Commissioned by

HIGH LEVEL PANEL *for* A SUSTAINABLE OCEAN ECONOMY

The Ocean as a Solution to Climate Change

Five Opportunities for Action

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About this Paper

Established in September 2018, the High Level Panel for a Sustainable Ocean Economy (HLP) is a unique initiative of 14 serving heads of government committed to catalysing bold, pragmatic solutions for ocean health and wealth that support the Sustainable Development Goals (SDGs) and build a better future for people and the planet. By working with governments, experts and stakeholders from around the world, the High Level Panel aims to develop a roadmap for rapidly transitioning to a sustainable ocean economy, and to trigger, amplify and accelerate responsive action worldwide.

The Panel consists of the presidents or prime ministers of Australia, Canada, Chile, Fiji, Ghana, Indonesia, Jamaica, Japan, Kenya, Mexico, Namibia, Norway, Palau and Portugal, and is supported by an Expert Group, Advisory Network and Secretariat that assist with analytical work, communications and stakeholder engagement. The Secretariat is based at World Resources Institute.

This report was prepared in support of the work of the HLP to provide the robust science base and practical recommendations for action across issues central to the attainment of a sustainable ocean economy. The arguments, findings, and recommendations made in this report represent the views of the authors. While the HLP supports the general thrust of the findings and recommendations, members have not been asked to formally endorse the report, and should not be taken as having done so.

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FOREWORD

The Ocean: From Victim to Solution

Concerned about the accelerating impacts of climate change, cognizant of the paucity of attention to ocean-based mitigation options, and motivated to accelerate progress to address climate change, the High Level Panel for a Sustainable Ocean Economy (HLP) asked us, the co-chairs of the HLP Expert Group, to convene an international team of scientists and other experts to evaluate the potential for ocean-based actions to contribute to reducing greenhouse gas (GHG) emissions.[1]

Previous and recent reports describe the important role of the ocean in climate change – including its uptake of heat and CO_2— and the serious consequences of climate change on ocean ecosystems. The most recent Intergovernmental Panel on Climate Change (IPCC) report, the Special Report on the Ocean and Cryosphere in a Changing Climate, highlights the dire impacts on the ocean that are already underway and provides a sense of even greater urgency to reduce GHG emissions aggressively.

This HLP report provides a timely pivot from ‘problem’ to a significant missing piece of the ‘solution’. Heretofore, climate mitigation policy has concentrated intensively on land-based mitigation activities. The HLP report offers the first comprehensive, integrated assessment of the mitigation potential of a suite of ocean-based activities: renewable energy, transport, food production, and ecosystems, and the potential future contribution from carbon storage if current concerns can be resolved. Each of these five areas is assessed for its potential to close the emissions gap in 2030 and 2050 relative to a 1.5°C degree and 2°C degree pathway. Moreover, each activity is also evaluated for its wider benefits to society (beyond mitigation). Finally, the report highlights the enabling policy measures and research required for success.

As co-chairs of the HLP Expert Group, we wish to warmly thank the authors, the reviewers, and the Secretariat at World Resources Institute for responding rapidly and effectively to the opportunity to conduct novel analyses, hold them up to scrutiny through peer review, and hopefully accelerate serious reductions of GHG emissions. With this report, we launch the first in a series of products of the HLP Expert Group that are responsive to the interests of the members of the HLP and designed to provide actionable analyses, syntheses, and recommendations for consideration by the HLP and other interested parties. Our goal is to deliver timely scientific analysis that responds directly to policy requests and societal needs.

We also thank the members of the HLP for their vision in suggesting this analysis. We hope they and other parties act on the report’s information with an urgency that is commensurate with the seriousness of the problem. Forward-looking policies that both combat climate change and enable a sustainable ocean economy are feasible and needed without delay.

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1. *This study was undertaken by the co-chairs of the HLP Expert Group, ably assisted by the Secretariat, at the request of the Members of the HLP. On behalf of the co-chairs, J. Lubchenco served as the report arbiter, overseeing the selection of authors, independent peer review, and approval of the final report. Co-chair P. Haugan, co-author and contributor to the report, was not involved in the arbitration process.*

Executive Summary

The ocean is a dominant feature of our planet, covering 70 percent of its surface and driving its climate and biosphere. The ocean sustains life on earth and yet is in peril from climate change. However, while much of recent attention is focused on the problems that the ocean faces, the ocean is also a source of potential solutions and innovation. This report explores how the ocean, its coastal regions and economic activities can provide opportunities in the fight against climate change.

Highlights

- Until recently, the ocean was thought to be so large that its response to climate change was thought to be minimal; it has now taken centre stage in the impacts and solutions.
- Ocean-based mitigation options to reduce or sequester and store emissions offer significant potential to contribute to global efforts to limit global warming and for achieving the goals of the Paris Agreement.
- Ocean-based mitigation options could reduce global greenhouse gas (GHG) emissions by nearly 4 billion tonnes of carbon dioxide equivalent (CO_2e) per annum in 2030 and by more than 11 billion tonnes per annum in 2050, relative to projected business-as-usual (BAU) emissions. Reductions of this magnitude are larger than the emissions from all current coal fired power plants world-wide and more than China's total emissions in 2014.
- Ocean-based mitigation options 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 percent on a 1.5°C pathway, and by about 25 percent on a 2.0°C pathway, by 2050.
- This report considers five areas of ocean-based climate action to mitigate GHG emissions: ocean-based renewable energy; ocean-based transport; coastal and marine ecosystems; the ocean-based food system (wild capture fisheries, aquaculture, and shifting human diets towards 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 exciting 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—offer the best combination of carbon mitigation and broader cobenefits.
- While innovation is required to improve many specific technologies and practices, four of the ocean-based climate action areas are ready to be implemented today (ocean-based renewable energy; ocean-based transport; coastal and marine ecosystems; the ocean-based food system). This could offer many cobenefits in terms of creating jobs, improving air quality and human health, and supporting livelihoods if implementation addresses trade-offs with sustainable development dimensions appropriately. The fifth, carbon storage in the seabed, has significant theoretical potential to divert carbon from the atmosphere, but it currently faces significant technical, economic, and sociopolitical challenges (e.g., environmental safety) that must be adequately explored prior to deployment at the scale required to make a substantive contribution to solving the climate problem.
- Ocean-based mitigation options must be accompanied by deep cuts in emissions across terrestrial GHG sources, including measures to phase out fossil fuels, create sustainable food systems, and increase carbon sequestration and storage in forests and other natural ecosystems.

Climate Change Threatens the Ocean

The world needs to move rapidly and systematically to reduce emissions of green house gases (GHGs) to the atmosphere if it is to avoid irreversible climate impacts (IPCC 2014; IPCC 2018). Greater efforts are essential to accelerate and scale decarbonisation of the economy and pursue a pathway to net-zero emissions by the middle of the century. The sooner widespread action begins, the more cost-effective it will be, and the greater the chance of avoiding the worst impacts of rapid human-driven climate change.

Following the findings of the IPCC Special Report on the implications of 1.5°C warming above the preindustrial period (IPCC 2018), it is now abundantly clear that stronger action to mitigate GHG emissions is a global imperative that will require an inclusive approach across the whole of the global economy. To date, much of the attention has been directed to the role of terrestrial sources of emissions and sinks. The ocean and its coastal regions, however, offer a wide array of additional potential mitigation options.

The ocean plays a fundamental role in regulating global temperatures. Not only does the ocean absorb 93 percent of the *heat* trapped by rising anthropogenic carbon dioxide (CO_2), but it also absorbs approximately 25 to 30 percent of anthropogenic CO_2 *emissions* that would otherwise remain in the atmosphere and increase global warming. The ocean also produces around 50 percent of the oxygen on the planet through the photosynthetic activity of marine plants and algae.

The ocean's ability to contribute to these fundamentally important services, however, is at risk (IPCC 2019). Ocean warming and acidification (the latter being a direct result of the extra CO_2 dissolving into the ocean) are damaging marine ecosystems and compromising the ability of the ocean to provide food, livelihoods, and safe coastal living on which billions of people depend (IPCC 2014, 2018, 2019).

Efforts to protect the ocean and its vitally important ecosystems cannot be considered in isolation from the challenge of stabilising the global climate. To secure the long-term health of the ocean and the livelihoods and economies that depend on it, atmospheric concentrations of GHGs must be urgently reduced. This report outlines a suite of options for how the ocean and coastal regions can contribute to lowering projected emission trajectories and help achieve the temperature stabilisation goals established in the Paris Agreement on Climate Change (UNFCCC 2015).

The Ocean is a Major Part of the Climate Solution

Ocean-based mitigation options do not feature as prominently as they could in countries' nationally determined contributions (NDCs) or long-term low greenhouse gas emission development strategies under the Paris Agreement. This report presents a wide array of potential ocean-based mitigation options and provides detailed analysis of their potential contribution to closing the emissions gap in 2030 and 2050 (Box ES-1).

Box ES-1. Why the World Needs to "Close the Emissions Gap"

Each year, the United Nation's Emissions Gap Report compares where global greenhouse gas (GHG) emissions are headed with where they need to be if the world is to avoid the worst impacts of climate change. Scientists first collect the latest information on countries' climate commitments, expressed in their nationally determined contributions (NDCs), and calculate their projected emissions pathway. They then compare this pathway with the latest models on how warming could be limited to either 1.5°C or 2.0°C, the temperature goals to which countries committed under the Paris Agreement of December 2015, and the limits scientists say are necessary for preventing some of the worst climate change impacts. The most recent report (UNEP 2018) concludes that unless countries strengthen their ambition and cut 2030 emissions beyond the targets established in their current NDCs, exceeding a temperature rise of 1.5°C "can no longer be avoided." And unless the emissions gap is closed by 2030, it is unlikely that warming can be held below 2.0°C.

Source: Levin et al. (2018).

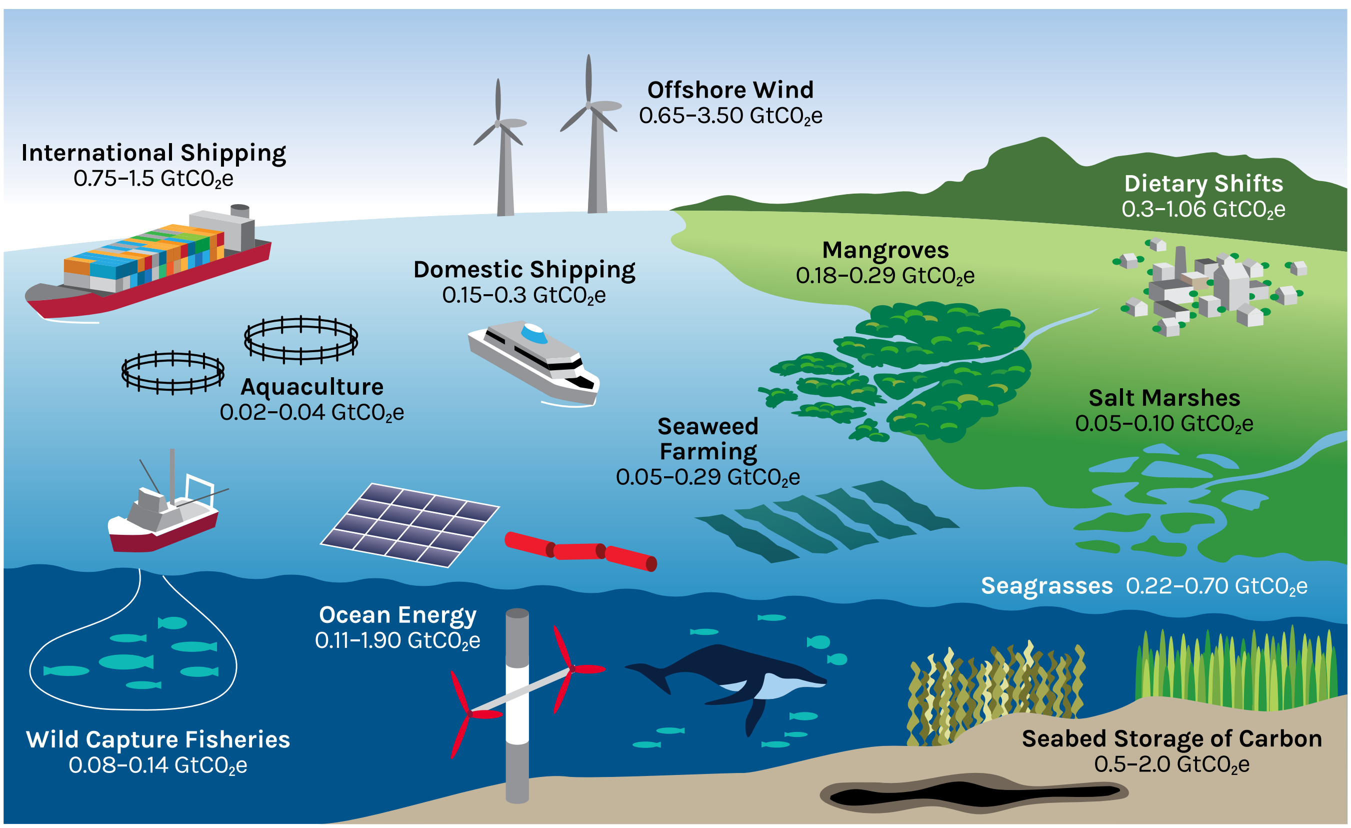
Five areas of ocean-based climate action are considered in this report:

- Ocean-based renewable energy, including offshore wind and other energy sources, such as wave and tidal power.
- Ocean-based transport, including freight and passenger shipping.
- Coastal and marine ecosystems, including protection and restoration of mangroves, salt marshes, seagrass beds, and seaweeds.
- Fisheries, aquaculture, and dietary shifts away from emission intensive land-based protein sources (e.g., red meat) towards low carbon ocean-based protein and other sources of nutrition.
- Carbon storage in the seabed.

Additional ocean-based carbon storage options, such as direct injection into the deep ocean, alkalinity addition, and iron fertilisation are discussed, but due to the current uncertainty regarding their viability and higher risk of adverse impact on the ocean, they have been excluded from the calculated mitigation potentials. Offshore oil and gas drilling, although the most significant source of ocean-based CO_2 emissions, is not discussed in the report, as it has been comprehensively tackled by other reports and its tracjectory is clear.

Within each area, this report assesses the set of individual mitigation options that could be undertaken, along with the technology developments and policies required to advance implementation. These mitigation options are summarised in Figure ES-1, along with their mitigation potential in 2050. We also examine current and future deployment scenarios and suggest research

Figure ES-1. Ocean-based Mitigation Options Explored in This Report and Associated Annual Mitigation Potential in 2050



Source: Authors

priorities to improve the feasibility and scale of each option. The inclusion of any particular mitigation option in this report does not imply endorsement.

This report concludes that actions across all five ocean-based climate action areas of intervention have the potential to reduce emissions by up to 4 billion tonnes of CO_2e per annum in 2030, and by more than 11 billion tonnes of CO_2e per annum in 2050, thereby making a significant contribution to closing the emissions gap in 2030 and 2050 as shown in Figure ES-2. Table ES-1 shows the total mitigation potential (expressed as a range) for each of the intervention areas.

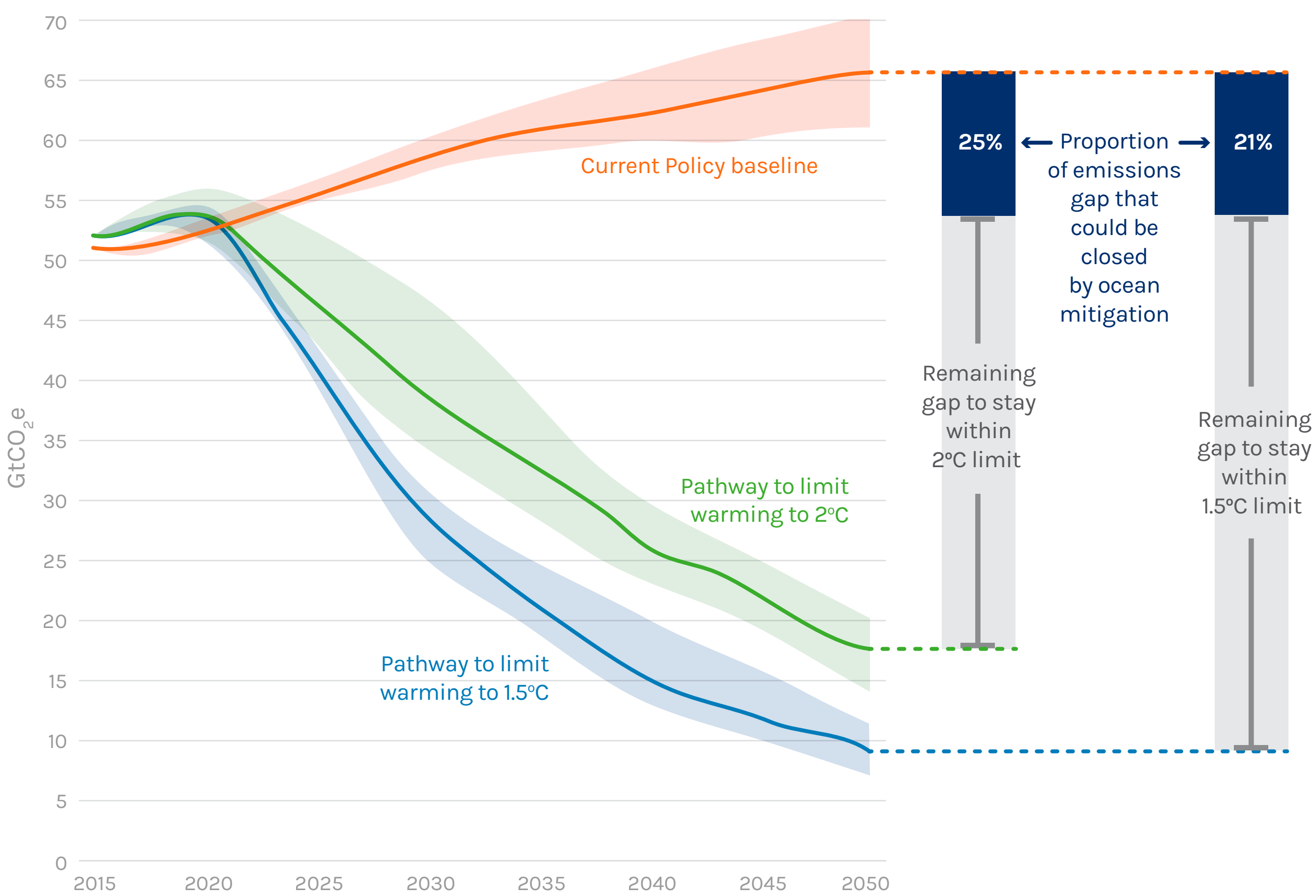
Figures ES-3 and ES-4 below show the emission reduction and/or sequestration potential of each area of ocean-based climate action, including individual mitigation options, for 2030 and 2050.

Table ES-1. Summary of Global Mitigation Potential Offered by Each Area of Ocean-based Climate Action

AREAS OF OCEAN-BASED CLIMATE ACTION	2030 MITIGATION POTENTIAL ($GTCO_2E$/YEAR)	2050 MITIGATION POTENTIAL ($GTCO_2E$/YEAR)
1. Ocean-based renewable energy	0.18–0.25	0.76–5.40
2. Ocean-based transport	0.24 – 0.47	0.9 – 1.80
3. Coastal and marine ecosystems	0.32–0.89	0.50–1.38
4. Fisheries, aquaculture, and dietary shifts	0.34–0.94	0.48–1.24
5. Carbon storage in the seabed (Action in this Area Requires Further Research Prior to Implementation at Scale)	0.25–1.0	0.50–2.0
Total	1.32–3.54	3.14–11.82
Total percentage contribution to closing emissions gap (1.5°C pathway)	4–12 %	6–21%
Total percentage contribution to closing emissions gap (2°C pathway)	7–19%	7–25%

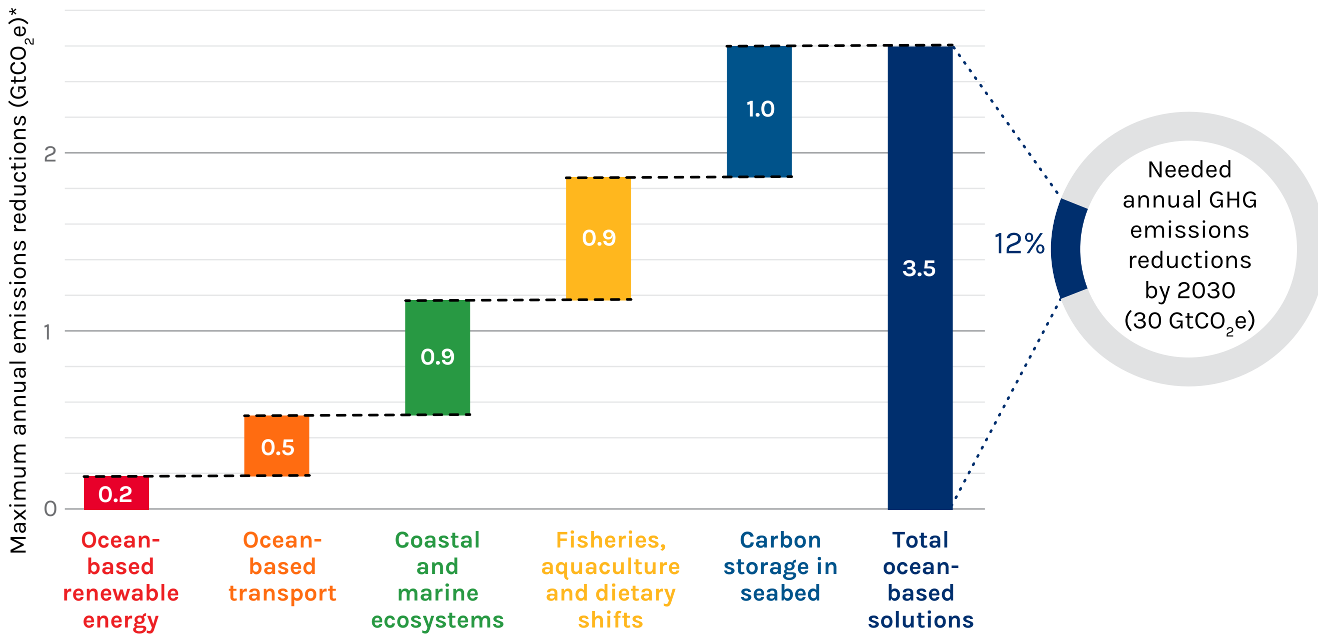
Source: Authors

Figure ES-2. Contribution of Ocean-based Mitigation Options to Closing the Emissions Gap in 2050



Source: Adapted from UNEP 2018, Climate Action Tracker (2018).

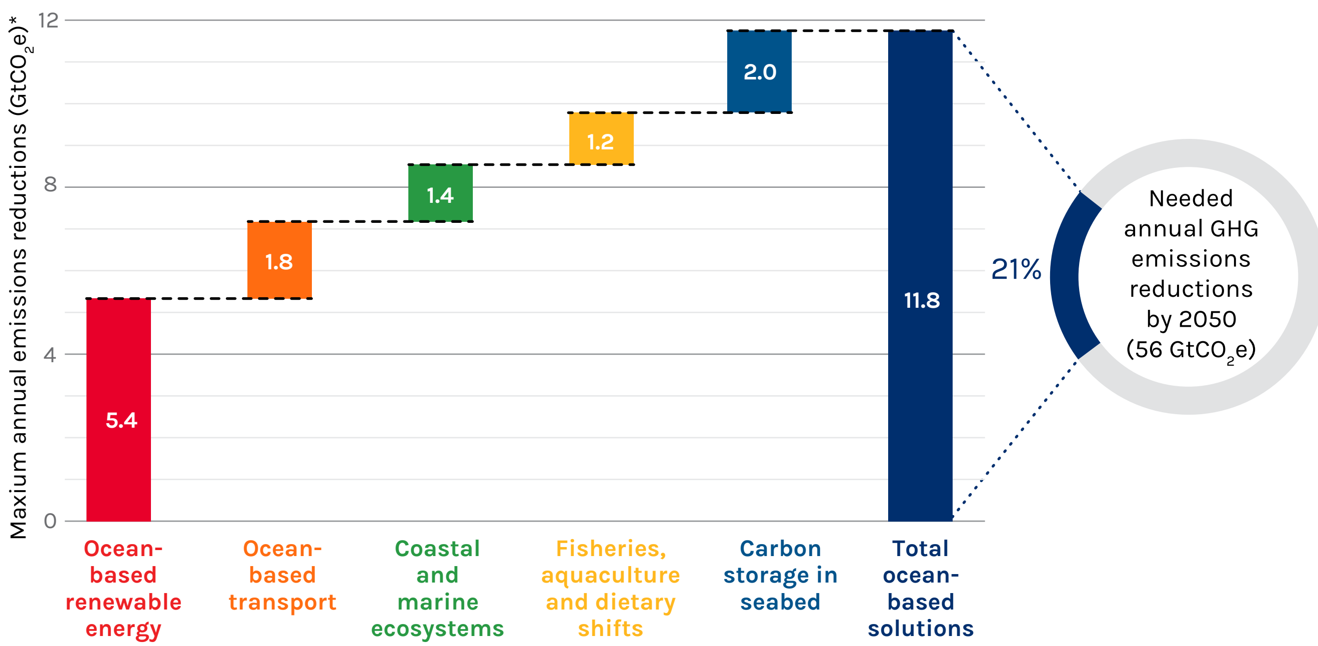
Figure ES-3. Contribution of Five Ocean-based Climate Action Areas to Mitigating Climate Change in 2030 (Maximum $GtCO_2e$)



*Notes: * To stay under a 1.5°C change relative to pre-industrial levels*

Source: Authors

Figure ES-4. Contribution of Five Ocean-based Climate Action Areas to Mitigating Climate Change in 2050 (Maximum $GtCO_2e$)



*Notes: * To stay under a 1.5°C change relative to pre-industrial levels*

Source: Authors

Ocean-based Mitigation Options

Scaling up ocean-based renewable energy (offshore floating and fixed wind installations, tidal and wave power), and decarbonising ocean-based transport offer some of largest mitigation potential in 2030 and 2050.

Utilising nature-based solutions, such as leveraging the ability of coastal and marine ecosystems to sequester and store carbon, also offer a sizable mitigation potential. Protection and restoration of these ecosystems provides valuable benefits by expanding sequestration and maintaining carbon stocks in soils and vegetation. Restoration also yields cobenefits to local communities via other ecosystems services, such as providing habitat for fish; supplying food, fibre, and traditional medicines; and reducing the impact of storms during extreme weather events. Seaweed aquaculture offers significant potential for developing low-carbon alternatives for food, feed, and many other applications.

Storage of carbon in the seabed has enormous theoretical potential to divert carbon from the atmosphere, but it currently faces significant technical, economic, and sociopolitical challenges (e.g., environmental safety) that must be adequately explored prior to deployment at the scale presented in this report. This report analyses the potential of seabed storage on the basis that it is the only ocean-based carbon, capture and storage (CCS) option that is currently being implemented at industrial scale (in Sleipner, Norway). However, given the technological, economic, social, and political barriers to implementing carbon storage in the seabed as a mitigation option, and the number of trade-offs and risks that must be reduced if ocean storage is to be widely used as a mitigation option, it is distinguished from the other four ocean-based mitigation options as it has certain dimensions that cannot be implemented in the short-term.

It is important to note that this report looks at the mitigation potential of each area of intervention at a global level. Not all options will be available or appropriate for all countries. Countries vary not only in their physical attributes (e.g., not all countries have mangroves), but also in their economic and social profiles (some countries have major fishing industries; some are high consumers of red meat; others engage actively in maritime trade). Therefore, while ocean energy and transport offer higher mitigation potential than nature-based solutions at the global level,

Table ES-2. Potential of Ocean-based Climate Action to Contribute to Current Policy for Closing the Emissions Gap in 2030 and 2050

	ANNUAL EMISSIONS ($GTCO_2E$)			GAP		TOTAL GHG MITIGATED $GTCO_2E$		% GAP CLOSED: 1.5°C		% GAP CLOSED: 2.0°C	
	CURRENT POLICY	1.5°C PATHWAY	2.0°C PATHWAY	1.5°C	2.0°C	MIN	MAX	MIN	MAX	MIN	MAX
Today	52	52	52	0	0	0	0	0.0	0.0	0.0	0.0
2030	58	28	39	30	19	1.3	3.5	4	12	7	19
2050	65	9	18	56	47	3.1	11.8	6	21	7	25

Source: Authors

Note: Estimates are base on comparision between multiple scenarios for annual emissions in 2020, 2030, and 2050. For those year, we compare '1.5°C', '2°C' and the 'Current policy' scenarios from UNEP 2018 and calculate the mitigation needed to fill the 'gaps' between the 'Current policy' and the '1.5°C', '2°C' respectivly. 'Min' refers to conservative ocean based mitigation potential, while 'Max' represents higher (more ambitious) potential projected in this paper. The total ocean-based mitigation (Table ES.1) was compared to the gap at 2030, and that at 2050, generating the percentage of the gap mitigated by ocean-based mitigation of GHG emissions.

restoration of vegetated coastal habitats ("blue carbon ecosystems") may provide the most viable and -cost-effective opportunity for contributing to global efforts to reduce GHG emissions for some individual countries or regions. In addition, the presence or absence of enabling factors, such as carbon market, may influence decisions and priorities, changing the economic potential of the options outlined in this report.

