Commissioned by

HIGH LEVEL PANEL *for*
A SUSTAINABLE
OCEAN ECONOMY

The Ocean as a Solution to Climate Change

Updated Opportunities for Action

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About the Ocean Panel

Established in 2018, the High Level Panel for a Sustainable Ocean Economy (Ocean Panel) is a unique initiative made up of serving world leaders who are building momentum for a sustainable ocean economy in which effective protection, sustainable production and equitable prosperity go hand in hand. By working collaboratively with a wide array of stakeholders, the Ocean Panel aims to identify bold solutions that bridge ocean health, wealth and equity and accelerate and scale responsive action worldwide.

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This report was prepared in support of the work of the Ocean Panel to provide a robust science and knowledge base and practical opportunities for action across issues central to the attainment of a sustainable ocean economy. The arguments, findings and opportunities outlined in this report represent the views of the authors alone. Ocean Panel members have not been asked to formally endorse the report and should not be taken as having done so.

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FOREWORD

In this critical decade for action on climate change, the High Level Panel for the Sustainable Ocean Economy (Ocean Panel) has expressed concern over the accelerating consequences of anthropogenic climate change on ocean health, but has understood the opportunities that the ocean and ocean economy can provide for significant climate action. The Ocean Panel has therefore commissioned a reassessment of how the ocean-based solutions originally explored in the 2019 report, *The Ocean as a Solution to Climate Change: Five Opportunities for Action,* have developed as potential tools for significantly reducing greenhouse gas emissions.[1]

The 2019 report provided a timely change from the ocean being seen as a 'victim' of climate change, as opposed to being a 'solution'. This report takes stock of the progress made since and provides refreshed estimates of the mitigation potential of those ocean-based opportunities (ocean-based renewable energy, ocean-based transport, marine conservation and restoration, ocean-based food, and marine carbon dioxide removal and carbon capture and storage). In addition, it considers the mitigation potential in decarbonising ocean-based tourism and the role that halting the expansion of and phasing down offshore oil and gas can play if replaced by zero emission energy. Emerging technologies for marine carbon dioxide removal are also described but found too immature to be included in numerical analyses. The wider societal benefits were also explored along with the push for strong policy measures, as well as highlighting key research gaps that need to be filled. The results of this analysis show that ocean-based climate solutions could assist in reducing the 'emissions gap' in 2050 by up to 35 percent on a 1.5°C pathway and up to 47 percent on a 2.0°C pathway. This reiterates the narrative of the first report, emphasising the value of the ocean as a key solution to the climate crisis, rather than a victim of it.

The present report comes at a vital time as policy makers, governments, and civil society reflect on progress made towards the goals outlined in the Paris Agreement on Climate Change. With the United Nations Conference on Climate Change (COP 28) and the release of the first Global Stocktake taking place this year, it is imperative that discussions focus on how to facilitate a better course for climate action. The Ocean Panel recognised this in their shared ocean action agenda, *Transformations for a Sustainable Ocean Economy: A Vision for Protection, Production and Prosperity,* wherein members committed to sustainably manage 100% of the ocean areas under national jurisdiction.

The Ocean Panel recognises that ocean action can realise a wide range of benefits towards a sustainable ocean economy, for both our planet and its people. The findings of this report reiterate this, pointing out that ocean-based climate solutions have wider benefits from ocean health to livelihoods and wider energy system and security benefits, where managed in a just transition. The Ocean Panel has called for a holistic approach to ocean management to unlock the full package of benefits, whereby Sustainable Ocean Plans are a key tool to support countries. We hope this report can contribute to the development of these tools and those discussions, and aid coastal and ocean states globally in their ocean management plans to ensure climate mitigation measures are recognised and included, alongside wider benefits. Implementation and achievement of the measures suggested will require a coherent approach to prioritising ocean-climate finance. It is important that, for those sectors which are still in the beginning stages of development, the use of public and private finance is incentivised.

As Lead Experts within the Ocean Panel Expert Group, we would like to warmly thank the authors, the reviewers, and the Secretariat at World Resources Institute for taking this opportunity to conduct this updated analysis, providing a thorough peer review of the final work, and helping to accelerate the reduction of anthropogenic emissions. The Lead Experts also extend our thanks to Ocean Panel members for their support, and hope that they and other parties act on the opportunities for mitigation presented here. Ocean-based policies that prioritise a sustainable ocean economy whilst also combatting the effect of climate change hold great potential for reducing emissions and need to be implemented without delay.

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Executive Summary

The ocean covers 70 percent of Earth's surface and acts as a vast storehouse for both carbon dioxide and heat, amongst providing other ecosystem services vital to humanity. Whilst climate change imperils marine life, the ocean is increasingly recognised as providing opportunities for solutions in the fight against climate change. This updated report lays out a series of feasible, ready-to-implement, scalable ocean-based solutions to climate change that can be pursued now. It also examines emerging technologies that may offer opportunity for combatting climate change in the near future.

Highlights

- Ocean-based climate change mitigation options have the potential to significantly reduce greenhouse gas (GHG) emissions and contribute to global efforts to reach the goals of the Paris Agreement on climate change.
- In 2019 the Ocean Panel commissioned an analysis that found that ambitious implementation of ocean-based climate solutions in five sectors (ocean-based renewable energy; ocean-based transport; marine conservation and restoration; ocean-based food, and marine carbon capture and storage) had the potential to reduce the 'emissions gap' between current and future emissions by up to 21 percent on a 1.5°C pathway, and up to about 25 percent on a 2.0°C pathway, in 2050.
- This report re-examines and updates the analysis in the report published in 2019, *The Ocean as a Solution to Climate Change: Five Opportunities for Action* (2019 Report), assessing the emissions reduction potential of solutions in two additional ocean sectors: offshore oil and gas, and ocean-based tourism.
- It finds that full implementation of ocean-based climate solutions that are ready for action now across the seven sectors could reduce the emissions gap by up to 35 percent on a 1.5°C pathway, and by up to 47 percent on a 2.0°C pathway, in 2050. This translates to an estimated reduction of between 1–4 Gt of carbon dioxide equivalent (CO_2e) per annum in 2030 and 4–14 Gt CO_2e in 2050, the upper range of which would be approximately equivalent to four times the 2021 emissions of 27 EU member states.[2]
- The significant increase in the potential of ocean-based sectors to contribute to emissions reductions compared to the estimates in the 2019 Report is a result, in large part, of considering the impact of halting the expansion of and phasing down offshore oil and gas extraction (about 20–30 percent of these reductions), which could contribute up to 5.3 Gt CO_2e in reductions annually in 2050 (equivalent to the annual emissions of 1.18 billion gasoline-powered cars).[3] These potential reductions are premised upon replacement by zero emission energy sources onshore or offshore and via a phased, demand-driven approach.
- Total government and industry pledges for offshore wind deployment have approximately doubled since the 2019 Report, although this potential now needs to be followed by their rapid deployment at a rate that is much greater than previous years. Global progress has also been made in maritime transport, with the recent revision of the International Maritime Organisation (IMO) GHG strategy increasing the likelihood of global emissions reductions being consistent with a 1.5°C temperature goal. If energy efficient measures are adopted by the cruise industry, the tourism sector could also make a valuable contribution.
- Stopping ecosystem loss and degradation must remain a top priority to avoid further release of GHG emissions from coastal and marine ecosystems.
- Unfortunately, there has been little progress in utilising low-carbon sustainable protein from the ocean to reduce emissions from food, making the initial projections in the 2019 Report potentially harder to reach without an acceleration of effort and ambition in the next few years. Human populations have risen and so has the demand for protein without an increase in sustainable options from the ocean. More must be done to raise awareness, send clear policy signals and invest in the enabling environment to take advantage of this opportunity.

