's absorption of anthropogenic CO_2 continues. While atmospheric CO_2 is the major driver of ocean acidification, eutrophication can exacerbate ocean acidification in coastal areas. In addition, permanence is crucial in considering carbon

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storage in the ocean given the ocean's high turnover rates. Therefore, it is essential to take advantage of forces that efficiently sequester carbon at least on a decadal time scale.

Nevertheless, there is a wide array of potential ocean-based mitigation options that can contribute to carbon-neutrality goals that would not add to burdens such as acidification. The ocean can contribute to mitigating climate change, while maintaining the carbon balance, and in doing so also safeguard marine biodiversity. Such ocean-based mitigation options have so far had insufficient exposure in nationally determined contribution (NDC) considerations or long-term low GHG emission development strategies under the agreements of the United Nations Framework Convention on Climate Change (UNFCCC), such as the Paris Agreement, although their potential is quite potent [2]. The most relevant potential ocean-based mitigation options to consider include, but are not limited to, the grooming, restoration and long-term climate-smart management of carbon-efficient ecosystems ("blue forests[1]"), the use of the ocean's inherent energy potential, minimizing the carbon footprint of ocean-based activities such as shipping, the use of the ocean floors' ability to store carbon and reusing carbon in marine production, as well as restructuring of the fisheries and human consumption of aquatic products toward low-carbon ocean-based protein and other sources of nutrition [1]. Other emerging opportunities that require further assessment include: resetting biomass goals for the management of fish and perhaps other large-bodied organisms to increase long-term living biomass and ensure adequate protection of carbon processing and storage functions in ocean ecosystems; protecting existing unfished stocks of mesopelagic fishes that rapidly and effectively move carbon into the deep sea through their vertical migrations; and large-scale investments in macroalgal production, especially in offshore waters, that can then be used—in part—for long-term sequestration, assuming that can be done with prudent climate and biodiversity side effects.

The ocean's potential to contribute toward China's 2060 Carbon-Neutrality goals has already been recognized by Chinese authorities. For example, the Ministry of Ecology and Environment (MEE) has been urging local governments to accelerate ecological restoration of oceanic habitats and organizing monitoring and evaluation on carbon sinks in the ocean.

1.2 Ocean's Health and Society

A healthy ocean environment that also meets people's other needs is a prerequisite. A healthy ocean is thus also necessary if we are to enable an efficient and beneficial utilization of the ocean-based carbon-goal opportunities. An ocean with ecosystem integrity, with properly functioning biogeochemical and physical processes which

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[1] "Blue forests" are coastal and marine ecosystems, including mangrove forests, seagrass meadows and tidal salt marshes, which have the ability to store carbon and provide a range of important ecosystem services for coastal communities.

have not suffered serious or irreversible harm, is required for the ocean, seas, and marine resources to successfully contribute to this end. The global ocean and marine ecosystems are changing rapidly due to the ongoing large-scale climate change which is causing wide-ranging effects such as ocean warming, acidification, and oxygen loss. Marine ecosystem degradation has also greatly accelerated during the last five decades due to the multitude of direct human-induced stressors affecting the ocean, including coastal reclamation of land, aquaculture, fisheries and pollution from land-based sources. China has been experiencing a similar trend since the 1950s, with 57% of the coastal wetlands, 73% of the mangrove coverage, and 80% of the coral reefs being lost. Along China's coasts, most of the seagrass beds have disappeared, two-thirds of the coastline is suffering from erosion, about 44,000 km^2 coastal seawater is severely polluted, and fishery resources have been severely depleted.

A healthy and resilient ocean that maintains its capacity to deliver food, income, support transportation, and many other elements of sustainable development will also contribute to human well-being. The ocean is one of the main repositories of the world's biodiversity. It constitutes over 90% of the habitable space on the planet and contains some 250,000 known species, with many more remaining to be discovered. Marine biodiversity plays an essential role in underpinning a healthy planet and social well-being. The fishery and aquaculture sectors are a source of income for hundreds of millions of people, especially in low-income families, and contribute directly and indirectly to their food security. One-third of the total human population, nearly 2.4 billion people, live within 100 km (60 miles) of an oceanic coast—and all human life is dependent upon the oxygen and freshwater it creates. The annual economic value of the ocean is estimated at USD 2.5 trillion, equivalent to the world's 7th largest economy. It provides nutrition, medicines, and mineral and renewable energy resources. It supports jobs in fishing, seafood, leisure, and science. Maintaining a healthy ocean is vital to improving global health and increasing global prosperity for everyone, expanding opportunities for all people, including women and underrepresented or marginalized groups. With all these as a background, there is a global recognition that saving our ocean must remain a priority and that careful management of this essential global resource is a key feature of a sustainable future (UN Sustainable Development Goal [SDG] 14). The effort needed to maintain and support healthy ocean systems will require and encourage scientific research and innovative technologies that connect ocean science with the needs of society, an opportunity that inter alia has been key in shaping the UN Ocean Decade which aims to encourage the production of "the science we need for the ocean we want," catalyzing transformative ocean science solutions for sustainable development.

Ecosystem-based integrated ocean management (EB-IOM) is an approach for ecosystems and resources management that involves finding a proactive balance between the use and protection of rich, productive ecosystems and the ecosystem services they provide, thus promoting an equitable system of conservation and sustainable use. Integrated management is considered an appropriate approach for ensuring the protection and sustainable use of the ocean and coasts, taking sufficiently into account knowledge and the particularities of the ecosystems to be managed. Fully integrated ocean management strikes a balance between the environment, economy, and society, and between short-term economic gains and long-term prosperity of the ecosystem services. EB-IOM provides a basis for the protection of the ocean ecosystem from unsustainable cumulative impacts caused by multiple maritime activities in different parts of the global ocean, as well as for the fair and balanced management of competition and conflicts between ocean users. This will benefit ocean ecosystems, the habitats and species within them, and humans who depend on them.

Framing the study by the principles and criteria of sustainable and inclusive management of the ocean, the special policy study (SPS) provides directions on ocean actions considering the carbon-neutrality goals. This study aligns the synergies between marine carbon and ecosystem-based management/governance, looking in particular at the following aspects relevant to delineation of China's ocean climate actions:

1. Nature-based Solutions (NbS) and other safe and effective marine CDR;
2. Non-damaging technological ocean-based carbon capture and storage, such as CCUS;
3. Reduction of the CO_2 footprint from ocean activities; and
4. Renewable energy.

This study has been carried out in the last year of CCICED Phase VI, and it has only unveiled the ocean's role in the international and national efforts required to tackle the global climate and biodiversity crisis, and to reach China's carbon-neutrality goals. The findings should be considered a transition to the next CCICED Phase, when further work will be required to provide concrete policy guidance on the issues raised in this study.

The study also recognizes gender equality as essential for the effective protection of oceans, the sustainable management of ocean and marine resources, and the accomplishment of the UN's SDGs. As such, the study notes the need to strengthen understanding of the requirements around gender-responsive and inclusive ocean management as part of a sustainable framework.

Several topics and actions discussed in this study interlink with and complement other ongoing studies under the auspices of CCICED, such as the special policy studies on climate, biodiversity, and Nature-based Solutions. Exploiting these interlinking issues is of similar importance as exploring the ocean's potential in mitigating climate change within the future SPS framework of CCICED.

2 Four Ocean-Based Approaches to Carbon Neutrality

For humanity to tackle the planetary challenges and crises that it faces today and in the future, a systemic, integrated, and holistic approach concerning ocean issues and the governance of this space must be taken. This also applies when exploring the opportunities provided by the ocean in contributing toward the carbon-neutrality goals. In this chapter, we explore four ocean-based approaches toward carbon neutrality. Next, this chapter describes the necessity to frame these approaches within an ecosystem-based, integrated, and holistic thinking. When exploring and implementing actions within these four approaches, there is also a valuable opportunity to consider how to promote gender equality and diversity, including the engagement of women in the efforts.

2.1 Marine Carbon Dioxide Removal and Nature-Based Solutions

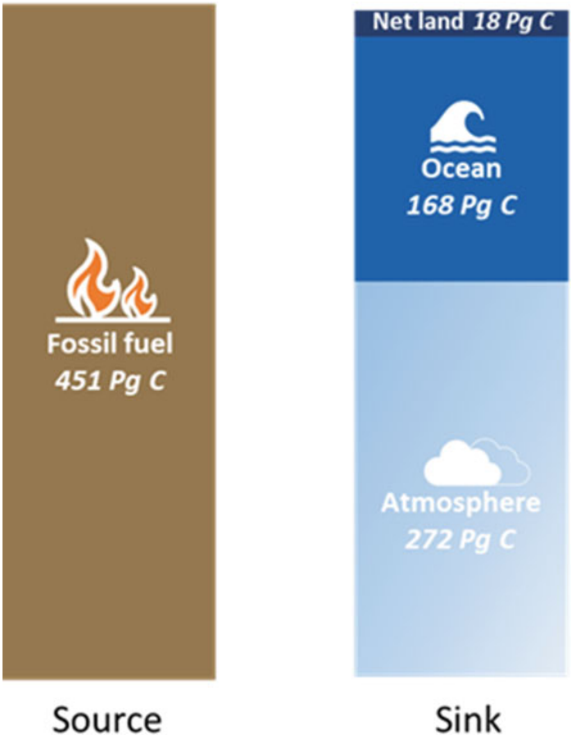
2.1.1 How the Ocean Takes Up Carbon

The ocean covers ~ 71% of Earth's surface; and contains 90% of the carbon on the Earth's surface. The ocean possesses much of the global capacity for atmospheric CO_2 sequestration and mitigated annually 22–26% of the anthropogenic CO_2 emissions comprised of fossil fuel burning and land-use change during 1960–2019 [3]. In the preindustrial era, the ocean was a net source of carbon to the atmosphere [4]. Now it is a substantial net carbon sink of around 1.9 Pg of carbon per year [3]. On long timescales, the land carbon sink is equivalent to accelerated GHG emissions associated with land-use change, leaving the ocean as the primary carbon sink of the last 200 years (Fig. 1) [5].

The injection of anthropogenic CO_2 into the atmosphere leads to an increase in the partial pressure of atmospheric CO_2. Driven by the partial CO_2 pressure difference between the air and the surface ocean, CO_2 diffuses into the ocean via air–sea interface exchange. Unlike many other gases, CO_2 combines with water to form a CO_2-carbonate system which is the most important buffering system in the ocean [6]. The CO_2-carbonate system holds the predominant available carbon as dissolved inorganic carbon (DIC, ~ 38,000 PgC) in the ocean, that is carbonic acid (dissolved CO_2 in water), bicarbonate ions (HCO_3^-) and carbonate ions (CO_3^{2-}), which are tightly coupled via chemical equilibrium. In addition, the ocean contains a pool of dissolved organic carbon (DOC, ~ 700 PgC), a substantial fraction of which has a turnover time of thousands of years [7]. The marine biota, predominantly phytoplankton and other microorganisms, represent a small organic carbon pool (~3 PgC), which is turned over very rapidly in days to a few weeks.