Wider Impacts of Ocean-based Climate Action

The IPCC Special Report on 1.5°C scenarios integrated an assessment of wider impacts; however, the ocean was not addressed comprehensively as a sector within this impacts analysis. This report aims to address this major knowledge gap by evaluating four sustainable development dimensions where wider impacts—beyond avoided or reduced emissions—may be expected:

- Environment (Impacts on marine and terrestrial biodiversity, water quality, land-use, coastal resilience, and adaptability of ecosystems and human settlements to climate change).
- Economy (Impacts on employment, household incomes, economic growth, supply of clean energy innovation, profit/revenue generated by firms, and supply of clean energy).
- Society (Impacts on human health outcomes, income inequality, quality of education, gender equity, poverty reduction, and food security targets).
- Governance (Effective, transparent and strong institutions, participation in global governance, strong national institutions, global partnership for sustainable development, capacity building)

The assessment was based on a review of literature and reveals that, while ocean-based mitigation options have both cobenefits and trade-offs, the cobenefits far outweigh the trade-offs.

Positive environmental impacts include high biodiversity benefits to marine and terrestrial ecosystems, higher ecosystem services (improvement in fisheries productivity and coastal tourism), reduced risk of ocean acidification, increased coastal resilience, and reduction in withdrawal/usage of water. Economic impacts or cobenefits that are positive include opportunities created by spillover from new or improved technologies, new local employment opportunities, energy savings from improvement in the design of vessels, and economic growth driven by a growing ocean-based economy.

Positive social impacts or cobenefits include reduced morbidity and mortality due to improved local air quality, positive health impacts from shifting diets away from meat towards low-carbon ocean-based protein, enhanced global food security, potential to ensure greater gender parity as ocean-based industries expand, and improved income opportunities and livelihoods in coastal areas.

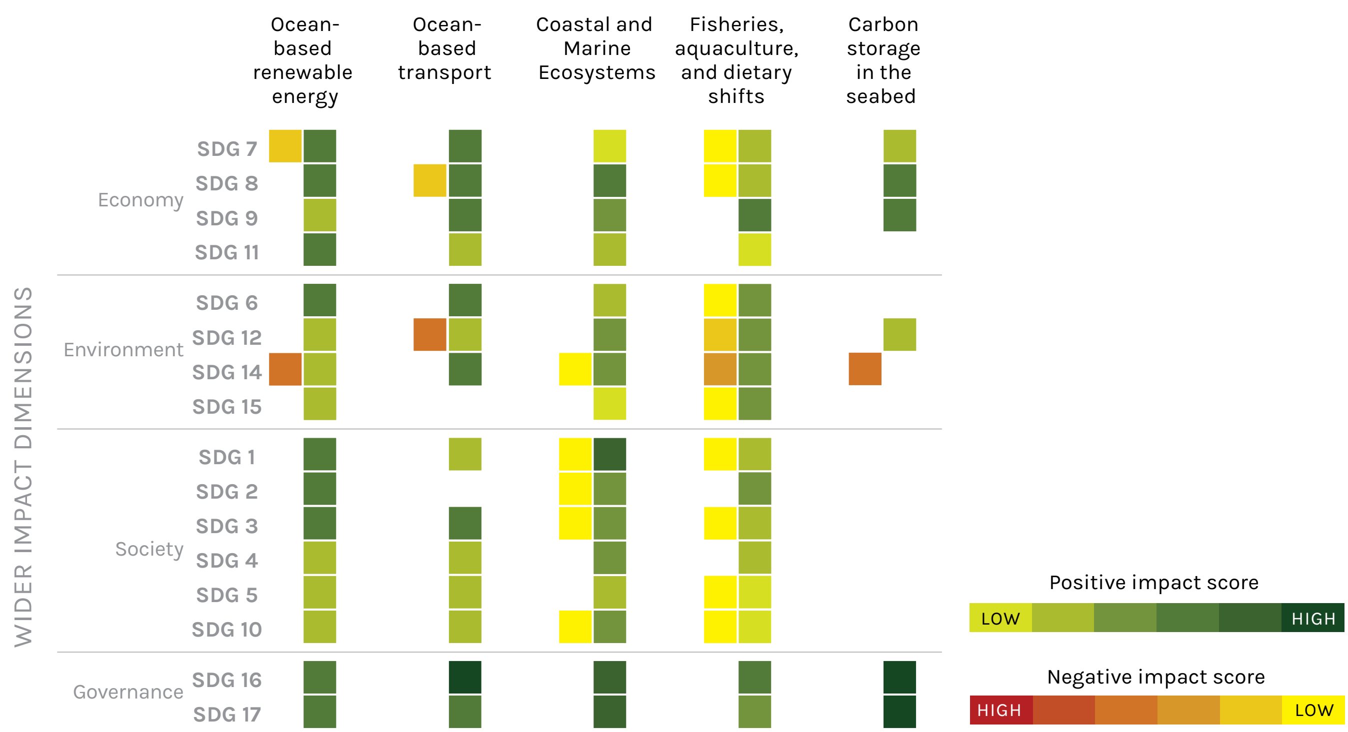
A number of negative effects or risks were identified when assessing the wider impacts of the mitigation measures on sustainable development, especially for the dimensions focusing on environment and society.

Policy design and implementation, along with contextual factors, play a key role in determining how mitigation options influence negative social outcomes. For example, mitigation options aimed at rebuilding fish stocks and other ocean biomass can negatively impact poverty reduction and employment targets and limit progress on food security targets in the short term. Lack of effective stakeholder engagement on "blue carbon" restoration projects (including exclusion of local community representatives from key international decision-making events) limit their access to ocean spaces and can lead to negative outcomes for small-scale fishers who heavily rely on local ecosystems for jobs, nutritional needs, and economic sustainability. In these instances, well-planned mitigation measures that follow best governance practices, with strong engagement of communities, nongovernmental organisations (NGOs), and governments, are essential to avoid worsening of inequalities and creation of new social injustices.

Environmental trade-offs and risks include the damage that can be done to coastal ecosystems or marine species by unplanned growth in coastal aquaculture or renewable energy installations. Seabed carbon storage approaches, if deployed unwisely, could contribute to ocean acidification and damage ocean ecosystems by impacting chemical, physical, and ecological processes at a large scale. While some of these risks can be adequately addressed via stakeholder engagement, inclusive management policies, careful monitoring, and effective marine planning, others will require further research on their implications. In some instances, there will be a need for significant action on the part of governments to ensure that negative impacts are reduced or resolved. Concerted action to address these negative impacts will help enhance the net positive outcome.

When looking at the five ocean-based areas as a whole, coastal and marine ecosystems, fisheries and aquaculture, and ocean energy have a positive impact on the largest number of sustainable development dimensions. When looking at individual mitigation options within the five ocean-based areas, nature-based interventions (especially protection and restoration of mangroves, seagrass and salt marsh) and offshore wind energy positively impact the largest number of sustainable development dimensions. The analysis showed that all ocean-based mitigation options will need strong national institutions, engagement of business and industry, and community involvement and international cooperation to ensure their planned implementation maximises the positive impact and limits the negative impact on sustainable development dimensions. The results of this analysis is shown in Figure ES-5.

Figure ES-5. Summary of Wider Impact of Ocean-based interventions on Sustainable Development Dimensions



List of Sustainable Development Goals reviewed:

Source: Authors

Notes: Wider-impact dimensions cover various sustainable development dimension indicators as well as 2030 Sustainable Development Goals (SDG). The figure shows the relative strength of the relationship between the ocean-based areas of interventions and the SDGs. The relationship between each ocean-based mitigation option and SDG is given a linkage score, positive scores shown by green boxes and negative scores shown by yellow/red boxes. Scores range from +3 (indivisible) to −3 (cancelling) (Nilsson et al. 2016). A zero score (no bar and no colour) means no impact was found in this review of the literature. For intervention areas where there is more than one mitigation option, an average of the linkage score is taken among the mitigation options in that area. Further information on the linkage scores and the associated confidence levels are provided in the Annex.

Delivering the Mitigation Potential of the Ocean

There is a small, but important window of opportunity within which the "Current Policy" emissions trajectory can be directed towards a pathway that is consistent with achieving the 1.5°C and 2.0°C temperature goals set by the Paris Agreement. While much of the required emission reductions must come from deep cuts within terrestrial-based activities, including the use of fossil fuel, this report identifies major ocean-based opportunities that could play a critical role in the transition to a low-carbon future and safer climate.

Achieving the mitigation potential identified in this report will not be possible without significant investment in research and development. It will also be necessary to provide strong incentives to align financial flows with the needs of the mitigation action opportunities available. Governments must send policy signals. Table ES-3 summarises the policy, research, and technology priorities for the short and medium term to support action in each of the areas of ocean-based climate action examined in this report.

One of the first opportunities that governments will have to comprehensively integrate ocean-based mitigation options into national plans and strategies for climate change is the reconsideration and updating of NDCs in 2020. This is an extremely important moment, as emphasised by the IPCC (2018): the chances of "failing to reach 1.5 degrees Celsius [will be] significantly increased if near-term ambition is not strengthened beyond the level implied by current NDCs." Given the consequences of failing to limit global average temperature rise to 1.5°C, or at least to "well below" 2.0°C, it is of great importance that actions begin immediately.

Table ES-3. Short- and Medium-term Policy, Research, and Technology Priorities Necessary to Deliver on Mitigation Potential of Ocean-based Climate Action Areas

	OCEAN-BASED ENERGY		
	POLICY	RESEARCH	TECHNOLOGY
Short-term Priorities (2020–2023)	▪ Undertake marine spatial planning ▪ Develop national targets to increase the share of renewable energy in the national energy mix ▪ Provide a stable economic and regulatory framework to stimulate investments in required infrastructure for an accelerated deployment of ocean-based energy systems	▪ Understand the impacts (positive and negative) of both fixed and floating offshore wind installations on marine biodiversity ▪ Undertake a detailed mapping of global renewable energy resources and technical potential	▪ Advance storage capacity and design ▪ Improve performance, reliability, and survivability, while reducing costs
Medium-term Priorities (2023–2025)	▪ Develop strategic national roadmaps for zero-carbon economy in 2050 ▪ Develop appropriate legislation and regulation	▪ Understand the potential benefits of co-location with other ocean-based industries (e.g., desalination plants and aquaculture) ▪ Explore the potential for installing large scale floating solar installations at sea (under wave conditions) ▪ Quantify the potential of Ocean Thermal Energy Conversion (OTEC)	▪ Advance technology that can move technologies into deeper water sites (e.g., development of floating offshore wind technologies) to open access to larger areas of energy resources

Table ES-3. Short- and Medium-term Policy, Research, and Technology Priorities Necessary to Deliver on Mitigation Potential of Ocean-based Climate Action Areas (continued)

	OCEAN-BASED TRANSPORT		
	POLICY	RESEARCH	TECHNOLOGY
Short-term Priorities (2020–2023)	▪ Redesign the Energy Efficiency Design Index (EEDI) formula to avoid vessels being suboptimised for the test only, to ensure that instead vessels are being optimised for minimised fuel consumption in real operation at sea. ▪ Adopt policy measures to go beyond Ship Energy Efficiency Management Plan (SEEMP) to incentivise the maximisation of operational efficiency of new and existing ships ▪ Adopt policies that can reduce the broader GHG emissions of shipping instead of CO_2 only, including well-to-tank emissions (WTW) of ship fuels	▪ Identify and rectify of market and nonmarket barriers and failures to enable larger uptake of more energy-efficient technologies and cooperation patterns ▪ Ensure continuous research on ship design, including hull forms and propulsion, with a focus on reducing energy usage per freight unit transported ▪ Increase focus on utilisation of wind, waves, ocean currents, and sun to reduce use of externally provided energy, i.e., both the carbon and non-carbon-based fuels carried on board	▪ Develop the necessary high efficiency hull forms and propulsion methods ▪ Develop and implement hybrid power systems, including combustion engines, fuel cells, and batteries technologies ▪ Develop and implement wind assistance technologies ▪ Develop more advanced weather routing systems to better utilise wind, waves, ocean currents, and tides to reduce the use of both carbon and non-carbon fuel carried on board
Medium-term Priorities (2023–2025)	▪ Develop policy to enable the business case for the adoption of low and zero carbon fuels by shipping (e.g. a carbon price) ▪ Commit to the timetable for shipping's transition to low- and zero-carbon fuels ▪ Develop national incentives for decarbonising domestic transportation ▪ Commit to decarbonisation of national energy systems faster or as fast as the transition in the international fleet	▪ Develop cost-effective production of low- and zero-carbon fuels, both from renewables and from carbon based in combination with carbon capture and storage (CCS) ▪ Develop cost-efficient hybrid setups on seagoing vessels to utilise the best of combustion, fuel cells, and batteries to reduce fuel consumption and local pollution ▪ Ensure safe storage and handling on ships and at the ship-shore interface of hydrogen/ammonia ▪ Ensure safe and efficient use of hydrogen and ammonia in internal combustion engines and fuel cells	▪ Advance technologies for producing hydrogen, both from renewables and carbon-based fuels ▪ Invest in technologies to store hydrogen (including cryogenic storage of liquid hydrogen, or carriers able to store at high-energy density) ▪ Invest in fuel cells for conversion of future fuels into on-board electricity, and internal combustion engines designed to operate on hydrogen/ammonia

Notes: Energy Efficiency Design Index (EEDI) of the International Maritime Organization (IMO).

Ship Energy Efficiency Management Plan (SEEMP) of the IMO.

Table ES-3. Short- and Medium-term Policy, Research, and Technology Priorities Necessary to Deliver on Mitigation Potential of Ocean-based Climate Action Areas (continued)

	COASTAL AND MARINE ECOSYSTEMS		
	POLICY	RESEARCH	TECHNOLOGY
Short-term Priorities (2020–2023)	▪ Enhance protection measures for mangroves, seagrass, salt marsh, and seaweed beds to prevent any further losses due to human activities ▪ Provide incentives for restoration of "blue carbon" ecosystems, through payments for ecosystem service schemes, such as carbon and nutrient trading credits ▪ Include quantified nature-based solutions within nationally determined contributions (NDCs) and other relevant climate policies for mitigation and adaptation ▪ Protect coral reefs as important and integrated coastal defence systems for ensuring the protection of coastal blue carbon ecosystems	▪ Undertake national-level mapping of blue carbon ecosystems ▪ Address biophysical, social, and economic impediments to ecosystem restoration to develop restoration priorities, enhance incentives for restoration, and increase levels of success ▪ Improve the IPCC guidance for seagrasses and other wetland ecosystems ▪ Develop legal mechanisms for long-term preservation of blue carbon, especially in a changing climate ▪ Understand the impacts of climate change on rates of carbon capture and storage, or the potential for restoration	▪ Advance biorefining techniques, allowing sequential extraction of seaweed products
Medium-term Priorities (2023–2025)	▪ Enhance and adopt carbon accounting methodologies for mangroves, seagrasses and salt marsh within national GHG inventories (IPCC 2013) ▪ Improve methods for monitoring mitigation benefits to enable accounting within national GHG inventories, and biennial transparency reports (BTRs)	▪ Undertake global-scale map of seaweed ecosystems ▪ Develop IPCC-approved methodological guidance for seaweed ecosystems ▪ Develop methods to fingerprint seaweed carbon beyond the habitat	▪ Develop and pilot offshore and multiuse sites, including seaweed aquaculture, in the open ocean

Table ES-3. Short- and Medium-term Policy, Research, and Technology Priorities Necessary to Deliver on Mitigation Potential of Ocean-based Climate Action Areas (continued)

	FISHERIES, AQUACULTURE, AND DIETARY SHIFTS		
	POLICY	RESEARCH	TECHNOLOGY
Short-term Priorities (2020–2023)	▪ Eliminate harmful fisheries subsidies (SDG14.6) ▪ Strengthen international tools to eliminate IUU fishing (SDG14.5) ▪ Avoid the transport of fish by air ▪ Reduce discards ▪ Reduce and eliminate hydrochlorofluorocarbons (HCFCs) in refrigerants ▪ Create incentives for shifting diets towards low-carbon protein (e.g., fish) and other food (e.g., seaweed) diets ▪ Create incentives to improve fishery management ▪ Create incentives for lower trophic-level aquaculture ▪ Devise sustainable finance mechanisms for small-scale fishery transitions to sustainable fishing	▪ Develop disaggregated global data sets for GHG emissions from wild catch fisheries and marine aquaculture ▪ Impacts of scaling marine aquaculture and associated sustainability considerations (e.g., low carbon and climate resilient, environmentally safe) ▪ Enhance understanding of how climate change and ocean acidification will impact aquaculture and fisheries	▪ Extend surveillance technologies for tracking fishing in the ocean and along coastal areas
Medium-term Priorities (2023–2025)	▪ Create incentives to switch from high-carbon land-based sources of protein to low-carbon ocean-based sources ▪ Improve fisheries management to focus on optimising biomass per harvest	▪ Explore potential impact of a carbon tax on red meat and other carbon intensive foods	▪ Develop and bring to scale high-technology digital aquaculture

Table ES-3. Short- and Medium-term Policy, Research, and Technology Priorities Necessary to Deliver on Mitigation Potential of Ocean-based Climate Action Areas (continued)

	SEABED CARBON STORAGE		
	POLICY	RESEARCH	TECHNOLOGY
Short-term Priorities (2020–2023)	▪ Invent in pilot projects to further explore potential environmental impacts ▪ Incentivise public/private partnerships	▪ Map global geophysical potential ▪ Understand the impacts of long-lasting containment of CO_2 in a deep seafloor environment	▪ Few major technical advances are required as seabed storage is already deployed at industrial scale
Medium-term Priorities (2023–2025)	▪ Develop national strategies and targets ▪ Develop regulatory frameworks to ensure environmental impact assessments and associated precautions are put in place.	▪ Understand the impacts of long-term storage on marine ecosystems ▪ Explore the integrity of long-term storage technologies (leakage)	▪ Scale up technologies in ways that are economically feasible

Source: Authors

Introduction

Efforts to protect the ocean and its vitally important ecosystems cannot be considered in isolation from the challenge of stabilising the global climate. To secure the long-term health of the ocean and the livelihoods and economies that depend on it, atmospheric concentrations of GHGs must be urgently reduced. This report outlines a suite of options for how the ocean and coastal regions can be a part of the solution set.

Climate Change Is a Key Threat to Ocean Systems

Climate change is one of the greatest challenges in history. The concentrations of atmospheric carbon dioxide (CO_2) and other greenhouse gases (GHGs) are increasing, causing rapid rates of warming on land and in the ocean. These changes are creating unprecedented challenges for natural and human systems (IPCC 2018). If unchecked, these changes will undermine and destabilise economies by driving increasingly unmanageable and dangerous impacts on the biosphere, human health, and global economies (Sumaila et al. 2019).

The ability of humans to obtain food and livelihoods from the ocean is being degraded as a result of these changes.

Prior to the industrial period (i.e., before ~1850), the global carbon cycle was in net balance, with CO_2-producing processes (e.g., respiration) being equal to CO_2-consuming processes such as photosynthesis and geochemical weathering. This balance resulted in the carbon cycle being relatively stable for thousands of years. Since the beginning of the industrial period, however, emissions of GHGs have grown rapidly as humanity felled forests, cleared land for agriculture, and began to exploit reservoirs of unoxidised carbon in fossil fuels. Rising concentrations of atmospheric CO_2 have already driven major changes to our planet. The global mean surface temperature (GMST) of the earth reached 1°C above the preindustrial level in 2017 (IPCC 2018).

The evidence accumulated by the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2014, 2018, 2019) suggests that the world will continue to face accelerating and life-threatening challenges if the GMST is not kept well below 2°C above the preindustrial period (conditioned before ~1850). This science-based conclusion led to the explicit goals of the Paris Climate Agreement (UNFCCC 2015) and subsequently the IPCC special report on the implications of 1.5°C warming above the preindustrial period (IPCC 2018).

The Paris Agreement goals aim to keep "global average temperature to well below 2°C above preindustrial levels and pursuing efforts to limit mean global temperature increase to 1.5°C above preindustrial levels" (UNFCCC 2015).

The increased concentration of atmospheric CO_2 has resulted in ocean warming as well as ocean acidification, which is a consquence of the increased absorption of CO_2 by the ocean (IPCC 2014). Changes in the temperature and chemistry of the ocean have had serious impacts on a wide range of biological phenomena, including the survival, reproduction, and growth of marine organisms. There is considerable evidence that the ocean is also becoming more stratified, which is affecting the mixing of the water column, and consequently the availability of nutrients and gases such as oxygen (Hoegh-Guldberg et al. 2014; Pörtner et al. 2014).

The ability of humans to obtain food and livelihoods from the ocean is being degraded as a result of these changes. While the intention of this report is not to review comprehensively the impacts of climate change on the ocean, which has been done more extensively elsewhere (IPCC 2014, 2018, 2019), it notes that a few regions do show "positive" outcomes from climate change on a short-term basis, such as the increased biomass caught by high-latitude fisheries over recent decades (Sundby et al. 2016). The great majority of oceanic changes from polar to equatorial regions (and from deep to shallow areas) are, however, negative (IPCC 2014, 2018; Gattuso et al. 2018).

The recent IPCC special report on 1.5°C (IPCC 2018) concluded that there was still time to limit global temperature rise to the vicinity of 1.5°C above preindustrial levels (IPCC 2018), if current efforts were escalated. This would require limiting further accumulated emissions of CO_2 after 2018, to approximately 420 gigatonnes of carbon dioxide equivalent ($GtCO_2$), which essentially gives the global community around 10 years at the current rate of annual emissions to bring fossil fuel emissions to net zero by mid-century (IPCC 2018). Significantly, however, limiting warming to 1.5°C above preindustrial levels will require annual emissions of CO_2 to fall below zero by 2050 (i.e., "negative emissions") (IPCC 2018). Achieving this goal will require additional novel technologies for removing large amounts of CO_2 from the atmosphere.

The Ocean Is Part of the Solution to Climate Change

Attention has only recently been drawn to the possible role of the ocean, with its vast size and productivity, in mitigating CO_2. The ocean already plays a dominant role in the global carbon cycle and is responsible for taking up 25 to 30 percent of anthropogenic CO_2 released into the atmosphere.

While changes to the carbon cycle are creating daunting challenges for the ocean and the ocean-based economy, the ocean-based economy offers opportunities for mitigating GHG emissions and hence contributing to land-based efforts to fight climate change. While the focus on ocean and coastal-based solutions for mitigating climate change is increasing (e.g., IPCC 2014, 2018; Gattuso et al. 2018), a comprehensive analysis of ocean-based mitigation options and their potential to contribute to reducing atmospheric greenhouse gases has so far been limited.

This report addresses this analytical gap through a detailed analysis of the opportunities as well as the challenges associated with implementing a series of ocean-based mitigation options. Each option is considered in the context of its role as a key sink or source of CO_2 and other GHGs.

In particular, this report assesses the mitigation potential and associated impacts (cobenefits and trade-offs) of a series of options in five prominent ocean-based areas of intervention:

- Ocean-based renewable energy, including offshore wind and other energy sources, such as wave and tidal power.
- Ocean-based transport, including freight and passenger shipping.
- Coastal and marine ecosystems, including protection and restoration of mangroves, salt marshes, seagrass beds, and seaweeds, as well as aligned ecosystems such as coral reefs which are important coastal barriers to waves and storms.
- Fisheries, aquaculture, and dietary shifts away from emission intensive land-based protein sources (e.g., red meat) towards low carbon ocean-based protein and other sources of nutrition.
- Carbon storage in the seabed.

Table 1 describes each area of ocean-based climate action and its associated mitigation options.

The ocean-based economy can provide significant opportunities for mitigating GHG emissions and contribute to land-based efforts to fight climate change.

Table 1. Mitigation Options in Five Areas of Ocean-based Climate Action

AREA OF ACTION	MITIGATION OPTIONS	DESCRIPTION
Ocean-based renewable energy	Scaling up harnessing of offshore wind	Fixed and floating offshore wind turbine installations
	Scaling up use of ocean energy	Energy extracted from ocean waves, tides, currents, salinity, and temperature differences. Floating photovoltaic solar energy
Ocean-based transport	Reducing emissions from domestic shipping	Following the International Maritime Organization (IMO) definition: shipping between ports of the same country; includes ferries
	Reducing emissions from international shipping	Following the IMO definition: shipping between ports of different countries. International shipping excludes military and fishing vessels; includes bulk carriers, oil tankers, and container ships
Coastal and marine ecosystems	Restoration of mangroves, salt marshes, and seagrass beds	Sequestration potential gained from the restoration of lost and degraded coastal ecosystems. Coastal wetland systems include mangroves, salt marshes, and seagrass beds, plus conservation and restoration of adaject islands, reefs and mudflats to slow the rate of erosion of coastal wetlands
	Avoided anthropogenic loss and degradation of mangroves, salt marshes, and seagrass beds)	Preventing the release of the high levels of sequestered carbon in soils and vegetation of coastal wetlands by protecting these ecosystems and avoiding further degradation.
	Upscaling of seaweed production via aquaculture	Sequestration potential through seaweed aquaculture, primarily via farmed seaweed products substituting for other products with higher GHG footprint, or new application with no or minimal footprint
	Restoration and protection of seaweed habitats	Sequestration potential from the restoration of degraded (and protection of) intact seaweed habitats
	End overexploitation of ocean biomass to support recovery of biodiversity and increase biomass	Role of marine mammals and fish stocks in the ocean carbon cycle, including death and sinking to the seabed floor
Fisheries, aquaculture, and dietary shifts	Reducing emissions from fishing vessels	Emissions from fuel use for inland, coastal, and deep-sea fishing (wild capture)
	Reducing emissions from aquaculture	Life-cycle emissions from aquaculture (including, if possible, supporting activities such as production of fish meal and fish oil)
	Increasing share of ocean-based proteins (from fish and other marine life) in diets	Switching emission intensive land-based sources of protein (notably beef and lamb) for low carbon ocean based sources of protein
Carbon storage in the seabed	CO_2 storage in the seabed	Geological storage offshore of captured CO_2 in the seabed.

Source: Authors

Methodology

This report assesses each option in the context of "mitigation potentials" (Figure 1). We explore the size of each potential, considering geophysical, technical, economic, and socio/political considerations that may affect their feasibility.

We identified mitigation options in each intervention area and assessed the scientific and research literature on the global contribution of each one to reducing atmospheric emissions in line with the goals of mean 1.5°C and 2.0°C pathways by 2030 and 2050. The year 2030 was chosen to highlight the potential benefits of including relevant ocean-based mitigation options in new or updated nationally determined contributions (NDCs) submitted by 2020. The year 2050 was chosen to highlight the possible contribution of ocean-based mitigation options to long-term strategies of reducing emissons to net zero by mid century (IPCC 2018).

GHG mitigation options in each intervention area were evaluated for their technical, economic, social, and political implications when deployed to reduce GHG emissions (in $GtCO_2e$) by 2030 and 2050. A lower and higher range was estimated in each case to assess how particular ocean-based mitigation options might be modified, or restrained, by other important issues (see the section "Wider impacts of Ocean-based Actions" for further details). This assessment also considered the implications for near-term United Nations Sustainable Development Goal (SDG) targets and indicators.

Underlying assumptions and approach

Because this report collates multiple analyses, the underlying assumptions and discussion will differ in some cases. Important examples include the size of future baseline emissions and assumptions about the costs of key technologies and inputs. These are discussed and outlined in more detail in subsequent sections of the report.

The following approach was applied to each ocean intervention area to ensure consistency and comparability:

- Identify the baseline emission projections for 2030 and 2050, based on literature review.
- Outline the mitigation options per intervention area that can be implemented by 2030 and by 2050 (including explicitly identified assumptions).
- Identify the range of abatement potential for each mitigation option in 2030 and 2050, either directly from the literature or through calculations based on available data in the literature.

The range of abatement potential estimates is presented to reflect uncertainties in the mitigation potential of both the intervention areas and at the global level.

Figure 1. Determining Mitigation Potential

Source: Authors

Note: While the geophysical scale of a mitigation opportunity may be large, each mitigation opportunity must be considered through technical (i.e., its feasibility) and economic (i.e., its cost) lenses, as well as for social and political considerations (i.e., do people want it). A high geophysical potential might exist, given a lack of technical, economic, or sociopolitical constraints. In reality, a much smaller amount of a mitigation potential tends to be available after these considerations.