Highlights (continued)

- Despite an increased awareness of the ocean's potential, there remains an urgent need to fill knowledge gaps in all ocean-based climate sectors to understand how to implement these solutions in a manner that also supports wider social, environmental, and Sustainable Development Goals, particularly the new Kunming-Montreal Global Biodiversity Framework.
- Achieving the identified mitigation potential will be dependent on the prioritisation of a more coherent approach to ocean-climate finance. An estimated US$2 trillion will need to flow into ocean-based climate solutions between 2030 and 2050 to achieve the mitigation potential identified. Some sectors, such as offshore wind, already have significant access to sources of finance, which has helped spur progress. Other areas, including marine conservation and restoration, require innovative approaches to reach the potential identified in this report, including the strategic use of public finance to mobilise and shift private finance at large scales.
- This report prioritises the implementation of technology and practices that are currently in use and under development that can support the achievement of the Paris Agreement. While research into new technology should be accelerated, this should not be a reason to delay the implementation of solutions that are ready for implementation.
- Potential impacts of the outlined mitigation opportunities must be carefully managed, particularly for solutions that are not yet mature and/or ready for implementation, notably the emerging approaches for marine carbon dioxide removal, some of which are explored in the present report but are highly uncertain and not deemed ready for implementation.
- All ocean-based climate solutions will require deepening political engagement, strengthening international and national institutions, greater engagement and coordination across businesses and industry, inclusion of communities and stakeholders, and robust monitoring and evaluation.
- Only an immediate and comprehensive transformation at a systemic level (going beyond incremental changes) can achieve the substantial reductions required to curtail GHG emissions. The overall objective of this transformation is to catalyse change by offering a pathway towards ambition and broadening opportunities for action that countries should consider as 2030 and 2050 rapidly approach.
- A rapid transition will be needed across all economic sectors worldwide. This demands international collaboration that prioritises an inclusive approach and supports countries and communities at risk of being marginalised during this transformative process.
- The solutions presented in this report are not a silver bullet and must be accompanied by deep cuts in emissions across all terrestrial sources of GHGs, including measures to rapidly phase down fossil fuels, create sustainable food systems, and increase carbon sequestration and storage in forests and other terrestrial ecosystems.

Purpose of report

This report presents an updated and expanded range of options for harnessing the potential of ocean-based climate solutions to urgently reduce global GHG emissions. These options can help reach the Paris Agreement goals of limiting global warming to well below 2°C, while pursuing efforts to limit the increase to 1.5°C above pre-industrial levels (UN Paris 2015). Limiting global warming to 1.5°C above pre-industrial levels by the end of this century requires human-caused CO_2 emissions to reach net zero by 2050. The original report, *The Ocean as a Solution to Climate Change: Five Opportunities for Action* (Hoegh-Guldberg et al. 2019, referred to herein as the 2019 Report) explored five ocean-based mitigation options or sectors: ocean-based renewable energy; ocean-based transport; marine conservation and restoration; ocean-based food (wild capture fisheries, aquaculture and shifting diets towards seafood); and marine carbon capture and storage. It found that full implementation of these solutions could contribute up to 21 percent of the annual emissions reductions needed to limit temperature rise to 1.5°C and 25 percent of the reductions needed to restrict it to 2.0°C in 2050 (Hoegh-Guldberg et al. 2019).

A lot has changed since 2019. Despite the significant attention that ocean-based climate solutions have received and the many initiatives and pledges from all ocean-based sectors, progress towards implementation is not on track to achieve the 2030 mitigation potential for many of the solutions explored in the 2019 Report. For many ocean-based climate solutions, this is because of the dramatic shift in economic and policy priorities following the global COVID-19 pandemic.

Unfortunately, the climate crisis has not slowed. As stated by United Nations Secretary-General Antonio Guterres, the world is now in the era of 'global boiling.' The latest assessment of the Intergovernmental Panel on Climate Change's Sixth Assessment Report (AR6) (IPCC 2023) makes clear that current policies fall far short of 'what is needed' to stabilise anthropogenic emissions and avoid the worst outcomes of rapid climate change. July 2023, the warmest month in history, was marked by unprecedented heat waves across North America, Europe and Asia, with record high global temperatures impacting ecosystems, communities and nations. The impact has exceeded predictions of the frequency and intensity of extreme events, such as bushfires, droughts, storms, coral mortality, and heatwaves.

The 2019 Report identified solutions that had the largest potential to cut emissions by 2030 and 2050, premised on significant investments in technology and implementation, greater collaboration and partnership, in addition to strong political will to implement the necessary policy and regulatory changes. Four years later, a lack of progress across several sectors may have put the 2030 emissions reduction potential out of reach or at great risk of becoming so. Rather than serve as a cause for despair, this updated report aims to provide impetus and guidance for the midcourse correction needed to deliver on the goals of the Paris Agreement and still contribute significant emissions reductions in 2050. It lays out a series of feasible, ready-to-implement, scalable options that the ocean economy can pursue based on technology that is mature and/or ready for commercial adoption now. It also examines emerging technologies for enabling ocean and coastal ecosystems to sequester and store more carbon, including through marine carbon dioxide removal (mCDR) technologies and approaches.

Harnessing the mitigation potential outlined in this report will still require major investment, collaboration and political leadership. The estimates provided are not pathways or trajectories, but rather a glimpse of what is possible if there is collective will, multi-sector collaboration and investment to pursue rapid implementation. Reflecting the need to intensify implementation and accelerate progress towards the goals of the UNFCCC Paris Agreement, this updated report expands its scope by adding two additional ocean sectors: ocean-based tourism and offshore oil and gas. It also considers additional solutions presented by emerging technologies for marine carbon dioxide removal.

The solutions explored in this report include:

1. Expanding marine conservation and restoration, including mangroves, tidal marshes, seagrass beds and wild seaweeds.
2. Scaling ocean-based renewable energy, primarily offshore wind, and continuing to invest in bringing other energy sources, such as tidal power and floating solar, to commercial scale.
3. Decarbonising ocean-based transport, including freight and passenger shipping, in line with the revised IMO GHG strategy.
4. Decarbonising ocean-based tourism, focusing on cruise vessels and utilising technological advances in marine transport.

5. Utilising low-carbon, ocean-based protein to reduce emissions from global diets, including replenishing sources of low-carbon protein such as from wild fish stocks.

6. Stopping the expansion of offshore oil and gas extraction along with a demand-led phase down of current production.

7. Investing in further research for marine-based carbon dioxide removal and continuing to develop carbon capture and storage below the seabed.

Along with an update on progress, this report highlights the steps that should be prioritised to accelerate implementation, and addresses the barriers or challenges that may impede progress initially identified in the 2019 Report but which have yet to come to fruition.

Rather than being policy prescriptive, the updated report objectively presents the opportunities and risks associated with each ocean sector, allowing industries and governments to make informed decisions relative to their activities, people and circumstances. Our report acknowledges uncertainties related to reporting emissions, unreliable data, and differing perspectives and maturity levels in different sectors (see Appendix A for methodology by sector). These uncertainties should not hinder implementation, but instead offer a transparent analysis to help governments swiftly reach the required median reduction to achieve net zero emissions and below.

Because the window for effective action is rapidly closing, actions should focus first on mature and commercially available solutions that can be quickly deployed at the lowest cost and where the social and environmental impacts are known and can be managed. Viability must be prioritised, especially where key technology pathways are uncertain. Deploying the strategies and technologies described in this report will require purposeful, coordinated and sustained effort. It will take strong political leadership with sufficient investment to quickly develop and deploy transformational technologies that can rapidly scale up.