Carbon is transported and sequestrated within the ocean by three mechanisms: (1) the "biological pump," (2) the "carbonate pump," and (3) the "physical pump." The biological pump utilizes autotrophy, such as photosynthesis by phytoplankton, to convert CO_2 and HCO_3^- into organic biomass, including particulate organic carbon (POC) and DOC. POC and DOC create a flux of carbon via gravity sinking, the vertical migration of midwater biota, diffusion, and advection from the surface to the deep ocean or seafloor sediments, where it is isolated from the atmosphere for decades to centuries. The carbonate pump is a process of ocean carbon sequestration driven by calcifying plankton, which releases CO_2 back into the atmosphere but

Fig. 1 Cumulative carbon sources and sinks since the start of the industrial revolution



sequesters part of it by more rapid sinking to the seafloor; this is why this process is also referred to as the carbonate counter pump. The physical pump is the physio-chemical process whereby carbon is transported from the ocean surface to its interior, where it can be stored for hundreds of years [8, 9].

In addition to the carbon sinks in oceanic regimes as described above, coastal ecosystems typically composed of mangroves, salt marshes, and seagrass meadows also sequester atmospheric CO_2 via high photosynthetic rates and rapid carbon sedimentation rates that result in accumulation in associated soils and sediments [10]. Non-vegetated tidal flats, which are rather extensive along the coasts have also been shown to be a potentially important carbon sink. A varying fraction of this carbon is buried in tidally inundated suboxic and anoxic sediments and thereby largely prevented from returning to the atmosphere [11]. Studies suggest that mangroves and coastal wetlands annually sequester carbon at a rate 10 times greater than mature tropical forests. They also store three to five times more carbon per equivalent area than tropical forests. Most coastal blue carbon is stored in the soil, not in above-ground plant materials as with tropical forests. This coastal wetlands carbon is now often regarded as coastal blue carbon. It has been gaining great attention due to its disproportionately large contribution to global carbon sequestration. This is also true in China where the three blue carbon ecosystems maintain high carbon accumulation rates. Among them, mangrove forests mainly on the southern coasts covers a total area of ~ 2.56 × 10^4 ha with a carbon buried rate of 0.28 TgC annually. Intertidal saltmarshes are widely distributed along the subtropical and warm temperature coasts, with a total area coverage of 10.2 ~ 3434 km^2, maintaining a carbon burial of 0.23–0.91 TgC annually. Seagrass beds are mainly distributed in the northern coasts around Bohai and along the tropical coasts with 1.68 × 10^4 ha of total areas, while their carbon burials remain unclear. It should be pointed out that these coastal blue carbon ecosystems are facing challenges of anthropogenic disturbance from coastal squeeze, water pollution, and urbanization as well as invasive species *Spartina alterniflora*. A grand challenging question thus points toward how these coastal blue carbon will evolve under future climate scenarios.

2.1.2 Approaches to Strengthen and Increase the Ocean Carbon Sink Within a Sustainable Framework

The ocean and its ecosystems hold great potential for uptake and longer-term sequestration of anthropogenic CO_2 for several reasons [12]: (1) the ocean acts as a large natural reservoir for CO_2, holding roughly 50 times as much inorganic carbon as the preindustrial atmosphere; (2) the ocean already removes a substantial fraction of the excess atmospheric CO_2 resulting from human emissions; and (3) there are a number of physical, geochemical, and biological processes that are known to influence air–sea CO_2 exchange and ocean carbon storage. The High Level Panel for a Sustainable Ocean Economy identified that ocean-based mitigation options could reduce global GHG emissions by about 4 billion tonnes of CO_2 equivalent per year in 2030 and by over 11 billion tonnes per year in 2050, reducing the emissions gap by up to 21% on a 1.5 °C pathway, and by around 25% on a 2 °C pathway [1].

Ocean-based CDR techniques can be identified in two broad categories—biological and chemical [12] (Fig. 2).

(1) Biological pathways include:

1. Nutrient fertilization: Addition of micronutrients (e.g., iron) to the surface ocean may, in some settings, increase photosynthesis by marine phytoplankton and can thus enhance uptake of CO_2 and transfer of organic carbon to the deep sea where it can be sequestered for timescales of a century or longer. As such, nutrient fertilization essentially locally enhances the natural ocean biological carbon pump using energy from the sun, and in the case of iron, relatively small amounts are needed. Of course, the abundant risks of artificial anthropogenic nutrification are also known in general, but inadequately known at scale in practice.
2. Artificial upwelling and downwelling: Artificial upwelling is a process whereby water from depths that are generally cooler and more nutrient and carbon dioxide rich than surface waters is pumped into the surface ocean. Artificial upwelling has been suggested to generate increased localized primary production and ultimately export production and net CO_2 removal. Artificial downwelling is the downward transport of surface water;

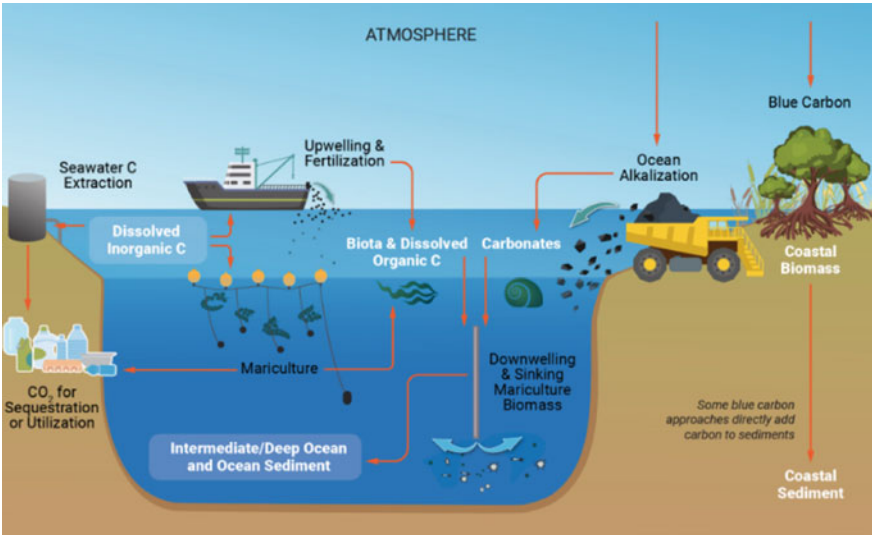


Fig. 2 Marine CDR (Energy Future Initiative [13])

this activity has been suggested as a mechanism to counteract eutrophication and hypoxia in coastal regions by increasing ventilation below the pycnocline and to carry carbon into the deep ocean.

3. Seaweed cultivation: The process of producing macrophyte organic carbon biomass via photosynthesis and transporting that carbon into a carbon reservoir removes CO_2 from the upper ocean. Large-scale farming of macrophytes (seaweed) can act as a CDR approach by transporting organic carbon to the deep sea or into sediments. Seaweed can also be processed to make long-life products or produce biofuel for carbon sequestration or utilization. It must be pointed that the risks of unintended ecological outcomes and cascades associated with large-scale deep-sea vegetative deposition remain unknown.
4. Recovery of ocean and coastal ecosystems: Carbon dioxide removal and sequestration through protection and restoration of coastal ecosystems, such as kelp forests and free-floating Sargassum, and the recovery of fishes, whales, and other animals in the ocean. Rebuilding global fish and perhaps large-bodied animal stocks toward higher abundance than supported by current management might also contribute to improved carbon processing and storage, though those outcomes remain inadequately evaluated. Precautionary management of emerging fisheries in the high latitudes and the mesopelagic realm until carbon processing consequences are better known and incorporated into goalsetting is also a possibility.

(2) Chemical pathways include:

  1. Ocean alkalinity enhancement: Chemical alteration of seawater chemistry via addition of alkalinity through various mechanisms including enhanced mineral weathering and electrochemical or thermal reactions releasing alkalinity to the ocean, with the ultimate aim of removing CO_2 from the atmosphere. Induced ecological cascades would need to be assessed and interpreted in light of the systems goals expressed in this document.
  2. Electrochemical approaches: Removal of CO_2 or enhancement of the storage capacity of CO_2 in seawater (e.g., in the form of ions, or mineral carbonates) by enhancing its acidity, or alkalinity, respectively. These approaches exploit the pH-dependent solubility of CO_2 by passage of an electric current through water, which by inducing water splitting ("electrolysis"), changes its pH in a confined reaction environment. As one example, ocean alkalinity enhancement may be accomplished by electrochemical approaches.

These CDR approaches broadly include both NbS and geoengineering-based approaches. NbS are defined as "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits." A major attraction of NbS as a strategy for climate change mitigation is that they can deliver multiple benefits. These benefits include retained and restored ecosystem services from forests, croplands, grazing lands, wetlands, and other coastal ecosystems that support human health and well-being [14], as well as biodiversity conservation and sustainable livelihood development. Geoengineering-based CDR often takes intervention techniques, which are more controversial but are emerging as potentially indispensable in meeting the goals of the Paris Agreement, if unintended negative consequences at scale can be understood and avoided [15].

It must be pointed out that all CDR measures have limitations and trade-offs. It is thus of vital importance to thoroughly assess CDR techniques, individually or collectively, and adopt ecosystem-based approaches to combatting climate change, but they must be considered comprehensively inclusive of their effect on ecosystems, their synergies with other land and ocean systems, and the impacts on the natural ocean carbon sink. For example, mangroves planted in Siangshan Wetland, northwestern Taiwan Island since 1997 resulted in negative impacts on the local ecosystem, including the loss of the benthic organisms and habitats for birds, sediment accumulation and flooding, and increased mosquito populations. A mangrove removal project was subsequently launched in 2015 [16]. Similar examples of replanting efforts with weak comprehensive assessments and large negative consequences are found globally. Thus, integrated ecosystem-based governance for both NbS and beyond is important. A successful example is offered in Case Study 1 demonstrating the co-benefits of ecosystem-based approaches between blue carbon and other ecosystem and societal services.

Case Study 1: Quanzhou Blue Carbon Project

The project is implemented in Luoyang River Estuary of Quanzhou Bay Wetland Nature Reserve in Quanzhou, Fujian Province, China. Established in Sept. 2003, this nature reserve aims to protect subtropical coastal wetlands, mangroves, waterfowls, Chinese white dolphins, and other rare animals and plants, with a total area of 7065 ha. The invasive smooth cordgrass, *Spartina alterniflora*, was first introduced to Luoyang River Estuary in 1982 and became invasive in the early 2000s. Since 2002, the local government and the nature reserve have continued to restore mangrove forests by clearing the invasive cordgrass. At present, the total mangrove area of the Luoyang River has increased from the original 17 ha to nearly 467 ha, becoming the largest artificial mangrove forest in China.

Luoyang River Estuary is also known for the Luoyang Bridge, a large stone bridge across the sea built during the Song Dynasty (1059 AD). Luoyang Bridge was one of the four famous bridges in ancient China. It has been of great importance to local transportation by land and sea for thousands of years. Local communities with a long history of maritime culture have been formed around this ancient bridge. Now, Luoyang Bridge has been listed as a heritage site of Quanzhou World Heritage of UNESCO (Quanzhou: The World Maritime Trade Center of Song and Yuan China). Now, the Luoyang Bridge and mangrove forests have formed a unique coastal landscape showing the harmonious coexistence of humans and nature.

In this project, a total of 29 ha of mangrove forests composed of two native species, *Kandelia obovata* and *Aegiceras corniculatum*, were restored by clearing the invasive cordgrass in 2010. In the project area, these newly restored forests formed a closed canopy after 10 years of management. The total carbon sequestered by the restored forests was calculated by the Methodology of Mangrove Afforestation for carbon trading developed by Blue Carbon Group of Xiamen University in 2011. Additionality and permanence of emission reductions from the project were tested. In total, 2000 t CO_2-e of emission reductions in the project area were traded on the platform of Xiamen Carbon and Emissions Trading Center. The Industrial Bank Xiamen Branch purchased and launched carbon–neutral air tickets with the cooperation of Xiamen Airlines, through which the passengers could participate in mangrove conservation and restoration by purchasing the tickets.