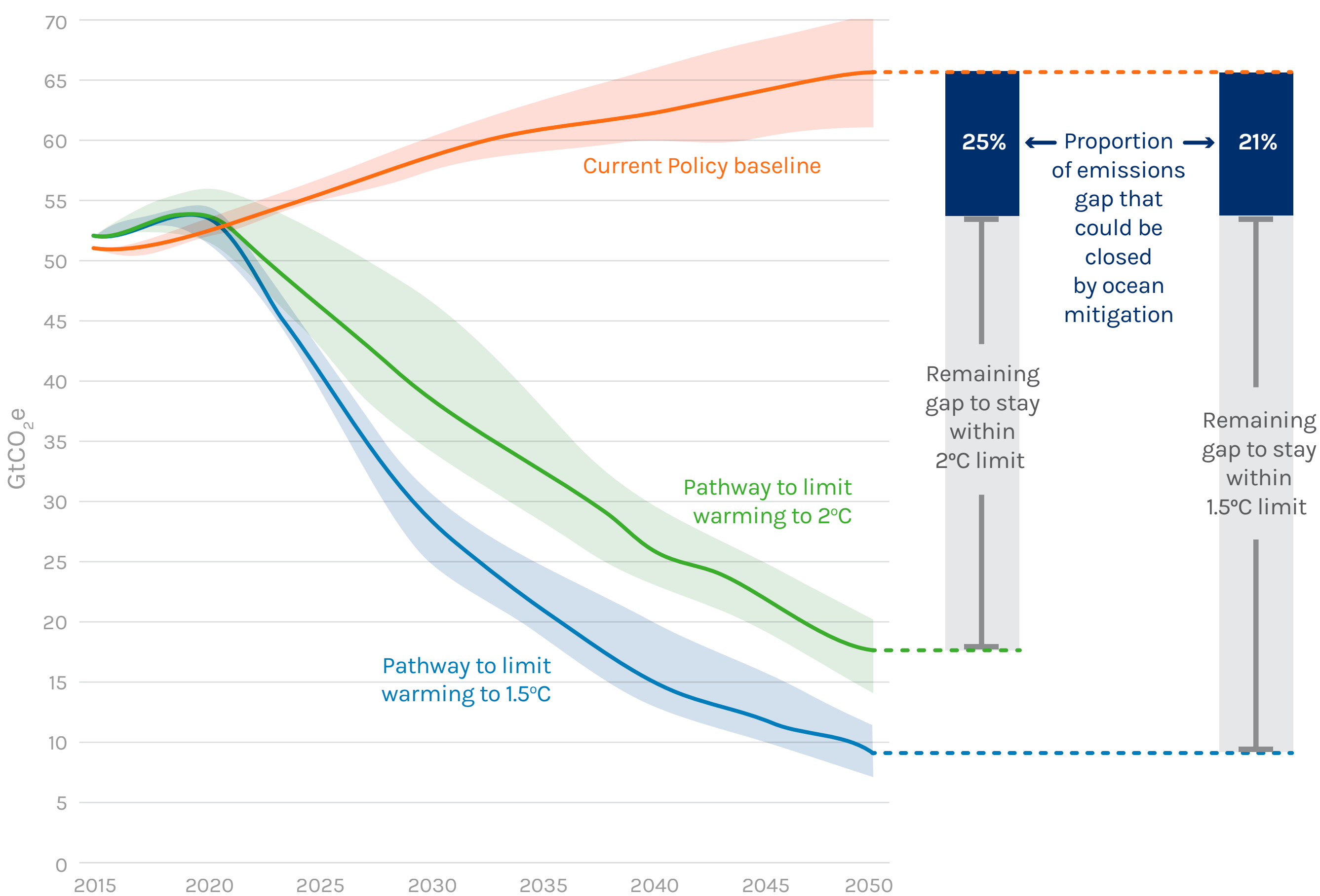
Determining the contribution of ocean-based climate action to closing the emissions mitigation gap

The calculated mitigation potential from each of the five ocean-based climate action areas were added together to produce a total GHG mitigation potential for the years 2030 and 2050. Each mitigation option was explored in the context of the contribution made to closing the emissions gap in 2030 and 2050 between the "Current Policy" (UNEP 2018) emissions pathway and pathways consistent with achieving the 1.5°C and 2.0°C goals of the Paris Agreement (UNFCCC 2015; IPCC 2018). The Current Policy pathway was chosen to reduce the potential for double counting and a median value was calculated from the high and low values provided in the Climate Action Tracker. The intervention areas and mitigation options that are discussed here are generally outside Current Policy and hence should be additional except for the chance of a very small overlap, which is accounted for in the ranges provided for each mitigation option.

The Current Policy trajectory is based on estimates of 2020 emissions that consider projected economic trends and Current Policy approaches (including policies at least through 2015), with estimates based on either official data or independent analysis (UNEP 2018). The pathways consistent with 1.5°C and 2.0°C above the preindustrial period were taken from mean values summarised from the scientific literature in the most recent UN Environment Programme Gap Report (UNEP 2018). The 1.5°C trajectories reach an emissions peak around 2020, then rapidly fall to approximately 45 percent below 2010 levels by 2030 (to ~28 $GtCO_2e$/year), reaching close to net zero by 2050 (~0-9 $GtCO_2e$/year) (Figure 2). Trajectories for 2.0°C show emissions decline by approximately 25 percent by 2030 (to ~40 $GtCO_2e$/year) in most pathways (10–30 percent interquartile range), reaching net zero by around 2070 (2065–2080 interquartile range). In the case of the Current Policy pathway, GHG emissions will rise from ~50 $GtCO_2e$/year in 2020 to ~65 $GtCO_2e$/year by 2050 (UNEP 2018). These extrapolated levels of emissions under Current Policy are consistent with the projections of the IPCC (IPCC 2018).

The pathways consistent with 1.5°C and 2.0°C above the preindustrial period were taken from mean values summarised from the scientific literature in the most recent UN Environment Programme Gap Report.

Figure 2. Contribution of Ocean-based Mitigation Options to Closing the Emissions Gap in 2050



Source: Adapted from UNEP 2018, Climate Action Tracker (2018)

Ocean-based Renewable Energy

This section analyses the potential mitigation impact of using ocean-based renewable energy sources of power (e.g. offshore wind and energy extracted from waves and tides) to displace coal fired power plants.

Many technologies are currently being assessed for their ability to harvest renewable energy from the ocean. Sources of power include offshore wind and energy extracted from waves and tides. Energy within the ocean can also be extracted from salinity and temperature gradients (e.g., by ocean thermal energy conversion [OTEC] or by heat pumps for heating and cooling). Lastly, floating solar photovoltaic (PV) systems are beginning to emerge in marine environments.

While the overall proportion of global electricity generation from ocean-based sources is currently less than 0.3 percent (IEA 2019), large projects are underway, and investments are being made in the full range of ocean-based energy options. These investments include promising options, such as floating PV panels (World Bank 2018) and strategies to meet sustainable energy demands of a growing blue economy. There is also potential to unlock co-location benefits with other offshore industries; for example, ocean-based energy could meet the increasing demand for energy-intense desalinated seawater (USDE 2019) or support marine aquaculture operations.

Mitigation Potential

Electricity and heat generation accounts for about 25 percent of global emissions (IPCC 2014). Mitigation opportunities include replacing fossil-based electricity supplies with renewable sources and electrification, and reducing demand from end-consumers in the transport, industry, and building sectors, and from desalination plants. Depending on the scale and pace of technological development, up to 75 percent of anthropogenic GHG emissions (excluding some emissions such as those from the agriculture sector and land clearing) in a business-as-usual (BAU) trajectory can be considered as the target for avoidance through electricity generation with renewable sources.

Renewable energy both from the ocean and from land is therefore well positioned to play an increasing role in sustainable development.

Thermal power plants (using coal, oil, or natural gas) and combustion engines can convert only a fraction of thermal energy into electricity or kinetic energy. Consequently, only a fraction (typically one-third) of primary energy supplied by fossil fuels has to be replaced by renewable sources (GEA 2012). Many thermal plants are also dependent on large volumes of freshwater for cooling. In addition, recent studies such as Grubler et al. (2018) show that extensive use of renewable energy in combination with energy efficiency measures could achieve global low energy demand (LED) scenarios without loss of welfare and well-being. Renewable energy both from the ocean and from land is therefore well positioned to play an increasing role in sustainable development.

Gross electricity generation in 2050 is projected to be between 42,000 and 47,000 TWh (TWh= terawatt hours; 1 TWh/year corresponds to continuous delivery of a power of 0.114 gigawatts (GW) (IEA 2017). The ocean offers abundant resources in excess of global energy demand, but economic constraints limit the contribution of energy generated offshore.

We consider two ocean-based renewable energy technologies—offshore wind (OSW) generation and other forms of ocean-based renewable energy (ORE), such as wave and tidal power. Estimates of the potential for electrical energy generated by OSW in 2050 are in the range of 650 to 3,500 TWh/year. Estimates of potential from ORE technologies in 2050 are in the range 110 to 1,900 TWh/year.

We find that if ocean-based renewable energy technologies displace coal-fired power plants, CO_2 emissions can be reduced by between 0.65 and 3.50 $GtCO_2e$/year in 2050 in the case of OSW, and by between 0.11 and 1.90 $GtCO_2e$/year in 2050 in the case of ORE. Total emission reductions would amount to 0.76 to 5.40 $GtCO_2e$/year in 2050.

Alternatively, if energy technologies with emissions equal to the present global mean for the electricity sector of 0.46 kg CO_2e/kWh were displaced, OSW could contribute a reduction of 0.30 to 1.61 $GtCO_2e$/year in 2050, and ORE could avoid 0.05 to 0.87 $GtCO_2e$/year in 2050.

This mitigation potential of ocean-based renewable energy generation is presented in Table 2.

Table 2. Mitigation Potential of Offshore Wind and Other Ocean-based Renewable Energy Technologies in 2030 and 2050

OCEAN-BASED CLIMATE ACTION AREA	MITIGATION OPTIONS	DESCRIPTION		2030 MITIGATION POTENTIAL ($GTCO_2E$/YEAR)	2050 MITIGATION POTENTIAL ($GTCO_2E$/YEAR)
Ocean-based renewable energy	Scaling up offshore wind	Fixed and floating offshore wind installations	coal displacement	0.17–0.23	0.65–3.50
			displacing current generation mix	0.08–0.11	0.30–1.61
	Scaling up other forms of ocean energy	Energy carried by ocean waves, currents, tides, salinity, and ocean temperature differences	coal displacement	0.006–0.016	0.11–1.90
			displacing current generation mix	0.003–0.007	0.05–0.87
TOTAL			coal displacement	0.18–0.24	0.76–5.4

Source: Author

Notes: To establish estimates of projected energy generation in 2030, we determined the Compound Annual Growth Rate (CAGR) between 2018 energy generation and projected 2050 energy generation (separate CAGR for OSW and ORE). The CAGR is assumed constant through 2050. The per annum CO_2 mitigation potential in 2030 and 2050 is then derived from the energy generation (see Methodology section). The lowest and highest values were used to calculate the range across "coal displacement" and "displacing current generation fuel mix" for 2030 and 2050. The range for "coal displacement" was chosen for the final totals.

Methodology

The GHG mitigation potential of ocean renewable energy sources is estimated on the basis of substituting fossil fuels used in electricity generation sources (Gattuso et al. 2018). Offshore wind, in particular, and other ocean-based renewable energy sources have theoretical potentials that are many times larger than present global electricity demand, and also larger than future energy demand, assuming full electrification (Bosch et al. 2018) (See Box 1). The more interesting challenge is the cost competitiveness of these technologies. Different assessments and estimates of future costs explain much of the range in potential emissions reduction contributions from offshore and ocean-based renewable energy (Box 1 and Table 3).

Several studies have included offshore wind and other ocean renewable energy technologies in scenarios projecting future energy demand and generation fuel mix. These studies span a range of future carbon emission scenarios for 2050 and are typically presented relative to a business-as-usual, control, or reference scenario. We reviewed 15 scenarios for 2050 in which ocean renewable energy technologies were considered (Table 3). Here, we present the future generation mix of ocean energy technologies associated with the low-emissions scenarios (2050 emissions ≤14 Gt), compiled from these studies.

The methodology used to produce the energy contribution potentials was to combine the range of scenarios summarised in Table 3 with the difference in CO_2 emissions between energy sources. We recognise that the future evolution of the energy mix, and therefore the substitution effect of ocean-based energy, will depend on a broader set of global development trends, including costs of technologies in other parts of the energy sector, such as hydrogen conversion technologies and energy efficiency.

By calculating mitigation potentials for substitution of coal and for substitution of an energy source with CO_2 emissions corresponding to the present global average, we expect to bracket a realistic range.

Table 3. Summary of Energy Scenarios Reviewed for Ocean-based Renewable Energy

SCENARIO	OSW GENERATION (TWH/YR)	ORE GENERATION (TWH/YR)
2018 (30) (Bahar, 2019)	53	1.2
2050 Reference (50). Same fraction as current, for assumed 2050 electricity demand of 50,000 TWh	112	2.5
2050 Drawdown Reference (50) (Project Drawdown, 2017)	57.2	2.1
2050 IEA WEO 2009 (45) (IEA, 2009)	555	25
2050 Teske (Reference (45) (Teske et al. 2011)	805	25
2050 IEA RTS (40) (IEA, 2017)	651	108
2050 ETP BLUE MAP (14) (IEA, 2010)	1568	133
2050 IEA 2DS (13) (IEA, 2017)	1436	536
2050 Teske E[R] (10) (Teske et al. 2011)	2711	678
2050 IEA B2DS (4.7) (IEA, 2017)	1531	637
2050 Teske Adv E[R] (3.7) (Teske et al. 2011)	3469	1943
2050 DRAWDOWN Plausible (Project Drawdown, 2017)	2078	1486
2050 DRAWDOWN (Project Drawdown, 2017)	3029	1745
2050 DRAWDOWN Optimum (Project Drawdown, 2017)	3159	1823
2050 OES Vision (OES, 2017)	–	1051
2050 IRENA (IRENA, 2018a)	1822	

Source: Authors

Note: OSW = Offshore wind; ORE = Ocean-based renewable energy.

Ocean-based technologies offer a renewable energy solution with low life-cycle carbon emissions (Table 4). Ocean-based renewable energy technologies are thus able to displace emissions associated with fossil-based electricity generation. The greatest emissions mitigation is obtained when displacing high-emitting electricity-generating technologies such as coal, which accounts for approximately 38 percent of global electricity generation (IEA 2019). The use of ocean-based technologies has the potential to displace approximately 0.35 to 0.9 kgCO_2e per kWh electricity produced, depending on the source of electricity being displaced.

Table 4. Estimated Life-Cycle Emissions of Energy Generation Technologies

ENERGY TECHNOLOGY	LIFECYCLE CARBON EMISSIONS KG CO_2E/KWH	LIFECYCLE CARBON EMISSION RELATIVE TO CURRENT MIX (%)
Coal	1.0 (0.67-1.7)	217
Natural Gas	0.476 (0.31-0.99)	103
Current mix	0.46	–
Solar PV	0.054 (0.019-0.2)	12
Concentrated Solar Power	0.025 (0.007-0.24)	5.4
Nuclear	0.016 (0.008-0.22)	3.5
Onshore wind	0.012 (0.002-0.088)	2.6
Offshore wind	0.012 (0.005-0.024)	2.6
Ocean	0.008 (0.002-0.022)	1.7

Source: OpenEI, 2019

Note: Bracketed values represent the range of reported emissions.

Box 1: Current Global Status of Implementation and Future Deployment

Current Global Status of Implementation

OFFSHORE WIND ENERGY

By the end of 2018, the total installed global capacity of wind energy amounted to 564 GW, of which 23 GW was offshore (IRENA 2019a). Annual offshore electricity production amounted to about 77 TWh (IEA 2018). Bottom-fixed wind turbines in shallow water depth (<40m water depth) dominate. Deepwater, floating support structures are used in only one wind farm, a 0.03 GW wind farm off the east coast of Scotland. Much of the available information on offshore wind used in this report (in particular experience with costs) is taken from Europe, where the majority of offshore wind installations are located. However, it is anticipated that Asia, especially China, will significantly increase installed offshore wind capacity in coming years. The specific rate of growth is, however, difficult to assess.

Over the past decade, the cost per MWh installed power has fallen and the capacity factor (ratio between realised energy output and theoretical maximum output) of new installations has increased. High capacity factors of OSW installations are a notable advantage: the 2018 mean capacity factor for European offshore wind farms of 36 percent far exceeded that of European onshore wind farms (22 percent). The operation and maintenance (O&M) cost per produced MWh is also expected to decline as turbines are designed to be more robust and better suited to the offshore environment. These factors contribute to reduced LCOE. Several other parameters are important when estimating the LCOE, including the connection between wind farms and the grid and the discount rate used in cost estimates. The increased size of turbines and wind farms, as well as the learning rate of the offshore wind industry, have all contributed to reduce LCOE. However, moving into deeper water and farther from shore has partly offset the cost reductions.

For projects commissioned in 2018, the average European LCOE was 134 US$/MWh. A project in China had an LCOE of US$105/MWh (IRENA 2019b). Contracts with record low costs, however, have been signed in the Netherlands (US$55/MWh to US$73/MWh), while the LCOE of a near-shore project in Denmark was US$65/MWh, excluding grid connection costs. No reliable data are available for floating systems, but for bottom-fixed systems, offshore wind without subsidies has proved cost-competitive with other electricity sources. This is the case even without a CO_2 tax, which would negatively impact competing power sources.

OTHER OCEAN RENEWABLE ENERGY

Estimated theoretical potentials for ocean renewable energy technologies (other than offshore wind) are listed below:

- **Tidal Range Energy:** The estimated global theoretical tidal range resource is around 25,880 TWh/year (constrained to regions with water depth of less than 30 metres, and a reasonable threshold for energy output). Considering the logistical issues of operations in ice-covered regions, the global annual potential energy from tidal range technologies is approximately 6,000 TWh, with 90 percent of this resource distributed across five countries (O'Neill et al. 2018).
- **Tidal Stream Energy:** The best estimates of the total global technical tidal stream energy resource is approximately 150 TWh/year, but the estimate is subject to high uncertainty (Yan 2015).
- **Wave Energy:** The total theoretical wave energy potential is estimated to be 32,000 TWh/year (Mørk et al. 2010), with estimates of the global technical potential ranging from 1,750 TWh/year (Sims et al. 2007) to 5,550 TWh/year (Krewitt et al. 2009).
- **Ocean Thermal Energy Conversion (OTEC):** OTEC is currently limited to the tropical regions (+/- 20 degrees latitude). Estimates of the global theoretical energy resource range from 30,000 TWh/year to 90,000 TWh/year. Global technical resource estimates range from 44,000 TWh/year to 88,000 TWh/year (Lewis et al. 2011).
- **Salinity Gradient**: According to Alvarez-Silva et al (2016) the theoretical global potential of power from utilizing the salinity gradient at the mouths of rivers world-wide has been estimated to be up to more than 15 000 TWh/year. Considering the river systems in

Box 1: Current Global Status of Implementation and Future Deployment (continued)

more detail, 3 600 TWh/y is more realistic. Accounting for extraction factors and other technical limitations, the globally technical extractable potential is estimated to be in the order of 625 TWh/year (Alvarez-Silva et al., 2016).

- **Floating solar PV systems**: Floating solar is presently in use predominently in water reservoirs and a small number of marine sites. Moving such systems to the ocean environment, the technical potential will depend upon the system's ability to operate in ocean waves. To ensure survival when facing extreme waves will drive the costs of the systems.

At the end of 2018, the total installed capacity of ocean energy technologies was 532.1 MWh (IRENA 2019a), consisting mainly of tidal barrage technology at two sites. Installed capacity in 2016 was 523.3 MWh, which generated 1023.3 GWh of electricity (IRENA 2019a), implying a mean capacity factor of 23 percent across the sector. Salinity gradient (energy available where freshwater meets salt water) and floating solar photovoltaic (PV) do not contribute significantly to installed capacity at present, but could contribute in future.

Estimates of LCOE are subject to a range of assumptions, including local conditions, which all affect costs. The estimated LCOE for wave energy is in the range of €330 to €630/MWh (IRENA 2014a). Tidal stream energy LCOE is currently in the range of €250 to €470/MWh (IRENA 2014b). At the current scale of deployment, LCOE of ocean thermal energy conversion is in the range of US$600 to US$940/MWh (IRENA 2014c).

Learning rates for ocean technologies are typically assumed to be around 15 percent (OES 2015), resulting in average LCOEs of €150 to €180/MWh for wave energy and of €200/MWh for tidal energy by 2030 (Cascajo et al. 2019; SI Ocean 2013). Due to the capital intensity of OTEC, interest and discount rates have a high impact on LCOE estimates for this technology. Economies of scale are expected to bring the LCOE into a range of US$70 to US$190/MWh for installed capacities exceeding 100 MWh (IRENA 2014c; OES 2015).

Future Deployment Scenarios (2030 and 2050)

OFFSHORE WIND ENERGY

According to IEA (2017), offshore wind generation grew fivefold over the period 2010 to 2015 and is expected to double between 2015 and 2020. James and Ros (2015) estimated that Europe alone has a 4,000 GW potential for floating offshore wind in water depths above 60 metres. This corresponds to about 15,000 TWh/year. National strategies in Europe, if implemented, sum to more than 70 GW of offshore wind capacity by 2030 (Ørsted 2019). The present offshore wind base is lower outside Europe, which increases the uncertainty of future scenarios. But a total installed capacity of 100 GW in Asia and 10 GW in the United States has been estimated for 2030 (GWEC 2017). Worldwide, offshore wind capacity could reach 120 GW in 2030 (GWEC 2017).

In 2018, the European Commission presented a strategic roadmap towards a zero-carbon economy in Europe by 2050 (European Commission 2018). The roadmap includes 70 GW of offshore wind in 2030, increasing to 600 GW in 2050, which corresponds to about 2,300 TWh/year. To achieve this level of installed power, a significant scaling-up in the installation rates of offshore wind is needed. Floating offshore wind may be key.

OTHER OCEAN RENEWABLE ENERGY TECHNOLOGIES

Electricity generation from other ocean renewable energy technologies increased by an estimated 3 percent per year in 2018 (IEA 2019). This rate of growth is not on track to meet the IEA Sustainable Development Scenario (SDS) target for ocean technologies of 15 TWh/year in 2030 (IEA 2019), which would require an annual growth rate of 24 percent. The IEA SDS corresponds to an emissions target of approximately 25 GtCO_2e/yr by 2030. By 2050, the projected power generation from ocean technologies is 108, 536, and 637 TWh/year for the IEA Reference Technology Scenario (RTS), 2 Degree Scenario (2DS), and Beyond 2 Degree Scenario (B2DS), respectively. The 2050 emissions associated with these three scenarios are 40.0, 13.0, and 4.7 GtCO_2e/yr, respectively. This corresponds to annual growth rates of ocean technologies of 15, 21, and 22 percent, respectively.

Policy Interventions Needed to Realise Mitigation Potential

Offshore wind energy resources alone would be sufficient to cover more than the world's electricity demand in 2050. However, significant scaling-up in the rate of deployment is needed for offshore wind to become the significant player indicated by its potential. For other ocean-based renewable energy technologies, additional policy support is required for research and development to enable the scale efficiencies and cost reductions that come with commissioning larger commercial plants.

The levelised cost of energy (LCOE) of ocean-based renewable energy is dominated by investment costs. This means that measures related to project finance and tax regimes can be crucial. Defining the interface between the offshore plant and onshore grid, ownership, and the regulation of electricity markets can make a big difference.

Other policy interventions can also support greater uptake of ocean energy technologies:

- Development of incentives (e.g., carbon taxes and innovative power purchase agreements) that can encourage the expansion of ocean-based energy systems.
- Marine spatial planning should integrate the future role of offshore renewable energy with the many other activities affecting ocean and coastal areas. Development of appropriate legislation and regulation of ocean-based renewable energy to allow easier integration in national electricity grids is also required.
- Establishment of national targets and strategies to increase the share of ocean-based renewable energy in the national energy mix.
- Stable economic and regulatory framework to stimulate investments in required infrastructure for an accelerated deployment of ocean-based energy systems.

Technology Needs

Energy development needs access to larger areas where ocean energy resources can be harvested. Innovations that can move technologies into deeper water sites will be required, for example, development of floating offshore wind technologies.

Improving performance, reliability, and durability, while reducing costs, are the key challenges confronting all ocean energy technologies. Much is to be gained through continued and expanded support for innovation.

However, technology improvements must take account of environmental and social constraints that, if ignored, will undermine efforts to achieve a successful energy transition (Box 2).

Priority Areas for Further Research

Technology innovations need to be underpinned by a high-resolution assessment of global ocean energy resources, in terms of both geophysical and economical potential.

Research on integrating renewable energy projects with other coastal activities (e.g. coastal defense, food production and aquaculture) requires further investigation in order to maximise potential synergies and co-benefits associated with co-location.

Advancing further pilots and testing on the ability of floating solar PV panels at sea (under wave conditions) and further quantification this potential, along with that of Ocean Thermal Energy Conversion (OTEC).

Box 2. Wider Impacts Associated with Scaling Up Ocean-based Renewable Energy

POTENTIAL COBENEFITS:

- Positive and long-term effects on ecosystems from offshore wind farm structures acting as artificial reefs.
- Human health benefits from reduced local air pollution in regions relying heavily on coal and oil to generate electricity
- Reduction in freshwater usage (overall) compared to generating power via fossil fuel.
- Job creation at regional and local levels, benefiting workers transitioning from declining fossil fuel industries. Total full-time employment in offshore wind in 2030 is estimated to be 435,000 (compared to about 38,000 in 2010)[a].
- Potential to generate employment opportunities for women and promote greater gender equity in the rapidly growing industry

POTENTIAL TRADE-OFFS

- The spread of invasive species, noise pollution, and disturbances to marine species from vibration.
- Collision risks to birds and the presence of electromagnetic fields disrupting marine life and benthic habitats.
- Emerging offshore ocean energy (such as tidal barrage, tidal current, wave energy, and thermal gradient) are yet to be deployed commercially at scale. Tidal barrage installations can cause disruption to estuarine ecosystems.

For a full exploration of the wider impacts associated with ocean-based renewable energy, see the section, Wider Impacts of Ocean-based Actions.

[a]OECD (2016).

Ocean-based Transport

This section analyses the potential mitigation impact of reducing emissions from domestic and international marine transport and shipping.

Current GHG emissions from global ocean transport (both international and domestic shipping of passengers and freight) are approximately 1 $GtCO_2e$ per year and represent around 3 percent of global anthropogenic CO_2 emissions (Buhaug et al 2009; Smith et al. 2014). Long-term trends in shipping indicate a strong increase in demand and gradual improvement in energy efficiency. Since 1970, energy efficiency has improved by only about 1 percent/year (Lindstad et al. 2013; Lindstad and Eskeland 2018). If current trends continue, demand is likely to grow by 3 percent/year, which would lead to GHG emissions approximately doubling in 2050, to roughly 2 $GtCO_2e$, compared to 2010. This is in sharp contrast to what is needed to keep global temperature rise well below 2.0°C and consistent with a 1.5°C increase (IPCC 2013) and align with the goals of the Paris Agreement (UNFCCC 2015).

Shipping is a significant source of emissions with identifiable reduction pathways, but it is also an enabler of world trade and economic development. In 2018, the United Nations International Maritime Organization (IMO) adopted its Initial Strategy (Resolution MEPC.304 [72]). An objective of the strategy was to reduce shipping GHG emissions by at least 50 percent in absolute terms by 2050, relative to 2008 emission levels. Whilst the minimum reduction (50 percent) would see shipping's relative share of total GHG emissions grow significantly under most Paris-aligned scenarios,[2] the strategy leaves open the possibility of greater ambition, that is, to set a total GHG reduction target for 2050 that is well above the minimum 50 percent. A more ambitious target will likely be considered in the Revised Strategy due for finalisation by 2023.

The energy intensity and the absolute GHG emissions of ocean-based transport can be reduced in the following ways:

- Technical and operational interventions to reduce energy consumption per tonne transported (reduced energy intensity).
- Substitution of low- and zero-carbon fuels (e.g., hydrogen, ammonia, some biofuels) for diesel and bunker oil (reduced absolute emissions).

The 50 percent GHG reduction target set by the IMO might be achievable with technical and operational measures alone. Achieving a greater level of reduction by 2050—or the full phaseout of GHG emissions from shipping, as called for in the Initial Strategy's vision statement—will be possible only with the introduction of low- and zero-carbon fuels to replace fossil fuels. In practice, a rapid and cost-effective reduction in GHG emissions will require both technical and operational interventions and a swift transition to low- and zero-carbon fuels.

Mitigation Potential

Ocean-based transportation has the potential for a roughly 100 percent reduction in operational net GHG emissions by changing the way it stores and consumes energy on board:

Batteries could be used to store electricity, particularly in ships on the shortest voyages.

Low/zero carbon synthetic or "e" fuels could replace fossil fuels. Examples include renewable hydrogen, hydrogen-based fuels such as ammonia, and fuels that have been post-processed with CO_2 to make hydrocarbons. These fuels differ from synthetic fuels made from gas or coal.

Biofuels could replace fossil fuels. However, it is commonly assumed that biofuels will have a limited role because of land and water constraints on sustainable supply and the fact that many biofuels are not, in fact, carbon-neutral (Searchinger et al. 2019).

Transitioning ocean shipping to more efficient and low- or zero-carbon fuels, and the mitigation potential in 2030 and 2050, is largely determined by the timescales needed to renew or retrofit the existing fleet and develop the infrastructure to use and supply these new energy sources.

2. *If shipping's emissions fall by 50% in absolute terms, to achieve the Paris Agreement temperature goals, other sectors will need to have fallen by more than 50% in absolute terms, and so shipping's relative share of total emissions will have grown.*

Table 5. Mitigation Potential of Ocean-based Transport in 2030 and 2050

OCEAN-BASED CLIMATE ACTION AREA	MITIGATION OPTIONS	DESCRIPTION	2030 MITIGATION POTENTIAL[a] ($GTCO_2E$/YEAR)	2050 MITIGATION POTENTIAL[b] ($GTCO_2E$/YEAR)
Ocean-based transport	Reducing emissions from domestic shipping	Following the IMO definition: shipping between ports of the same country. Domestic shipping excludes military and fishing vessels, Includes ferries. This definition is consistent with the IPCC Guidelines 2006.	0.04-0.07	0.15-0.3
	Reducing emissions from international shipping	Following the IMO definition: shipping between ports of different countries. International shipping excludes military and fishing vessels; includes bulk carriers, oil tankers and container ships. This definition is consistent with the IPCC Guidelines 2006.	0.2-0.4	0.75-1.5
Total			0.25-0.5	0.9-1.8

Source: Authors

Notes:
a. Achieved predominantly through technical and operational interventions to reduce energy intensity per tonne transported.
b. Achieved predominantly through substitution of low- and zero-carbon fuels.