The report focuses on ocean sectors, recognising that there is not always a clean separation between ocean-based and land-based action. Notably, for the reduction of offshore oil and gas to have the desired effect onshore or offshore zero emission energy sources need to be scaled up as a replacement. Marine transport is dependent on ports and connected to land transport. We mention such 'fuzzy' boundaries where appropriate, rather than attempting to define sharp boundaries between ocean- and land-based sectors.

Key findings

This report provides new estimates of the annual mitigation potential in 2030 and 2050 for the seven ocean-based sectors summarised in Table ES-1.

These new estimates expand on the 2019 Report by offering two different sets of 2030 and 2050 mitigation potential, distinguished by the solutions included in each. A range is provided for each ocean-based sector based on specific assumptions and uncertainties (Appendix A, Table A-1).

Solutions that are already mature or at the early adoption stage and have accepted management processes are deemed ready to implement. Full implementation of these across all seven ocean sectors has the potential to reduce annual emissions by 1.1–4.5 Gt CO_2e per annum in 2030, or by 4.4–13.8 Gt CO_2e in 2050 (Table ES-1, as depicted in Figure ES-1), closing the emissions gap to the 1.5°C pathway by between 11 and 35 percent in 2050 (Table ES-2).

If additional solutions at the protype, demonstration or concept stages are also included in these projections, then there is potential to reduce annual emissions by 1.2–6.0 Gt CO_2e per annum in 2030, or by 4.9–22.7 Gt CO_2e in 2050 (Table ES-1), closing the emissions gap to the 1.5°C pathway by between 12 and 58 percent in 2050 (Table ES-2). It is important to note that the significant increase in additional solutions identified in 2050 comes from marine CDR options (up to 9 Gt CO_2e of the upper limit), much of which have yet to be fully tested, costed, de-risked or otherwise developed for use. Realising the potential of such options depends not only on funding research, technology development and demonstration, but also understanding unknown impacts may emerge, giving rise to unforeseen risks and complexities, including potentially 'game-changing' or 'show-stopping' implications. For example, ocean iron fertilisation may have unintended negative effects on fisheries (Tagliabue et al. 2023). Other options in early stages, such as the sinking of biomass from seaweed farming, may encounter similar challenges.

Table ES-1. Updated global mitigation potential (Gt CO_2e/year) offered by each ocean-based sector

OCEAN-BASED SECTOR	SOLUTIONS INCLUDED	MITIGATION OPTIONS INCLUDED IN 2030 AND 2050 PROJECTIONS	2030 MITIGATION POTENTIAL (GT CO_2E)	2050 MITIGATION POTENTIAL (GT CO_2E)
Marine conservation and restoration	Ready to implement	▪ Sequestration from restoration and protection of coastal wetlands (mangroves, tidal marshes and seagrasses) ▪ Avoided anthropogenic degradation/impacts on coastal wetlands (mangroves, tidal marshes and seagrasses)	0.03–0.11	0.05–0.29
	All	The above in addition to the following: ▪ Sequestration and storage from protection and restoration of wild seaweeds (kelps)	0.03–0.14	0.05–0.31
Ocean-based renewable energy	Ready to implement	▪ Scaling offshore wind ▪ Scaling tidal barrage ▪ Floating solar	0.60–0.6	3.20–3.60
	All	The above in addition to the following: ▪ Scaling ocean wave energy ▪ Scaling tidal stream energy ▪ Scaling energy capture of ocean temperature differences (thermal gradient) ▪ Scaling salinity gradient	0.60–0.70	3.25–4.47
Ocean-based transport	Ready to implement	▪ Reducing emissions from international and domestic shipping and marine transport through efficiency measures ▪ Reducing emissions from international shipping through retrofitting to accommodate alternative lower carbon fuels ▪ Zero emission vessels	0.25–0.60	0.80–2.00
	All	As above		
Ocean-based tourism	Ready to implement	Reducing emissions associated with cruise tourism	0.01–0.02	0.05–0.10
	All	As above		

Table ES-1. Updated global mitigation potential (Gt CO_2e/year) offered by each ocean-based sector (Continued)

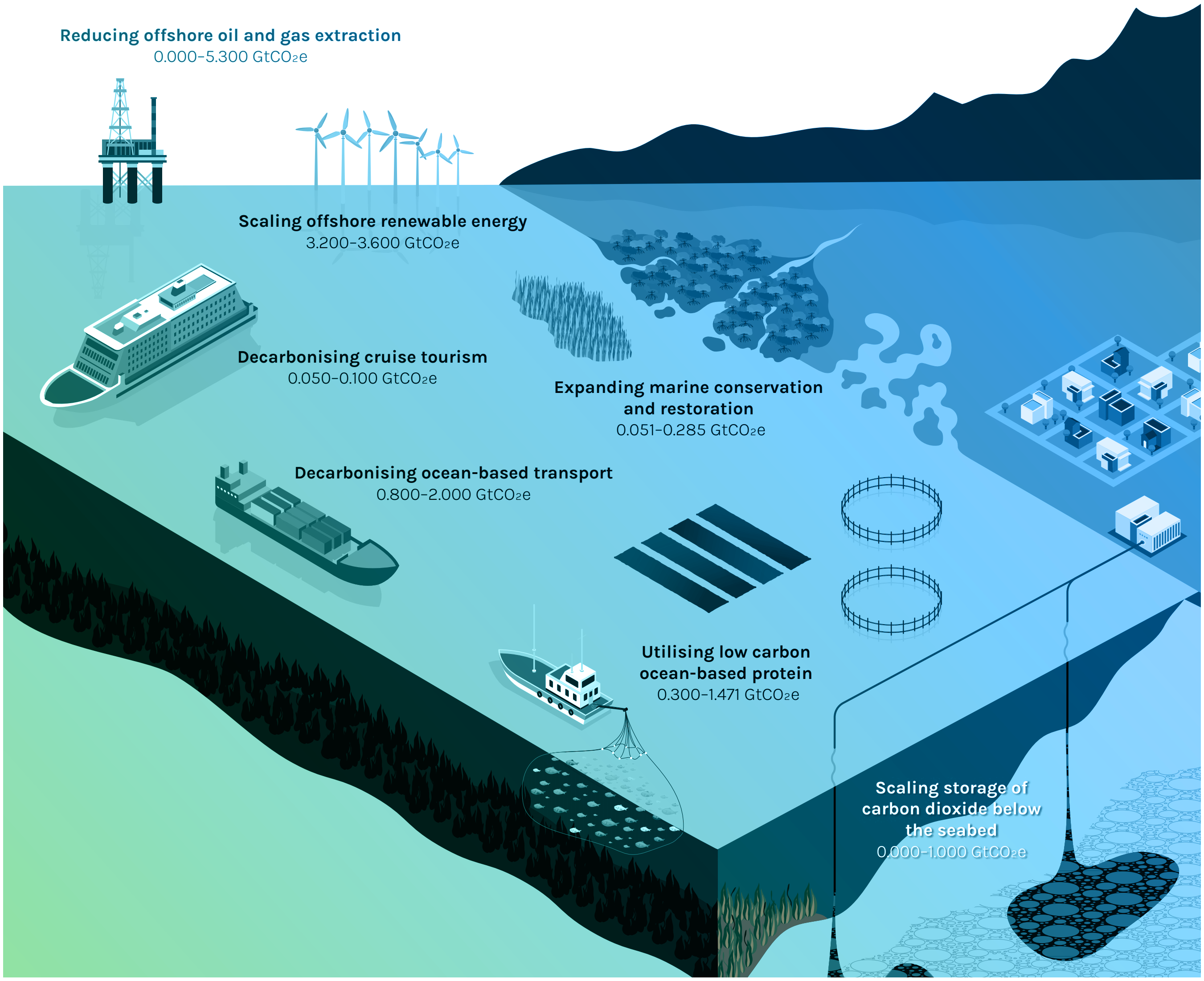
OCEAN-BASED SECTOR	SOLUTIONS INCLUDED	MITIGATION OPTIONS INCLUDED IN 2030 AND 2050 PROJECTIONS	2030 MITIGATION POTENTIAL (GT CO_2E)	2050 MITIGATION POTENTIAL (GT CO_2E)
Ocean-based food	Ready to implement	▪ Reduction in fuel use intensity from rebuilding depleted wild stocks ▪ Improved feed conversion ratios for aquaculture ▪ Complete avoidance of deforestation in the supply chains of feed ingredients from soy, palm, and other crops as well as in the feeds of poultry and livestock systems providing by-products ▪ Shifting all energy inputs to farms are derived from electricity generated from renewable sources, rather than fossil fuels onsite or in electricity grids ▪ Potential emissions avoided by behavioural shifts away from high emissions land-based proteins and towards lower emissions seafood systems	0.24–0.92	0.30–1.47
	All	As above		
Offshore oil and gas	Ready to implement	Stopping the expansion of offshore oil and gas extraction along with a demand-led phase-down of current production	0.00–1.80	0.00–5.30
	All	As above		
Marine carbon dioxide removal and carbon capture and storage	Ready to implement	CO_2 storage below the seabed	0.00–0.32	0.00–1.00
	All	The above in addition to the following: Ocean nutrient fertilisation ▪ Ocean alkalinity enhancement ▪ Direct ocean removal ▪ Seaweed cultivation and carbon sequestration (including both active sinking and passive sequestration associated with seaweed farming for harvest)[b]	0.10–1.82	0.40–9.00
TOTAL	Ready to implement		1.13–4.45	4.40–13.78
	All mitigation options		1.23–5.99	4.85–22.65