In this project, the invasive vegetation was removed, and the restored mangrove wetlands provides habitats for waterbirds, e.g., the Chinese Egret (Egretta eulophotes, vulnerable species on IUCN Red List) and greatly increased the biodiversity of the Luoyang River Estuary [17], reflecting the synergistic effects of biodiversity conservation and carbon sequestration. Furthermore, the mangrove wetlands enhance the landscape of the ancient

Luoyang Bridge, and benefit the local community by improving the living environment and increasing their income from ecotourism. Thus, the project also embodies the synergistic development of biodiversity, climate, and community.

2.1.3 Knowledge and Policy Gaps

For decision-makers, the emerging knowledge gaps related to the ocean carbon sink that are of paramount importance for our environment and society can be categorized as:

1. Understanding whether the ocean will continue as a sink for human-produced CO_2 and its climate change mitigation capacity, such as regarding climate-carbon coupled systems, zero-emission strategies and actions; and how will the coastal blue carbon evolve?
2. The vulnerability of ocean/marine ecosystems to increasing CO_2 levels.
3. Adaptation options and needs to changing ocean/marine conditions.

Research and development policy needs with respect to ocean-based CDR include:

1. Defining the RD&D (research, development, and demonstration) portfolio of specific biological and nonbiological CDR pathways for technology development, optimization, and scalability, including anticipating new and emerging pathways, as well as their likely risks and co-benefits.
2. Improving the methods for monitoring, quantifying, and verifying CDR benefits, ecosystem effects, and life-cycle impacts, including under future conditions anticipated through climate change.
3. Developing predictive modelling and planning tools for siting and operations.
4. Creating markets for co-products from ocean CDR pathways and integration into carbon markets, and for co-benefits of NbS where the carbon benefits are inadequately known in terms of high-quality carbon credits.
5. Creating enabling national and international governance and finance frameworks.

2.1.4 Priority Actions

1. Ecosystem-based mitigation and adaptation action can be synergized while also positively impacting the ocean carbon sink. Mitigation action includes reducing GHG emissions to minimize ecosystem consequences, using ecosystem-based CDR to advance climate action and benefit ecosystems, and minimizing pollution to enhance the natural capacity of ecosystems to store carbon. Adaptation approaches such as disaster risk management, sustainable and climate-smart management, and implementing marine spatial planning and protected

areas rely heavily on data, modelling, policies, and mitigation action that reduce the chance for tipping points to occur. Successful adaptation increases climate resilience through technological innovation, partnerships, and codesign of solutions. Ecosystem-based approaches should be enforced in both mitigation and adaptation. In general, all goalsetting for coastal and ocean uses should also factor in an assessment of the degree to which opportunities for climate adaptation and mitigation are adequately known and accounted for.

2. China has been practicing ecosystem restoration projects to different extents along the China coasts with successes and failures. This is also true in area-based management practices such as marine protected areas (MPAs). Revisiting these practices by considering experiences and lessons (including from a gender-equality perspective) and articulating new policies and best practices is urgently needed in developing carbon-neutrality strategies which are underway.
3. Urgent and deep emissions reductions are vital to protect the ocean from further climate change impacts. However, the ocean is also a space where mitigation can take place. Most importantly, Earth system models show that after peak emissions are reached, atmospheric CO_2 will begin to decline. This will lead to a weakening of the ocean and land sink as projected under RCP 2.6 [18] (Dai et al., 2022 and references therein). To maintain atmospheric CO_2 and temperature at low levels, not only does anthropogenic CO_2 in the atmosphere need to be continuously removed by CDR, but anthropogenic CO_2 stored in the ocean and land needs to be removed when it outgasses to the atmosphere. This must be considered when designing future pathways. Ocean-based solutions provide excellent opportunities for both mitigation and adaptation and should be considered in Nationally Determined Contributions and UNFCCC deliberations, and this shall take international and collective efforts while China is in a good position to promote ocean-based carbon solutions.

Key recommendation: Accounting for ocean CO_2 sinks in international climate reporting

Given the ocean's sustained and paramount role in mitigating anthropogenic CO_2 over the last 200 years, it is fundamentally important to note that such an ocean carbon sink could be dramatically reduced if pCO_2 in the ocean is not synergized with the air pCO_2 under low-emissions conditions when designing future pathways. ***We call upon establishing an international task force with a mandate to promote the ocean carbon sink as a potential NDC and as part of UNFCCC deliberations***.

2.2 *Offshore Carbon Capture, Utilization, and Storage*

2.2.1 *The Ocean's Role in Capturing, Utilizing, and Storing CO_2*

To reach the target of carbon neutrality by 2060, greenhouse gases emitted by carbon sources into the atmosphere must be mitigated and preferably permanently sequestered. Several methodologies have been presented to potentially mitigate CO_2 emissions, such as increasing energy efficiency, replacing coal-fired power plants with natural gas, enhancing wind and nuclear power plants, biomass creation, reforestation, and carbon capture, utilization, and storage (CCUS), etc. Compared to more natural ways (see Sect. 1 in Chap. 2), technological methodologies are potentially faster and more complete on carbon sinks. To realize one-off GHG removal, the produced CO_2 is expected to be captured and compressed, transported via ship or pipeline to offshore platforms, and injected into sub-seabed reservoirs for permanent isolation from the atmosphere [19, 20]. Thus, a technically feasible full chain of offshore CCUS is formed (Fig. 3) and can be developed by mobilizing contractors and suppliers [18]. Like any other large-scale industrial operation, of course, the potential risks—especially at scale—must be fully characterized and unacceptable risks mitigated.

In 2020, China emitted 10.67 Gt CO_2, with coal, oil, and gas contributing 70%, 15%, and 6%, respectively. The coal-burning power plants alone accounted for 50% of China's fossil fuel-related CO_2 emissions. To reduce the consumption of coal, China has justified ongoing efforts to support the use of renewable energy and natural gas, combined with improving the ambient air quality as one of the country's strategies. In addition to this, CO_2 separation and capture from industrial processes are also undertaken, such as H_2 manufacture, synthetic ammonia, limestone calcination, and

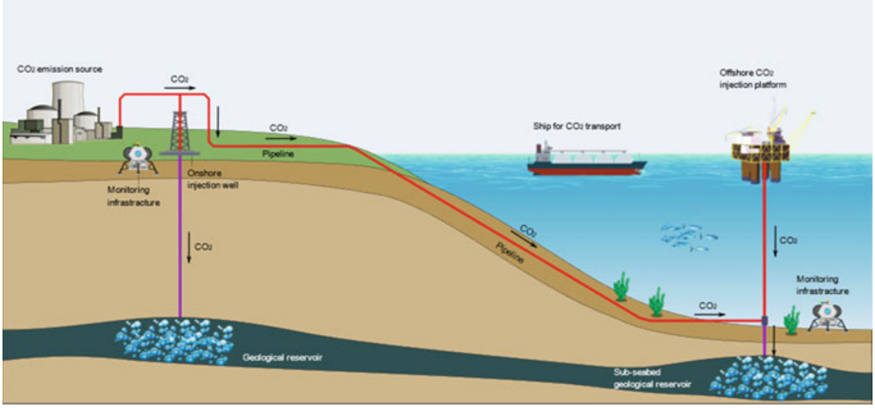


Fig. 3 Key elements and processes in offshore CCUS. Offshore CCUS captures CO_2 from industrial emission sources, transports it via either pipeline or ship, and injects it into sub-seabed geological reservoirs, contributing to the isolation of CO_2 from the atmosphere

ethylene oxide production. Further, to prevent emissions from these plants, advanced low-carbon coal technologies are promoted with a number of action plans released to require the adoption of high-efficiency and the development of CCUS retrofits. In China, a significant portion of the electricity mix is still from coal generation. The more worrying thing is that some of the world-class CO_2 emission sources are from relatively newly-built power plants, the average age of which is less than 15 years, which could still be operating in 2060. This poses a particular challenge to achieving the national goal of net-zero emission, and the geological storage has the greatest potential to realize the one-off carbon removal. In the east region, more than 43% of coal-fired power plants could be suitable for CCUS retrofits, which account for more than 35% of the cumulatively CO_2 volume to be captured. To permanently isolate the captured CO_2 from the atmosphere, particularly for the coastal region with significant carbon emissions, offshore geological storage with carbon source-sink matching is introduced.

Of the 34 provinces in China, 13 are along the coast, which occupy less than 14% of the nation's territorial area. These coastal regions contribute 64% of national GDP, account for 43% of the country's energy use, and possess 39% of the country's population. As is expected, China's economy was dominantly driven by these developed coastal regions in the last 40 years, showing significant regional economic differences [21]. While contributing to the economy, these regions also account for $\sim$ 41% of the country's annual CO_2 emissions, that is, $\sim$ 4.2 Gt [22, 23], scattering notable CO_2 emission hotspots in the east and southeast. In coastal provinces such as Guangdong and Fujian, fossil fuels are widely used to provide energy supplementation [19], and the location of large stationary sources, e.g., power plants, refineries, and cement plants [18] are heavily scattered along the coast. Not far from the coastal region are the 11 offshore sedimentary basins that spread $\sim$ 1.7 million square kilometres, the geologic storage capacity of which is accounted $\sim$ 573 Gt CO_2 [24]. This provides potential large-scale carbon storage reservoirs far exceeding that would be captured annually and can provide sufficient permanent geologic sequestration capability for more than 100 years' carbon storage, addressing long-term greenhouse gas emissions.

To safely and permanently lock CO_2 in deep underground geological reservoirs, offshore CCUS storage sites should be carefully selected. In the sedimentary basins offshore China, deep saline formations with layers of porous and permeable rocks are widespread, involving Miocene deltaic, coastal plain, and neritic clastic rocks. The regional seal-capped tertiary strata of these basins contain thick and high-quality aquifers, which are of mainly neritic and deltaic facies having lateral continuity. The utilization of the substantial pore space in these basins for CO_2 storage would require an efficient injection strategy to maximize the dissolution, residual trapping sealing, capping, and permanence. Recent research has shown that basalt deposits can quickly incorporate injected CO_2 to form carbonate minerals, which can permanently convert the injected CO_2 into immobile stone, and thus reduce the risk of leakage into the ocean and environmental pollution. In addition, the basalt deposit also has a translational impact on informing the fate of injected CO_2-bearing magnesium silicates and reactive calcium.

In the last decade, CCUS facilities have been commissioned in China, Australia, Brazil, Canada, Saudi Arabia and the United Arab Emirates [25]. CCUS in China has been investigated both onshore and offshore [16, 19, 26–29]. Onshore geologic reservoirs in China are mostly located in the northern and western regions, which are distant from the industrialized and populated coastal region and may raise extra costs and safety issues. In contrast, offshore CCUS will not have issues like ownership, holdings, activities, CO_2 contamination of drinking water aquifers, and potential damage to agricultural and industrial operations, etc. [30], as the offshore storage site is in no one's backyard. Therefore, offshore CO_2 storage offers potential jurisdictional simplicity. Further, the relatively easier management of sub-seabed saline formation pressure would reduce the offshore storage costs.