Producing synthetic (“e”) fuels, electricity, and bioenergy at volumes required by ocean-based transport will likely still have significant upstream emissions by 2030, and only a small subset of the fleet is likely to be “zero-carbon-fuels ready” by 2030. The mitigation potential in this time period is therefore mainly driven by the opportunity associated with energy efficiency maximisation. The upstream emissions and therefore the life-cycle (or well-to-wake) emissions for each of these pathways may remain significant until a broader transition to a zero-carbon energy system has been completed.

Nevertheless, if we assume that, by 2050, there will be a fully decarbonised land-side energy system associated with the production of shipping fuels, and that this is a timescale over which the whole ocean-based transport fleet could be “zero-carbon-fuels ready,” there is a clear potential for 100 percent GHG reduction.

This mitigation potential is presented in Table 5.

Methodology

We use a business-as-usual (BAU) emissions trajectory out to 2050, based on an estimate of growth in demand for shipping. The BAU scenario used here is taken from the Third IMO GHG Study (Smith et al. 2014), where demand is estimated to align with IPCC scenario RCP 2.6 (Residual Concentration Pathway 2.6, which is approximately associated with a 2°C temperature rise) and SSP 4 (Shared Socioeconomic Pathway 4, which assumes continued global inequality and increasing disparities in economic opportunity).

This BAU scenario applies existing IMO policy (including the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) regulations) and estimates that total GHG emissions from international shipping will grow from about 800 Mt in 2012, to 1100 Mt in 2030, and to 1,500 Mt in 2050. There is no projection for GHG emissions from domestic shipping in the Third IMO GHG Study, so we derive the domestic shipping BAU by applying the growth rates of international shipping to the 2012 domestic shipping inventory (taken from the Third IMO GHG Study).

Using the BAU scenario as a baseline level of emissions, the mitigation potential is quantified by applying a percentage reduction (defined below) to the emissions in both 2030 and 2050. The group of technologies that can mitigate domestic and international shipping emissions are similar, so the same percentage reduction is applied to both fleets.

To estimate mitigation potential in 2030, a 39 percent emissions reduction is assumed as the upper bound, taken from Bouman et al. (2017). This paper reviewed multiple papers and models to produce consensus estimates of the mitigation potential, both of individual mitigation options and the options in combination. By 2030, the authors estimated that, relative to BAU, the median reduction potential across their surveyed literature was 39 percent. Of all the papers reviewed, the lowest estimate of emissions reduction potantial by 2030 is 20%, this value is used to set the lower bound in the range of reduction potential. The mitigation potential in 2050 assumes a 100 percent emissions reduction at its upper bound. This is based on the assumption described in the preceding section that, if all vessels move to full use of nonfossil fuels from renewable feedstocks, then operational and upstream GHG emissions can be reduced to zero. The lower bound reduction potential is set at 50%, taken as the minimum interpretation of the IMO's Objectives in the Initial GHG Reduction Strategy.

The estimate of mitigation potential is thus based on a number of assumptions:

- The speed of policy implementation to enable or require the shipping industry to invest in the necessary changes to fleet and infrastructure (in particular with respect to low- and zero-carbon sources). We assume that clear policies incentivising shipping's decarbonisation are in place by 2025. Later adoption of policy could jeopardise the achievement of these mitigation potentials in 2030 and 2050.
- The 2030 GHG reduction potential is estimated by aggregating savings across a large number of technological and operational efficiency interventions.[3] If savings are individually or collectively lower (or higher) because of currently unforeseen performance characteristics or interactions between the different interventions, then there could be a significant impact on the abatement potential achieved in 2030.
- The extent to which the wider energy system is decarbonised with sufficient supply of zero-carbon electricity to enable shipping fuels to be produced with zero emissions. We assume that the wider energy system has fully decarbonised by 2050 and that renewable hydrogen (zero carbon in production) is available in sufficient volumes. If that is not the case, then significant upstream emissions may still occur and offset some of the mitigation potential achieved through operational emission reductions.
- Demand growth is assumed to broadly follow the IMO's RCP 2.6 SSP 4 scenario. However, demand growth could be significantly higher or lower, with direct consequences for the BAU emissions and therefore (in proportion) the GHG mitigation potential of a fully decarbonised ocean transport industry.

Policy Interventions Required to Realise Mitigation Potential

The majority of the mitigation potential in ocean-based transportation is significantly influenced by one global body: the IMO. Domestic shipping is regulated by national governments, but often by flowing through IMO regulation. This section discusses interventions that can be undertaken by the IMO, national governments (including supranational organisations such as the European Union), and private sector organisations. Private sector initiatives may be voluntary, shifting behaviour and removing existing barriers to decarbonisation, or mandated by national or global policy in due course.

3. Bouman et al. (2017) presented the results of a review of nearly 150 studies, to provide a comprehensive meta-analysis of CO_2 emissions-reduction potentials and measures. They identified 22 types of measures for which reliable and comparable data are available in the peer-reviewed literature.

The key actions needed are immediate improvements in energy efficiency to reduce fuel consumption, followed as quickly as possible by policy interventions that can incentivise shipping to transition away from fossil fuels, and private sector initiatives that enable adoption of low- and zero-carbon fuels. The following considerations are relevant:

- Cost-effective energy efficiency improvements can be made today, before the arrival of new fuels and their associated infrastructure.
- Current energy efficiency policy (IMO regulations on energy efficiency design index, EEDI) and energy efficiency management (SEEMP) are inadequate. EEDI has significant failures in its design (see section below), and Ship Energy Efficiency Management Plan (SEEMP) is only a guideline, with no mandatory target.
- Energy efficiency improvements can reduce the impact on shipping and trade of moving to higher-cost low- and zero-carbon fuels.
- Policy needed to stimulate low- and zero-carbon fuels and support innovation may take longer to implement at IMO. In contrast, existing policy frameworks at IMO may be more easily and quickly used to drive improvements in energy efficiency and energy intensity.

International Maritime Organization Strategy for GHG Reduction

Emissions from the shipping and aviation industries were not explicitly included in the Paris Agreement. The expectation was that their respective UN agencies, IMO, and the International Civil Aviation Organization (ICAO), would lead on GHG-reduction efforts and develop global regulations. Another factor is that the majority of GHG emissions from shipping and aviation occur in international waters or airspace, and there is no obvious way to allocate national responsibilities for mitigation.

The IMO's Initial Strategy was adopted in 2018, partly as a clear statement of how IMO intended to fulfil its responsibility under global efforts to combat climate change. It is closely linked to the Paris Agreement both in terms of its mitigation goals and its adherence to the principle of Common but Differentiated Responsibilities and Respective Capabilities.

The IMO's Initial Strategy lays out three groupings of candidate policy interventions (short, medium, and long term), which, if effective, could realise most of ocean-based transport's mitigation potential. The IMO does not define the specific time frame corresponding to short, medium, and long term, or whether the time frames refer to a policy's design, adoption, or implementation. However, the time frames are understood to correspond approximately to implementation timescales of before 2023 (short), 2023 to late 2020s (medium), and 2030 onward (long)). In practice to have good likelihood of meeting the IMO's objectives, clarity of policy direction is important and urgency of implementation is high (because of the long timescales of asset lives relative to decarbonisation objectives). For these reasons all policy recommendations are for the short and medium time frame only.). This report proposes a number of priority actions that IMO should undertake to maximise the potential for decarbonisation of ocean-based transport:

SHORT TERM:

- Redesign of the EEDI formula so that it is fit for purpose (see section above) and addresses all in-service GHG emissions.
- Adoption of policy measures that go beyond SEEMP to incentivise maximum operational efficiency of the existing and new fleet by no later than 2030.
- Adoption of policy to reduce GHG emissions from shipping other than CO_2, in particular methane (CH_4) emissions associated with methane slip[4] and volatile organic compound (VOC) emissions associated with certain cargoes. To enable this, it will be necessary to develop CO_2 equivalent emission factors for all major fuel and machinery combinations on a tank-to-wake (TTW) basis, including for use in the redesigned EEDI formula.
- Commitment to a timetable for shipping's transition to low- and zero-carbon fuels that will prompt early action and send a clear signal that investment should flow into fleets and related infrastructure.

4. Unburned methane emissions released during vessel operation via fossil fuel combustion in the engine.

MEDIUM TERM:

- Development of policy to measure, report, and verify well-to-tank (WTT) emissions for ship fuel and fuel supply chains.
- A "medium-term" policy measure entering into force, no later than 2025, that strongly incentivises the adoption of low- and zero-carbon fuels by shipping. Options include the following:
  - A price on carbon (or GHG) emissions to simultaneously close the price gap between conventional and low- and zero-carbon fuels and enable competitive pricing for all options that reduce the GHG intensity of shipping. Revenues raised by such a measure should be disbursed to assist research, development, and demonstration (RD&D), and, if necessary, to address disproportionate negative impacts on vulnerable member states.
- Standards that prescribe the carbon or GHG intensity of operation or the fuel used in ocean-based transport, whilst finding alternative (non-revenue disbursement) mechanisms to enable efforts on RD&D and address disproportionate negative impacts on vulnerable member states.

Box 3. International Maritime Organization's Existing Regulation: EEDI and SEEMP, and Their Limits and Challenges

The EEDI and SEEMP policies were first implemented in 2013 (IMO 2011, Psaraftis 2019). They target minimum performance requirements for ship design (EEDI), and recommendations for how energy efficiency could be managed in operation (SEEMP). A number of studies on trends in ship design efficiency during the early years of these regulations (Faber et al. 2016) show that many ships have performed far better than the EEDI requirements (i.e., their CO_2 emissions have been significantly lower than the required threshold). The implication is the requirement could have been more stringent (and recently the standards have been tightened and dates of alteration to phase 3 stringency brought forward for some ship types).

However, as the stringency of the regulation increases, so does the incentive to "game" the system. Ship design can be optimised to pass the short calm water trial in which EEDI is measured. Calm water trials bear little resemblance to normal operating conditions, where ships encounter strong winds and waves. Unless the EEDI is adjusted to include a performance threshold for rougher conditions, GHG emission targets will be set too low, and emissions could potentially increase (Lindstad et al 2019). It is easy to make hull form modifications that improve calm water performance even of full-bodied "bulky" hulls. However, these modifications generally increase fuel consumption under real operating conditions. By contrast, hull forms optimised with respect to performance in realistic sea conditions cannot prove their worth when tested in calm water.

In addition, the regulation has no mechanism to ensure that the fuel used when ships are tested will also be used in operation, when a ship has multiple fuel options. A ship could complete its certification and trials using low-carbon fuel, gaining an excellent EEDI "score" but then switch to higher-carbon fuel in operation.

As EEDI is currently designed, the regulation influences only design specification. Experience in other sectors has shown that regulation that does not also incentivise efficiency in operation may not achieve the magnitude of savings expected from an extrapolation of the design efficiency standards. Studies specifically on EEDI have projected that it may contribute as little as 3 percent to actual operational CO_2 reduction (Smith et al. 2016).

The SEEMP regulation is mandatory in that a ship must be equipped with SEEMP documentation (i.e., an energy efficiency management plan), but there is no mandate for what must be specified within the documentation. As such, the regulation is a guideline and cannot be relied upon to overcome the known market barriers and failures and drive carbon intensity reduction in line with Paris Agreement and IMO objectives.

Source: Authors

National government actions

Some governments have identified opportunities for economic benefit from emission reductions in the shipping sector (Bell et al. 2019) and have introduced incentives or other measures. For example, the United Kingdom has adopted the Clean Maritime Plan; several Scandinavian countries have set domestic shipping emission-reduction commitments; the Marshall Islands has included specific reductions for shipping emissions in its nationally determined contribution (NDC); China has shown leadership at the IMO on the topic of National Action Plans. The plans are initiatives, led through the IMO, that provide support for regional Maritime Technology Cooperation Centres and for shipping energy efficiency measures undertaken by 10 national governments within a Global Maritime Energy Efficiency Programme (GloMEEP).

Key elements in government actions taken to date include the following:

- Incentivising decarbonisation of domestic ocean-based transportation, if possible at a rate of transition faster than that achieved in the international fleet through IMO regulation. Domestic fleets are populated with smaller ships and therefore better suited to pilots and tests of fuels and technologies, which in turn can help to de-risk and reduce costs for larger, high seas, and ocean-based transportation.
- Enabling decarbonisation of national energy systems at least as fast as the rate of transition in the international fleet, and with sufficient additional energy supply capacity to meet a relevant proportion of the international fleet's energy demands.
- Providing national support for development of low- and zero-carbon energy production capacities, and storage and refuelling infrastructure in ports and harbours.
- Forming partnerships, particularly in support of small island developing states (SIDS) and least developed countries (LDCs) with significant domestic or regional shipping decarbonisation challenges, to work together on joint objectives.

Private sector actions

The private sector has traditionally led efforts to address shipping issues, such as safety and oil spill risks. While there are examples of such leadership in the areas of energy efficiency and decarbonisation (Scott et al. 2017), early initiatives have not matched the ambition of the Paris Agreement. In part, this is because earlier voluntary initiatives have stayed close to IMO policy, which remains conservative for fear of creating commercial disadvantages for its members and potentially reducing membership. Market barriers and failures inhibit action (Rehmatulla 2014), but where an opportunity aligns with wider stakeholder objectives, further action can be taken. Examples include the following:

- Further work to understand where market and nonmarket barriers and failures to decarbonisation occur and can be removed. For example, ensure that authorities setting rules in ports, fairways, and pilotage and sailing restrictions do not unnecessarily penalise ship length, given this is a low-cost means of reducing GHG intensity of shipping.
- As demonstrated in the Poseidon Principles (www.poseidonprinciples.org), encourage/regulate the financiers of shipping to be held more accountable for management of the long-run risks of shipping decarbonisation. This aligns with the increasing general prioritisation of finance to put a price on climate-change mitigation and adaptation-related risks. This can ensure that finance is no longer directed towards "standard" designs, which are optimised on cost at the expense of energy efficiency. It can ensure financing of a decarbonisation-aligned fleet that will avoid risks of asset stranding and maximise investment in the most efficient tonnage.
- Encourage/regulate the charterers of shipping to measure, report, and be held more accountable for operational GHG emissions for which they have responsibility (e.g., Scope 3 emissions). This can help address the lack of a clear market signal that ensures the energy efficiency and carbon intensity differential across the fleet is reflected in the prices paid by charterers, and which is needed to ensure that the shipowners have the full economic incentive to invest in solutions that achieve GHG reduction. This also ensures, in addition to policy on operational emissions, that where charterers have opportunities to contribute towards achieving GHG reduction, they seek to do so.

Technology Needs

The greatest need is to accelerate and scale up deployment of energy efficiency interventions. Many feasible solutions are ready to implement but are being adopted in low volumes because of market barriers and failures. These need to be overcome through effective national government and IMO policy (Rehmatulla 2014). Market barriers and failures present the main obstacle, but faster technological progress and implementation of demonstration projects have potential to produce greater understanding of performance benefits, performance improvement, and cost reduction (Lindstad et al. 2015, Lindstad and Bø 2018). Current promising but low-volume solutions include the following:

- Energy efficiency technologies (e.g., air lubrication, waste heat recovery, batteries [Lindstad et al. 2017b]) and hybrid engines (Lindstad and Bø 2018) that help smooth and manage demands for power from internal combustion engines and enable them to operate more optimally. Cold ironing (also known as "shore power") and digital solutions help enable operational efficiency improvements.
- Wind assistance technologies (kites, sails, and rotors that can directly harness renewable wind energy for propulsion).

There also remains a need to develop supply chains and technologies for the use of new low- and zero-carbon fuels on board. These are all at lower readiness level (LR and UMAS 2019) and unlikely to be feasible without significant incentives from IMO and national government policy, in addition to private sector action (LR and UMAS 2019). Specific technologies include the following:

- Electrolysers and equivalent as well as related technologies for producing hydrogen from electricity.
- Carbon capture and storage (for use with production of hydrogen from fossil feedstock).
- Storage technologies for hydrogen (including cryogenic storage of liquid hydrogen or carriers able to store at high-energy density).
- Fuel cells for conversion of future fuels into on-board electricity, and internal combustion engines designed to operate on hydrogen/ammonia.

Priority Areas for Further Research

Minimising energy consumption remains of high importance as the lowest-cost means of reducing emissions in the short term. It is now predominantly a function of implementing best practice in the design and operation of ships, and introducing sufficient policy incentives and private sector initiatives to overcome market barriers and failures that are currently preventing full adoption. The energy efficiency area represents a market opportunity if improved technologies become more widely deployed, but it will be a diminishing priority for further research.

Enabling the necessary switch to low- and zero-carbon fuels requires rapid progress in a number of areas (LR and UMAS 2019), both to confirm the most cost-effective transition pathway for shipping and to help reduce the costs of that pathway. Our recommended priorities focus on hydrogen and ammonia, even though other fuels are often considered for the future of ocean-based transport. Until a long-term solution has emerged, the interim "transition" steps that might be compatible with that solution (e.g., the fuels and their production pathways) will remain unclear.

SHORT-TERM:

- Cost-effective production of low-carbon hydrogen and ammonia from fossil fuel feedstocks in combination with carbon capture and storage.
- Safe storage and handling of hydrogen and ammonia on ships and at the ship-shore interface.
- Safe and efficient use of hydrogen and ammonia in large (e.g., 1 MW+) internal combustion engines and fuel cells.

MEDIUM TERM:

- Cost-effective production of zero-carbon hydrogen/ ammonia using renewable electricity and electrolysers.

These research areas represent large future market opportunities in terms of the provision of hardware and technology; production of future fuels; provision of services related to managing the design, implementation, and operation of assets; and ownership and operation of other related assets. Those opportunities are relevant to corporate and national interests and are especially important for countries with significant maritime or renewable fuel interests and an associated industrial strategy. Countries and corporate entities will need to proactively position themselves to capitalise on these opportunities.

Box 4. Wider Impacts Associated with Reducing Emissions from Ocean-based Transport

POTENTIAL COBENEFITS:

- Reduction in seasonal "hotspots" of ocean acidification caused by strong acids formed from shipping emissions
- Beneficial impact on human health, particularly for people living in port cities and coastal communities, including from reduction in the sulphur content of fuel oil used by ships.
- Upgrade in technological capabilities in marine transport will bring efficiency.

POTENTIAL TRADE-OFFS:

- Cost to industry of switching to alternative fuels will be high; however, increased costs are likely to have a marginal impact on the price of traded commodities (Haim et al. 2019)

For a full exploration of the wider impacts associated with ocean-based transport, see the section Wider Impacts of Ocean-based Actions of this report.

Source: Authors

Coastal and Marine Ecosystems

This section analyses the potential mitigation impact of conserving and restoring coastal and marine ecosystems, including mangroves, salt marshes, seagrass beds, seaweed aquaculture, and marine fauna.

An overview of the current state of each ecosystem is provided below.

Mangroves, salt marshes, and seagrass beds

Mangroves, salt marshes, and seagrass beds are highly productive vegetated coastal ecosystems, which are referred to as "blue carbon" ecosystems, analogous to "green carbon" ecosystems on land (Nelleman et al. 2009). They are hotspots for carbon storage, with soil carbon sequestration rates per hectare up to 10 times larger than those of terrestrial ecosystems (Mcleod et al. 2011). Most of their carbon (50–90 percent) is stored within the soils where saltwater inundation slows decomposition of organic matter, leading to accumulation of extensive soil carbon stocks.

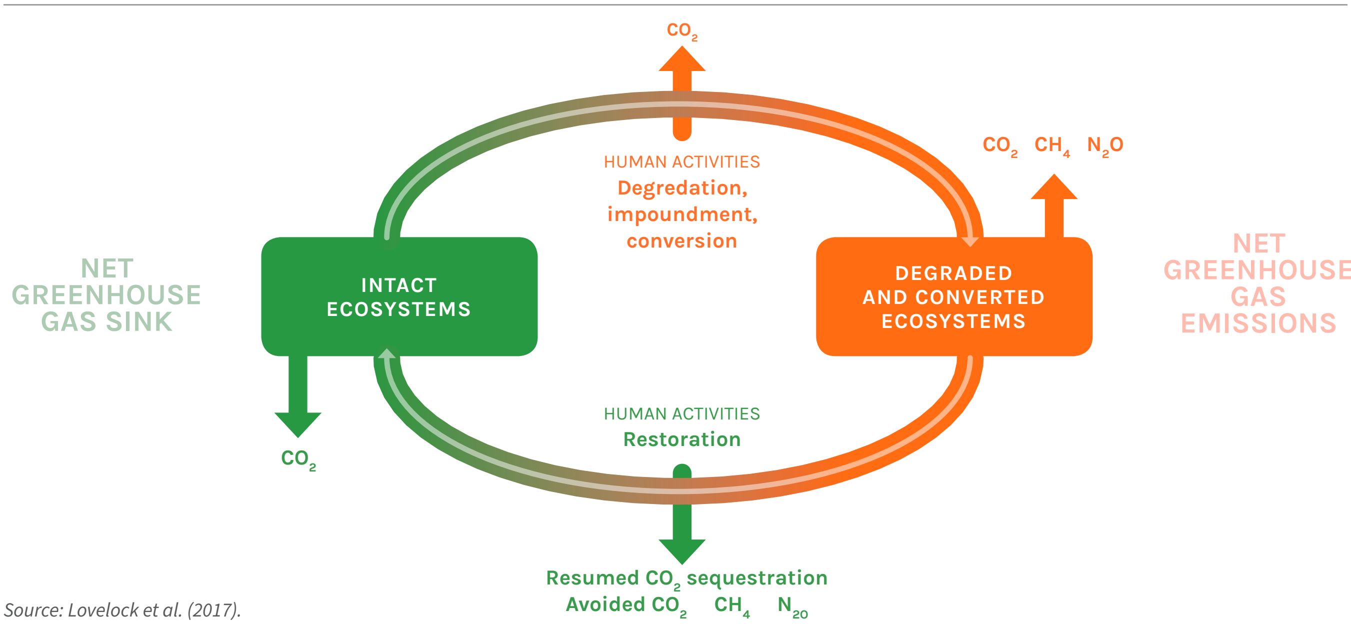
When these ecosystems are degraded and converted, carbon in their biomass and soils, which may have accumulated over hundreds or thousands of years, is oxidised and emitted back to the atmosphere in a matter of decades (Figure 3). Thus, protection of blue carbon ecosystems offers an efficient pathway to avoid CO_2 emissions, particularly for nations with large areas of coastal vegetation and high rates of loss. For example, conversion of mangroves to aquaculture accounts for 10 to 20 percent of CO_2 emissions associated with land-use change in Indonesia (Murdiyarso et al. 2015).

Between 20 and 50 percent of global blue carbon ecosystems have already been converted or degraded, leading some analysts to conclude that restoring wetlands can offer 14 percent of the mitigation potential needed to hold global temperature to 2°C above the preindustrial period (Griscom et al. 2017). Rates of mangrove loss have declined from 2.1 percent/year in the 1980s (Valiela et al. 2001) to 0.11 percent/year in the past decade (Global Mangrove Watch 2018; Bunting et al. 2018), thanks to improved understanding, management, and restoration (Lee et al. 2019). However, mangrove areas still emit an estimated 0.007 $GtCO_2e$/year (Atwood et al. 2017).

Rates of loss and degradation of seagrass cover are between 2 and 7 percent/year, mainly due to pollution of coastal waters (Duarte et al. 2008; Waycott et al. 2009). Emissions are estimated at 0.05 to 0.33 $GtCO_2e$/year (Pendleton et al. 2012), although gains in cover have recently been observed in Europe (de los Santos et al. 2019). Global rates of salt marsh loss are uncertain (1–2 percent per year), but losses are estimated to be responsible for 0.02 to 0.24 $GtCO_2e$/year (Pendleton et al. 2012).

The area covered by blue carbon ecosystems is equivalent to only 1.5 percent of terrestrial forest cover, yet their loss and degradation are equivalent to 8.4 percent of CO_2 emissions from terrestrial deforestation because of their high carbon stocks per hectare (Griscom et al. 2017).

Figure 3. The Carbon Cycle in Coastal and Marine Ecosystems



Source: Lovelock et al. (2017).

Seaweeds (macroalgae)

Globally, the most extensive and productive coastal vegetated ecosystems are formed by seaweeds, which are a diverse group including brown algae (e.g., kelps), red algae, and green algae. Their areal extent is estimated—though with large uncertainty—to be 3.5 million km2 of coastal regions (Krause-Jensen and Duarte 2016). Seaweeds are mainly attached to rocks or occasionally free-floating. They lack root structures that would sequester and trap soil carbon, which means that the climate mitigation value of wild seaweed habitats is largely through the export of organic carbon in plant biomass to sinks located in shelf sediments and in the deep ocean (Krause-Jensen and Duarte 2016). Thus, the loss of seaweed habitats reduces carbon sequestration but does not result in emissions of CO_2 to the atmosphere from sediments below the habitats, as occurs in mangroves, salt marshes, or seagrass beds.

Globally, seaweed carbon sequestration is estimated to be 0.64 (range 0.22–0.98) $GtCO_2e$/year, representing 11 percent of annual global net seaweed primary production (Krause-Jensen and Duarte 2016). Recent studies also underline the large carbon export fluxes of seaweeds (Filbee-Dexter et al. 2018; Queirós et al. 2019; Ortega et al. 2019).

While there is no overall assessment of the global rate of change of seaweed habitats and the net area lost, it is estimated that kelps (brown canopy-forming seaweeds) have experienced a global average annual loss rate of approximately 0.018 percent/year over the past 50 years, with large geographic variability (Krumhansl et al. 2016; Wernberg et al. 2019).

Marine fauna

Marine fauna (fish, marine mammals, invertebrates, etc.) influence the carbon cycle of the ocean through a range of processes, including consumption, respiration, and excretion. When marine fauna die, their biomass may sink to the deep ocean. In addition, their movement between habitats promotes mixing within the water column, contributing to increased phytoplankton production.

Marine fauna accumulate carbon in biomass through the food chain—starting with photosynthesizing plants that are consumed by animals, which in their turn are consumed. Although there are large data gaps, a first-order assessment estimates that 7 $GtCO_2e$ has accumulated within marine fauna biomass (Bar-On et al. 2018). However, the net carbon sequestration benefit from marine fauna, once allowance is made for respiration over the lifetime of the animal, respiration and carbon output from the species feeding on feces and carcasses prior to final burial in the seafloor, remains unclear.

Marine fauna activity can stimulate production by plants (Lapointe et al. 2014) and phytoplankton, leading to sequestration of 0.0007 $GtCO_2e$/year (Lavery et al. 2010). Populations of vertebrates are an important component of the carbon cycle in ocean ecosystems (Schmitz et al. 2018), including predators which can regulate grazers (Atwood et al. 2015) and should be given consideration when developing policies to secure nature-based carbon functions. However, there is currently insufficient data to estimate the global mitigation potential of protecting or restoring populations of fish and marine mammals to previous levels. Impacts of increased marine protected areas and fishery management practices on climate mitigation should be a priority research area.

Mitigation Potential

The mitigation potential of these coastal and marine ecosystems are examined by considering three mitigation options:

- Conserving and protecting blue carbon ecosystems, involving halting the loss and degradation of these ecosystems, thus avoiding direct land-use change emissions and additional emissions from alternative land use, such as agriculture.
- Restoration and expansion of degraded blue carbon ecosystems, involving rehabilitating the soil and associated organisms and thereby restoring their ability to sequester and store carbon.
- Expansion of seaweed (macroalgae) through aquaculture, to increase availability for alternative food, feed and fuel products to replace land-based options.

We estimate the total potential mitigation contribution from coastal and marine ecosystems as between 0.50 and 1.38 $GtCO_2e$/year by 2050. This estimate is similar to that of Gattuso et al. (2018), who estimated a cumulative mitigation of 95 $GtCO_2e$ by 2100 (a mitigation potential of 1.1 $GtCO_2e$/year by 2050). Due to lack of data, the estimated total mitigation contribution from marine and coastal ecosystems does not include the potentially significant mitigation effects associated with the conservation and restoration of wild seaweed or marine fauna. The greatest uncertainties in estimates concern ecosystem area and rates of change for seagrass and salt marshes. The estimated mitigation potential of conserving and restoring the marine ecosystems for which data are adequate (mangroves, seagrass beds, and salt marshes) along with the mitigation potential that could be achieved through avoided emissions by using seaweed as a food, feed or fuel replacement is summarised in Table 6.