Notes:
Ready-to-implement solutions are those assessed for the purposes of this report as mature or at the stage of early adoption; see Figure ES-3 and Table 2 for more details.

All mitigation solutions include those ready to implement as well as those that are only at the prototype, demonstration and concept stage; see Figure ES-3 and Table 2 for more details.

Source: Authors.

Figure ES-1. Annual emission reduction potential in 2050 for solutions that are ready to implement now



Note: Ready-to-implement solutions are those assessed for the purposes of this report as mature or at the stage of early adoption (see Figure ES-3).

Table ES-2 and Figure ES-2 outline the potential impact that such emissions reductions would have in closing the emissions gap in 2030 and 2050.

Table ES-2. Contribution to closing the emissions gap in 2030 and 2050 of solutions that are ready to implement (mature or early adoption technologies and approaches according to Figure ES-3 and Table 2)

	ANNUAL GLOBAL EMISSIONS (GT CO_2E)			GAP TO PATHWAY, BASED ON UNEP CURRENT POLICY SCENARIO (GT CO_2E)		TOTAL GHG MITIGATION POTENTIAL (=GT CO_2E)		% GAP CLOSED: 1.5°C PATHWAY		% GAP CLOSED: 2°C PATHWAY	
	Current policy	1.5°C pathway	2°C pathway	1.5°C pathway	2°C pathway	Min	Max	Min	Max	Min	Max
Today	58	58	58	0	0	0	0	0	0	0	0
2030	58	33	41	25	17	1	4	5	18	7	26
2050	49	10	20	39	29	4	14	11	35	15	47

Notes: Estimates are based on comparing multiple scenarios for annual emissions in 2023, 2030 and 2050. For those years, we compare '1.5°C', '2°C' and the 'current policy' scenarios from UNEP (2022) and calculate the mitigation needed to fill the 'gaps' between the 'current policy' and the '1.5°C' and '2°C', respectively. Min refers to conservative ocean-based mitigation potential, while Max represents higher (more ambitious) theoretical potential projected in this report. The total ocean-based mitigation was compared to the gap at 2030, and that at 2050, generating the percentage of the gap (in each case) mitigated by ocean-based mitigation of GHG emissions. GHG = greenhouse gas; UNEP = United Nations Environment Programme.

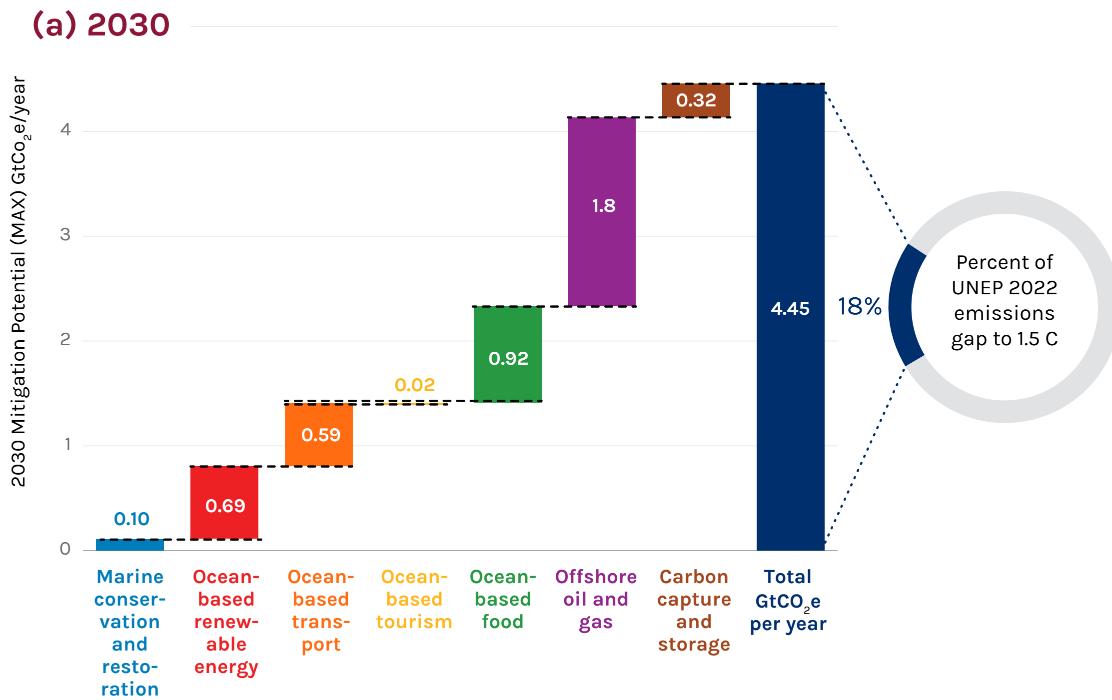
Source: Authors.