2.2.2 Current Status of Offshore CCUS

An increasing number of countries and organizations have adopted net-zero emissions targets, drawing attention to the need for CCUS. To date, there are 21 CCUS facilities around the world with the capacity to capture up to 40 Mt CO_2 each year [24]. Some of these facilities have been operating since the 1970s and 1980s, when natural gas processing plants in Texas began capturing CO_2 and supplying it to local oil producers for enhanced oil recovery (EOR) operations. Since these early projects, CCUS deployment has expanded to more regions and more applications. The first large-scale CO_2 capture and injection project with dedicated CO_2 storage and monitoring was commissioned at the Sleipner offshore gas field in Norway in 1996, which has now stored more than 20 Mt CO_2 in a deep saline aquifer. For technical and commercial reasons, the CO_2 needs to be removed from the gas before it can be sold; a CO_2 tax on offshore oil and gas activities introduced by the Norwegian government in 1991 made the project commercially viable [31]. Norway is also funding the development of a full-chain CCUS project (Langskip), involving CO_2 capture at a cement factory and a waste-to-energy plant and its storage in a large facility in the North Sea—Northern Lights—being developed by a consortium of oil and gas companies. More countries are now developing offshore CCUS strategies, for instance, the Netherlands is expanding its Sustainable Energy Transition Scheme to a wider set of clean energy technologies, including CCUS and low-carbon hydrogen; and the UK government has also announced significant public funding for new offshore CCUS projects [24].

To date, four large-scale offshore CCUS projects (Sleipner, Snøhvit, Quest, IBDP) are launched internationally, with which $\sim$4 Mt CO_2 per annum together are dedicated to being injected into geologic saline formations [32], while the underlying deployment of offshore CCUS technology in China is at a pilot scale. In 2021, China launched its first offshore CCUS project in the Pearl River Mouth Basin of the north South China Sea, to explore the storage of CO_2 in a sub-seabed saline aquifer. In this project, the injection of 1.46 Mt CO_2 into sub-seabed saline formations by 2026 was planned, which would achieve a near-zero emissions of offshore oil production [33]. This is currently generating valuable information about the costs, operation, and market conditions for offshore CCUS in China, providing a prior feasibility test of long-term performance and security of offshore CO_2 storage as an attractive and efficient long-term strategy [31, 34], particularly for those industrialized coastal provinces to achieve their "ahead of time" carbon-neutrality claims.

2.2.3 Knowledge and Policy Gaps

The cost of CCUS is highly variable, e.g., the cost of CO_2 transport via pipeline depends on the pipeline length, diameter, terrain and route, from 2.0 to 15.3 USD per ton CO_2 per 250 km; storage in depleted oil and gas fields is less expensive than storage in saline reservoirs, from 8 to 25 USD per ton CO_2 [35]. Many of the early CCUS projects focused on industrial applications where CO_2 can be captured and utilized. For example, in natural gas processing, any CO_2 contained in the gas usually needs to be separated out to meet market requirements or prior to liquefaction for liquefied natural gas (LNG) production to avoid the CO_2 freezing and damaging the production facilities. In other applications, such as bioethanol production or steam methane reformers to produce hydrogen, the CO_2 stream is relatively concentrated, which reduces the cost and the amount of energy required in the capture process. Until the 2000s, virtually all the CO_2 captured globally at large-scale facilities came from gas processing plants, but other sources now make up about one-third of the total [24].

CCUS deployment tripled over the last decade, albeit from a low base, but it has fallen well short of expectations. In 2009, the IEA roadmap for CCUS set a target of developing 100 large-scale CCUS projects between 2010 and 2020 to meet global climate goals, storing around 300 Mt CO_2 per year. Actual capacity is only around 40 Mt—just 13% of the target. Investment in CCUS has also fallen well behind that of other clean energy technologies. Annual investment in CCUS has consistently accounted for less than 0.5% of global investment in clean energy and efficiency technologies [24].

There are several reasons CCUS has not advanced as fast as needed; many planned projects have not progressed due to commercial considerations as they are expensive, and there is a lack of consistent policy support. In the absence of an incentive or emissions penalty, CCUS may simply not make any commercial sense, especially where the CO_2 has no significant value as an industrial input. The high cost of installing the infrastructure and difficulties in integrating the different elements of the CO_2 supply chain, technical risks associated with installing or scaling up CCUS facilities in some applications, difficulties in allocating commercial risk among project partners, and problems securing financing have also impeded investment. CCUS is also often viewed as a fossil fuel technology that competes with renewable energy for public and private investment, although, in practice, it has substantial synergies with renewables [24].

Despite the relatively fewer concerns of safety and easier management of formation pressure for the deployment of offshore CCUS [36, 37], policy-makers and communities retain doubts about its viability and effectiveness due to the existing uncertainties in high costs and the technology's maturity [31, 32]. Such uncertainties largely reflect the lack of integrated applications of large-scale commercial operations [30]. Moreover, the full-chain CCUS operation requires significant energy, which poses an efficiency penalty, as well as generating GHG emissions. This is expected to be reduced by the improvements in technology and the risk-premium reduction faced by first-movers [38], while it is heavily dependent on offshore CCUS-focused regulatory policies.

In China, regulation of the offshore disposal of CO_2 and ocean jurisdiction remain unclear, including the development of appropriate procedures and standards for undertaking a full-chain offshore CCUS, as well as concrete legal framework to guide public participation and consultation of offshore CCUS [37]. Because of this, CCUS project developers could purposely withhold information or even ignore the public perception. This leads to significant uncertainties and hinders offshore CCUS activities along with little guidance provided to treat future projects. To avoid such "interaction without rules," associated regulations and laws at the national, provincial, and local levels are expected to be formulated as a specific and legitimate mandatory basis prior to large deployment of offshore projects [39].

Regarding the diversity of involvement, the CO_2 emission sources in China are scattered in the main industrial clusters along the coast, while the offshore geological investigation and exploration are operated by various enterprises, such as large state-owned petroleum companies. Moreover, offshore CCUS research and development are conducted by research universities and institutes [40] and financial support and debts are provided by public sector banks. The integration of the development of offshore CCUS is often inefficient. For example, research institutes play an important role in developing offshore CCUS-related techniques, economic, and political framework, the feasibility of which has rarely been proved by commercial-scale offshore projects, as very few opportunities are given to reduce the associated risks. Particularly for the implementation of new projects, despite some research results suggesting offshore CCUS success, the associated risks are relatively high for long-term commercial adoption and commitment to carbon credits [34].

2.2.4 Priority Actions

In the coming decades, to ensure that offshore CCUS is an attractive and available option, important actions can be taken by the government and industry in China, involving continuing technology innovation, cost reduction, boosting CO_2 storage development, and risk management in both environment and commercial debt [37]. To facilitate the reduction of the cost of offshore CCUS, commercial-scale adoption of the technology is necessary, and initiatives of environmental policy should be supported by the Chinese government to incentivize first-of-a-kind construction.

This is particularly important as it will allow for learning, feasibility testing, and risk reduction for accelerating commercial implementations [34].

China should formally announce its intention to prioritize offshore CCUS to provide the impetus for government agencies, companies, financial institutions, civil society organizations, and partners to work together to create and implement a robust CCUS-focused financial supporting environment. China could pursue the following near-term windows of opportunity to communicate its ambition and commitment to offshore CCUS. Specifically, actions can be taken as follows.

1. **Develop a financial framework to build a regulated free market environment**

In China, an acceptable risk allocation of commercial debt has yet to be demonstrated, and a "standardized" financial template has yet to be developed due to the lack of consistent offshore CCUS development [30]. Large-scale offshore CCUS projects are complex and expensive, where debt could potentially be available, particularly for early offshore projects where grant funding can help to close a significant financial gap [30].

The state-owned enterprises of China have been major players in the execution of CCUS projects, which have a duty to fulfill their social function. However, they often face incentive opportunities and frameworks to access financing that differ from their private sector counterparts, particularly for those operating in more regulated market environments, such as the Shenhua Group and the China Huaneng Group [30]. For private ownership in the orbit of free initiative, they can carry out activities in a free competition environment [41]. Such competition in offshore CCUS can either be a priority to access the best CO_2 storage location or a shared preferred offshore CO_2 storage site. This could provide a guidance to construct CO_2 transporting networks with the lowest costs and the best storage options [37].

To make offshore CCUS projects commercially viable, a tax on CO_2 emissions from the industry could be introduced by the Chinese government. This would provide a strong revenue and viable incentive which will draw down the cost of offshore CCUS as that has been introduced by Norway and the United States (45Q tax credit) for CO_2 utilization and storage [42, 43]. While uncertainty does exist in all CO_2 pricing systems, the 45Q tax credits allot more than USD 35per ton for CO_2 utilization and more than USD 50 per ton for permanent sequestration of CO_2 in geologic reservoirs [44]. This helps business provide offshore CCUS solutions for developing supply chains in a coordinated manner [37]. If China introduces a carbon tax, it should avoid most part of offshore CCUS costs for the infrastructural establishment of the supply chain, involving the construction of offshore pipelines and platforms [45].

2. **Demonstrate full-chain offshore CCUS project with cross-disciplinary engagement**

In terms of designing offshore CCUS projects, a wide range of procedure and risks must be specifically examined and evaluated. This involves coordination in studying the feasibility of storage reservoirs, carbon source-sink database, identifying knowledge gaps, front-end engineering, and design (FEED), leakage monitoring, as well as external quality assurance, etc. Moreover, specific non-technical uncertainties would need to be addressed, involving full-chain supply, regulatory framework, liabilities, financial drivers, social acceptability, as well as making a case for gender considerations in the regulatory framework to ensure that women have equal opportunities in offshore CCUS projects. All these essential factors would require a clear regulatory framework to be established. Therefore, continuous research on full-chain CCUS technologies and the development of pilot demonstration offshore CCUS projects should be carefully conducted, which will accelerate incremental steps toward maturing offshore projects and minimizing uncertainties and comprehensive risks [46]. The current challenge is to break through science, technology, finance, governance, and social barriers to enable widespread deployment of offshore CCUS projects.

To date, the total cost of offshore CCUS exceeds 350 CNY per ton in China without an industrial utilization to take economic benefits [47]. To increase the economic effect, offshore CO_2-enhanced oil recovery (CO_2-EOR) [26] can be introduced, where oils in geological layers could be substituted by the injected supercritical CO_2 [48]. Through CO_2-EOR, most of the injected CO_2 will be permanently locked in the geological reservoir under the right conditions as well as improving the recovery of oil [43], making it a cost-effective way of reducing carbon emissions. Such implementation can effectively make the cost of storage negative from incremental oil production. It can yield an additional 5–17% of a reservoir's original oil in place more than conventional oil production practices (typically producing 35–50% of it). In China, CO_2-EOR has been estimated to offer > 100 Mt CO_2 per year of storage resources, while the economic viability of it is subject to the cost per ton of CO_2 delivered and the evolution of the oil price [49, 50]. However, the reservoir capacity of offshore oil and gas fields is relatively small compared to that of saline formations offshore China, which makes the demand for CO_2 for EOR projects decline over time [37]. Therefore, it is expected that offshore CO_2-EOR activities may exist in the near to medium term, while CO_2 storage in saline aquifers will be in the medium to long term.

Among the sedimentary basins offshore China, $\sim 2.5\%$ are oil and gas fields, leaving existing infrastructures for CO_2 transportation and injection. The advantage of existing infrastructure and framework in mature fields could be taken for carbon offsets, which significantly reduces the level of public funding and policy support, benefiting the maturation of carbon market-based mechanisms [51]. For near-term large-scale storage in depleted fields, these infrastructures could potentially be reused to reduce the costs of constructing new offshore facilities, particularly in the case of short-term underinvestment [52]. However, some existing offshore facilities are aging and the window of opportunity to reuse existing facilities could be limited. Hence, it is required to develop multiple phases of technical evaluation and possibility timelines and ranking availabilities of these platforms.