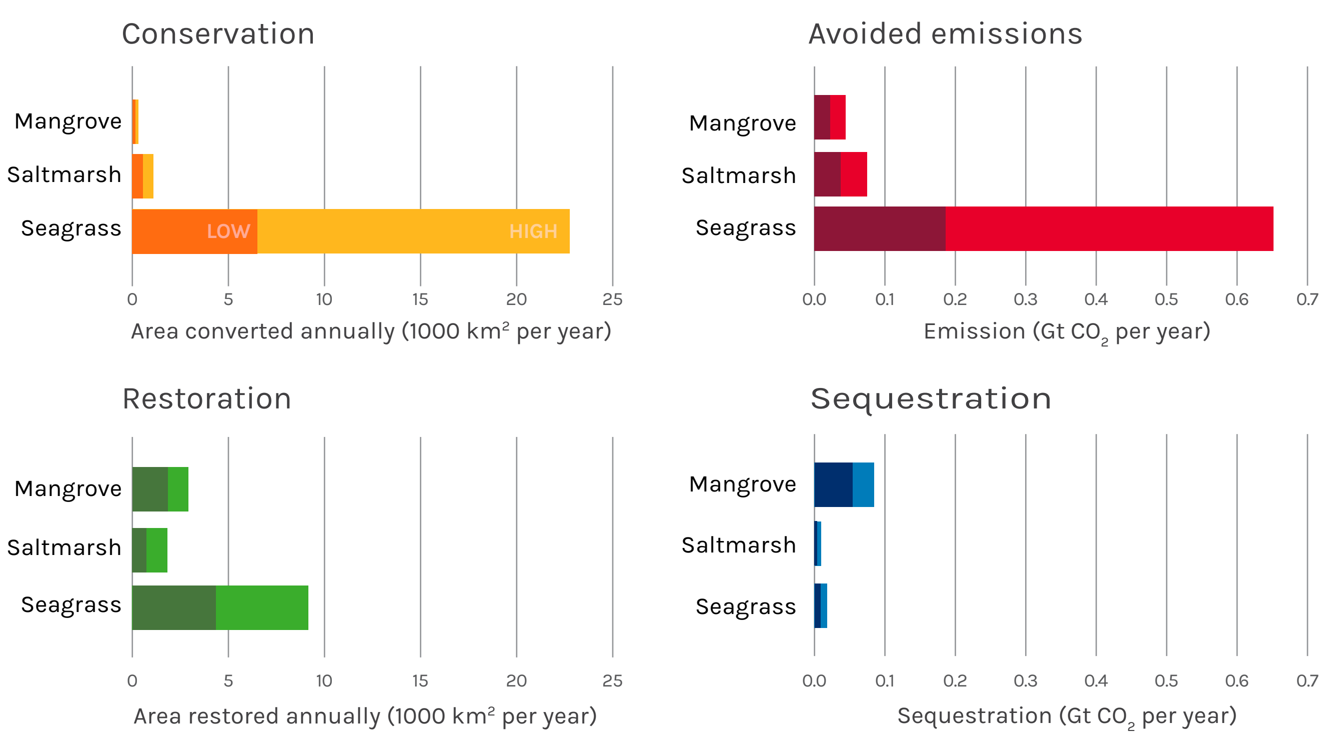
Mangroves, saltmarshes, and seagrass beds

Figure 4 shows the estimated mitigation potential of coastal and marine ecosystems via the two main pathways: (1) Protection and conservation of ecosystems avoids emissions of carbon that is currently stored in soils and vegetation, and (2) Restoration of ecosystems sequesters and stores carbon as vegetation grows.

Figure 5 compares the mitigation potential of land-based ecosystems to blue ecosystems. Although the mitigation potential of restoring green ecosystems, notably forests, is greater in total, the mitigation potential of blue ecosystems per unit area is very high.

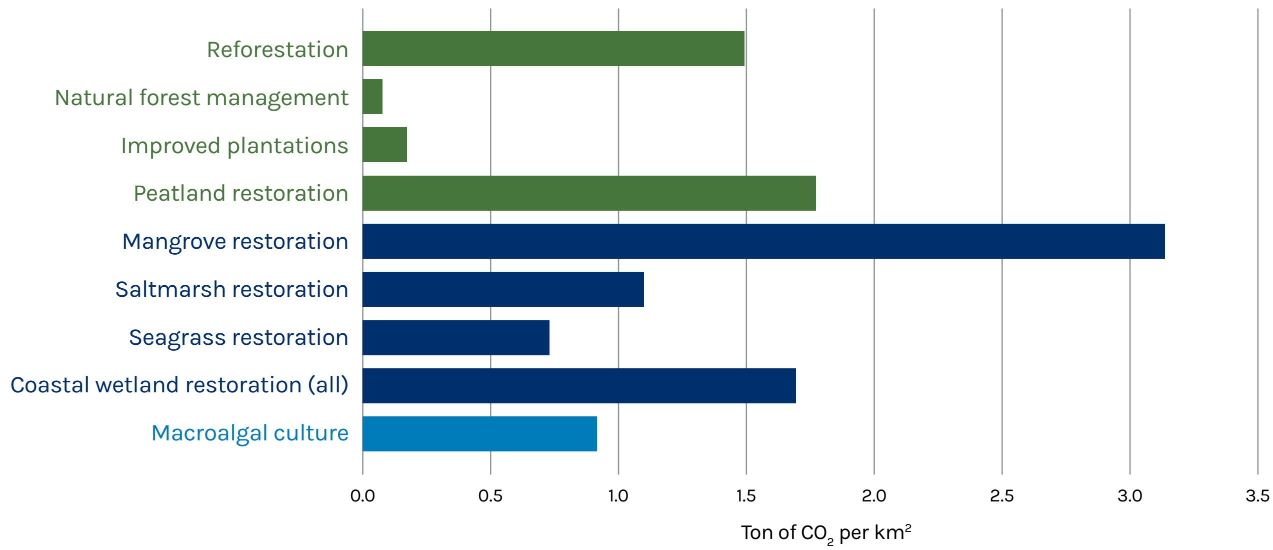
Achieving high levels of mitigation through conservation and restoration is dependent on increased investment in protection, restoration, and enabling the expansion of ecosystem cover where sea level rise provides new

Figure 4. Comparison of Conservation and Restoration Pathways for Coastal and Marine Ecosystems



Sources: For area change are in Table 7, Global Mangrove Watch (2018); Bunting et al. (2018) (mangroves); McOwen et al. (2018) (salt marsh cover); Bridgham et al. (2006) (salt marsh loss); Unsworth et al. (2018) (seagrass cover); Duarte et al. (2008), Waycott et al. (2009) (seagrass loss); Krause-Jensen et al. (2016) (seaweed cover); for emission and removals IPCC 2013 Wetland Supplement; and calculations of sequestration from the authors.

Figure 5. Mitigation Potential per Unit Area of Restoring Land-based and Marine Ecosystems



Sources: Blue bars represents data from Griscom et al. (2017), macroalgal culture: yield data from World Bank (2016), biomass-carbon-conversions from Duarte et al. (2017).

opportunities. However, ambitious conservation and restoration targets must be considered within local socioeconomic contexts to prevent perverse outcomes (Herr et al. 2017; Lee et al. 2019; Lovelock and Brown 2019).

Efforts to restore blue carbon ecosystems are growing in number, area, and success (Unsworth et al. 2018; Lee et al. 2019; Gittman et al. 2019, Kuwae and Hori 2019), but are still relatively small scale in most instances. (An exception is the 589 km2 of salt marsh restoration in the United States between 2006 and 2015 [Gittman et al. 2019]). Low-end estimates of mitigation likely to be achieved through restoration by 2050 are 0.2 $GtCO_2e$/year, reflecting limited restoration activities and success.

Estimates of CO_2 emissions associated with avoided anthropogenic degradation of mangrove, salt marsh, and seagrass ecosystems are sensitive to uncertainties in global cover and rates of loss, which is particularly the case for seagrass and wild seaweeds. Estimates of salt marsh area and losses of salt marsh area are also uncertain (McOwen et al. 2019). Losses of mangrove ecosystems have slowed in the last decades, and thus emissions associated with their losses have also declined compared to those estimated by Pendleton et al. (2012).

Expansion of seaweed through aquaculture

The protecting and restoration of wild seaweed habitats also holds potential for GHG emissions mitigation, but knowledge gaps are currently too large to estimate the potential contribution because the extent of lost macroalgal habitats that could be restored is unknown. Moreover, methods and success rates of restoration and protection measures (including sustainable harvest methods) need be explored and reviewed.

Projections of mitigation from seaweed farming could reach 0.05–0.29 $GtCO_2e$/year by 2050. However, there are uncertainties in rates of expansion of the industry and the proportion of production that would be sequestered.

Scaling up seaweed production via aquaculture offers different potential mitigation pathways:

- Seaweed products might replace products with a higher CO_2 footprint, thereby avoiding emissions (rather than directly contributing to sequestration) in fields such as food, feed, fertilisers, nutraceuticals, biofuels, and bioplastics (World Bank 2016; Lehahn et al. 2016; Duarte et al. 2017). The extent of this mitigation pathway is currently not known.

- Addition of seaweeds to animal feeds might lead to reduced enteric methane emission from ruminants, a potential technology that is currently being explored and may substantially increase the mitigation potential of seaweeds (Machado et al. 2016). In vitro experiments have shown that the red alga, Asparagopsis taxiformis, can reduce methane emissions from ruminants by up to 99 percent when constituting 2 percent of the feed; and several other species, including common ones, show a potential methane reduction of 33 to 50 percent (Machado et al. 2016). However, this alga is not yet farmed, and many steps are required before large-scale mitigation can be achieved.
- Farmed seaweeds, similar to wild seaweeds, contribute to carbon sequestration through export of dissolved and particulate carbon to oceanic carbon sinks during the production phase (Zhang et al. 2012; Duarte et al. 2017).

This mitigation potential is presented in Table 6.

Table 6. Summary of Mitigation Potential from Blue Carbon Ecosystems, 2030 and 2050

OCEAN-BASED CLIMATE ACTION AREA	MITIGATION OPTION	DESCRIPTION	MITIGATION POTENTIAL, 2030 (GTCO$_2$E/YEAR)	MITIGATION POTENTIAL, 2050 (GTCO$_2$E/YEAR)
Coastal and Marine Ecosystems	Conservation: potential mitigation from halting loss and degradation of ecosystems (avoided emissions)	Mangroves	0.02–0.04	0.02–0.04
		Salt marsh/tidal marsh	0.04–0.07	0.04–0.07
		Seagrasses	0.19–0.65	0.19–0.65
		Seaweeds	Knowledge gaps currently too large (see text)	Knowledge gaps currently too large (see text)
	Restoration: potential mitigation from restoring and rehabilitating ecosystems and organisms	Mangroves	0.05–0.08	0.16–0.25
		Salt marsh/tidal marsh	0.004–0.01	0.01–0.03
		Seagrasses	0.01–0.02	0.03–0.05
		Seaweeds	Knowledge gaps currently too large (see text)	Knowledge gaps currently too large (see text)
	Increased seaweed production via aquaculture		0.01–0.02	0.05–0.29
	End overexploitation of the ocean to support recovery of biodiversity and increase biomass		Knowledge gaps currently too large (see text)	Knowledge gaps currently too large (see text)
Total			0.32–0.89	0.50–1.38

Source: Authors

Methodology

Mangroves, saltmarshes, and seagrass beds

Avoided emissions associated with halting ecosystem conversion were estimated from ecosystem aerial cover (km^2), mean carbon stocks in soils, and biomass per area from default emission factors (IPCC 2013), and estimated rates of loss (Table 7). The range of CO_2 sequestration potential per unit area for each ecosystem was calculated using default emission/removal factors from IPCC (2013). Our estimates are conservative because we do not include CO_2 emissions from previously degraded and converted ecosystems where soil carbon continues to emit CO_2 over time; these emissions may reach 0.7 $GtCO_2e$/year (Pendleton et al. 2012).

The range in potential mitigation that could be achieved through restoration of mangrove, salt marsh , and seagrass ecosystems varied with the level of effort and investment. We considered two scenarios: a moderate restoration effort recovering about 40 percent of historical ecosystem cover by 2050, which is consistent with Global Mangrove Alliance goals; and a much more aggressive scenario of complete restoration of pre-1980s cover. Restored areas would amount to 225,000 km^2 of mangroves (Valiela et al. 2001), 600,000 km^2 of seagrass (Mcleod et al. 2011), and doubling of the current area of salt marsh to 110,000 km^2 (Gittman et al. 2019). Mitigation benefits under these scenarios are likely conservative because avoided methane(CH_4) emissions from alternative land uses such as aquaculture and rice production could be substantial. Thirty percent of mangrove ecosystems in Southeast Asia have been converted to aquaculture and 22 percent to rice cultivation (Richards and Friess 2016). Both land uses can produce high nitrous oxide(N_2O) and CH_4 emissions (IPCC 2006, 2013, 2019).

Seaweeds (macroalgae)

To estimate the mitigation potential of seaweed farming by 2030 and 2050, two scenarios were considered (Table 6). The assumptions underlying the two scenarios are given below:

Table 7. Global Extent and Loss Rates of Blue Carbon Ecosystems

ECOSYSTEM	AREAL COVER (KM^2)	RECENT RATES OF LOSS (%/YEAR)
Mangroves	138,000	0.11
Salt marshes	55,000	1–2
Seagrasses	325,000	2–7
Seaweeds	3,540,000	Not known

Sources: Global Mangrove Watch (2018); Bunting et al. (2018) (mangroves); McOwen et al. (2018) (salt marsh cover); Bridgham et al. (2006) (salt marsh loss); Unsworth et al. (2018) (seagrass cover); Duarte et al. (2008), Waycott et al. (2009) (seagrass loss); Krause-Jensen et al. (2016) (seaweed cover).

1. Seaweed farming develops at 8.3 percent/year (the current rate, calculated on the basis of the increase in the farmed and harvested production of green, red, and brown macroalgae between 2000 and 2017) (FAO 2018), 100 percent of production is assumed sequestered, and farming and processing are assumed CO_2-neutral. Conversion factors from wet weight to carbon are from Duarte et al. (2017). Average annual yield is 1,000 tonnes dry weight/km^2 (current best practices) (World Bank 2016). Estimated production by 2030 (9.4 Mt dry weight/year, equivalent to 2.3 megatonnes of carbon/year [MtC/year)] and 2050 (49.3 Mt dry weight/year, equivalent to 12.2 MtC/year) would require an area of 9,383 and 49,348 km^2, respectively. This represents 0.02 and 0.1 percent, respectively, of the global area suitable for macroalgal aquaculture (estimate based on suitable temperature and nutrient conditions, Froehlich et al. 2019).
2. Seaweed farming develops at 14 percent/year from 2013 onward (rate assumed in a scenario developed by the World Bank [2016]), 100 percent of production is assumed sequestered, and farming and processing are assumed to be CO_2-neutral. Conversion factors from wet weight to carbon are from Duarte et al. (2017). Average annual yield is 1,000 tonnes dry weight/km2 (current best practices) (World Bank 2016), leading to production of 324 Mt dry weight/year, equivalent to carbon assimilation of 80 MtC/year by 2050.

We adopted the scenario of a 14 percent annual increase in production to provide an upper limit of the sequestration potential by 2030 and 2050, and we further assume that farming could proceed at this rate of increase without meeting constraints before 2050. An even higher production estimate of 10 billion tonnes dry weight/year was recently proposed (Lehahn et al. 2016), indicating that our estimated upper limit of seaweed production is not unrealistic.

The assumption that 100 percent of the seaweed harvest is sequestered is highly unlikely, as seaweeds are farmed for many other, and more economically profitable, purposes than carbon sequestration. Also, energy is required in the production process. However, carbon sequestration through export of the “nonseen production” during farming will contribute to the sequestration potential (Duarte et al. 2017). Recent estimates suggest that this export may constitute 60 percent of what is eventually harvested (Zhang et al. 2012). Assuming that 25 percent of the seaweed export is sequestered (Krause-Jensen et al. 2016), the projected seaweed aquaculture would have an associated sequestration of nonseen production of 0.0013 to 0.0027 $GtCO_2e$/year by 2030 and 0.0067 to 0.044 $GtCO_2e$/year by 2050.

marine and coastal ecosystems are also vulnerable to failure due to socio-economic factors, including inadequate and inappropriate incentives. Social safeguards, similar to those developed for forests, should be developed.

To maximizes the mitigation benefit of seaweed farming, it is essential that farms do not harm wild blue carbon ecosystems (mangroves, seagrasses, saltmarshes, and seaweeds). Conversely, sustainable seaweed farming may have the benefit of reducing the harvest of wild seaweeds.

Risks, underlying assumptions

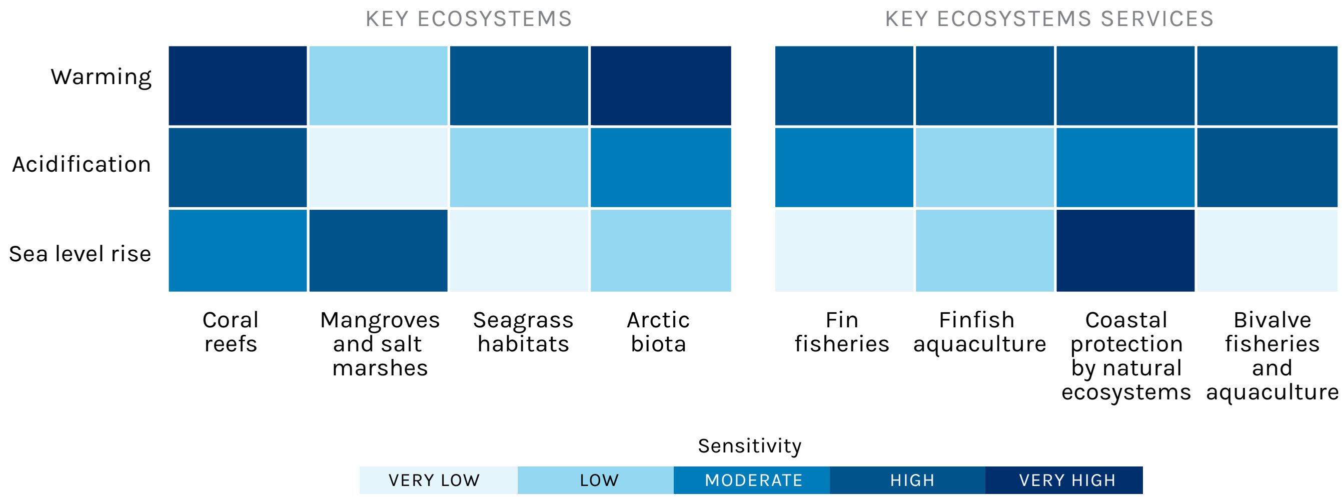
Climate change is likely to have variable impacts on coastal marine ecosystems and their CO_2 mitigation potential (Figure 6). Marine heat waves may adversely affect the mitigation contribution from seagrass beds and seaweeds (Arias-Ortiz et al. 2018; Wernberg et al. 2019). Warming may result in ecosystem losses at their equatorial distributional range limit (Wilson et al. 2019) and increases at the polar distribution range (Krause-Jensen and Duarte 2014; Marba et al. 2018).

The area of mangroves and salt marshes may also be adversely affected by sea level rise in some regions (Lovelock et al. 2015) but could expand in others (Schuerch et al. 2018), increasing their mitigation benefits (Roger et al. 2019). Sea level rise will affect habitat areas for all coastal vegetated ecosystems, and thus their mitigation potential (Lovelock et al. 2015; Saunders et al. 2013; Schuerch et al. 2018). The impact of sea level rise on these ecosystems will be strongly influenced by human activity (e.g., sediment supply, land-use changes, population, and seawall defenses); the effects of climate change on adjacent ecosystems such as coral reefs (Saunders et al. 2013), mudflats or barrier islands; and GHG emissions from freshwater wetlands (Luo et al. 2019).

Extreme events could also reduce the effectiveness of restoration. While small-scale seaweed cultivation is considered low risk, a large-scale expansion of the industry requires greater understanding of impacts and the balance of environmental risks and benefits that seaweed cultivation projects can offer (Campbell et al. 2019).

In addition to climate change, marine and coastal ecosystems are also vulnerable to failure due to socio-economic factors, including inadequate and inappropriate incentives (Herr et al. 2017, Lee et al. 2019). Social safeguards, similar to those developed for forests (Chhatre et al. 2012), should be developed.

Figure 6. The Effects of Climate Change on Coastal Marine Ecosystems Will Vary



Sources: Gattuso et al. (2018).

Policy Interventions Needed to Achieve Mitigation Potential

The following policy interventions are recommended to support the realisation of the mitigation potential outlined in this chapter:

SHORT TERM:

- Enhance protection measures for mangroves, seagrass beds, salt marshes, and seaweed beds to prevent further losses due to human activities. Measures could include increasing the size and effectiveness of Marine Protected Areas, but should also address underlying causes of loss, such as overexploitation, pollution, hydrological changes, and climate change impacts.
- Increase incentives for restoration of blue carbon ecosystems by paying for ecosystem service schemes, using mechanisms such as carbon and nutrient trading credits (Herr et al. 2017).
- Develop incentives for sustainable seaweed farming (Froehlich et al. 2019).
- Promote adoption of improved accounting for mangroves and salt marshes within national GHG inventories (IPCC 2013).
- Include blue carbon solutions in nationally determined contributions (NDCs) and other relevant climate policies for mitigation and adaptation (Herr and Landis 2016).
- Recognise the wider ecosystem services of these habitats beyond carbon sequestration and quantify their mitigation of coastal eutrophication and benefits for biodiversity, fisheries, coastal protection, fisheries and aquaculture, and their adaptation, to develop appropriate financial and regulatory incentive tools.
- Link conservation and restoration of mangroves, salt marshes, seagrass beds, and seaweeds to achieving the UN Sustainable Development Goals.
- Develop and implement social safeguards. Although restoration of blue carbon ecosystems provides important opportunities for mitigation, inadequate policies for restoration of mangroves for carbon could give rise to perverse outcomes (Friess et al. 2019a). Safeguards are required to ensure that, for example, restoration projects do not prevent local communities from accessing marine resources (McDermott et al. 2012).

MEDIUM TERM:

- Improve IPCC guidance for seagrass management and develop IPCC GHG inventory guidance for seaweed ecosystems.
- Improve methods for monitoring mitigation benefits to enable standardised accounting within national GHG inventories, and more comparable biennial transparency reports (BTRs).
- Increase the development of sustainable seaweed aquaculture globally.
- Increase investment in conservation and restoration of blue carbon ecosystems through innovative finance (insurance, debt swaps, taxes, and credits) and public-private partnerships.

Technology Needs

Restoration of mangroves and salt marshes is technically feasible at large scale (Lewis et al. 2015; Esteves and Williams 2017; Lee et al. 2019; Gittman et al. 2019). Many constraints are imposed, however, by social and economic factors, including unclear land tenure, poverty, overexploitation, and lack of investment (Lee et al. 2019). Seagrass restoration at large scale faces significant technical impediments, for example, successful handling of and propagation from seagrass seeds (Statton et al. 2013). Successful seagrass restoration requires management of offsite factors, such as improvement of water quality (Unsworth et al. 2018).

Costs of restoration vary among ecosystems and among developed and developing economies (Bayraktarov et al. 2016). A review of costs per area of habitat revealed that marginal costs do not decline with increasing area of restoration projects, indicating that economies of scale have not yet been achieved. There are opportunities for improving methodologies, which could result in an increase in the scalability and effectiveness of restoration (Bayraktarov et al. 2016).

Seaweed farming is in operation in several countries, with more than 99 percent of production found in seven Asian countries (China, Indonesia, the Philippines, the Republic of Korea, the Democratic People's Republic of Korea, Japan, and Malaysia). Farms in the region vary from large industrial enterprises to smaller family-run businesses (World Bank 2016; Chopin 2017; FAO 2018). Currently, seaweed farming is not optimised for carbon sequestration or global large-scale production, as most of the production is for human consumption (FAO 2018). Increasing the role of seaweed culture in mitigation will require a worldwide and sustainable expansion of the industry, of the sort that is underway in Canada (Chopin et al. 2015) and Norway (Skjermo et al. 2014). Realising greater mitigation potential will also require the development of novel products, such as bioactive compounds and biomaterials.

Emerging biorefining techniques, with sequential extraction of products, are likely to markedly increase cost-effectiveness and scale of production (Chopin 2018a; Sadhukhan et al. 2019). The possibility also exists to develop more offshore, integrated multitrophic aquaculture, including seaweed aquaculture, in the open ocean (Buck et al. 2018).

Priority Areas for Further Research

Significant gaps exist in the knowledge base and practical application of ocean-based mitigation options. Increasing efforts to produce national-level maps of blue carbon ecosystems would help monitor the success of restoration efforts and enable more accurate quantification of carbon sequestration in ecosystems under the full range of environmental conditions. This in turn would improve estimates of the likely impacts of restoration on mitigation potential. Building research capacity for an initial global-scale map of seaweed ecosystems would also contribute to improving available data, including developing IPCC-approved methodological guidance similar to that available for mangroves and salt marshes.

Research that explores the biophysical, social, and economic impediments to restoration, as well as enabling factors (e.g., value chain assessments), is needed to develop ecosystem restoration priorities, enhance incentives for restoration, and promote more successful restoration outcomes (Lee et al. 2019). Relevant information would include assessments of the wider cobenefits of increasing seaweed area and carbon sequestration (Box 4), such as climate change adaptation, enhanced biodiversity, and improved ecosystem services (Krause-Jensen et al. 2018).

Deeper knowledge of the impacts of climate change is needed to more fully understand the risks to mitigation posed by climate change. The carbon sequestration and avoided emission benefits of ecosystem restoration are currently restricted to just a few sites, and more evidence is needed.

There is insufficient documentation on the global extent, production, carbon fluxes, and burial rates of the various groups of seaweeds. There is also insufficient information on how seaweeds respond—in terms of area and performance—to management efforts and methods that aim to restore and protect them, especially in the context of natural variability, human-caused stressors from local to global level, and climate change impacts. Methods to fingerprint seaweed carbon and other blue carbon sources beyond the habitat are also critical to link management action to carbon sequestration beyond the habitat, yet these methods remain poorly developed. Jurisdictional issues would also be a challenge to implementation.

The research agenda also must address the global potential for carbon sequestration through sustainable seaweed farming and processing and/or biorefining of seaweed products, circular management of nutrients, offshore production platforms, and the ecological impacts (positive and negative) of large-scale seaweed farming. Restoration of seaweed beds is developing, but, to the best of our knowledge, no reviews of methods and success rates are available.

Box 5. Wider Impacts Associated with Utilising Coastal and Marine Ecosystems for Carbon Sequestration and Storage

POTENTIAL COBENEFITS:

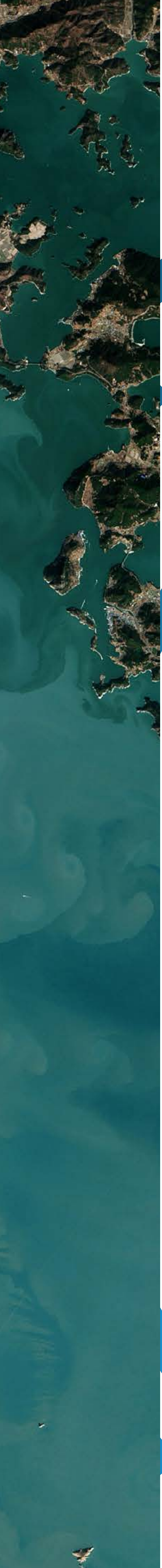
- Increased climate change adaptation benefits from healthier coastal and marine ecosystems. Vegetated habitats protect coastal infrastructure and buffer acidification.
- Higher biodiversity benefits, with healthy marine and coastal ecosystems supporting a range of terrestrial and marine species.
- Provision of nutritious food through support of fisheries, plus other benefits, including traditional medicine by mangroves, salt marsh, sea grasses, and seaweeds for local communities.
- Higher ecosystem services (increase in fisheries productivity, coastal protection, and coastal tourism) from protected and restored mangroves, salt marsh, and sea grasses. Fair distribution of payments to local communities from restoration work could help meet decent work and economic growth targets.
- Integration of social and gender dimension into coastal and marine restoration work will increase its effectiveness.
- Expanding seaweed production contributes to meeting global food security targets, and offers a pathway to develop alternative food, feed, and fuels that do not require arable land. The farming also offers climate change adaptation benefits. The rapidly growing business has generated jobs, predominantly in developing and emerging economies.

POTENTIAL TRADE-OFFS:

- Pushing forward blue carbon projects internationally, without considering social safeguards and demands of local small-scale fishers and other stakeholders who are heavily dependent on the resource for economic sustainability, can have unintentional negative consequences on societal well-being.
- Small-scale cultivation of seaweeds is considered low-risk. However, expansion of the industry will necessitate a more complete understanding of the scale-dependent changes and risks (facilitation of disease, alteration of population genetics, and wider alterations to the physiochemical environment).
- Mitigation options to recover ocean biomass can negatively impact poverty reduction and employment targets, and limit progress on food security targets in the short term.

For a full exploration of the wider impacts associated with coastal and marine ecosystems, see the section, Wider Impacts of Ocean-based Actions.

Source: Authors



Fisheries, Aquaculture, and Shifting Diets

This section analyses the potential mitigation impact of reducing the carbon footprint of ocean-derived food production (wild capture fisheries and aquaculture) and the potential reductions from shifting diets to include more low-carbon sources of ocean-based protein.

There are two principal ways in which ocean-based foods can contribute significantly to climate change mitigation. One seeks to reduce the carbon footprint of ocean-derived food production. For example, changing fuel sources in vessels and technological advances in production techniques can alter the emissions associated with seafood from both wild-caught fisheries and ocean-based aquaculture. The other seeks to identify emission reductions from potentially shifting more GHG-intensive diets to those that include more GHG-friendly seafood options, if those seafood options can be provided on a sustainable basis.

Different types of food, produced in different places by different means, can vary by more than an order of magnitude in the total GHGs they emit across their full life cycle. The composition of global diets, therefore, has a major effect on global emissions (Poore and Nemecek 2018; Searchinger et al. 2019).