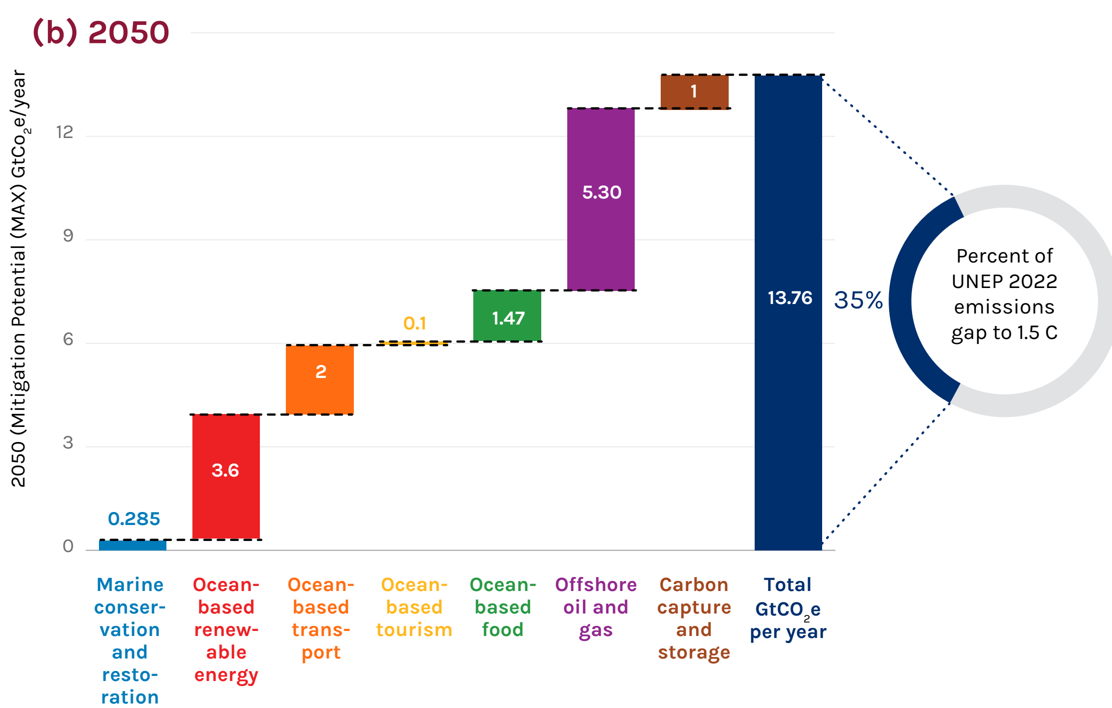
...solutions relying on technologies that are mature or in early adoption are ready to implement now...

The projections included in this report assume high rates of change over the next two decades. These are feasible, but based on the slow progress seen since 2019, will rely on unprecedented levels of cooperation and collaboration. Development and deployment will require rapidly scaling up global supply chains, learning and sharing lessons on best practices to increase the speed of deployment, reduce costs, and minimise technological incompatibilities and other problems.

This readiness framework should guide prioritisation of those approaches that are ready to implement now as opposed to those that will require greater investment, and carry more uncertainty in terms of viability and broader environmental and social impact (e.g. the range of marine carbon dioxide removal technologies included in this report). This framework should also serve as a basis to inform investment in research, piloting and capacity building to support the achievement of the mitigation potentials identified for each sector.

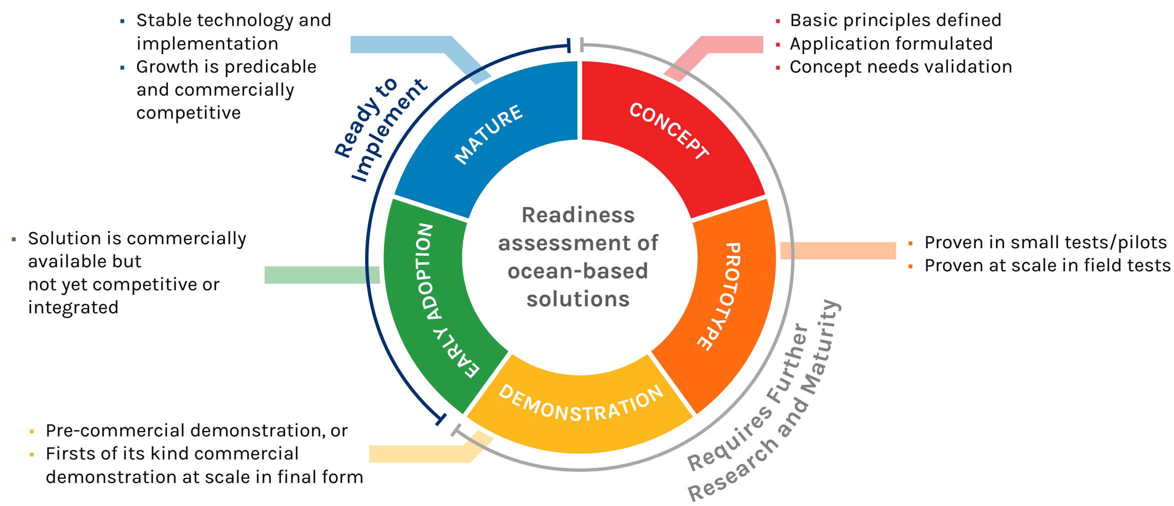
Figure ES-2. Maximum potential contribution of ready-to-implement ocean-based mitigation options to closing the emissions gap in (a) 2030 and (b) 2050





Note: Ready-to-implement solutions are those assessed for the purposes of this report as mature or at the stage of early adoption.

Figure ES-3. Technology readiness framework



MARINE CONSERVATION AND RESTORATION

- Sequestration from restoration and protection of coastal wetlands (mangroves, tidal marshes, and seagrasses)
- Avoided anthropogenic degradation/impacts on coastal wetlands (mangroves, tidal marshes, and seagrasses)
- Sequestration and storage from protection and restoration of wild macroalgae (kelp forests and other seaweeds)

OCEAN-BASED RENEWABLE ENERGY

- Scaling offshore wind
- Scaling tidal barrage
- Floating solar
- Scaling ocean wave energy
- Scaling tidal stream energy
- Scaling energy capture of ocean temperature differences (thermal gradient)
- Scaling salinity gradient

OCEAN-BASED TRANSPORT

- Reducing emissions from domestic shipping and marine transport through efficiency measures
- Reducing emissions from international shipping through energy efficiency measures
- Reducing emissions from international shipping through retrofitting to accommodate alternative lower-carbon fuels
- Zero emission vessels

OCEAN-BASED TOURISM

- Reducing emissions associated with cruise tourism

OCEAN-BASED FOOD

- Reduction in fuel use intensity to harvest fish and shellfish that results from rebuilding depleted stocks
- Avoided emissions if increased harvest achieved via rebuilding stocks is consumed in place of higher emissions land-based animal products
- Improved feed conversion ratios
- Avoidance of deforestation in the supply chains of feed ingredients from soy, palm and other crops as well as in the feeds of poultry and livestock systems providing by-products
- Ensuring all energy inputs to farms are derived from electricity generated from renewable sources, rather than onsite fossil fuels or in electricity grids
- Increasing share of ocean-based proteins in diets

OFFSHORE OIL AND GAS

- Stopping expansion of offshore oil and gas extraction and exploration and phasing down current production

MARINE CARBON DIOXIDE REMOVAL AND CARBON CAPTURE AND STORAGE

- CO_2 storage below the seabed
- Ocean nutrient fertilisation
- Ocean alkalinity enhancement
- Direct ocean removal
- Seaweed cultivation and carbon sequestration (including both active sinking and passive sequestration associated with seaweed farming for harvest)

Note: Current deployment of these sectors will be unavailable to bring the global climate back to equilibrium without major emission reductions. Farmed seaweed can also contribute to emissions reduction by substituting products with higher CO_2 footprint or being used as feed supplement to reduce ruminant CH_4 production (see 2.5 Ocean-based food).

Source: Authors, adapted from the technology readiness level scale applied by the IEA (2020).