To guarantee regulated income for service providers on full-chain CCUS components, a future model should be presented to separate the procedure of CO_2 transport and storage from capture [37]. This will allow agencies with offshore CCUS expertise to concentrate on CO_2 transport and storage while carbon emitters focus on capture [41]. However, such a model will require a thorough monitoring, reporting, and verification system to account for captured, transported, and stored CO_2.

To manage carbon storage from the emission sources, flexible services such as bookable storage should be presented, that is, temporal and spatial source-sink matching. To efficiently perform the carbon source-sink matching, the nearest suitable geological storage reservoir is usually required to be identified for each emission source [31]. Emissions from power plants in the industrialized east and southeast China would potentially be the first selection to store offshore.

3. Perform detailed site characterization and prevent environmental risks

The initial development of dedicated offshore CCUS projects is a costly and time-consuming process. For large-scale CO_2 storage beneath the seabed, detailed geological mapping and site characterization of abandoned drills and possible reservoirs are needed. These necessary works require substantial capital investment, which deters independent bodies from investing in offshore storage infrastructures and related technologies, particularly when combined with the uncertainty of future revenue. China has large state-owned enterprises, where direct investment can be used to support early offshore CCUS projects, such as funding site characterization and sharing data and knowledge. This could boost the deployment of offshore CCUS, guarantee sufficient investment returns, and help mature the carbon market through procurement policies [24, 37].

Safety is a key issue the government and society are concerned about regarding offshore CCUS. Ensuring the integration of sub-seabed geologic reservoirs is a substantial challenge, where the sub-seabed CO_2 leakage could lead to negative reaction in the marine ecosystem [53]. Assurance of environmental performance of CCUS with thorough research and assessment should be a prerequisite for solution to environmental problems and ensure that the problem is not transformed into another one. Any form of CCUS should adhere to strict environmental and social safeguards in order to minimize negative consequences, and must be applied as a means of minimizing atmospheric carbon as opposed to prolonging reliance on fossil fuels or carbon-rich lifestyles. Hence, careful selection and long-term monitoring of undersea geologic reservoirs are therefore required [54, 55].

Renewable energy and other green technologies should be mainstreamed in CCUS projects. To supply energy to the offshore CCUS infrastructure, low-carbon opportunities from wind, solar, wave, and tides could be introduced [41] (see Sect. 44 in Chap. 2). This would offer sustainable development of offshore CCUS in the long run, not only for storing captured CO_2 from the coastal industry sectors, but also for sequestering CO_2 from direct air or ocean capture in the future.

Key Recommendation: Accelerating research on carbon dioxide removal

Noting that there would be unavoidable emissions from fossil fuel burning even under carbon-neutrality scenarios, accelerating technology innovation of marine CDR, offshore CCUS, and development of its governance framework will become increasingly urgent. ***We advise the establishment of policy and financial frameworks for accelerating research for scalable ocean-based carbon dioxide removal (CDR) and offshore carbon capture, utilization, and storage (CCUS).***

2.3 Reduction of the CO_2 Footprint from Ocean Activities

2.3.1 Ocean-Based Activities Contributing to Carbon Release

Not only do human activities produce huge amounts of CO_2 on land, but ocean-related industries also continue to produce anthropogenic emissions. With its productive ecosystems, the ocean itself is a powerful carbon-sequestering zone, absorbing about one-third of anthropogenic CO_2 emissions [56]. Human activities in the ocean and coastal zones not only increase total CO_2 emissions but also reduce the ocean's ability to absorb CO_2 by causing the degradation and even destruction of marine ecosystems. Reducing CO_2 emissions from ocean activities and restoring the carbon sequestration function of marine ecosystems will help society adapt to and mitigate the climate change crisis.

Shipping

The maritime shipping industry is one of the major contributors to anthropogenic carbon emissions in the ocean, mainly from the usage of fossil fuels to power its ships. According to estimates by the International Maritime Organization (IMO), 0.1 Gt CO_2e is generated by the combustion of ship fuels, currently accounting for nearly 3% of total human activity emissions [1].

Currently, heavy fuel oil (HFO), which is used in most ship engines, generates serious air pollution represented by sulphur dioxide. As a result, some shipowners are building new ships with more environmentally friendly power systems or modernizing existing ships with alternative fuels such as liquefied natural gas (LNG). While such efforts may lead to improvements in air pollution, they have had limited success in addressing climate change. Even though LNG can reduce CO_2 emissions by 25% compared to existing heavy fuel oil, the methane released by its combustion remains a greenhouse gas with a very high heat-trapping capacity. At the current stage of technology, clean energy sources that can completely replace fossil fuels in shipping do not yet exist.

Capture Fisheries

Like the shipping industry, carbon emissions from marine capture fisheries are also mainly from vessel fuel consumption. A secondary consideration, still inadequately understood, has to do with emissions associated with seafloor disturbance from fishing gears, especially on the continental shelf. In 2016, global CO_2 emissions from fuel combustion in capture fishing vessels were about 207 Mt CO_2e, with motorized vessels accounting for about 98% of emissions, industrial fishing for 77% of global capture fisheries emissions, and small-scale fisheries for 23% [57]. Considering that carbon emissions from illegal, unreported, and unregulated (IUU) fishing are difficult to include in statistics, the actual emissions may be even higher [58]. The carbon emissions from fisheries targeting different species also vary, with demersal fish, crustaceans, and pelagic fish (> 30 cm) accounting for 42%, 24%, and 23% of total emissions, respectively [59].

Despite the gradual increase in carbon emissions from marine fisheries, global fish catches are on a declining trend [56]. Fuel-intensive fishing gears, such as dredging, bottom trawling, and beam trawling, not only emit more greenhouse gases but also tend to damage important habitats for aquatic animals such as the seafloor and coral reefs, further depleting fishery resources and affecting the carbon sink function of marine ecosystems [60]. This unsustainable pattern of fishery resources exploitation will lead fishers to continue to intensify their fishing effort, which in turn will result in increased fuel use per unit of catch, creating a vicious cycle of CO_2 emissions and marine ecosystem degradation. It has been shown to be possible to rebuild marine fish populations with effective stock-scale management, at least to levels associated with maximum sustainable yield. New research has suggested that rebuilding target fish populations to higher levels could not only increase carbon stored in living biomass—and potentially sinking to the seafloor—but also have indirect effects on carbon processing and sequestration through ocean ecosystem structure and function. In addition, precautionary management in emerging fisheries—especially at high latitudes where maximum fish productivity is most likely to increase [61] and related to ecosystem compartments known to be essential to downward fixed carbon movement, including in the mesopelagic realm—could help protect these as-yet inadequately understood but potentially large carbon processing and storage functions.

Mariculture

The carbon footprint of mariculture is thought to originate mainly from the upstream, such as the production process of different aquafeed ingredients, and the downstream, such as processing and transportation, and the upstream and downstream carbon footprint of mariculture is often higher than the carbon emissions from fish farms. The main species of mariculture in China are bivalves and algae, which account for 81.6% of national mariculture production in 2020 [62]. The culture of these low trophic levels species relies on almost no feeding, so there is basically no feeding pollution and corresponding feed production carbon footprint. Mariculture of these non-fed species is mostly carried out in cages or rafts at sea or in mudflats, so the external inputs and pollution outputs are low [63]. However, the large-scale reclamation of coastal wetlands by mariculture activities or the unreasonable layout of nets can also lead to serious pollution of organic matter, nutrients, and heavy metals, which affect the water quality of the aquaculture area and the surrounding seawater [64], further degrade coastal ecosystems, such as mangroves, seagrass beds, and salt marshes and their ecological service functions, thus weakening the ocean's ability to sink and store CO_2. It is important to note that increasing macroalgal-related carbon fixation only results in climate benefits when some part of that production is dedicated to long-term storage through non-respiring product mixes. Related opportunities may exist in using cultured seaweed to reduce net GHG emissions associated with terrestrial agriculture through soil amendments or through methane production inhibition in livestock if that pathway turns out to be actionable at scale.

The Post-harvest Processing and Distribution of Aquatic Products

There is a significant demand for energy in post-harvest refrigeration, processing, and transportation of aquatic products. From the perspective of life-cycle assessment (LCA), the post-harvest refrigeration (onboard and onshore), processing, and marketing of seafood, whether captured or farmed, are all part of the life cycle of seafood, and the energy inputs in these processes also generate large amounts of CO_2 emissions. Projections indicate that future demand for energy in the seafood chain will continue to increase. Though relatively more energy options are available to sectors of the chain other than fishing, the price of alternative energy sources will be reflected in the end product, with the potential to affect food security [65].

Through the application of emerging technologies and the promotion of management measures, it is possible to reduce carbon emissions from human activities involving the sea and to enhance the function of the ocean as a carbon sink. Studies have predicted the carbon-reduction potential of various sectors with full potential: maritime transport has the potential to reduce GHG emissions as much as 0.24–0.47 Gt CO_2 equivalent by 2030, and as much as 0.9–1.8 Gt CO_2 equivalent by 2050. The conservation of coastal ecosystems has the potential to reduce GHG emissions by 0.32–0.89 Gt CO_2 equivalent by 2030 and up to 0.5–13.8 Gt CO_2 equivalent by 2050. Marine capture fisheries and mariculture have the potential to reduce GHG emissions by 0.34–0.94 Gt CO_2 equivalent by 2030 and up to 0.48–1.24 Gt CO_2 equivalent by 2050 [1].

2.3.2 Assess Mitigation and Adaptation Strategies

Shipping

The bottleneck for decarbonization and emission reduction in the shipping sector is that zero-carbon technologies that can be extensively applied to vessels have not yet been established. Technologies for the commercial preparation of alternative zero-emission fuels, such as hydrogen and ammonia, are still in the development stage, with uncertain progress. Another challenge is that ocean-going vessels often require large amounts of fuel storage and must be able to obtain rapid replenishment at port. Batteries using renewable energy sources can only be used on short voyages such as ferries or coastal trips. Nuclear energy as a shipping fuel is only used on military or special-purpose ships in very few countries due to safety risks and is not ready to be promoted in the civilian sector.

In addition, another difficulty in reducing carbon emissions from the shipping sector is the difficulty of clearly assigning emissions responsibility to the appropriate country. Different choices based on where the ship's fuel is sold, where the ship is registered, and where the ship's cargo is sourced or destined will all result in very different emission responsibilities and associated costs for each country. IMO is coordinating maritime emissions among more than 170 member countries, but each has varying interests.

Most shipowners are in favour of using market-based instruments of carbon pricing to address emissions. This echoes the calls from the international trading industry, and more than 90% of the world's merchant ships are driven by trade. The trade industry has asked IMO to prioritize the implementation of a carbon tax in shipping to encourage shipowners to invest in the development and application of alternative fuel technologies. But some shipowner representatives also favour letting political forces set the rules so that the shipping industry follows through with compliance. For IMO, it needs to develop international standards around the core issue of who is responsible for emissions, and it needs countries with large fleets to actively participate to drive the standards on the ground. But IMO's resolution will take years to develop and even longer for its member states to ratify.