Ocean foods have the potential to play a significant role in emission reduction efforts if their production is sustainable.

There are also opportunities for efficiency gains by reducing waste in the seafood supply chain (Springmann et al. 2018). More than one-third (by weight) of all food that is produced is currently lost in the supply chain (Gustavsson et al. 2011), and even higher fractions may be lost in some seafood supply chains (Love et al. 2015).

The largest potential mitigation gains, however, are likely to be found in shifting diets away from terrestrial animal-based protein, particularly beef cows and other ruminants, towards plant- and ocean-based options that have been identified as having a lower carbon cost. The world's population continues to grow, and so does demand for food, although projections of food demand are highly uncertain. Rising affluence and the spread of "Western diets" is encouraging the consumption of more animal protein. These trends will continue to drive growth in GHG emissions unless dramatic changes occur in the scale and composition of foods that are selected for human consumption (Springmann et al. 2018).

Estimates of global food-related GHG emissions early in this century range from 4.6 to 13.7 billion tonnes of CO_2e (Tubiello et al. 2013; Smith, et al. 2014; Poore and Nemecek 2018). By 2050, these emissions are projected to grow between 80 and 92 percent (summarised in Springmann et al. 2018.) In addition to rising GHG emissions, the environmental consequences of producing ever-increasing quantities of food with the current dietary mix of species are projected to be severe in terms of water scarcity, soil degradation, and habitat loss, among others (Tilman and Clark 2014; Springmann et al. 2018). Without significant reductions in agricultural emissions, it will almost certainly be impossible to keep planetary warming constrained to 2°C or less above preindustrial levels (Springmann et al. 2018).

Fortunately, there are several pathways that could collectively drive large emission reductions, and ocean foods have the potential to play a significant role in these efforts if their production is sustainable. Food from the sea, produced using best practices, can (with some notable exceptions) have some of the lowest GHG emissions per unit of protein produced of all protein sources (Gonzáles 2011; FAO 2012; Nijdam et al. 2012; Parker et al. 2018; Hallström et al. 2019). Increasing the fraction of ocean-based food in the global diet, and reducing the share of animal-based foods, would contribute significantly to climate change mitigation.

Mitigation Potential

We estimate that, with strategic policy and investment actions to change how seafood is provided and increase its share in the collective human diet, seafood could contribute potential mitigation of between 0.34 and 0.94 $GtCO_2e$ by 2030, and between 0.48 and 1.24 $GtCO_2e$ by 2050, relative to business-as-usual projections. Our estimates are explained more fully in the Methodology section.

Reducing emissions from wild capture fisheries

Current fuel use and GHG emissions from global wild-capture fisheries up to 2011 were modelled by Parker et al. (2018). They estimated global fishing emissions in 2011 at 179 $MtCO_2e$, or 2.2 kg CO_2e per live weight kilogram of landed fish and shellfish. Global fishing thus accounts for roughly 4 percent of global food system production emissions. Modelling was based on the aggregation and weighting of extant fuel-use data, specific to target species, gear, and/or fishing country, with corrections to account for upstream emissions from fuel production and transport, as well as non-fuel emissions from vessel construction, gear manufacture, refrigerant use, and other factors.

Reductions in emissions from wild-capture fisheries can be achieved in ways ranging from technological advances in engine efficiency or hull design to changes in skipper behaviour, such as speed reductions and willingness to fish in poor conditions. However, while technological changes, such as gear design and engine retrofits, have been demonstrated to influence fuel-use rates in individual vessels (e.g., Parente et al. 2008; Khaled et al. 2013; Sterling and Goldsworthy 2007; Latorre 2001), the effects of such changes at the fleet level are unclear and can be overshadowed by variation in stock abundance or structural changes to the fishery (Ziegler and Hornborg 2014; Farmery et al. 2014; Pascoe et al. 2012). A more consistently reliable driver of emissions within a fishery is catch per unit effort, reflecting both effort (e.g., days fished) and available biomass (Parker et al. 2017; Ziegler et al. 2016).

Our estimate of mitigation potential in this case is consequently focused on the potential for future changes in effort and landings, while acknowledging that technological and behavioural factors will play a role, either positively or negatively. Arnason et al. (2017) developed a future scenario to optimise the economic performance of global fisheries. Compared to wild capture landings in 2012, they estimated that, in theory, wild fish catch could increase by 13 percent by 2030, with significantly less fishing effort expended. Applying their effort and landings projections to Parker et al.'s (2017) emissions model, this increase in efficiency could reduce GHG emissions by a total of 81 MtCO_2e, or to roughly half of current fishing emissions (Table 7).

Reducing emissions from aquaculture

Global analyses of the complete GHG footprint of aquaculture are lacking, and many systems that make up a large portion of global production have not been sufficiently assessed. However, some clear patterns have emerged from the literature to date. In particular, the largest source of emissions in finfish and crustacean aquaculture is commonly the feed provided for their growth (Henriksson et al. 2012; Parker 2018; Pelletier et al. 2009; Pelletier and Tyedmers 2010; Robb et al. 2017). Minimizing the carbon profile of aquaculture feeds therefore can represent a substantial source of future emission reductions, or at least avoidance of emissions increases.

The composition of fish feeds varies greatly, especially across herbivorous, omnivorous, and carnivorous species (see the feed ingredients database: http://afid.seafdec.org.ph). Two of the key components of many feeds for omnivorous and carnivorous species have historically been fish meal and fish oils, which are products derived primarily from forage fish fisheries and increasingly from trimmings of other species during processing. These components promote vibrant fish growth and are also sources of key nutrients shown to have significant benefits for human health (Kris-Etherton et al. 2002).

There are active debates concerning the logic behind feeding wild fish to farmed fish rather than using the wild fish for direct human consumption (Naylor et al. 2000, 2009; Tacon and Metian 2008). In addition, the global supply of fish meal is now at a historical high and may be near biological limits (Costello et al. 2012). As a result, the continued growth of fed aquaculture has driven dramatic increases in the price of fish meal and incentivised reductions in the fish meal and fish oil content of many aquaculture feeds (McGrath et al. 2015; Rana et al. 2009).

To date, the primary replacements for fish meal have been soy and other agricultural crops, which often have high GHG emissions (Pelletier and Tyedmers 2007; McGrath et al. 2015). More recent substitutes for fish meals and oils include a range of livestock-derived inputs (e.g., blood, meat, and feather meal), which typically have even higher levels of GHG emissions (Parker 2018; Pelletier et al. 2009). Many of these substitutes, and particularly those derived from some crops, can have trade-offs in terms of fish and crustacean growth and health, especially for farmed predators. Consequently, efforts are now being made to identify new, highly nutritious, and ideally, low-impact feed sources. Some of the most promising options are a variety of protein concentrates derived from a range of single cell organisms including yeast, bacteria, or microalgae (Sarker et al. 2018). Although the motivation for this innovation was to provide better quality feeds, one of the fortunate benefits is that some of these alternative feed inputs have significantly lower GHG emission intensities than soy-based protein (Couture et al. 2018). Other emerging feed alternatives, however, can have substantially higher emissions with few benefits relative to soy protein (Couture et al. 2018).

Because of the limited nature of fish meal and the reduction in fisheries that provide it, future aquafeeds will need to use alternative sources for meal and oil. Given current projections for aquaculture growth (SOFIA 2018), we estimate that targeting new low-emission alternatives as replacement feed components, rather than soy-based protein or other high-GHG sources, could avoid annual emissions from the industry by 16 $MtCO_2e$ by 2030 and 43 $MtCO_2e$ by 2050. If the pace of aquaculture growth increases further because of projected growth in demand (Waite et al. 2018), these emissions savings could increase by more than one-third. Since many options are emerging to replace the fish meal fraction in feeds, realising potential emissions cobenefits will require incentives. For example, a well-structured price on carbon, detailed full life-cycle assessments of emissions from new feeds, targeted investments, information, and certification campaigns would help prioritise low-emission feed options. If shifting demand (see below) drives even faster growth in aquaculture relative to other sources of animal protein, these savings could grow proportionately.

One promising strategy is to incentivise lower consumption levels of particularly impactful foods (i.e., most animal-based products) through education, but also through market mechanisms that increase the price of GHG-intensive foods.

Reducing emissions by shifting diets

Food will play an increasingly large role in future climate change mitigation efforts (Tilman et al. 2001, 2011; FAO 2012, Poore and Nemecek 2018; Springman et al. 2018; Searchinger et al. 2019). GHG emissions from food systems are high, particularly from livestock production, and demand for animal-based food is projected to increase dramatically by 2050 (Searchinger et al. 2019). Since different foods vary widely in their embedded GHG emissions per unit of protein (Poore and Nemecek 2018), changes in the composition of future diets could greatly affect the emissions consequences of growth in demand (González et al. 2011).

If we look only at food system emissions of methane and nitrous oxides, which will not be affected by advances in low-emission energy sources, the business-as-usual scenario projects that GHG emissions will grow from 5.2 $GtCO_2e$ in 2010 to 9.7 $GtCO_2e$ in 2050 (Springmann et al. 2018). Of that projected growth, over 75 percent will come from projected growth in animal products.

The primary pathways for reducing these potential impacts are efficiency gains (e.g., reducing food loss and waste, feed conversion ratios, and growth periods for livestock) and dietary shifts in terms of food choices and levels of consumption.

Changing behaviour on a scale necessary to shift diets enough to materially affect projected GHG emissions is an immense challenge. One promising strategy is to incentivise lower consumption levels of particularly impactful foods (i.e., most animal-based products) (Poore and Nemecek 2018; Springmann et al. 2018) through education, but also through market mechanisms that increase the price of GHG-intensive foods. Another strategy targets people's self-interest and stresses the benefits of reduced animal food consumption for human health. There is a strong alignment between dietary changes that would improve human health and those that would benefit the environment (Tilman and Clark 2014).

Sustainable growth in seafood production and consumption, particularly from aquaculture, is at the core of these potential benefits. Such growth would necessitate improvements in ocean and coastal management to ensure that harvests can not only be increased, but also sustained. Springmann et al. (2018) suggest that an aggressive dietary shift at a global scale could reduce annual emissions by 4.7 $GtCO_2e$—more than offsetting projected growth of emmisions under the business-as-usual scenario. Pathways to achieve such a scale of behaviour change are not clear. More

Table 8. Summary of 2030 and 2050 Mitigation Potential by Mitigation Option

OCEAN-BASED CLIMATE ACTION AREA	ACTIVITY	DESCRIPTION	MITIGATION POTENTIAL, 2030 ($GTCO_2E$/YEAR)	MITIGATION POTENTIAL, 2050 ($GTCO_2E$/YEAR)
Fisheries, aquaculture and dietary shifts	Reducing emissions from wild capture fisheries	Emissions from fuel use for inland, coastal, and open ocean fishing (wild capture)	0.081	0.137
	Reducing emissions from aquaculture	Life-cycle emissions from aquaculture (new feeds to replace fish meal and soy-based proteins)	0.016	0.043
	Increasing share of ocean-based proteins in diets	Ocean-based proteins are substantially less carbon intensive than land-based proteins (especially beef and lamb). Therefore, actions that shift diets to lower carbon protein, including ocean-based proteins, reduce emissions	0.24–0.84	0.30–1.06
Total			0.34–0.94	0.48–1.24

Source: Authors

conservatively, we estimate that two practical scenarios could achieve significant emission reductions—a carbon tax and aggressive health campaigns on diets and human health—leading to emission reductions of 0.24 to 0.84 $GtCO_2e$ by 2030 and 0.30 to 1.06 $GtCO_2e$ by 2050 (Table 8). Both scenarios would see the ocean playing a significantly larger and beneficial role in global food systems.

This mitigation potential is presented in Table 8.

Methodology

This section describes our approach to estimating emission reductions that could be achieved by improving efficiency and yield in wild capture fisheries, improving performance of aquaculture, and shifting the dietary choices of consumers.

Wild Capture Fisheries

REDUCING EMISSIONS BY IMPROVING FISH CATCH EFFICIENCY

One basis for determining the extent to which effort relative to catch could be reduced worldwide is the modelling done by Arnason and colleagues (2017) in the *Sunken Billions* report. They estimated that an optimal economic scenario for the entire global fishing fleet would, relative to 2012, is likely to produce 13 percent more catch, using 56 percent as much effort (targeting maximum economic yield). While fuel use would not be perfectly correlated with effort in such a scenario, if we assume equal reductions in fuel use and effort, we can estimate the fuel use (and associated emissions) required to catch that future optimal harvest using the Parker et al. (2018) model. Our calculations assume a uniform change in landings and fuel use across all species groups and gear types, remodelled from Parker et al. (2018). This is likely an overly optimistic scenario, given the challenges to fisheries management globally, the uneven and insufficient implementation of effective management techniques, and the as yet unrealised recommendation of Arnason and colleagues to direct global fisheries towards their optimal future. Further, it fails to address technological and behavioural changes that may accompany changes in effort and landings, whether positive or negative.

The result of higher catches for less effort is roughly a halving of emissions intensity from 2.2 kg CO_2e per kg landed to 1.1 kg CO_2e. Total emissions from the global fishing industry would decline from 179 $MtCO_2$e to 98 $MtCO_2$e, a reduction of 81 $MtCO_2$e. These emission reductions could be achieved rapidly if countries adopt management reforms to align fishing effort with values appropriate for achieving maximum sustainable yields. Such a scenario would also eventually provide approximately 10 percent more fish and shellfish from the ocean than the current scenario, (Parker et al. 2018) based on the suggested landings in Arnason et al. (2017), compared to the 2011 landings modelled by Parker et al. (2018). Such gains would occur gradually after the effort reductions, since they depend on the recovery of fish stocks.

REDUCING EMISSIONS BY INCREASING FISHERY YIELDS

We estimate the additional protein provided by assuming an average flesh yield from live weight of 50 percent and protein content of 20 percent. This yields an additional 863 million kg of protein annually once stocks are rebuilt. While the degree to which that additional protein would be available to offset alternative animal protein sources would rely on numerous factors, we calculate the optimal case, assuming that all additional protein from fisheries replaces (does not add to) more emissions-intensive land-based protein sources.

We use pork to represent an average land-based protein (Poore and Nemecek 2018), as it has a middle-range emissions profile. If we assume the emissions from producing 100g of protein from pork are 7.6 kg CO_2e (Poore and Nemecek, 2018), compared to 1.1 kg CO_2e for average fish and shellfish, we derive a potential emissions offset of 6.5 kg CO_2e for every 100g of additional fishery-sourced protein, or a total annual emissions reduction potential of 56.1 $MtCO_2$e by 2050 (Table 8).

Table 9. Projected Emission Reductions from Improving Fishing Efficiency under Two Scenarios

MEASURE	UNIT	2011 BASELINE	OPTIMAL SCENARIO
Fish landings	Million tonnes	81.1	89.7
Emissions from fishing	Million tonnes CO2	179.0	98.0
Emissions intensity	CO2e/kg fish landed	2.2	1.1
Additional harvest	Million tonnes	Not available	8.6
Additional protein	Million kg	Not available	863.0
CO2e offset per 100g protein	kg CO2e	Not available	6.5
CO2e reduction from substituting seafood for land-based protein	Million tonnes CO2	Not available	56.1
CO2e reduction from reduced fishing effort per unit catch	Million tonnes CO2	Not available	81.0
Total CO2e reduction from wild fisheries	Million tonnes CO2	Not available	137.1

Sources: Authors (2011) baseline scenario from Parker et al. (2018). Optimal scenario remodelled from effort and catch estimates in Arnason et al. (2017).

The combined emissions reduction potential of global fisheries, assuming optimal effort to catch ratios from Arnason et al. (2017), and 100 percent substitution of available fish protein for average animal-based protein sources, is 137.1 MtCO_2e. Since these benefits require the inherent delay of population recovery of the fished stocks, we assume these added reductions are achievable by 2050.

Aquaculture

FAO projects that global aquaculture production will grow at an annual rate of 2.1 percent from 2017 to 2030 (SOFIA 2018), with annual production reaching 110 Mt by 2030. The Food and Agriculture Organization (FAO) does not currently project to 2050, but if we assume a similar annual growth rate of approximately 2.0 percent from 2031 to 2050, total aquaculture production (excluding plants) would be approximately 163 Mt live weight in 2050—essentially double the 2017 production or an additional 80 Mt live weight.

The projected growth in aquaculture production could affect GHG emissions in two ways. Growth could influence the mix of animal proteins that is consumed. We address this issue below in the section on shifting diets. Secondly, constraints on the availability, and rising cost, of fish meal from wild fisheries, will mean that the fraction of fish meal in farmed fish diets will continue to decline. Fish meal is likely to be replaced primarily by agricultural products like soy and/or livestock by-products unless new alternative feeds are adopted. Fortunately, we have seen great innovation in the development of new protein-rich feed inputs. Although the GHG emissions expected from many of these alternatives have not been thoroughly analysed, feeds derived from single-celled yeast and microalgae appear to have dramatically lower GHG emissions per unit of protein (Couture et al. 2018, unpublished) than alternatives like soy. If we assume that aquaculture production in 2050 is double what it is today and has a similar product mix (i.e., fed species versus shellfish, etc.), the use of new low-emission alternative feeds for the feed fraction that is currently fish meal would reduce projected feed-based emissions by more than 43 MtCO_2e in 2050. At the extreme, if these alternative feeds provided all the required additional feeds needed to support projected aquaculture growth, emissions would be reduced by nearly 259 MtCO_2e in 2050, relative to the emissions from a predominantly soy-based or emission-equivalent feed.

Dietary shifts to ocean proteins

Conservative estimates focused only on methane and nitrous oxide emissions suggest that aggressive dietary changes could reduce global annual GHG emissions in 2050 by nearly 5 GtCO_2e, while simultaneously improving human health (Springmann et al. 2018; Willett et al. 2019). The challenge is to bring about significant behaviour change on the part of billions of people. To estimate what fraction of the potential gains from shifting diets might realistically be achievable, we examine the potential effects of two policy approaches—a carbon tax that applies to food systems and media campaigns focused on improving human health through diet.

> Feeds derived from single-celled yeast and microalgae appear to have dramatically lower GHG emissions per unit of protein than alternatives like soy.

Carbon taxes have been proposed as a market-based tool to reduce GHG emissions from livestock production systems. In theory, a well-designed tax that encompasses more than just carbon emissions would make GHG-intensive food products, such as beef and lamb, relatively more expensive and steer consumers towards lower-carbon substitutes such as pork, seafood, chicken, or vegetable proteins. There are many practical and political challenges to designing and implementing GHG pricing in the agricultural sector. Several studies, however, have concluded that taxes could result in substantial reductions in GHG emissions (Tallard 2011; Havlik et al. 2014; Wirsenius 2010). Modelling suggests that a global price on methane emissions from livestock ranging from US\$15/tCO_2e to US\$100/tCO_2e would reduce methane emissions by 2.8 percent and 9.9 percent, respectively (Tallard 2011). See also research in the previous section whereby the addition of some types of seaweed to livestock diets can lead to a large decline in methane emissions. After applying emissions intensities (Gerber et al. 2013) to forecasted production of terrestrial animal proteins in 2030 (Alexandratos and Bruinsma 2012), these reductions in livestock emissions would amount to 237 to 840 $MtCO_2e$/year. Extending this estimate out to 2050, these same percentage reductions in livestock emissions would lead to avoided emissions of 0.30 to 1.06 $GtCO_2e$/year, a portion of which will come from shifts to ocean-based proteins.

Shifting diets through media and educational campaigns

The projected health benefits of reducing meat consumption are so large that GHG emissions mitigation could potentially be achieved as a cobenefit of behaviour change motivated by people's interest in their personal health (Willett et al. 2019). Numerous campaigns on other health-related issues provide insights on the magnitude of expected behaviour changes. In multiple meta-analyses (Snyder et al. 2004; Elder et al. 2004; Abroms and Maiboch 2008) on campaigns on seat belt use, smoking, cancer screening, alcohol use, and many other topics, the sobering result was that the observed effects were moderate—typically 15 percent or fewer people changed targeted behaviours. Lessons learned from past campaigns could help maximise the impacts of future campaigns on diets, but expectations for near-uniform adoption of behaviour change are clearly unrealistic. Applying the median (11 percent) and upper bound (15 percent) of these past experiences to the projected benefits of global adoption of a less-GHG–intensive diet (4.7 $GtCO_2e$ estimated by Springmann et al. 2018) suggests that effective campaigns focusing on health benefits of dietary change could potentially yield reductions between 0.52 and 0.71 $GtCO_2e$ by 2050.

Policy Interventions Required to Achieve Mitigation Potential

Achieving a level of efficiency gains in wild fisheries that would drive emission reductions requires more effective management of fisheries around the world. Several global analyses highlight where fisheries are working well and where there are needs for significant reforms (e.g., Arnason et al. 2009; Sumaila et al. 2012; Costello et al. 2016), and help identify which management practices are linked to success or failure in fisheries management (e.g., Kelleher et al. 2009; Evans et al. 2011; Allison et al. 2012; Barner et al. 2015; Lubchenco et al. 2016; Costello et al. 2016; Lester et al. 2017). The lessons of this rich literature are that there are robust solutions for a wide range of fisheries issues. Yet, the problems persist and grow. The challenge is to scale the successes more quickly than the problems grow. Achieving this goal requires national recognition of the nature of each country's fisheries challenges and the benefits of improved management (Box 6), and a concerted effort to draw on the lessons of others to drive more rapid change.

Significantly altering the behaviours of a broad section of society, even for actions that are both in the interest of the planet and of individual people, is surprisingly challenging. The two broad approaches of sending clear market signals via carbon or other food-related taxes that embed broader environmental and social costs of different food choices in prices, and motivating lifestyle changes need to be coupled. The two policy approaches, if synergistic, can help to realise greater GHG emissions mitigation.

Technology Needs

Unlike other categories in this assessment, the largest gains from changes in the global food system do not depend on the development of new technologies. Rather, the benefits depend on scaling solutions globally that have already been demonstrated in specific places. Although this requires new innovative approaches, new market solutions, and new campaigns, it is not heavily dependent on new technological advances.

Priority Areas for Further Research

Data sources for GHG emissions from fisheries, both farmed and wild-caught, would better inform potential policy interventions.

Box 6. Wider Impacts Associated with Reducing Emissions from Fisheries and Aquaculture and Shifting Diets to Ocean-based Proteins

POTENTIAL COBENEFITS:

- Even moderate shifts in diet from high meat consumption towards ocean-based protein have well-documented human health benefits.
- Moving to diets that are less dependent on animal products would slow the growth in demand for land and freshwater to support livestock agriculture.
- Growth of marine aquaculture will create jobs. Total direct employment in the industry is estimated to be 3.2 million in 2030 under business-as-usual projections (an increase of 1.1 million above 2010 levels)[a].
- Innovations in developing fish meal substitutes and improving feed efficiency will be crucial to support a rapidly growing aquaculture industry and meet global food security targets.
- Replacing fish meal of future feeds with crops instead of animal by-products requires less water; reducing feed conversion ratio in aquaculture production decreases upstream water usage.
- Structural changes to fisheries that reduce fuel consumption will be economically beneficial.

POTENTIAL TRADE-OFFS:

- Offshore marine aquaculture is associated with multiple environmental challenges (such as eutrophication, disease, and risk of invasive species). These risks are also to some extent associated with land-based farming.
- Unplanned growth in shrimp aquaculture has caused widespread loss of mangrove ecosystems, leading to large CO_2 emissions, salinisation of soils and freshwater reserves, erosion, and loss of coastal resilience to flooding.
- Increased inclusion of terrestrial plant-based ingredients in fish feed for a growing aquaculture industry could lead to competition for land, causing social and environmental conflicts that may in turn affect the resilience of the global food system. However, the land and water demands of land-based agriculture, especially livestock production, are far greater on a unit output basis.

For a full exploration of the wider impacts associated with fisheries and aquaculture, see the section, Wider Impacts of Ocean-based Actions.

Source: Authors

Notes: a. OECD 2016.

Carbon Storage in the Seabed

This section analyses the potential mitigation impact of storing carbon in the seabed.

The ocean naturally contains nearly 150,000 $GtCO_2e$. This dwarfs the 2,000 $GtCO_2e$ in the atmosphere and 7,300 $GtCO_2e$ in the land-bqa biosphere. Each year, as a consequence of human activities, approximately 10 billion tonnes of CO_2, or about 25 to 30 percent of anthropogenic CO_2 emissions, enters the ocean (Global Carbon Project 2018). As a result, there is considerable theoretical potential to store CO_2 (once captured and compressed) in the ocean in ways that substantially reduce adverse environmental impacts relative to the environmental impacts that occur as a result of atmospheric release of CO_2 (GESAMP 2019).

However, any proposals for ocean-based carbon storage, including storage in the seabed, must be considered in light of the substantial risks to the ocean environment and its ecosystems (Kroecker et al. 2013; Gattuso et al. 2015; Pörtner et al. 2018) and the associated technical, economic, social, and political challenges. Options for ocean carbon storage differ, depending on whether the source CO_2 is concentrated, (e.g., captured from power plant flue gas) or diffuse (e.g. atmospheric CO_2). The options may also differ as to whether the stored CO_2 is concentrated (e.g., in storage reservoirs) or is to be diffused (e.g., mixed into deep ocean waters). The options also differ in the form in which the CO_2 is sourced (from power plants, the atmosphere, or biomass) and in which it is stored (as molecular CO_2, as ions with charge balanced by added alkalinity, or as organic carbon). Table 9 summarizes the options most often discussed for ocean-based carbon storage.

Note that vertical ocean pipes are not addressed in this document because the most reliable available science indicates that such pipes would bring carbon-enriched water up from the deep, and thus not be effective at storing carbon in the ocean (Dutreuil et al. 2009; Oschlies et al. 2010; Kwiatkowski et al., 2015). Furthermore, several studies have suggested that CO_2 extraction from seawater would be feasible at commercial scale; however, insufficient information is available to assess the feasibility and system-level effectiveness of these options. For example, Willauer et al. (2014) describe a CO_2 -removal process that involves an effluent returned to the ocean with a pH of 6, with no consideration of how that effluent might affect the ocean environment.

The storage of highly concentrated and compressed CO_2 streams in the seabed is the only option that is currently deployed at industrial scale and is therefore the only option that has a reasonable likelihood of being deployed at large scale by 2030 and beyond. To date, sub seabed storage has been used only to facilitate the extraction of natural gas from the Norwegian coast. Thus, the net flux of carbon has been from the seafloor to the atmosphere, not the other way around. The process returns excess CO_2 back to the sub surface that comes up with the natural gas. If not for extracting the natural gas, the CO_2 have have remained in the sub surface. The rest of the options presented in Table 10 remain untested at an industrial scale.

All assessments of ocean-based carbon storage potential should therefore be greeted with considerabe caution. Further research is necessary to narrow the uncertainties and ensure informed decision-making about the viability of ocean-based carbon storage. As a result of the significant gaps in knowledge in terms of ability to scale the range of ocean-based storage options and the very real risks to ocean ecosystems, the only option that has been assessed in this report is seabed storage. The full range of options contained in Table 10 is discussed in Box 7 at the end of this section.

Mitigation Potential

Carbon capture and storage of CO_2 in the seabed requires that CO_2 be concentrated, compressed, and transported to the deepwater injection site. Based on a number of studies, Adams and Caldeira (2008) concluded that the costs for capture and compression from a fossil fuel power plant would be around US$20 to US$95 per tonne of CO_2 captured, and the cost of transportation approximately US$1 to US$10 per tonne of CO_2.

The cost of geological storage was estimated at US$0.5 to US$10.0 per tonne of CO_2 injected, and US$5 to US$30 per tonne of CO_2 (>1000 m).

Electricity generation accounts for about 25 percent of global GHG emissions (IPCC 2014) with up to 10 percent (or about 2.5 percent of the total) of electricity generation being located near enough to the ocean to make ocean disposal of power plant CO_2 economically feasible (SRCCS 2015). Thus, the total potential for ocean-based carbon storage by seabed storage may be up to 2.5 percent of global CO_2 emissions. At 2018 global CO_2 emission rates, this would yield an estimated mitigation potential of 1 $GtCO_2e$. As it would be extremely difficult to retrofit most existing power plants with carbon capture and storage facilities and pipes to the deep ocean by 2030; the economic potential in 2030 is likely to be less by a factor of 10 (about 0.1 $GtCO_2e$).