As identified above, solutions relying on technologies that are mature or in early adoption are ready to implement now and would deliver on the emissions reductions identified in Table ES-1 and Table ES-2. However, if current uncertainties regarding emerging technology for ocean energy, seaweed and marine carbon dioxide removal were resolved, an additional 9 Gt CO_2e could be possible as shown in Table ES-3 below (see Table ES-1 for further details).

Table ES-3. Contribution towards closing the emissions gap in 2030 and 2050 of solutions explored in this report (mature, early adoption, demonstration, prototype, and concept technologies and approaches according to Figure ES-3 and Table 2)

	ANNUAL GLOBAL EMISSIONS (GT CO_2E)			GAP TO PATHWAY, BASED ON UNEP CURRENT POLICY SCENARIO (GT CO_2E)		TOTAL GHG MITIGATION POTENTIAL (GT CO_2E)		% GAP CLOSED: 1.5°C PATHWAY		% GAP CLOSED: 2°C PATHWAY	
	Current policy	1.5°C pathway	2°C pathway	1.5°C pathway	2°C p athway	Min	Max	Min	Max	Min	Max
Today	58	58	58	0	0	0	0	0	0	0	0
2030	58	33	41	25	17	1	6	5	24	7	35
2050	49	10	20	39	29	5	23	12	58	17	78

Note: Estimates are based on comparing multiple scenarios for annual emissions in 2023, 2030 and 2050. For those years, we compare '1.5°C', '2°C' and the 'current policy' scenarios from UNEP 2022 and calculate the mitigation needed to fill the 'gaps' between the 'current policy' and the '1.5°C', and '2°C' respectively. 'Min' refers to conservative ocean-based mitigation potential, while 'Max' represents higher (more ambitious) theoretical potential projected in this report. The total ocean-based mitigation was compared to the gap at 2030, and that at 2050, generating the percentage of the gap (in each case) mitigated by ocean-based mitigation of GHG emissions.

Source: Authors.

For estimates based on the five sectors presented in the 2019 Report, including those not yet ready for implementation, please see Appendix B.

Progress since 2019

Despite the challenges faced globally in the four years since the 2019 Report was published, many new initiatives have emerged to accelerate global progress on ocean-based climate solutions (Northrop et al. 2022). Notably, there has been an increase in ocean-based climate solutions included in national climate commitments, known as Nationally Determined Contributions (NDCs), communicated pursuant to the Paris Agreement. An analysis of the 106 new and updated NDCs communicated in 2022, found that 77 (73 percent) include at least one target, policy or measure aimed at ocean-based climate actions (Khan and Northrop 2022).

Of the sectors initially explored in the 2019 Report, the most significant acceleration in new global initiatives has been in offshore wind. In addition to private sector initiatives, several coastal nations have committed to ambitious domestic targets for offshore wind deployment since 2019, driving innovation in turbine technology, grid integration and environmental impact assessments.

Marine transport has garnered growing attention as well, culminating in the IMO's revised strategy committing to the adoption of GHG pricing as well as a fuel standard, and for this policy measure combination to 'commit to the contribution to a level playing field and a just and equitable transition'. With the progressive outcomes in the IMO's revised strategy, there is now an excellent opportunity for a global policy-driven transition of international shipping, and GHG reductions close to those consistent with the 1.5°C temperature Paris goal.

Progress on restoring and protecting marine and coastal ecosystems is expected to be boosted based on the targets agreed to under the Kunming-Montreal Global Biodiversity Framework in December 2022 and associated commitments to mobilise greater public and private sector finance. Unfortunately, there has been little progress in improving fisheries and aquaculture management and shifting diets to foods harvested sustainably from the ocean. At the international level, this sector needs greater political attention and policy action to help it accelerate the achievement of its emissions reduction potential.

Despite the significant hardships faced by the tourism industry over the past four years, and the economies that rely on it—primarily small island developing states—the potential for tourism to contribute to global efforts to reduce emissions is gaining traction at the international level through organisations such as the Glasgow Declaration on Climate Action in Tourism.

MARINE CONSERVATION AND RESTORATION

In the past four years, countries have made progress in protecting and conserving mangroves (Spalding et al. 2022), recognising that coastal ecosystems could provide significant climate mitigation benefits alongside climate adaptation, biodiversity and other co-benefits. However, hot spots of degradation remain, and stopping this will take focused action from national governments and partners (Schindler Murray et al. 2023). Protecting and restoring other blue carbon (all biologically driven carbon fluxes and storage in marine systems that are amenable to management) (IPCC 2019) ecosystems, such as seagrass meadows, tidal marshes and seaweed forest, could also contribute to reduced emissions to varying extents, but the policy and financial support needed to accomplish this is lacking (Howard et al. 2023; Pessarrodona et al. 2023; Schindler Murray et al. 2023). Knowledge of the global cover of seagrass and tidal marshes has improved since the 2019 Report (McKenzie et al. 2020; Murray et al. 2022), leading to estimates of emissions from their loss to be lower than reported in the 2019 Report.

Restoring natural coastal ecosystems is vital but can take time (i.e. decades). Healthy coastal ecosystems are carbon sinks and can help reach net zero targets. Restoration also offers extensive co-benefits, including habitats, biodiversity, food and feed, climate change adaptation, fisheries and aquaculture that can contribute to achieving multiple Sustainable Development Goals (SDGs) (Duarte et al. 2020; Schindler Murray et al. 2023). Yet globally, we find that the total area undergoing restoration has not increased since 2019 to the scale needed to meet emissions reduction and biodiversity targets. Approaches that can help accelerate restoration include engaging local communities, equitably sharing benefits and co-benefits, and resolving uncertainties over land tenure (Conservation International et al. 2022).

In addition, since the 2019 Report, new ideas have emerged for managing marine ecosystems to help mitigate climate change. These include regulating bottom trawling as well as conserving and restoring tidal mudflats. Achieving carbon sequestration by preserving and restoring marine fauna is also increasingly being explored (Malhi et al. 2022), but mitigation estimates still need to be made. More research is needed to understand the full mitigation potential of these activities and their role in enhancing climate change adaptation and resilience.

OCEAN-BASED RENEWABLE ENERGY

Since 2019 many countries raised their ambitions for scaling offshore renewable energy (ORE). In 2019, total pledges for ORE ranged in mitigation potential, from 0.3–2.5 Gt CO_2e per year in 2050. Now total pledges have reached a GHG mitigation potential of between 3.3–4.5 Gt CO_2e per year in 2050, assuming that ORE replaces the current mix of energy (GWEC 2023). Although this is very promising, implementation often lags behind stated political ambitions and the current pace is too slow to reach the target for net zero in 2050 (IRENA 2023). Deployment rates for offshore wind energy in 2020, 2021 and 2022, for example, were about 6, 21 and 9 GW per year respectively, equivalent to a mitigation potential of 0.01–0.03 Gt CO_2e per year, assuming displacement of current energy mix (IEA 2021a; GWEC 2023). 2021 was a record year in offshore installations driven by special conditions in China (termination of attractive financial support scheme at end of year) (GWEC 2023). By the end of 2023, a cumulative total of about 63 GW of offshore wind capacity will have been installed worldwide. To meet net zero in 2050, more than that would need to be installed every year. The deployment rate would need to be 70–80 GW per year between 2030 and 2050 (IEA 2021a). The Global Offshore Wind Alliance, an organisation working to accelerate deployment of offshore wind technologies, (GWEC 2023) aims to add an average of 35 GW per year in the 2020s and a minimum of 70 GW per year from 2030 onwards. This rivals the present pace of onshore and offshore wind energy deployment combined. The goal is to reach cumulative capacity of 380 GW by 2030 and 2,000 GW by 2050. However, supply chain disruptions over the past two years have illustrated what could go wrong. After falling rapidly over the last several decades, costs for materials have risen, and may have slowed implementation. Materials will need to be affordable and available to keep up with demand and meet existing targets and pledges.