Currently, feasible decarbonization measures for the shipping industry in the short term include advancing the design of more efficient ship power systems, switching to cleaner fuels, building supporting port facilities, and establishing responsible parties for emissions. Long-term adaptation and response measures should focus on developing clean energy sources with zero emissions.

Capture Fisheries

Given the lack of breakthroughs in clean energy technologies for ships, capture fisheries face the same dilemma as the shipping industry. In addition to the issue of improving vessel fuel, capture fisheries can reduce their carbon footprint mainly by transforming fishing gear, such as promoting the transformation of fossil fuel-intensive gear, including dredging, bottom trawling, and beam trawling to methods with a lower carbon footprint, such as gillnets and longline fishing. This switch could also lessen the trawling-based GHG footprint exacerbated by seafloor sediment disturbance. Fisheries management should also phase out environmentally harmful vessel fuel subsidies and fuel tax exemptions while providing financial and other incentives to shift fishing gear/practices, such as the allocation of exclusive fishing quotas or fishing areas for more energy-efficient practices.

In addition, the management authorities and distribution industry should highlight the nurturing of low-carbon awareness among consumers and prioritize the provision of products with a low carbon footprint to the market. The increase in consumer demand for the corresponding products will facilitate the fishing industry to shift to fishing gear and fishing methods that consume less energy and have less environmental impact.

Finally, goalsetting in fisheries should be examined to assess the degree to which current practices support effective carbon processing and storage through ecosystem structure and function. "Climate-precautionary management" could become a new target for fisheries sustainability.

Mariculture

The sustainable management, conservation, and restoration of marine and coastal zone ecosystems are essential for the continued provision of carbon sequestration and other critical ecosystem services [66]. Artificial wetland restoration, through the planting of specific plants (e.g., seepweed and reeds) in farmed areas, can absorb pollutants in the trail water [57]. The degradation of ecosystem services caused by aquaculture can be mitigated by restoring coastal ecosystems through the recovery of farmed mudflats by the "returning aquaculture land to beach" policy. Policies to prevent the conversion of these ecosystems to other land uses, such as strict management of coastal development practices and spatial planning of the coastal zone, can also ensure that important habitats in the coastal zone are protected (see also Sect. 1.3). In addition, promoting the use of low-carbon footprint and wild fish-free aquafeeds can help reduce CO_2 emissions from aquaculture.

Other than reducing the negative impacts of mariculture, the mariculture sector can actively address climate change by increasing sinks by cultivating certain species (e.g., seaweed and bivalves). Seaweed culture is one of the largest scalable NbS [67] and the main embodiment of "carbon sink mariculture." Global seaweed absorbs 61–268 Tg CO_2 equivalent per year. Seaweed has the function of CO_2 capture, acting as a powerful carbon sink, and helps to protect coastal land from flooding and erosion; seaweed helps decarbonize the economy by replacing emission-intensive products; seaweed can also be used as biofuel to replace fossil fuel emissions; as animal feed, it can reduce the methane emissions of farm animals and thus contribute to CO_2 emission reduction.

Integrated multi-trophic aquaculture (IMTA) is a system that grows organisms of different trophic levels in appropriate proportions to create a balance between environmental sustainability, economic stability, and social acceptability. Considering that macroalgae-dominated IMTA can reduce pollution from mariculture itself, increase the climate resilience of coastal societies, and economically compensate seaweed farmers through carbon trading [68], macroalgae IMTA can be considered a powerful nature-based solution tool for mitigating and adapting to climate change.

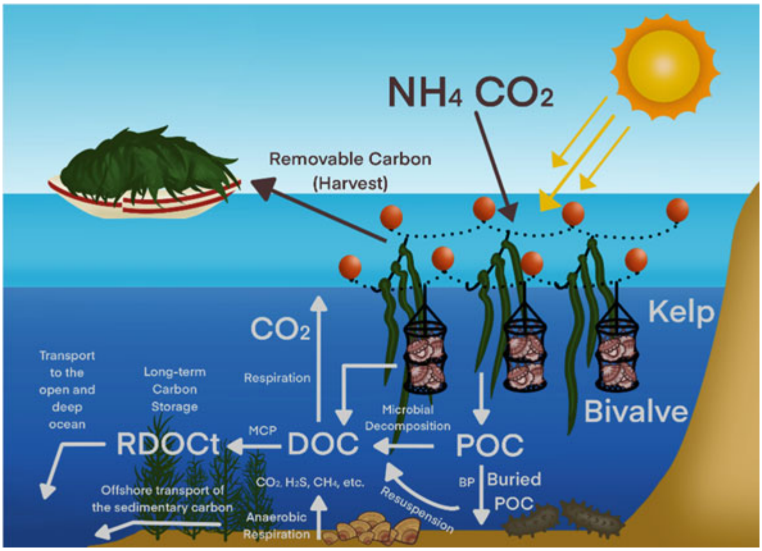


Fig. 4 Carbon pathways of integrated mariculture of seaweed and shellfish. POC: particle organic carbon; DOC: dissolved organic carbon, RDOCt: refractory dissolved organic carbon; MCP: microbial carbon pump

The IMTA mode of kelp and scallops as the main cultured species in Sanggou Bay, China, can be considered a typical NbS case (Case Study 2).

Case Study 2: Integrated Multi-trophic Aquaculture, Sanggou Bay

Sanggou Bay in Shandong Province is one of the sea areas where mariculture is the most maturely developed in China. Integrated multi-trophic aquaculture emerged as early as the 1980s in Sanggou Bay [69], with kelp (*Laminaria japonica*) and scallop (*Chlamys farreri*) as the main cultured species, and has gained worldwide recognition and promotion. Such mode is essentially a nature-based solution: shellfish excrete inorganic nitrogen by feeding on phytoplankton and organic debris in seawater, while algae need to absorb inorganic nitrogen through photosynthesis to grow and reproduce. The integrated model of shellfish and algae achieves a balance of inorganic nitrogen supply and demand in the sea, and algae can also release dissolved oxygen to prevent seawater hypoxia, which not only reduces pollution from mariculture activities, but also improves production and quality performance and provides certain ecosystem service functions. After decades of development, characteristics of different water layers have been fully utilized to adjust the culturing depth and further formed a three-dimensional mixed mariculture mode in Sanggou Bay, including seaweed, wakame, scallops, oysters, abalone, and other species.

In addition to food supply and water purification, the carbon sequestration capacity of the cultured species makes the Sanggou Bay mariculture system have the function of climate change regulation (Fig. 4). Large algae consume inorganic carbon through photosynthesis, and shellfish form shells by absorbing bicarbonate ions in seawater, and the carbon thus fixed can be removed from the ocean through harvesting. Studies have shown that kelp aquaculture contributes the most to carbon sequestration in Sanggou Bay, over 80% [70]. Based on the typical culturing density, the carbon sequestration capacity of kelp per unit area is outstanding, three to four times the carbon sequestration capacity of common afforestation tree species on land [71]. As the world leader country in shellfish and algae aquaculture, China has the potential to achieve the dual goals of food security and climate change mitigation through such activities. In 2022, China has completed the first-ever mariculture carbon sink transaction in Fujian Province, and with the improvement of such incentive systems in the future, ecosystem-based mariculture will also have an excellent prospect of sustainable development.

The Post-harvest Processing and Distribution of Aquatic Products

Reducing the carbon footprint of marine aquatic products generated during the post-harvest process relies mainly on the reduction and transformation of energy consumption. At the macro level, the carbon footprint can be reduced at the processing and transportation stages of seafood through changes in power generation, improvements in transmission and distribution efficiency, and optimization of seafood transportation processes. At the local scale, promoting consumers' choice of locally produced seafood can also reduce redundant transportation and thus carbon footprint, as well as reduce seafood waste (e.g., promoting the input of residues from seafood processing into aquaculture) [72]. Considering that current studies on LCA of seafood are not comprehensive, a better understanding of the whole chain and data collection would contribute to carbon-reduction actions.

Unlike the harvest process of seafood (including capture and mariculture), which is often dominated by individual and small-scale operators, the post-harvest process of seafood is more industrial. Management and industry associations should actively encourage the relevant enterprises to obtain corporate social responsibility certification to reduce the carbon footprint in the production process, while also reducing other negative environmental externalities, promoting employment, and strengthening labour rights protection. Meanwhile, enterprises can build a positive image through the process, meet management requirements, and enhance corporate sustainability. Considering the fact that the majority of the world's seafood processing workers are women [73], CSR certification will also be a powerful tool to promote women's rights.

2.3.3 Knowledge and Policy Gaps

The ocean is the link among continents and countries around the globe, and ocean-related human activities have distinctive cross-border characteristics, thus posing a serious challenge to global governance efforts to reduce a sector's carbon footprint. This challenge is first and foremost reflected in the shipping industry's efforts to decarbonize. Even with the revolutionary breakthroughs in science and technology that have made it possible to power ships with low- or even zero-carbon fuels, the responsibility and costs of the transition are still difficult to precisely assign to countries. As the pivot for coordinating the global shipping industry, IMO is required to establish a guiding framework for the industry to reduce carbon emissions. However, defining the responsibility for carbon emissions generated by shipping activities involves a huge conflict of interest among different countries. IMO has difficulty coordinating effectively if the high-level political forces of the major shipping countries cannot reach a consensus.

Compared to the shipping industry, capture fisheries have weaker cross-border characteristics and clearer management boundaries. However, capture fisheries are the pillar of employment and livelihoods for many people, and small-scale fisheries composed of artisanal workers have a vast scale, especially in developing countries. The fishing gear and fishing methods employed by fishers are often constrained by geography, catch composition, and even cultural traditions, which are highly region specific and difficult to quickly transform. Meanwhile, regarding the fully exploited status of global fishery resources, the economic profits of capture fisheries are relatively limited and unstable, making it difficult for fishers to bear the additional costs of transition (e.g., changing fishing gears and fishing methods). The combination of these factors makes it rather difficult to establish carbon-reduction awareness among capture fishers. In addition, as marine aquatic foods are increasingly transported and distributed, carbon-reduction-driven changes may also bring about wide-ranging food security issues, thus posing the challenge of transboundary governance. If the WTO succeeds in reaching an agreement on fisheries subsidies, it would be an enforceable global rule that would not only help address overfishing but also have an indirect impact on carbon emissions. New approaches to fisheries management that result in better biological and economic performance can help address these problems, as could the decision for fair compensation of some avoided harvest to help attain climate goals, should that prove feasible. Fishers and fishing interests—especially small-scale fisheries—would need to be intimately involved in the discussions about how to approach these problems over time.

In terms of global aquatic food production, mariculture is increasingly replacing marine capture. Although estimates of carbon emissions from mariculture are unclear, there is still a need to establish a carbon-reduction awareness in the aquaculture industry. Along with economic development, growing consumer preference for high-value aquatic foods is likely to lead to more feed being put into the aquaculture of these high-trophic-level species; and rapidly developing recirculating aquaculture systems often require high levels of energy. In addition, post-harvest processes such as preservation, transportation, and marketing of aquatic foods (both captured and cultured) also contribute significantly to carbon emissions. To develop corresponding carbon-reduction policies, it is necessary to strengthen research on the LCA of aquatic foods and to cover the complete industry chain. It is worth noting that mariculture itself (i.e., carbon sink aquaculture) can also be a powerful tool for climate change adaptation and mitigation. Algae and bivalves are good at capturing carbon, and their culturing processes require little feed, thus producing a negative carbon footprint. However, incentives to promote such aquaculture practices (e.g., carbon trading mechanisms) are still in the initial stages.