Table 10. CO_2 Characteristics of Storage Options for Deep Sea and/or Seabed Storage

OPTION	CO_2 SOURCE	CO_2 STORAGE RESERVOIR	INITIAL CO_2 STORAGE FORM	TECHNICAL READINESS	COST PROFILE	PRINCIPAL ENVIRONMENTAL CONCERNS	KEY REFERENCES
CO_2 injection to seabed	Power plant	Geologic reservoirs beneath seafloor	Molecular CO_2	High to medium	High	Operational activities; leakage to ocean; impacts on deep sea ecosystems	SRCCS (2005)
CO_2 storage contained on top of the seafloor (CO_2 injection into CO_2 lakes or containment vessels)	Power plant	Reservoirs on seafloor separated from the ocean by physical or chemical barrier	Molecular CO_2	Low	High	Leakage to ocean; damage to seafloor; operational activities; impacts on deep sea ecosystems	SRCCS (2005); Palmer et al. (2007)
CO_2 injection into deep ocean	Power plant	Deep ocean	Molecular CO_2	High	High	Ocean acidification; leakage to atmosphere; operational activities; impacts on deep-sea ecosystems	SRCCS (2005)
Carbonate dissolution (CO_2 release to the ocean, buffered by dissolved carbonate minerals)	Power plant	Ocean	Bicarbonate ions	Medium	High	Possible contaminants; local impacts on ecosystems	SRCCS (2005); Rau and Caldeira (1999)
Alkalinity addition	Atmo-sphere	Ocean	Bicarbonate ions	Medium	High	Unintended ecosystem effects	SRCCS (2005)
Ocean fertilisation	Atmo-sphere	Ocean	Organic carbon	Low	Medium	Interference with marine ecosystems; ocean acidification; leakage to atmosphere	Williamson et al. (2012))

Source: Authors

Notes: "Power plant" is used to refer generically to concentrated CO_2 streams, and "Atmosphere" to diffuse sources. For technical readiness, "High" means could likely be accomplished within several years; "Medium" means no major technical barrier; "Low" means that there are substantial uncertainties regarding technical feasibility and/or geophysical effectiveness. For costs, "High" means comparable to carbon capture from power plants with geologic storage on land; "Medium" means lower, but still substantial, costs. These evaluations represent subjective assessments by the authors on the basis of available information. The "CO_2-storage reservoir" and "Initial storage forms" columns in Table 9 indicate that in the case of some ocean storage options, the storage is isolated from the large volume of ocean seawater. In other options, the carbon is distributed through the ocean volume but primarily in forms that do not exchange with the atmosphere or cause ocean acidification. Lastly, some proposed options simply transfer molecular CO_2 to the deep ocean; in which case storage might not be permanent and would contribute to ocean acidification and impacts on marine organisms and ecosystems.

By 2050, a greater fraction of the technical potential might be achieved and the environmental risks suitably understood and mitigated so that other ocean-based storage options might be developed, so it is conceivable that several billion tonnes of CO_2e could be stored in the ocean each year by 2050. However, this has not been included in our calculations for this report, given the degree of current uncertainty of the technical, environmental, social, and political feasibility of these additional options.

The first three options shown in Table 9 involve different forms of carbon capture and storage for coastal powerplants and as such should also be considered as interchangeable. Based on this, and the assumptions and limitations outlined above, it is possible to propose a total mitigation potential in 2030 of 0.25 to 1.0 $GtCO_2$e, and of 0.5 to 2.0 $GtCO_2$e in 2050 (Table 11).

Methodology

The physical potential of sub-seabed storage is thought to be very large, as there is an abundance of settings in which CO_2 could potentially be stored. The physical capacity of carbon storage in the marine environment has been estimated to exceed 10,000 Gt of CO_2 (36,000 $GtCO_2$) in the seafloor surrounding the contiguous United States alone (House et al. 2006). This is similar in magnitude to the total amount of the fossil fuel resource (IPCC 2014). More realistically, the capacity for storage in the seafloor will depend on costs of transport of CO_2 from the concentrated source, and the cost of emplacement in seabed geologic formations.

On the time frames considered here (2030 to 2050), seabed storage will be limited not by geophysical capacity, but rather by techno-economic and possibly sociopolitical factors.

Costs are somewhat higher than for land-based geologic carbon storage, but, even in the ocean case, the primary cost driver is the cost of separating and compressing the relatively pure CO_2 stream (SRCCS 2005). In the 1.5°C stabilisation scenarios considered by the IPCC SR15 (2018), total carbon capture and storage amounts to year 2050 (cumulative) are typically about 100 $GtCO_2$, but range to over 400 $GtCO_2$ in some models. The corresponding magnitude for 2030 is of the order of several billion tonnes of CO_2.

If seabed storage were to comprise 30 percent of total carbon capture and storage, that would suggest an average rate of seabed carbon storage of the order of 1 $GtCO_2$/year. It is reasonable to presume that the most advantageous settings would be used first, so it is plausible that half of the average rate could be reached by 2030, approximately 0.5 $GtCO_2$/year. As a rough approximation of uncertainty, we halve and double these values.

Policy Interventions Needed to Achieve Mitigation Potential

Seabed storage would occur in territorial waters so the primary regulatory bodies would be national. The primary environmental concerns, if everything works as planned, involve local environmental disturbance from industrial operations. International implications arise related principally to the risk or event of failure. Continuing to increase scientific understanding is essential if these technologies are to be used safely and without unintended consequences.

Technology Needs

Carbon storage in the seabed does not involve major technical advances and is an extension of activities that are already being carried out on land. Scaling up

Table 11. Mitigation Potential of Carbon Storage Options in 2030 and 2050 ($GtCO_2$e)

OCEAN-BASED CLIMATE ACTION AREA	MITIGATION OPTION	DESCRIPTION	MITIGATION POTENTIAL, 2030 ($GTCO_2$E/YEAR)	MITIGATION POTENTIAL, 2050 ($GTCO_2$E/YEAR)
Seabed carbon storage	CO_2 storage in the seabed	Geological storage offshore of CO_2 below the seabed	0.25–1.00	0.5–2.0
TOTAL			0.25–1.00	0.5–2.0

Source: Authors

Note: These values represent reasonable estimates of the lower and upper bounds of potential deployment rate in a highly aggressive mitigation scenario.

the technologies to match the scale of the problem, however, is a major challenge.

An exception, where technological advances are required, would be materials science questions relating to long-lasting containment of CO_2 in a deep seafloor environment. For the most part, noncost barriers primarily have to do with unintended environmental consequences, effectiveness, and verifiability, and not the state of technological development.

Priority Areas for Further Research

The primary barriers to use of the ocean as a carbon storage reservoir involve environmental concerns (Box 7). However, if done properly, some of these techniques could potentially isolate CO_2 away from both the atmosphere and the majority of ocean waters for millions of years.

Other techniques might have cobenefits, for instance, reducing associated impacts such as ocean acidification. On the other hand, seabed storage of CO_2 approaches, if deployed unwisely, could contribute to ocean acidification and damage ocean ecosystems by impacting chemical, physical, and ecological processes at a large scale.

Further research will help us understand the full implications of carbon storage options. Box 8 profiles the status of current knowledge for the other ocean-based carbon storage options not quantified in this report.

Box 7. Wider Impacts Associated with Options for Seabed Storage

POTENTIAL COBENEFITS:

- Potential benefits in terms of direct job creation, as well as job retention in harder-to-abate sectors (e.g., heavy industries and fossil fuel based sectors) by allowing them to function with appropriate CCS infrastructure investment/development.

POTENTIAL TRADE-OFFS:

- Injection of CO_2 into submarine geological structures has the potential for CO_2 to leak back into the marine environment, affecting the health and function of marine organisms, especially with respect to the resulting localised ocean acidification. The gravity of the impacts at community level is unknown.
- Potentially serious impacts on little-understood deep-sea ecosystems, which are the largest habitat on the planet.

For a full exploration of the wider impacts associated with ocean-based transport, see the section Wider Impacts of Ocean-based Actions of this report.

Source: Authors

Box 8: Additional Ocean-based Carbon Storage Options Not Quantified in this Report

Containment of CO_2 on the Seafloor

Below about 3,000m depth, compressed CO_2 is denser than seawater and so will tend to sink or remain on the seafloor. This has led to the proposal that CO_2 might be stored in lakes on the seafloor (Shindo et al. 1993). However, in the absence of a physical or chemical barrier, such CO_2 lakes would be expected to dissolve into the overlying seawater (SRCCS 2005). Little work has gone into developing such barriers, although it has been estimated that the cost of creating a physical barrier would be small, perhaps as low as US$0.035 per tonne of CO_2 stored (Palmer et al. 2007). Because of the vastness of the seafloor, there is no practical constraint on the amount of CO_2 that could be stored in this way, and if concerns over physical integrity of the barrier and effects on the underlying seafloor can be addressed, the primary determinant of the scalability of this approach is likely to be the costs of producing a relatively pure CO_2 stream, and those of transporting and emplacing the captured CO_2 in these storage reservoirs.

Because containment of CO_2 on the seafloor has never been demonstrated for any substantial amount of time, the lower

Box 8: Additional Ocean-based Carbon Storage Options Not Quantified in this Report (continued)

bound on the potential for this technology class must be regarded as zero. However, if demonstrated containment can prove cost-effective, the potential for containment storage on the seafloor could be as large as that estimated for sub-seabed storage.

Injection of CO_2 into the deep ocean

Injection of CO_2 into the deep ocean is much simpler than storage beneath or on the seafloor. Deep-sea disposal and containment of CO_2, however, raises concerns about environmental effects (e.g., impacts of ocean acidification) and leakage back to the atmosphere. As noted above, most of the waste CO_2 released to the atmosphere by human activities will ultimately reside in the ocean. Therefore, placing CO_2 in the ocean instead of in the atmosphere could be expected to reduce the climatic consequences of CO_2 emission. It would also tend to reduce the amount of ocean acidification experienced in the ocean surface but at the cost of increased ocean acidification in the deep ocean. If the entire ocean were allowed to have the same pH change as the near-surface ocean (about 0.1 pH units), the ocean could store a total of about 2,000 $GtCO_2$ (SRCCS 2005). Over one-quarter of this amount (GCP 2018) has already been absorbed from the atmosphere, leaving about 1,500 $GtCO_2$ of storage capacity. If a pH change of 0.2 were deemed to be acceptable (corresponding to an atmospheric CO_2 concentration of about 600 parts per million [ppm]), the amount of remaining storage capacity would be about 3,300 $GtCO_2$ (or roughly 10 percent of the estimated remaining fossil fuel resource).

Such changes in the chemistry of the ocean would be accompanied by a growing list of impacts on organisms, such as reef-building corals, seaweeds, invertebrates, and fish, among many others (Kroecker et al. 2013; Gattuso et al. 2015; Hoegh-Guldberg et al. 2014, 2018). In addition to decreasing the ability of organisms to maintain shells and skeletons, a wide variety of other impacts have been reported from disruptions of reproduction, gas exchange, and neural systems (Kroecker et al. 2013). Damage to deepwater ecosystems has been reported, and, though its extent has not been well documented, it is suspected to be large. These impacts have generated considerable concern about such fundamental changes to biological systems, especially given the long time (>10,000 years) it takes to reverse this change through the dissolution of carbonates and other processes (IPCC 2013).

Direct injection into the deep ocean is likely to be comparable to the cost of injecting CO_2 into the seabed. However, there is real concern about using the ocean waters as a waste disposal site for CO_2 from human industrial processes. Furthermore, storage of CO_2 freely dissolved in the deep ocean eventually exchanges with the atmosphere, so the isolation of CO_2 is not permanent. Therefore, it is far from certain that global political systems will encourage and credit deep-sea CO_2 injection. A reasonable estimate on the lower bound of conceivable deployment rate in a highly aggressive mitigation strategy would therefore range from zero to the rate estimated for seabed disposal.

Carbonate dissolution

Most of the ocean acidification caused by adding CO_2 in the ocean will ultimately be neutralised over the longer term by the dissolution (and slower accumulation) of carbonate minerals on the seafloor, and from rock weathering products delivered to the ocean by rivers. Carbonate minerals will not dissolve in the surface ocean due to high levels of carbonate saturation (i.e., concentrations that are so high that they promote precipitation not dissolution). This fact led to the idea of using power plant flue gases to dissolve carbonate minerals, which would allow CO_2 to be stored in the ocean with little adverse impact on ocean pH or mineral saturation states in the ocean (Rau and Caldeira 1999; Caldeira and Rau 2000). About 2.5 tonnes of carbonate minerals would need to be dissolved, however, for each tonne of CO_2 stored in this way. This would require a huge and unprecedented mining infrastructure and would entail massive materials-handling costs and logistics.

The costs have been estimated to be lower than for injection of relatively pure CO_2 streams for cases in which the power plant is coastally located with access to carbonate mineral resources, because this approach does not require costly separation of CO_2 from power plant flue gases and subsequent pressurisation (Rau and Caldeira 1999). However, since such facilities have never been built, cost estimates must be regarded as speculative. Regardless, such approaches would likely be cost-competitive only in locations where both carbonate minerals and CO_2 could be delivered to the ocean at low cost, which is likely to be the case for less than 10 percent of total power plant CO_2 emissions. Environmental concerns include the effects of a large scale-up of carbonate mineral mining and possible impacts on the marine environment of contaminants or incompletely dissolved particles.

Rau and Caldeira (1999) estimated that perhaps 10 percent of electricity production might be located suitably near carbonate minerals to make carbonate dissolution a cost-effective approach to carbon storage. However, there are environmental concerns about processing large amounts of seawater through carbonate reactors and using the ocean as a waste disposal site.

Box 8: Additional Ocean-based Carbon Storage Options Not Quantified in this Report (continued)

A plausible range for this approach might therefore be from 0 to 10 percent of the magnitude estimated for all of carbon capture and storage (IPCC 2018).

Alkalinity addition

The acidity caused by CO_2 in the ocean, and the propensity of CO_2 to de-gas from the ocean to the atmosphere, can be reduced or eliminated by the addition of alkaline (also known as basic) minerals (Renforth and Henderson 2017). Addition of these minerals to the ocean (Kheshgi 1995) could result in the ocean absorbing additional CO_2 from the atmosphere (González and Ilyina 2016). Over 2.5 tonnes of rock would need to be mined and crushed to a fine powder (to overcome slow dissolution kinetics) for each tonne of CO_2 stored in the ocean in this manner. As with carbonate dissolution, this option raises concerns related to huge expansion of mining infrastructure (silicate rock mining might need to expand by three orders of magnitude) (González and Ilyina 2016). Further, many of the proposed silicate source rocks contain substantial amounts of heavy metals (Hartmann et al. 2013) and thus raise concerns about introduction of heavy metals into the marine environment. Because silicate rocks are abundant in Earth's crust, there is no practical physical constraint, but if applied at scale, such ocean CO_2 storage would represent "an unprecedented ocean biogeochemistry perturbation with unknown ecological consequences" (González and Ilyina 2016).

Renforth and Henderson (2017) estimate the potential for very ambitious rates of deployment: A 50 $MtCO_2$/year initial investment (roughly equivalent to the emissions of 10 of the largest cement plants in operation), followed by ramping up this capacity by about 7 percent per year, could achieve mitigation of 0.1 $GtCO_2$/year by 2020. If the same initial investment were ramped up by about 10 percent per year, mitigation could reach 1 $GtCO_2$/year. These might be considered plausible upper bounds. The lower bound must be considered zero, because it is not clear that the international community will accept adding large amounts of dissolved and/or particulate matter to the ocean as a climate mitigation strategy.

Ocean fertilisation

Ocean fertilisation has been proposed as a means of transferring carbon from the atmosphere to the ocean. The basic idea is to add inorganic nutrients to the near-surface ocean, thereby stimulating biological production of organic matter. Some of this organic matter would sink to the deeper ocean, where it would be metabolised and dissolved in the deeper ocean waters. Some additional CO_2 would be absorbed from the atmosphere to replace the carbon that was removed by this additional biological activity. Some researchers have advocated fertilising the ocean with major nutrients that are often limiting, such as phosphate or nitrogen (Harrison 2017).

Because of the large amounts of nutrients involved, however, most of the focus has been on environments in which the major nutrients are abundant, but other minor nutrients such as iron limit marine productivity (Williamson et al. 2012). The efficacy of ocean fertilisation is reduced by shallow oxidation of sinking organic matter with the relatively rapid return of carbon to the surface ocean. This phenomenon has also attracted concern regarding the increased respiration rates stimulated by the additional organic carbon falling into the deep ocean, leading to decreased oxygen at depth and an increased risk of dead zones (Hoegh-Guldberg et al. 2014). Further, fertilisation with micronutrients utilises major nutrients that might otherwise have supported productivity elsewhere; some local increase in productivity may come at the expense of decreased productivity elsewhere at a later time.

The geophysical potential of ocean iron fertilisation has been estimated to be in the range of 0.25 to 0.75 $GtCO_2e$/year averaged over a 100-year period (Williamson et al 2012). Small-scale experiments to date suggest that adding iron dramatically changes the composition of the phytoplankton, which in turn triggers changes in zooplankton, fishes, and other higher trophic species. Many of these consequences are little understood. Concerns regarding effectiveness, permanence, verification, and unintended consequences, combined with concerns about disposing of CO_2 in deeper ocean waters, mean that the lower bound on potential must be regarded as zero. The geophysical potential of ocean fertilisation is estimated to be about 1.8 $GtCO_2e$/year. Plausibly, 10 percent of this geophysical potential could be achieved by 2030 and about half by 2050.

While the geophysical potential of ocean-based storage of captured CO_2 is large, the technical and economic mitigation potential is likely to be constrained by the technical challenges of making carbon capture and storage economically viable. Some of these technologies are likely to be technically feasible and cost-effective. Given the importance of reducing the amount of excess CO_2 in the atmosphere and ocean, understanding the full set of the impact of these solutions on ecosystems, such as the deep sea, is critical.

Source: Authors

Wider Impacts of Ocean-based Actions

This section presents analysis of the wider impacts (both positive and negative) of each of the five ocean-based intervention areas on the long-term Sustainable Development Dimensions and 2030 Sustainable Development Goals.

Increased efforts to reduce GHG emissions will affect multiple dimensions of long-term sustainable development, well-being, and governance in the form of cobenefits and trade-offs (IPCC 2018). Many interventions are likely to affect countries' ability to achieve targets established within the framework of the UN 2030 Sustainable Developmental Goals (SDGs). Taking these wider impacts into account can help provide a more informed and holistic picture of pursuing ocean-based climate solutions.

The IPCC Special Report on 1.5°C scenarios integrated some of these wider impacts into its assessment of mitigation options; however, the ocean received relatively little attention. We address this major knowledge gap by focusing on four dimensions where wider impacts may be expected: the environment, the economy, society, and governance. These dimensions, their associated impact categories, and relevant UN SDGs are mapped in Table 12.

Methodology

Wider impacts are evaluated with a weighted scoring method and an associated assessment of confidence levels. Our method is based on a similar approach adopted in Chapter 5 of the IPCC 1.5°C Special Report (Roy et al 2018). Based on a review of the existing literature and expert judgment (Box 8), the performance of each ocean-based mitigation option was assessed within each of the wider-impact dimensions (Table 12). The impact was described, scored, and weighted based on the following factors:

- **Direction of impact:** The positive and/or negative direction of the impact of the mitigation option on the wider-impact dimensions and SDG goals was recorded. If a mitigation option was identified as having both a positive and negative impact, both were recorded. The net direction of impact was determined by the sum of the positive and negative impact scores.

Table 12. Wider Impact Dimensions Explored in the Report

WIDER-IMPACT DIMENSIONS	ASSOCIATED IMPACT CATEGORIES	LINKS WITH NEAR-TERM SUSTAINABLE DEVELOPMENT GOAL TARGETS AND INDICATORS
Environment	Impact on marine and terrestrial biodiversity, water quality, land use, and adaptability of ecosystems and human settlements to climate change	SDGs 6, 12, 14, 15
Economy	Impact on employment, household incomes, profits and/or revenues of firms, innovation, supply of clean energy, and economic growth	SDGs 7, 8, 9, 11
Society	Impact on human health outcomes, poverty reduction and food security targets, regional income inequality, quality of education, and gender equity	SDGs 1, 2, 3, 4, 5, and 10
Governance	Impact on national and local institutions, participation in global governance, global partnership for sustainable development, and capacity building	SDG 16 and 17

List of Sustainable Development Goals reviewed:

Source: Authors

- **Linkage score:** The strength of the relationship between the mitigation option and the indicator was scored. Scores range from +3 (indivisible) to −3 (cancelling), with a "zero" score indicating 'consistent', but with neither a positive nor negative impact (Nilsson et al. 2016). A zero score also indicates that no relevant literature was found during this review
- **Confidence in assessment:** The confidence assessment was developed to reflect the robustness of the linkage scores. Confidence levels ranging from high to low were determined based on the level of evidence (number of studies and other articles) and level of agreement on the evidence presented in the literature. For each linkage score, an assessment of confidence was assigned, where increasing levels of evidence and degrees of agreement are correlated with increasing confidence (Mastrandrea et al. 2010).

Box 9. Literature Review Method and Types of Evidence Analysed

A two-step procedure was followed as part of a review of the literature on wider impact analysis. First, the databases Scopus and Google Scholar, and the search engine Google were used in a literature search using various combinations of keywords and short search strings such as "Ocean energy" AND "sustainability," "Ocean" AND "CCS," AND "sustainability." Second, the findings from the literature review were recorded and scored. Additional evidence was included based on feedback obtained through the expert review process. The types of evidence and number of studies are summarised in the table below. Please refer to Annex for further information on the scores and confidence assessments.

TYPES OF LITERATURE	DESCRIPTION	NUMBER
Case study	Case studies specific to countries or region	10
Experimental	Results based on experiments	11
Project-based	Results reported based on project-level impacts	2
Quantitative analysis	Studies that have employed econometric, graphical, or statistical tools to find the impact of any intervention. This includes meta-analysis, scenario analysis, spatial analysis, and other modelling assessments	46
Review paper	Studies that exclusively mention "review" in their objective or methods	16
Summary paper	This includes commentary, newspaper articles, discussion papers, policy briefs, and newsletters from international organisations	14
Website	Relevant information (such as examples of ongoing restoration programmes) provided on web pages owned and curated by international organisations	5
Report	Policy and analysis reports from international organisations, such as OECD, ETC, IRENA, FAO, IEA	31
Qualitative	Academic papers and reports that present qualitative discussion of the impact of policies and international agreements	4
Total number		**139**

Source: Authors

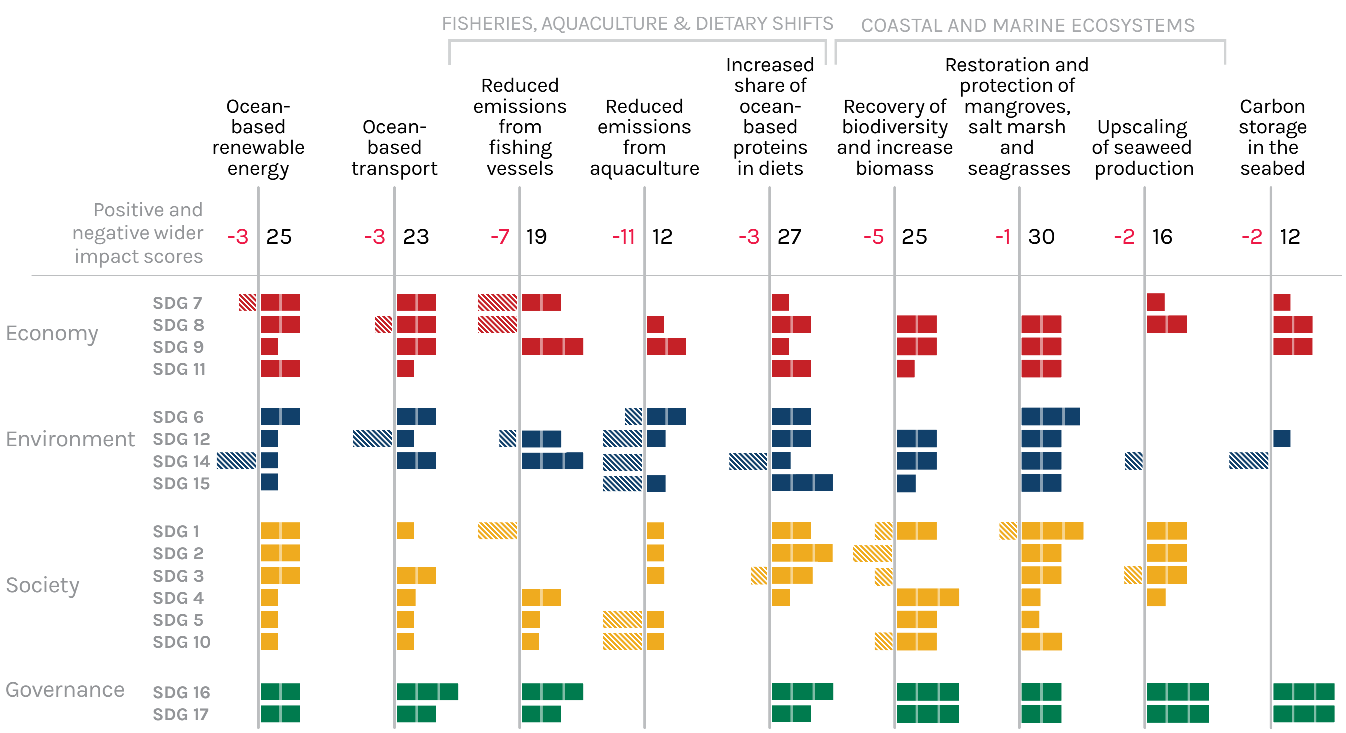
Note: OECD = Organisation for Economic Co-operation and Development; ETC = Energy Transmissions Commission; IRENA = International Renewal Energy Agency; FAO = Food and Agriculture Organization of the United Nations; IEA = International Energy Agency.

General Findings of the Wider-Impacts Analysis

All mitigation options demonstrated both positive and negative impacts, with varying strengths, across the four wider-impact dimensions (Figure 7). The headline messages can be broadly summarizeds as follows:

- All ocean-based mitigation options generate many cobenefits. Overall, cobenefits outweigh trade-offs and risks. However, these risks and trade-offs cannot be ignored, and concerted action to address negative impacts will help enhance net positive outcomes.
- Of the five ocean intervention areas, protecting and restoring coastal and marine ecosystems, fisheries and aquaculture, and ocean-based energy have a positive impact on the largest number of sustainable development dimensions. When looking at individual mitigation options, protection and restoration of vegetated coastal habitats (mangroves, salt marshes and seagrasses) and offshore renewable energy positively impact the largest number of sustainable development dimensions.

Figure 7. Linkage Scores of Ocean-based Interventions and Selected Mitigation Options across the Wider Impact Dimensions



List of Sustainable Development Goals reviewed:

Source: Authors

Notes: Wider-impact dimensions cover various sustainable development dimension as well as 2030 Sustainable Development Goals (SDG). The figure shows the relative strength of the relationship between a selected set of ocean-based mitigation options and the SDGs. For each mitigation option, the positive linkage score with a particular SDG (depicted with solid bars) is shown in the right-hand column and negative linkage score (depicted by shaded bars) in the left-hand column. Scores range from +3 (indivisible) to −3 (cancelling) (Nilsson et al. 2016). A zero score (no bar and no colour) means no impact was found in this review of the literature. Each colour represents a particular wider impact dimension: Red bars for economy (SDG 7, 8, 9, 11); blue bars for environment (SDG6, SDG12, SDG14, SDG15); yellow bars for society (SDG1, SDG2, SDG3, SDG4, SDG5, SDG10) and green bars for Governance (SDG 16, SDG 17). Further information on the linkage scores and the associated confidence levels are provided in the Annex.

- Mitigation options were observed to have the strongest links with the social and economic dimensions, implying that implementing these options in a sustainable manner would result in benefits in terms of higher employment in ocean-based industries, gains from technology spillover, increase in revenues and profits to firms, improvement in livelihoods of local communities, better human health outcomes, contribution towards global food security targets, and potential to ensure greater gender parity as ocean-based industries expand.
- Protection and restoration of mangroves, salt marshes, and seagrasses has the highest number of and most strongly positive impacts on all the environmental dimensions assessed, indicating that there is potential to achieve many environmental cobenefits, including increased biodiversity-related services, coastal resilience, and climate change adaptation benefits.
- Trade-offs and risks are varied. Mitigation options aimed at recovering ocean biomass can negatively impact poverty reduction and employment targets and can limit progress on food security targets in the short term. Lack of community-level engagement on blue carbon restoration work can lead to negative outcomes for small-scale fishers who play a strategic role in providing jobs, supplying nutritional needs, and maintaining economic sustainability. Environmental risks include impacts on coastal ecosystems or marine species from unassessed growth in ocean-based activities. Shifting diets, fisheries, and aquaculture have a negative impact on the largest number of sustainable development dimensions.
- Some of these risks and trade-offs can be adequately addressed via stakeholder engagement, inclusive management policies, monitoring, and effective marine planning. Others will require further research on their implications and in some instances will call for significant action on the part of decision-makers and policy implementers to ensure that negative impacts are reduced.
- All ocean-based mitigation options will need strong national institutions; engagement by business, industry, and communities; and international cooperation to ensure their effective implementation.

Detailed Findings of the Wider-Impact Analysis

Ocean-based Renewable Energy

Effective marine spatial planning, in combination with emerging ocean energy technologies, will be effective in mitigating biodiversity loss from ocean energy technologies and reinforcing biodiversity cobenefits (high confidence).

Offshore wind structures have positive and long-term effects on marine species because they provide new habitat in the form of artificial reefs and because fishing, mainly trawling, tend to be restricted in their vicinity (IRENA 2018a: Dinh and McKeogh 2018). In contrast to offshore oil and gas installations, there is little risk of pollution, and no need for the development of new sites in response to long-term exhaustion of the resource (Spalding and Fontaubert 2007). Risks of developing ocean-based energy include biological invasions, noise and disturbance vibrations to marine species, collisions between birds and wind turbine rotors, and the presence of electromagnetic fields that can disrupt marine life and benthic habitats (MERiFIC 2012; IRENA 2017; Langhamer 2012). However, studies have shown that most perceptions of environmental impacts from ocean-based renewable devices arise from uncertainty or lack of definitive data about the real impacts (Copping et al. 2016). While it is important to acknowledge all the impacts on the marine environment as ocean-based renewable industry develops, some of the perceived risks are likely to be small and can be avoided or mitigated (Copping et al. 2016). In the case of risks like collision with seabirds and impacts on migratory cetaceans, marine spatial planning appears to be appropriate mechanism to reduce risks to manageable levels (Best and Halpin 2019).