Research and development of tidal (use of tidal movements or currents to generate power) and wave (capturing energy from wind-driven oscillations in water level) sources of energy continues, but the technologies have not converged towards solutions suited for large, industrial-scale installation. So, these technologies are not expected to contribute significantly to the global electrical energy production by 2030. A technological breakthrough can make wave or tidal energy viable in certain locations. Floating solar energy systems are an even newer technology that has a promising outlook, although these systems currently require calm ocean areas.

OCEAN-BASED TRANSPORT

Since 2019, new data from the fourth IMO GHG study (Faber et al. 2020) has lower projections for the growth of trade. These estimates reduce a key driver of energy demand and emissions for shipping and could make GHG reduction objectives easier to reach. They also reduce the mitigation potential of transitioning to less polluting fuels. Significant progress has been made in identifying transition pathways for the sector. Multiple studies have identified ammonia and methanol as the most likely successors to hydrocarbon molecules, leading to trials and pilot projects (Gielen et al. 2022; Rouwenhorst et al. 2022) and nations collaborating to de-risk hydrogen-derived fuels (IEA 2022a). Investment and commitments in green hydrogen and ammonia since 2019 adds up to roughly three exajoules (EJ). This equals approximately one-third of international shipping's energy demand. Despite this momentum, the volume of green hydrogen/ammonia projects passing key investment milestones are lagging behind what would be needed to reach the maximum mitigation potential identified in the 2019 Report of nearly 100 percent reduction in operational net GHG emissions.

Changes in finance, policy, demand, and civil society engagement are helping drive commitments to lower emissions from ocean transport, and to identify and systematically evaluate key metrics and near-term targets that are compatible with Paris Agreement goals (Baresic and Palmer 2022). This means there are frameworks now for 'course-correcting' ocean transport's decarbonisation, which can boost confidence in the feasibility of a successful 1.5°C-aligned transition. The IMO's revised and more ambitious GHG Reduction Strategy is now nearing the sector's maximum abatement potential, setting a real expectation that enacting future policies, and ratcheting up existing ones, can maximise cost-effectiveness and foster equity and sustainable development.

Achieving the GHG reductions of the IMO's revised strategy will require a significant investment, primarily on land, into renewable energy and green hydrogen production, some of which could be efficiently deployed in developing countries (Campbell et al. 2023). In terms of implementation, over 200 zero emission pilot and demonstration projects are currently in the pipeline, with an increase of almost 100 percent since 2019. The Green Shipping Challenge has been issued by the United States and Norway in 2022 culminating in 50 new announcements from countries, ports and companies to align themselves with the goal of limiting global temperature rise to 1.5°Celsius above pre-industrial levels.

OCEAN-BASED TOURISM

A detailed discussion of ocean-based tourism was not included in the 2019 Report. Since then, however, greater attention has been given to emissions from ocean-based tourism causes and what can be done to reduce them. The cruise sector is particularly carbon-intensive, relative to other forms of tourism, and is growing fast (Gössling et al. 2023); hence the need to lower its energy use and environmental footprint. The progress made so far has been led by the private sector. Major cruise ship operators have launched plans to reduce their carbon intensity by an annual rate of 2 percent with longer-term pledges envisioning zero emission ships and net zero CO_2 emissions by 2050 (Royal Caribbean Group 2021; Hurtigruten Group 2022). These positive steps, however, fall short of what is required. With a projected annual passenger growth of 6 percent, reducing carbon intensity by just 2 percent means ever higher emissions. The sector's carbon reduction targets are insufficient to align with the Paris Agreement's 1.5°C or 2°C scenarios needed to prevent the most catastrophic impacts of global warming.

Given this situation, progress needs to accelerate. One way to change this trajectory is to facilitate and incentivise adequate decarbonisation via government intervention. This could take the form of stringent legislation and regulation at both the national level and potentially the port level, compelling the industry to significantly improve its environmental performance (IMO 2023c). The task at hand requires a balanced blend of proactive industry actions, regulations, innovative technology and a scaling down of passenger numbers to ensure the cruise sector contributes meaningfully to the global efforts to mitigate climate change (Gössling et al. 2023). Another way to reduce emissions from ocean-based tourism could be to involve cruise lines, making binding commitments to absolute emission reductions.

OCEAN-BASED FOOD

The 2019 Report detailed how changing wild capture fishery and aquaculture practices and substituting low-carbon sources of food from the ocean for high-emitting land-based proteins, could help limit the worst impacts of climate change. Unfortunately, there has been little progress towards meeting this goal (FAO 2022). Indeed, the intervening years may have pushed it further out of reach. Human populations have risen and so has the demand for protein, and the need for sustainable protein sources with low carbon footprints will only grow more acute.

Food from the ocean could exhibit a lower carbon footprint than land-based animal agriculture when managed sustainably (which many fisheries currently are not; FAO 2022). For example, on average, approximately 200 t CO_2e is emitted from agricultural production per tonne of beef consumed, whilst the equivalent weight of farmed fish is about 30 t CO_2e (Searchinger et al. 2019). Moreover, certain types of oceanic food production, such as seaweed farming, may sequester carbon. Rapidly growing seaweeds absorb large amounts of carbon through photosynthesis, which is converted into biomass. However, most seaweeds are cultivated to be processed, and this represents only a transient type of sequestration with little prospect of long-term storage (Troell et al. 2023). Some of the carbon in farmed seaweed biomass may be transported to ocean sediments and deep water, either intentionally or unintentionally, where it is removed from the carbon cycle for a time (Duarte et al. 2022b; Duarte et al. 2023; Hurd et al. 2022). Moreover, should the harvested seaweed be used as, for example, food, feed or fertiliser, it can further contribute to offsetting emissions from other more carbon-intensive sources and products (Duarte et al. 2022a; Spillias et al. 2023b). More must be done to raise awareness, send clear policy signals and invest in the enabling environment to take advantage of these opportunities.

OFFSHORE OIL AND GAS

Reducing offshore oil and gas production and consumption was not considered in the 2019 Report as an ocean-based climate mitigation option. However, the IPCC AR6 Synthesis Report (IPCC 2023) suggests that cumulative future CO_2 emissions over the lifetime of existing fossil fuel infrastructure globally (if historical operating patterns are maintained) will likely exceed the total cumulative net CO_2 emissions in pathways that limit warming to 1.5°C. Developing new fossil fuel infrastructure in addition to what already exists will result in additional CO_2 emissions compared to if existing infrastructure only is maintained. Thus, in order to remain consistent with a 1.5°C warming pathway, governments and industry should not look to pursue new oil and gas operations, whether offshore or onshore (IPCC 2023). Reducing oil and gas consumption is critical for meeting global climate commitments and the offshore component can be considered as an ocean-based solution to climate change. Currently, nearly 30 percent of all oil and gas production comes from offshore areas (EIA 2016; IEA 2019) with most of the offshore production and investment being concentrated in just a few regions (Rystad Energy 2023). Halting the expansion of offshore oil and gas extraction, and gradually phasing down current production and consumption through energy demand shifts, could avert 5.30 Gt CO_2e a year of emissions in 2050.