2.3.4 Priority Actions

Reducing the carbon footprint of ocean-related human activities is largely dependent on technological advancements and breakthroughs and is obviously difficult to achieve overnight. However, we should quickly establish and consolidate a distinct awareness of carbon reduction in marine industries, incorporate gender-equality considerations, develop a progressive planning route, and start working on it from now on.

In the short term, actions that can be undertaken by industries include:

1. Strengthen ship design optimization and power technology innovation to improve the efficiency of fossil fuel for shipping vessels.
2. Implement stricter fisheries management measures, restrict high-energy fishing gear and fishing methods such as bottom trawling, and gradually eliminate fuel subsidies for fishing vessels.
3. Develop specific types of mariculture (e.g., algae and bivalves) to achieve synergy between increasing carbon sinks and ensuring food security.
4. Elucidate gender relations in fisheries and aquaculture by collecting sex-disaggregated data where possible to identify challenges toward gender equality and visualize women's contributions to sustainable and low-carbon seafood production and promote their effective participation in decision making.
5. Conduct scientific coastal zone spatial planning, promote establishment of fully protected MPAs, strengthen the conservation and restoration of coastal wetlands, thus adequately realizing the carbon sink function of coastal ecosystems, and better link MPA network design with larger-scale management programs for fisheries and biodiversity.

In the medium and long term, actions that could be undertaken include:

1. Encourage research and development of low/zero-emission marine fuels and corresponding ship power systems to achieve technological breakthroughs.
2. Begin research to assess opportunities for "climate-smart" fisheries management, engaging both adaptation and potential mitigation approaches.

3. Promote innovation in financial instruments and social capital input mechanisms (including gender-related measures) to increase investment in sustainable blue economy activities, including green technology to reduce carbon emissions and environmental damage, and conservation and restoration of blue carbon ecosystems.
4. Encourage scientific researchers to assess the carbon emissions of marine aquatic foods over their complete life cycle to provide a basis for policy intervention.
5. Raise public awareness on low-carbon footprint food consumption habits and promote the production of low-carbon aquatic foods from the demand side.

At the same time, carbon reduction in marine industries involves political, scientific, industrial, and public communities, and requires a strong alliance of stakeholders at all scales, from global to local. At the international level, international organizations that play a global coordinating role in marine industries, such as IMO and FAO, should accelerate the establishment of a framework for carbon reduction-oriented industry standards and reasonably allocate responsibility for emissions in cross-border issues. Similarly, regional scientific institutions like PISCES could provide leadership in assessing the science behind climate-smart fisheries. At the national level, countries with significant influence in each industry should take the lead in promoting global cooperation, take the initiative to undertake governance responsibilities, and promote the sharing of key technologies while optimizing institutional arrangements and implementing ambitious incentives in domestic governance to promote the carbon-reduction transition of corresponding industries. At the societal level, enterprises should actively respond to governance requirements, fulfill their social responsibilities, build certification mechanisms, and provide abundant and high-quality climate-friendly products and services.

Key Recommendation: Develop a green marine industry

Recognizing that ocean-related industries will continue to produce anthropogenic emissions, ***We recommend aiming for more ambitious goals, including within the International Maritime Organization (IMO), toward dedicated efforts to accelerate the low-carbon transformation and upgrading of the marine industry and stimulate scientific and technological research and development of clean fuels, including establishing "green corridors" between ports to accommodate the use of renewable fuels for the deep-sea fleet***.

2.4 Ocean Renewable Energy

The Ocean Economy in 2030, a major report issued by the Organisation for Economic Co-operation and Development (OECD) in 2016, estimates the gross value added (GVA) of the Blue Economy at more than USD 3 trillion by 2030 (at 2010 prices), and at 2.5% of total global GVA. Within this, ocean energy is notable as an emerging sector, defined by the key role that cutting-edge science and technology play in the delivery of projects and technology. There are significant areas of collaboration and overlap between ocean energy development and the development of our existing maritime infrastructure and capacity. For example, the UK maritime sector contributes GBP 14.5 billion to the UK economy, and directly supports an estimated 186,000 jobs [74]

Ocean Renewable Energy (ORE) is notable as an emerging sector of the maritime industry. China, the world's biggest energy consumer, is stepping up on using a larger portion of renewable energy in the overall energy mix and proposing higher green power consumption targets, including in the ORE area. Achieving the needed renewable energy transition will not only mitigate climate change but also stimulate the economy, improve human welfare, and boost employment worldwide.

In 2020 the CCICED Special Policy Study on *Global Ocean Governance and Ecological Civilization: Building a Sustainable Ocean Economy for China* completed an in-depth study on ORE [73]. The following descriptions and observations draw on and build on the findings of the report from that study.

2.4.1 Utilizing the Ocean to Produce Renewable Energy

ORE technologies (wind, wave, current, tidal range, ocean thermal) are at different stages of development and each presents its own unique challenges and opportunities. The optimal portfolio of future ORE options will vary in different places around the world. ORE, specifically offshore wind, has seen and will likely experience rapid growth in installed capacity, such that environmental, socio-economic, and technical challenges need to be considered, especially as these new industries move toward scale. Achieving a viable cost of electricity is a significant challenge to the offshore wind industry but provides an even bigger challenge to other ORE technologies. Understanding and assessing the environmental impact of ORE installations, operations, and decommissioning is substantially challenged due to such things as baseline data, socio-economic situations, and diverse developing technologies. Full-scale development of ORE affects or is also affected by numerous stakeholders. Understanding who the stakeholders are and how they are engaged in the process is necessary for improving the responsible development of ORE technologies. Key stakeholders may include fishers, community members, regulators, developers, scientists, and tourists that depend on the specific ORE project and the specific location.

The seabed off China's east coast is characterized by soft, silty soils which are unlike soil conditions in other countries contemplating significant ORE growth. This causes difficulty regarding structural foundation type and installation techniques. Furthermore, the technical challenges for the offshore wind industry are much greater in other typhoon-prone regions, where the weather conditions can be quite impactful on turbine performance. China's current legal system of environmental consideration related to ORE activities is limited, and further regulations need to be developed.

2.4.2 Current Status of Developing and Utilizing ORE

China is particularly active in developing offshore wind technologies, an area which is set to become an important sector for the global energy future, while also demonstrating wave and tidal energy technologies. The Chinese government has made a commitment that the proportion of non-fossil fuel energy will be 20% by 2030, and an operational installed capacity of ORE (offshore wind) in 2019 reached 3.7 GW in total, with another 13 GW under construction and over 41 GW permitted. The development of offshore wind in China reached a turning point in 2018, moving toward zero subsidies. China's first auction for offshore wind projects in 2019 achieved a price of electricity at 0.75 Yuan/kWh, lower than the guide price of 0.8 Yuan/kWh. China has become also one of the few countries in the world that have mastered the technology of large-scale tidal current energy development and utilization.

ORE is a fast-growing ocean economy that is advancing the goals of a low-carbon and circular economy. Only recently, offshore wind technology reached a policy turning point, while other ORE technologies are at an early stage of development. Nevertheless, there are encouraging signs that the investment cost of technologies and the price of electricity generated will decline further toward commercially viable ORE energy generation. Enhancing knowledge of the ORE technologies' potential impacts is crucial to informing future growth plans and effectively licensing ORE activities. Ongoing review of environmental impacts associated with the growing ORE sector and emerging ORE technologies will ensure that the best and most up-to-date information is available to decision-makers, developers, and stakeholders. Furthermore, the opportunity of integrating emerging ORE technologies into military applications, electricity generation for remote communities, freshwater generation, or aquaculture applications, could be further opportunities. ORE technologies offer opportunities for China to develop a new domestic industry and take advantage of engaging in global markets.

2.4.3 Knowledge and Policy Gaps

Knowledge production and management play a significant role in many kinds of industries to deal effectively with changes, increasing their productivity and paving the way to development and innovation. One example from **data sharing**: Ørsted A/S successfully shared data from earlier generations of offshore wind farms with technical universities aiming at further improving wind farm design and inspiring future engineers to join the green energy industry. Sharing this data has led to improvements in wind-flow modelling and monitoring of wind turbines.

Before the ocean energy sector can reach the bankability and commercial viability necessary for industrial roll-out, the first ocean energy pilot projects must reach financial close. Demonstration and pre-commercial farms and plants require a specific financing solution, as high levels of uncertainty and risk make them unsuitable for commercial debt or pure revenue-based finance. Thus, we recommend the creation of an **Investment Support Fund** for ocean energy farms that creates a fund providing flexible capital and enabling further private capital to be leveraged, and an **Insurance and Guarantee Fund** to underwrite various project risks. The latter would be targeted to cover risks such as availability, performance, unforeseen events, failures, etc.

National authorities need to adequately **support new technologies** as they emerge and move through demonstration and pre-commercial stages to reach industrial roll-out. An explicit distinction must be made between support for mature technologies and support for emerging technologies. Emerging technologies such as ocean energy require investment- or project-specific support rather than pure revenue support.

Overall, the development of ORE in China is highly dependent on revisions of regulations and policies from the central government, such as the Renewable Energy Law and in upcoming Five-Year Plans for China's National Economy and Social Development. Additionally, policies at the provincial/regional level—and the interplay between central and provincial levels—play a crucial role. China can be a world leader in the movement toward sustainability through ORE.

2.4.4 Priority Actions

The following actions emphasize that an industrial supporting policy mechanism should be established and improved. Furthermore, the scale of ORE utilization should be promoted, while financial or venture capital communities as well as private capital should be encouraged by governmental policies. Finally, offshore wind should be accelerated while environmental and socio-economic impacts assessed; mechanisms to accelerate commercial realization of other ORE technologies should be supported by the government.

Policy

1. Industrial supporting policy mechanisms should be established and improved.
2. Scale up of ORE utilization should be promoted.
3. Develop ocean-related taxonomy principles and criteria.
4. Enable RD&D to address challenges to reduce costs further to reach parity with other energy technologies.
5. Enhance capacity to accelerate innovative and resilient technology development.

6. Engage at an early stage with a wide range of stakeholders including fishers, community members, regulators, developers, scientists, and tourists—ensuring the expression of perspectives from women, as well as underrepresented or marginalized groups.
7. Integrating emerging ORE technologies into wider applications such as military applications, electricity generation for remote communities, desalination, hydrogen production, or aquaculture applications.

Market

8. Assessing the creation of an Investment Support Fund and an Insurance and Guarantee Fund.
9. Financial or venture capital communities, as well as private capital, should be encouraged by governmental policies.
10. Develop and adopt blue bond standards on ORE.
11. Strengthening the global export and market opportunities.
12. Scaling up ORE industry, creating jobs, and taking advantage of opportunities within its competency to global markets.

Offshore Wind

13. Offshore wind should be accelerated while environmental and socio-economic impacts assessed. Understanding scaling needs while also establishing key pilot projects will be important.
14. Increase offshore wind deployment by addressing many strategically important goals such as decarbonization, security of supply, and new business opportunities.

Marine Energy

15. Tidal current energy research and development should be encouraged by government as expected to be the next type of ORE.
16. Mechanisms to accelerate the commercial realization of ORE technologies (wind, wave, current, tidal range, ocean thermal) should be supported by the government.

Key Recommendation: Developing climate-smart ports

Ocean renewable energy (ORE) is notable as an emerging sector of the maritime industry. Achieving the needed renewable energy transition will not only mitigate climate change but also stimulate the economy, improve human welfare, and boost employment worldwide. ***We recommend that transportation systems of large coastal cities and the shipping sector should be decarbonized through scaling up offshore wind production and promoting hydrogen and ammonia production and that other potentially high-value ocean energy approaches be developed as quickly as possible***.