Ocean-based renewables will have a positive impact on reducing water use compared to fossil fuel–based technologies (medium confidence).

Offshore wind uses no water directly, and there should be an overall reduction in freshwater use compared to generating power from fossil fuels (Macknick et al 2012). There is potential to develop ocean energy technologies for a range of purposes, including desalination for drinking water (OES 2011).

Replacing fossil fuels with ocean-based renewable energy contributes to positive health outcomes (medium confidence).

The health benefits of moving to ocean-based renewable energy for power generation would be significant, particularly for regions that rely more heavily on coal and oil to generate electricity. Offshore wind in the Mid-Atlantic region of the United States could produce health and climate benefits estimated at between US$54 and US$120 per MWh of generation, with the largest simulated facility (3,000 MW off the coast of New Jersey) producing approximately US$690 million in benefits (Buonocore et al. 2016).

Moving to ocean-based renewable energy for power generation leads to positive human health outcomes, job creation, economic growth and promotes scientific research.

Expansion of ocean-based renewable energy has the potential to promote gender equity (low confidence).

A survey by IRENA revealed that women represent a higher proportion of full-time employees in the renewable energy industry, compared to their representation in the global oil and gas industry (IRENA 2019). However, their participation is still low in science, technology, engineering, and mathematics (STEM) jobs compared to administrative jobs. Greater participation of women would allow the sector to unleash female talent while ensuring equitable distribution of socioeconomic opportunities (IRENA 2019).

Expansion of ocean-based renewable energy leads to job creation and economic growth (high confidence)

Estimates predict direct full-time employment in offshore wind will be around 435,000 globally by 2030 (OECD 2016). Analysis by Ocean Energy Systems shows that deployment of other forms of ocean energy (tidal range, wave power, and ocean thermal energy) can provide significant benefits in terms of new jobs and additional investments (OES 2017). Ocean-based renewable energy has the potential to provide employment to coastal communities and will benefit workers transitioning from declining offshore fossil fuel industries (Poulsen and Lema 2017; IRENA 2018; Scottish Enterprise 2016). However, the net global impacts of ocean-based energy on jobs are uncertain.

Opportunities for innovation are expected to emerge with expansion of clean ocean energy, promoting scientific research and resulting in upgraded technological capabilities (high confidence).

The ocean-based energy industry has experienced rapid growth in installed capacity, ongoing improvements in costs and performance, and increased technological sophistication (IRENA 2018). Innovations in clean ocean energy include the potential to be integrated into and codeveloped with algae-growing facilities and aquaculture farms, and the ability to provide emission-free and drought-resistant drinking water to larger municipalities along the coast (OES 2015; Dirks et al. 2018; Buck et al. 2018). These technologies simultaneously help reduce GHG emissions and increase energy security and diversity (Dinh and McKeogh 2019). Further, there is a trend towards locating offshore energy production to support the expansion of offshore aquaculture production. A number of projects worldwide have started to invest in technologies and system design needed to enable species farming in high-energy environments (Buck et al. 2018).

Ocean-based Transport

Reducing emissions from shipping vessels will help mitigate ocean acidification (medium confidence).

Strong acids formed from shipping emissions can produce seasonal "hotspots" of ocean acidification in ocean areas close to busy shipping lanes. Hotspots have negative effects on local marine ecology and commercially farmed seafood species (Hassellöv et al. 2013).

Cleaner marine shipping fuels will reinforce positive human health outcomes (high confidence).

Reduced sulphur content of fuel oil used by ships will have beneficial impacts on human health, particularly the health of people living in port cities and coastal communities. Cleaner marine fuels are estimated to reduce premature mortality and morbidity by 34 percent and 54 percent, respectively. This represents a roughly 2.6 percent global reduction in cardiovascular and lung cancer deaths caused by small particulate matter ($PM_{2.5}$) and a roughly 3.6 percent global reduction in incidence of childhood asthma (Sofiev et al. 2018).

Mitigation options to reduce emissions from shipping can encourage innovation and upgrade the technological capabilities of the sector (high confidence).

Rapid development in power train technology will enable international maritime transport to use alternative and less-polluting fuels, such as hydrogen. The design of ships is being improved to enable them to move more quickly through water, while using less fuel. A complex array of internet-of-things sensors is being developed that will allow collection of data around tidal streams, wind strength, and visibility. This information can be used to reduce vessel waiting time, enable optimisation of routes, and support the concept of autonomous ships.

Reducing emissions from shipping could potentially have a marginal impact on the price of internationally traded commodities (medium confidence).

While there could be efficiency and energy savings from better design of ships and route optimisation, the cost to the shipping industry of switching to alternative fuels will be high (ETC Mission Possible 2018; Kizielewicz 2016; Sislian and Jaegler 2016). This could result in significant increases in voyage and freight costs. However, at least one study finds that these costs will have a marginal impact on the final product price of internationally traded commodities (ETC Mission Possible 2018).

Coastal and Marine Ecosystems

Vegetated coastal and habitats (Blue Carbon ecosystems) contribute to climate change adaptation by increasing coastal resilience and reducing the impact of sea level rise (very high confidence). Mitigation options that help recovery of ocean biomass can also result in climate change adaptation benefits (high confidence).

Vegetated coastal habitats reduce coastal flooding by slowing water flow rates and absorbing storm surges. They accrete vertically over time and thereby reduce the impacts of sea level rise and flooding (Duarte et al. 2013). Communities with more extensive mangrove forests experience significantly lower losses from exposure to cyclones than communities without mangroves (Hochard et al. 2019). Increased abundance of marine species is expected to enhance the productivity of surrounding areas, which can help buffer against climate impacts and increase their resilience (Gattuso et al. 2018).

Increased abundance of marine species is expected to enhance the productivity of surrounding areas, which can help buffer against climate impacts.

Vegetated coastal habitats offer high biodiversity benefits to terrestrial and marine ecosystems, including fisheries (very high confidence).

Vegetated coastal habitats are used by a remarkable number of marine and terrestrial animals (Li et al. 2018; Rog et al. 2016), including species important for fisheries (Carrasquila-Henao and Juanes 2017). Dense vegetated habitats buffer acidification as primary production creates high net pH (Kapsenberg and Cyronak 2019; Hendriks et al. 2014; Krause-Jensen et al. 2016; Wahl et al. 2018). Dense mangroves trap and stabilise sediments that buffer the effects of floodwaters and tidal movements, and are coming to be recognised as valuable natural systems that can play an important role in wastewater treatment systems (Ouyang and Guo 2016).

Integration of social and gender considerations into restoration policy for vegetated coastal habitats can promote gender equity and educational opportunities (medium confidence).

Local educational institutions and programmes spread awareness in communities about the ecological importance of mangrove forests and encourage community members to get involved in mangrove restoration efforts. Integrating social and gender considerations into restoration practice promotes effectiveness of restoration work (Broekhoven 2015; de la Torre-Castro 2019). Also, increasing women participation in decision-making and valuing the traditional and reproductive work of women in households will be important to ensure better governance and policy reform (Gissi et al. 2018; Torre-Castro 2019).

Restoring and protecting vegetated coastal habitats has the potential to create jobs, promote economic growth, and enhance research. Involvement of small-scale fishers and local stakeholders throughout the decision-making process is crucial to ensure delivery of net positive social outcomes. (high confidence)

Blue carbon projects require development of good practice methods and monitoring (Needelman et al. 2019). Manuals have been developed that support project developers through the various phases of carbon project implementation, including feasibility and site selection, documentation, registration, implementation, and carbon asset management (Emmer et al 2014). Job creation could follow successful restoration of coastal ecosystems; however, delivering jobs and other positive social outcomes are dependent on the participation of the affected communities throughout the policy development and implementation stages. Pushing forward blue carbon projects without social safeguards to consider demands from local small-scale fishers and other stakeholders who are heavily dependent on coastal resources for economic sustainability can have unintended negative consequences on societal well-being (Barbesgaard 2018; Bennett 2018; Friess et al. 2019).

Seaweed farming has low levels of environmental risks identified for small-scale cultivation projects (high confidence).

Seaweed farming may deliver a range of services and benefits and has the associated great advantage of not requiring arable land and irrigation (Duarte et al. 2017). The seaweed farming also offers climate change adaptation benefits (Duarte et al. 2017, Froelich et al. 2019). However, while small-scale cultivation projects are considered low risk, expansion of the industry will require a more complete understanding of the scale-dependent changes to balance environmental risks and benefits (Campbell et al. 2019). Risks include spreading disease, changing population genetics, and altering the wider local physiochemical environment (Campbell et al. 2019). If not appropriately located, seaweed farms could also affect seagrass beds, and thereby disturb important flows of ecological goods and services (Eklöf et al. 2005). Spatial planning, ongoing monitoring, and proper management are key to mitigating these impacts.

Seaweed production can lead to job creation, economic growth, and enhanced research (medium confidence). It has a potential role in providing affordable energy (low confidence).

The seaweed cultivation industry currently accounts for around 51 percent of total mariculture production and was valued at US$11.7 billion in 2016 (FAO 2018; Chopin 2018b). The rapidly expanding business is providing many jobs, predominantly in developing and emerging economies (Cottier-Cook et al. 2016). Seaweed biomass has potential as a source of various biofuels although it is evident that there are significant technological hurdles to be overcome before seaweed biofuel is viable in either energy or economic terms (Milledge et al. 2014).

Seaweed farming and restoring wetlands strengthen capacity to meet food security targets (medium confidence). Healthy mangroves positively impact health outcomes for coastal communities through provision of food and medicine to local residents (medium confidence).

Expansion of seaweed farming in several continents is contributing to global food security, supporting rural livelihoods, and alleviating poverty (Cottier-Cook et al. 2016). Healthy mangroves are important to human societies, providing a variety of ecological services that are critical to human livelihoods and food security, such as providing nursery grounds for important species, improving fisheries production, and filtering and detoxifing water (Ramsar Convention on Wetlands 2018). Mangroves are a direct source of food and traditional medicine for local inhabitants (Bandaranayake 1998).

Mitigation options to rebuild ocean biomass can contribute to poverty reduction (low confidence).

Marine protected areas have contributed to poverty reduction by improving fish catch, creating new jobs in tourism, strengthening local governance, benefitting human health, and enhancing women's opportunities (Leisher et al. 2007). Marine protected areas require monitoring and continuing study that will contribute to our ecological understanding of the ocean and promote scientific innovation (Nippon Foundation 2017).

Mitigation options to rebuild ocean biomass can also negatively impact poverty reduction and employment targets, and can limit progress on food security targets (low confidence).

Marine protection can have negative relationships with ending poverty and reducing inequalities (Singh et al. 2018). For example, ending overfishing and harmful fishing subsidies can conflict with targets related to youth employment if fleet capacity is reduced (Singh et al. 2018). These trade-offs may be avoided through stakeholder consultation and implementation. Conflicts may be temporary and, in the long term, potential increases in marine productivity could increase jobs and resources for people. Evidence shows that declines in fish catch pose risks of nutritional deficiency, especially in developing countries (Golden et al. 2016), and reforms to fishery management could dramatically improve overall fish abundance (compared to BAU) while increasing food security and profits (Costello et al. 2016). However, designating marine protected areas may restrict coastal people's access to local marine resources, which could limit progress on SDG targets associated with ending hunger (Singh et al. 2018).

Fisheries, Aquaculture, and Dietary Shifts

Aquaculture can present numerous societal and environmental challenges. Unplanned aquaculture expansion in some regions has negatively impacted other coastal and terrestrial ecosystems (high confidence).

Aquaculture is associated with multiple environmental impacts, such as eutrophication and spread of invasive species. Unplanned growth in shrimp aquaculture has led to the loss of mangrove ecosystems (Valiela et al. 2001; Richards and Friess 2017), which has in turn led to large CO_2 emissions (Murdiyarso et al. 2015), salinisation, erosion, and reduced coastal resilience (Hochard et al. 2019). Integration of mangroves into aquaculture landscapes may restore some ecosystem services (Hochard et al. 2019; Lee et al. 2019).

Improvement in feed conversion ratio and use of plant-based ingredients in aquaculture feed rather than animal by-products to meet the demand of the rapidly growing marine aquaculture sector can potentially reduce water use (medium confidence).

Given the global supply of fishmeal may be near biological limits (Costello et al. 2012), ensuring that feed for a rapidly growing aquaculture sector comes from terrestrial crops or seaweeds rather than animal by-products would have a positive impact on water use. Reduction in feed conversion ratio in aquaculture production also reduces upstream water use. However, increased inclusion of terrestrial plant-based ingredients may lead to competition for land and water, causing social and environmental conflicts, which may in turn affect the resilience of the global food system (Pahlow 2015; Pelletier et al. 2018; Troell et al. 2014; Blanchard et al. 2017; Malcorps et al. 2019). Many traditional crop-based substitutes are themselves carbon-intensive to produce; they can also adversely affect fish or crustacean growth and health, especially for farmed predator species. Consequently, there have been significant efforts in recent decades to identify new, highly nutritious, and, ideally, low-impact feed sources.

Consuming ocean-based proteins, in moderate quantities, have well-documented health benefits.

Reducing high levels of meat consumption among some populations and substituting by balanced ocean-based protein has positive human health benefits. The overall impact depends on whether ocean-based protein is sourced from sustainable production sources or from indiscriminate expansion of aquaculture that could negatively impact coastal ecosystems (high confidence).

High consumption of saturated fats, present in a red meat–based diet, has been linked to cardiovascular disease and certain forms of cancer. Consuming ocean-based proteins, in moderate quantities, ensures a higher intake of bioactive compounds as well as micronutrients, fibre, and omega-3 fatty acids, all of which have well-documented health benefits (Tilman and Clark 2014; Gonzalez Fischer and Garnett 2016; Simões-Wüst and Dagnelie 2019; Blas et al. 2019; Hollander et al. 2018; Oita et al. 2017). A significant shift from red meat among today's high consumers would dramatically reduce the land and water demands of livestock production (especially cows and sheep) (Poore and Nemecek 2018; Nijdam and Westhoek 2012) and would also reduce the carbon emissions associated with land clearance for pasture (Searchinger et al. 2019).

Mitigation options related to increasing ocean-based protein in diets and reducing emissions in fisheries and aquaculture would result in job creation and savings for households, and encourage technological innovation (high confidence).

The Organisation for Economic Co-operation and Development (OECD) estimates that employment in industrial-scale marine aquaculture will be 3.2 million in 2030, an increase of 1.1 million from 2010 levels. As fuel is a particularly high cost for fishers in developing countries (Lam et al. 2011), structural changes to fisheries that reduce fuel consumption will be economically beneficial. Innovations in developing fish meal substitutes and improving feed efficiency will be crucial to support a rapidly growing aquaculture sector.

Storing Carbon in the Seabed

There are large uncertainties regarding the environmental implications of carbon storage options in the ocean (high confidence).

The discussion below does not capture the impacts of carbonate dissolution, alkalinity addition, or ocean fertilisation, which has not been quantified in this report due to the high degree of risk and relatively unknown impacts at this stage. It only considers the impacts of seabed carbon storage. For further information on the broader set of options and why they are not viable at this time, please refer to the section on Carbon Storage in the Seabed.

The injection of CO_2 into submarine geological structures could potentially result in leakages of CO_2 back into the marine environment (Rastelli et al. 2016), affecting the health and function of marine organisms (Queirós 2014). However, there is uncertainty about the gravity of the impacts of CO_2 leakage, especially at the species community level (Adams and Caldeira 2008). Recent evidence indicates that leakage can be reduced if storage sites are well chosen, and well managed and monitored (van der Zwaan and Gerlagh 2016). However, understanding the full range of impacts on ecosystems associated with these solutions is of critical importance. Scientific understanding must be advanced if these technologies are to be used safely and without unintended consequences.

Offshore investments in seabed storage can lead to job creation, economic growth, and innovation (low confidence).

Potential benefits in terms of direct job creation, as well as job retention in harder-to-abate sectors (e.g., heavy industries and fossil fuel based sectors) by allowing them to function with appropriate CCS infrastructure investment/development. A study estimated that carbon capture and storage investments in UK would lead to the creation or retention of 225,600 jobs and a cumulative £54 billion in gross value added (GVA) by 2060 (East Coast UK Carbon Capture and Storage Investment Study 2017). Evidence indicates a strong need for policy innovation to kick-start carbon capture and storage infrastructure investment (Goldthorpe and Ahmed 2017).

The purpose of the analysis of the wider impacts of ocean-based interventions is to provide insight into the cobenefits as well as risks and trade-offs associated with specific mitigation actions. The approach used here aims to help policymakers evaluate the climate benefits in the context of multiple cobenefits and trade-offs that arise from implementing various ocean-based mitigation options. It is our hope that this report will enable discussion of the corrective measures that might be needed to alleviate unintended consequences of actions and avoid unnecessary risks and trade-offs. The analysis does not attempt a cost-benefit assessment of the mitigation options, which should be a key step in the implementation of any ocean-based mitigation option.

There are large uncertainties regarding the environmental implications of carbon storage options in the ocean.

Conclusion

This report establishes the potentially significant role of the ocean in limiting global temperature rise, in line with the goals of the Paris Agreement on Climate Change. Analyses in this report reveal that ocean-based mitigation options can make a significant contribution to narrowing the emissions gap that lies between a pathway based on "Current Policy" and the desired pathway that would hold global warming to 1.5°C above preindustrial levels. Ocean-based interventions could close up to 21 percent of the emissions gap by 2050. If the world pursues the less ambitious target of 2.0°C, ocean-based interventions could close 25 percent of the emissions gap by 2050.

Many of the mitigation options presented in this report can be implemented now with technologies that are already available. To realise these benefits, however, will require significant steps over the coming years—especially with respect to clear policy signals from governments, as well as a greatly increased and targeted investment in research and development.

The options outlined in this report are important not only to support efforts to decarbonise the global economy in line with the goals of the Paris Agreement. They also offer an array of valuable cobenefits in terms of enhanced human health and well-being. In this regard, they contribute to improving the resilience of coastal communities and infrastructure, expanding jobs and economic opportunities, enhancing biodiversity, and strengthening food security. Many of these wider benefits are synergistic with and will support the achievement of the UN Sustainable Development Goals by 2030. However, risks of negative wider impacts cannot be ignored and require detailed attention in policy development, and project planning and implementation. This must be the responsibility of all involved stakeholders—governments, the private sector, researchers, project managers, and local communities.

When considering the political implications of this report, the message is clear. Bold political leadership and clear policy signals will be required to capitalise on the full potential of the solutions explored in this report, coupled with strong national institutions and international cooperation to ensure their effective implementation. Table 13 outlines the policy and research actions that must be established over the next 10 years if we are to make significant progress in closing the emissions gap and avoid a climate crisis.

Ultimately, the ocean, its coastal regions, and the economic activities they support should be a source of inspiration and hope in the fight against climate change. With the backdrop of a growing climate catastrophe, the timing of this report is critical, and there could not be a more compelling case for urgent action.

Table ES-3. Short- and Medium-term Policy, Research, and Technology Priorities Necessary to Deliver on Mitigation Potential of Ocean-based Climate Action Areas

	OCEAN-BASED ENERGY		
	POLICY	RESEARCH	TECHNOLOGY
Short-term Priorities (2020–2023)	▪ Undertake marine spatial planning ▪ Develop national targets to increase the share of renewable energy in the national energy mix ▪ Provide a stable economic and regulatory framework to stimulate investments in required infrastructure for an accelerated deployment of ocean-based energy systems	▪ Understand the impacts (positive and negative) of both fixed and floating offshore wind installations on marine biodiversity ▪ Undertake a detailed mapping of global renewable energy resources and technical potential	▪ Advance storage capacity and design ▪ Improve performance, reliability, and survivability, while reducing costs
Medium-term Priorities (2023–2025)	▪ Develop strategic national roadmaps for zero-carbon economy in 2050 ▪ Develop appropriate legislation and regulation	▪ Understand the potential benefits of co-location with other ocean-based industries (e.g., desalination plants and aquaculture) ▪ Explore the potential for installing large scale floating solar installations at sea (under wave conditions) ▪ Quantify the potential of Ocean Thermal Energy Conversion (OTEC)	▪ Advance technology that can move technologies into deeper water sites (e.g., development of floating offshore wind technologies) to open access to larger areas of energy resources

Table 13. Short- and Medium-term Policy, Research, and Technology Priorities Necessary to Deliver on Mitigation Potential of Ocean-based Areas of Intervention (continued)

	OCEAN-BASED TRANSPORT		
	POLICY	RESEARCH	TECHNOLOGY
Short-term Priorities (2020–2023)	▪ Redesign the Energy Efficiency Design Index (EEDI) formula to avoid vessels being suboptimised for the test only, to ensure that instead vessels are being optimised for minimised fuel consumption in real operation at sea. ▪ Adopt policy measures to go beyond Ship Energy Efficiency Management Plan (SEEMP) to incentivise the maximisation of operational efficiency of new and existing ships ▪ Adopt policies that can reduce the broader GHG emissions of shipping instead of CO_2 only, including well-to-tank emissions (WTW) of ship fuels	▪ Identify and rectify of market and nonmarket barriers and failures to enable larger uptake of more energy-efficient technologies and cooperation patterns ▪ Ensure continuous research on ship design, including hull forms and propulsion, with a focus on reducing energy usage per freight unit transported ▪ Increase focus on utilisation of wind, waves, ocean currents, and sun to reduce use of externally provided energy, i.e., both the carbon and non-carbon-based fuels carried on board	▪ Develop the necessary high efficiency hull forms and propulsion methods ▪ Develop and implement hybrid power systems, including combustion engines, fuel cells, and batteries technologies ▪ Develop and implement wind assistance technologies ▪ Develop more advanced weather routing systems to better utilise wind, waves, ocean currents, and tides to reduce the use of both carbon and non-carbon fuel carried on board
Medium-term Priorities (2023–2025)	▪ Develop policy to enable the business case for the adoption of low and zero carbon fuels by shipping (e.g. a carbon price) ▪ Commit to the timetable for shipping's transition to low- and zero-carbon fuels ▪ Develop national incentives for decarbonising domestic transportation ▪ Commit to decarbonisation of national energy systems faster or as fast as the transition in the international fleet	▪ Develop cost-effective production of low- and zero-carbon fuels, both from renewables and from carbon based in combination with carbon capture and storage (CCS) ▪ Develop cost-efficient hybrid setups on seagoing vessels to utilise the best of combustion, fuel cells, and batteries to reduce fuel consumption and local pollution ▪ Ensure safe storage and handling on ships and at the ship-shore interface of hydrogen/ammonia ▪ Ensure safe and efficient use of hydrogen and ammonia in internal combustion engines and fuel cells	▪ Advance technologies for producing hydrogen, both from renewables and carbon-based fuels ▪ Invest in technologies to store hydrogen (including cryogenic storage of liquid hydrogen, or carriers able to store at high-energy density) ▪ Invest in fuel cells for conversion of future fuels into on-board electricity, and internal combustion engines designed to operate on hydrogen/ammonia

Table 13. Short- and Medium-term Policy, Research, and Technology Priorities Necessary to Deliver on Mitigation Potential of Ocean-based Areas of Intervention (continued)

	COASTAL AND MARINE ECOSYSTEMS		
	POLICY	RESEARCH	TECHNOLOGY
Short-term Priorities (2020–2023)	▪ Enhance protection measures for mangroves, seagrass, salt marsh, and seaweed beds to prevent any further losses due to human activities ▪ Provide incentives for restoration of "blue carbon" ecosystems, through payments for ecosystem service schemes, such as carbon and nutrient trading credits ▪ Include quantified nature-based solutions within nationally determined contributions (NDCs) and other relevant climate policies for mitigation and adaptation ▪ Protect coral reefs as important and integrated coastal defence systems for ensuring the protection of coastal blue carbon ecosystems	▪ Undertake national-level mapping of blue carbon ecosystems ▪ Address biophysical, social, and economic impediments to ecosystem restoration to develop restoration priorities, enhance incentives for restoration, and increase levels of success ▪ Improve the IPCC guidance for seagrasses and other wetland ecosystems ▪ Develop legal mechanisms for long-term preservation of blue carbon, especially in a changing climate ▪ Understand the impacts of climate change on rates of carbon capture and storage, or the potential for restoration	▪ Advance biorefining techniques, allowing sequential extraction of seaweed products
Medium-term Priorities (2023–2025)	▪ Enhance and adopt carbon accounting methodologies for mangroves, seagrasses and salt marsh within national GHG inventories (IPCC 2013) ▪ Improve methods for monitoring mitigation benefits to enable accounting within national GHG inventories, and biennial transparency reports (BTRs)	▪ Undertake global-scale map of seaweed ecosystems ▪ Develop IPCC-approved methodological guidance for seaweed ecosystems ▪ Develop methods to fingerprint seaweed carbon beyond the habitat	▪ Develop and pilot offshore and multiuse sites, including seaweed aquaculture, in the open ocean

Table 13. Short- and Medium-term Policy, Research, and Technology Priorities Necessary to Deliver on Mitigation Potential of Ocean-based Areas of Intervention (continued)

	FISHERIES, AQUACULTURE, AND DIETARY SHIFTS		
	POLICY	RESEARCH	TECHNOLOGY
Short-term Priorities (2020–2023)	▪ Eliminate harmful fisheries subsidies (SDG14.6) ▪ Strengthen international tools to eliminate IUU fishing (SDG14.5) ▪ Avoid the transport of fish by air ▪ Reduce discards ▪ Reduce and eliminate hydrochlorofluorocarbons (HCFCs) in refrigerants ▪ Create incentives for shifting diets towards low-carbon protein (e.g., fish) and other food (e.g., seaweed) diets ▪ Create incentives to improve fishery management ▪ Create incentives for lower trophic-level aquaculture ▪ Devise sustainable finance mechanisms for small-scale fishery transitions to sustainable fishing	▪ Develop disaggregated global data sets for GHG emissions from wild catch fisheries and marine aquaculture ▪ Impacts of scaling marine aquaculture and associated sustainability considerations (e.g., low carbon and climate resilient, environmentally safe) ▪ Enhance understanding of how climate change and ocean acidification will impact aquaculture and fisheries	▪ Extend surveillance technologies for tracking fishing in the ocean and along coastal areas
Medium-term Priorities (2023–2025)	▪ Create incentives to switch from high-carbon land-based sources of protein to low-carbon ocean-based sources ▪ Improve fisheries management to focus on optimising biomass per harvest	▪ Explore potential impact of a carbon tax on red meat and other carbon intensive foods	▪ Develop and bring to scale high-technology digital aquaculture
	SEABED CARBON STORAGE		
	POLICY	RESEARCH	TECHNOLOGY
Short-term Priorities (2020–2023)	▪ Invest in pilot projects to further explore potential environmental impacts ▪ Incentivise public/private partnerships	▪ Map global geophysical potential ▪ Understand the impacts of long-lasting containment of CO_2 in a deep seafloor environment	▪ Few major technical advances are required as seabed storage is already deployed at industrial scale
Medium-term Priorities (2023–2025)	▪ Develop national strategies and targets ▪ Develop regulatory frameworks to ensure environmental impact assessments and associated precautions are put in place.	▪ Understand the impacts of long-term storage on marine ecosystems ▪ Explore the integrity of long-term storage technologies (leakage)	▪ Scale up technologies in ways that are economically feasible

Source: Authors

Glossary

2DS	2°C Scenario (IEA) consistent with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100.
AR	Assessment Report
AR5	Fifth Assessment Report of the IPCC
B2DS	Beyond 2°C Scenario (IEA)—innovation pipeline for reducing global temperatures below the 2DS scenario
BAU	Business as usualusual
BTRs	Biennial transparency reports
CAGR	Compound annual growth rate
CCS	Carbon capture and storage
CO_2	Carbon dioxide
COP	Conference of the Parties to the United Nations Framework Convention on Climate Change
DW	Dry weight
FAO	Food and Agriculture Organization of the United Nations
GHG	Greenhouse gas
GMST	Global mean surface temperature
$GtCO_2e$	Gigatonnes of equivalent CO_2
GVA	Gross value addedadded
GWEC	Global Wind Energy Council
HCFC	Hydrochlorofluorocarbon
IEA	International Energy Agency
IMO	International Maritime Organization
IPCC	International Panel on Climate Change
LCOE	Levelizedlevelised cost of energy
LED	Low energy demanddemand
Milankovitch cycle	The collective effects of changes in the earth's movements on its climate over thousands of years

Montréal Protocol	Montréal Protocol on Substances that Deplete the Ozone Layer (a protocol to the Vienna Convention for the Protection of the Ozone Layer) is an international treaty designed to protect the ozone layer by phasing out the production of numerous substances that are responsible for ozone depletion
MW	Megawatt
NDCs	Nationally determined contributions
O&M	Operation and maintenance
OECD	Organisation for Economic Co-operation and Development
ORE	Ocean-based Renewable Energy
OSW	Offshore wind
OTEC	Ocean Thermal Energy Conversion
Paris Agreement	Adopted on December 12, 2015, at the twenty-first session of the Conference of the Parties to the United Nations Framework Convention on Climate Change, held in Paris from 30 November to 13 December, 2015
RCP	Representative Concentration Pathway (RCP) is a GHG trajectory adopted by the IPCC for AR5 in 2014
RD&D	Research, development, and demonstration
SDG	Sustainable Development Goal
SSP X	Shared Socioeconomic Pathways
TWh/yr	Terawatt hour per year
UN	United Nations
UNEP	United Nations Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change
VOC	Volatile organic compound

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