3 Sustainable Management of the Ocean as a Solution for Achieving Carbon Neutrality

3.1 The Need to Consider the Ocean System Holistically

To tackle societal challenges from climate change, biodiversity loss, and inequality, we need to strike a proactive balance between production and protection, and the ocean has a critical role in addressing these challenges. However, the importance of the ocean as part of the solution for meeting global challenges has long been overlooked. For humanity to tackle the planetary challenges and crises that it faces today and in the future, a systemic, integrated, and holistic approach concerning ocean issues and the governance of this space must be taken. In this sense, we argue that integrated ecosystem-based integrated ocean management (EB-IOM) approach is fundamental for achieving the carbon-neutrality goals, protecting biodiversity, and developing an ecological civilization. IOM considers multiple uses and pressures simultaneously, and helps reconcile competing uses with the objective of ensuring the sustainability of societies and marine ecosystems. The need for a comprehensive perspective on the management of marine ecosystems and their resources is now widely recognized at all levels of governance. Clear and directed actions are needed to limit the threats and minimize the impacts on the ocean, and thereby laying the foundation for the ocean's ability to continue to serve as a basis for human and planetary life.

A holistic and integrated management can support more effective use of carbon storage in ecosystems, the decarbonization of marine industries, and the transition to low-carbon ocean-based activities. In an increasingly busy ocean space, there are opportunities to maximize economic growth and meet the needs of people without compromising the environment, but rather restoring and/or regenerating it. This could be unlocking the co-location benefits with other offshore industries; for example, ocean-based energy could meet the increasing demand for energy-intense desalinated seawater or support marine aquaculture operations, as well as offer protection of critical ocean ecosystems and biodiversity at the same time. Any such ocean-based activities should not be undertaken in isolation but rather in a cross-sectoral and integrated way. This will avoid stranded assets, and with long-term marine spatial planning in ocean and coastal spaces, benefits will be accrued in terms of economic, human, and environmental health.

An integrated approach that is climate smart and focuses on NbS, integrating well-managed MPAs and other effective area-based conservation measures alongside sustainable infrastructure development, will be vital to protect and support coastal communities and marine habitats. This could increase seafood production, enable pharmaceutical innovation, enhance climate change mitigation and adaptation, meet energy needs, and protect, regenerate, and restore biodiversity and cultural values (www.oceanpanel.org).

This climate-smart integrated approach has proved to be economically smart and viable as well. Recent research has found that investing USD 1 in key ocean actions can yield at least USD 5 in global benefits, often more, over the next 30 years. Specifically, investing USD 2 trillion to USD 3.7 trillion globally across four key areas—conserving and restoring mangrove habitats, scaling up offshore wind production, decarbonizing international shipping and increasing the production of sustainably sourced ocean-based proteins—from 2020 to 2050 would generate USD 8.2 trillion to USD 22.8 trillion in net benefits, a rate of return on investment of 450%–615% [75].

Globally, there are still many challenges relating to the lack of truly integrated approaches, insufficient involvement of local stakeholders, inadequate harnessing of and respect for science and knowledge, weak adaptation to climate change, inadequate enforcement of existing and often complex governance frameworks, knowledge and capacity shortages, incomplete legislation, and poor coordination and integration among ministries, other governmental bodies, civil society organizations, and research institutions [76]. There also needs to be a recognition that ecosystem-based ocean management and governance requires gender-sensitive and gender-responsive planning, implementation, monitoring and evaluation at project, policy, and grassroots levels to be successful. China, housing great technological and economical resources, has the capacity to implement a wide variety of adaptive and mitigative measures that will have an impact on societal development nationally as well as internationally. A key to achieving ecological civilization and carbon neutrality lies in implementing a cross-sectoral knowledge and EB-IOM.

3.2 Approaches to Sustainable Ocean Management Toward Carbon Neutrality

Ocean-based mitigation options offered through sustainable ocean management could reduce the "emissions gap" (the difference between emissions expected if current trends and policies continue and emissions consistent with limiting global temperature increase) by up to 21% on a 1.5 °C pathway and by about 25% on a 2.0 °C pathway, by 2050 [1]. There are five main areas, in the context of sustainable ocean planning, that will make considerable strides toward mitigating GHG emissions and thus carbon neutrality: ocean-based renewable energy; zero-emission maritime transport; stewardship of coastal and marine ecosystems; the ocean-based food system (wild capture fisheries, aquaculture, and shifting human diets toward food from the sea); and carbon storage in the seabed. Ocean-based renewable energy production currently offers the greatest potential for delivering clean energy and reducing GHG emissions, with the expansion of floating wind and solar facilities being important frontiers. When wider impacts on the environment and social well-being are considered, nature-based interventions—especially protection and restoration of mangroves, seagrass and salt marshes (i.e., blue forests)—offer the best combination of carbon mitigation and broader co-benefits for people, the economy, and the planet.

Blue forests hold enormous potential for capturing and storing CO_2. Research indicates that marine flora and fauna are substantially more efficient than terrestrial forests in capturing CO_2 (particularly mangroves, which capture several times more CO_2 than trees on land). Preventing the loss of natural habitats, restoring natural conditions if destruction has occurred, and ensuring that any future activities are conducted in a regenerative manner—NbS—must be a key strategy in reaching the carbon-neutrality goals.

Here, coastal wetlands play a particular role, being effective at sequestering carbon and serving as key habitats for many marine species, and an important source of food and livelihoods. Since urbanization, especially the development of coastal cities, poses a challenge for preserving natural habitats, measures such as an **ecological damage compensation system** should be assessed. In support of a compensation scheme, a **natural capital accounting system** could be further developed. Fenichel [77] discusses a system of national accounts with multiple indicators and how they should be applied to the sustainable ocean economy, and the Global Ocean Accounts Partnership (https://www.oceanaccounts.org/) looks at developing a shared technical framework for ocean accounting. Although central authorities like the Ministry of Ecology and Environment will oversee such instruments, local involvement and engagement are very important [75]. Conservation measures at sea should also be given adequate attention, for example, assessment and development of MPAs, as well as seaweed farming which is increasingly gathering attention for its multiple benefits (especially climate change and food security related), and a rapidly expanding global market and demand.

MPAs and other area-based conservation measures offer a range of benefits which includes the creation of employment opportunities, enhancing production of fisheries adjacent to the protected area, increased carbon sequestration through healthy marine ecosystems and the protection of critically important biodiversity. MPAs should not only be viewed as a mechanism to deliver on the targets of the SDGs but also seen as part of a country's infrastructure and invested in as such. Financial support and investment for protected areas and other area-based conservation measures, and providing incentives for sustainable seaweed farming, could be considered within China and along the BRI via international collaborations**.**

Second, achieving a sustainable ocean economy ("blue economy") requires innovation and development of new, **climate-smart technologies** in both existing and new ocean-based industries. The need for developing these green technologies has implications for all ocean-based industries in China. Examples from the maritime sector could be to establish early national targets and strategies to support decarbonization of vessels, and to incentivize sustainable, low-carbon ports that support the transition to decarbonized marine transport and shipping fleets—and possibly some parts of the fishing fleet—through renewable energy and zero-carbon fuel supply chains. Another example, from the aquaculture sector, could be to put into place policies and management frameworks to minimize the environmental impacts of aquaculture, including inefficiencies in the feed supply chain, and enable the acceleration of fed and non-fed aquaculture production that fits local environmental, governance, and economic priorities. Targeted **government procurement and investment in**

addition to preferential fiscal and tax policies in green technologies could help industries overcome financial obstacles which sometimes impede the creation of environmental technologies. Internationally, through the **BRI**, China could be proactive in developing offshore wind and green solutions in ports, fishing vessels, mariculture, and tourism, as well as promoting the concept of integrated ocean management as a management principle [1].

Third, knowledge is a fundamental value for societal development. The use of **scientific knowledge and monitoring** relevant to the sustainable and climate-smart management of marine ecosystems and economies should be encouraged and enforced by providing mechanisms and opportunities for access to a common knowledge base. This would underpin coordinated and holistic use of knowledge in instituting overarching policies on the development of the ocean economy and the implementation of EB-IOM. Maintaining an up-to-date knowledge basis (science and technology) and data sharing capabilities requires investments in national and regional systematic programs for data and knowledge gathering and technology development, as well as innovative methods for disseminating data and knowledge. Investing and engaging in the **IOC Ocean Decade** would be an important international contribution by China.

Fourth, by active participation and spearheading relevant discussions in key **international processes and fora** that provide a framework for sustainable ocean management, China will contribute to global ambitions for reaching carbon neutrality. Central bodies here are the Paris Agreement (UNFCCC), the Biodiversity Convention (CBD), the ongoing discussions on Biodiversity Beyond National Jurisdiction, the International Maritime Organization, and the International Seabed Authorities. By doing so, China would inter alia also contribute to the timely development of appropriate legal and environmental framing of novel and emerging ocean industries, such as ORE, seabed minerals, and biotechnology. Great care must be taken to ensure that any areas to which China contributes are science based and avoid any consequences that may further compromise the health of the ocean.

3.3 Priority Actions

The following priority actions are suggested to support the implementation, and the continuous development of knowledge-based and EB-IOM in all marine areas of China, and in areas where China has influence.

1. Halt the net loss of (and increase the extent and improve the condition of) coastal and marine ecosystems, in particular critical ecosystems such as mangroves, seagrass beds, salt marshes, kelp forests, sand dunes, reefs, and deep ocean ecosystems. Improve climate-ready management of those ecosystems.
2. Use NbS in planning and developing coastal infrastructure to reduce grey infrastructure where possible, incentivize their use to sequester and store carbon and improve coastal resilience.

3. Establish and effectively manage science-based networks of MPAs and other effective area-based conservation measures that conserve biodiversity while also delivering climate, food, socio-economic, and cultural benefits. Link those explicitly to larger-scale management programs for fisheries, biodiversity protection, and other natural amenities.
4. Collaborate with all relevant partners, including Indigenous People and stakeholders, through relevant global and regional organizations to promote sustainable management of all marine and coastal ecosystems. Enhance the participation of women and their financial profile in all aspects of the ocean economy.
5. Capitalize on knowledge and spatial analysis tools to identify carbon sequestration potential and optimal locations for MPAs and other effective area-based conservation measures in the development of Sustainable Ocean Plans.

Key recommendation: Capture and storage of CO_2 by nature itself

To tackle societal challenges caused by climate change, biodiversity loss, and inequality, we need to strike a balance between production and protection, and the ocean has a critical role to play in addressing these challenges. The ecosystem-based integrated ocean management (EB-IOM) approach is fundamental for achieving the carbon-neutrality goals and developing an ecological civilization. ***Immediate action should be taken, from local to national levels, seeking to avoid further marine habitat and coastal wetland destruction, and where possible, mitigate those losses: (i) By 2030, restore degraded/destroyed coastal wetlands and protect critical marine habitats; (ii) By 2030, invest in, and implement, a resilient network of MPAs (including national parks, nature reserves, and marine redlines), to protect large-scale marine habitats that contribute significantly to carbon storage and marine biodiversity through NbS; and (iii) Incorporate climate-smart management of these blue carbon ecosystems into China's national GHG inventory following the approved IPCC guidelines and China's NDCs, and explore collaborations with BRI-countries to facilitate similar measures through international collaboration***.

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