Realising the full potential of this solution and ensuring that halted offshore expansion is not simply replaced by expanded onshore operations requires reductions in fossil fuel demand driven by a range of decarbonisation levers such as energy efficiency measures, renewables expansion, greater electrification, and the use of green hydrogen. Many of these technologies are passing key economic tipping points and are already more attractive to investors than their hydrocarbon counterparts. For example, wind and solar are already the cheapest forms of new energy globally, and cost reductions are anticipated to continue (IRENA 2022; Lazard 2022; Systemiq 2023). Importantly, negative emission technologies cannot be used as a substitute for halting offshore oil and gas expansion, nor should they promise future emissions reductions to excuse ongoing search and extraction of oil and gas.

MARINE CARBON DIOXIDE REMOVAL AND CARBON CAPTURE AND STORAGE

Since 2019, interest in mCDR has surged (GESAMP 2019; Moniz et al. 2020; National Academies of Sciences, Engineering, and Medicine 2021; Lebling et al. 2022; Ocean Visions n.d.). While promising, ocean-based CDR technologies remain at early stages of development. None of them has undergone fit-for-purpose field testing in ocean environments. Such field testing is critical for making evidence-based assessments of efficacy and impacts on marine ecosystems. Because mCDR activities show substantial CDR potential, further research and investment of resources (time, energy, and people) is needed. Advancing the science and engineering aspects of mCDR is important but must be matched by associated investigations of policy, governance, socio-economic and ecological impacts of any potential future deployments. Many of these questions and technologies still need further study and hence are not assessed as ready for implementation for the purposes of the present report.

FINANCE

Since the 2019 Report was issued there has been an increase in public and private finance to deliver ocean-climate mitigation solutions. As an example, in Europe €41 billion was invested into offshore wind in 2021 (Wind Europe 2023), though the level of investment in 2022 was significantly lower.

While larger ocean sectors in particular have access to commercial finance and the capital markets to fund the required transition, this report suggests that at least US$1 trillion of additional finance is needed between now and 2030 to facilitate a rapid transition to achieve the ocean-climate solutions outlined, supporting sectors at various stages of development, including research and technology, as well as delivery of adequate risk management and environmental impact assessment, governance and regulatory structures, with a particular emphasis on creating opportunities in the Global South. Innovative finance mechanisms including blended finance approaches to a sustainable blue economy will be key, with increased engagement of public finance institutions to facilitate flows based on blue finance guidelines (IFC 2022).

It is expected that more of the ocean-climate solutions will be mainstreamed and have access to commercial finance beyond 2030. Needless to say, an overall investment of at least $2 trillion[4] from 2030 to 2050 will be required to reach scale across the ocean sectors (GIH 2018; Krishnan et al. 2022; Morgan Stanley 2023).

Wider impacts

This report also includes an updated analysis of the assessment of wider impacts (both positive and negative) of each type of ocean intervention and mitigation option. The steps needed to cut GHG emissions will ripple across multiple dimensions of long-term (mid-century and beyond) sustainable development, well-being and governance. They will yield co-benefits and require trade-offs (IPCC 2018, 2023. Some will affect countries' ability to achieve targets established within the framework of the UN 2030 SDGs. Taking these wider impacts into account can help provide a more informed and holistic picture of pursuing ocean-based climate solutions.

This report concludes that while many ocean-based mitigation options discussed bring both co-benefits and trade-offs, the benefits of solutions ready to implement generally far outweigh the potential downsides of deployment and/or full implementation. Trade-offs do, however, need to be considered.

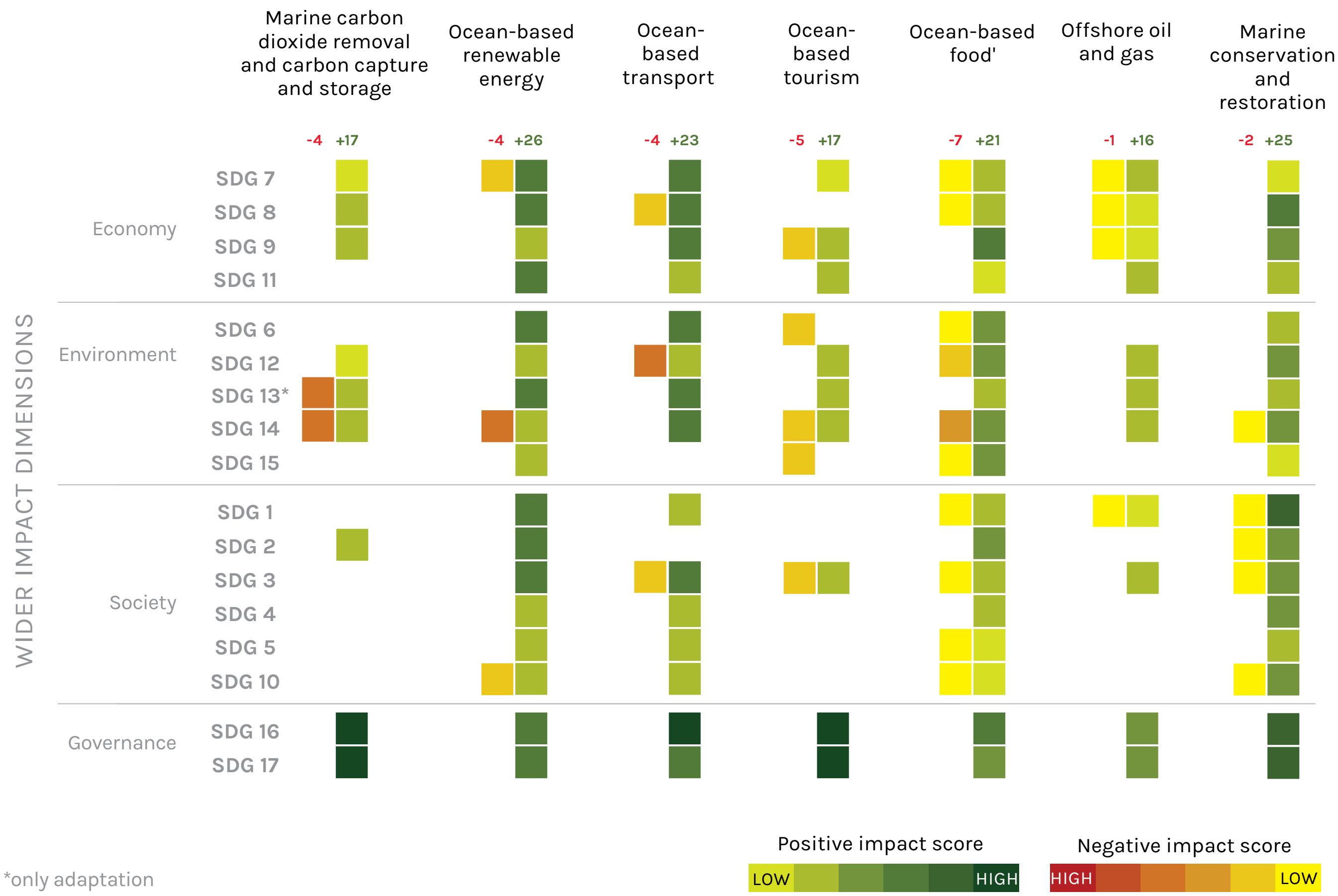
Positive environmental consequences include major biodiversity benefits to marine and terrestrial ecosystems, enhanced ecosystem services (improvement in fisheries productivity and coastal tourism), reduced ocean acidification, greater coastal resilience, and less withdrawal/usage of water. Positive economic impacts can include economic growth through new local employment opportunities in the ocean economy, improved incomes and livelihoods in coastal areas, lower fuel costs for more energy efficient vessels and better health and food security resulting from shifting diets.

Several potentially negative repercussions were identified as well. These include the potential environmental, economic and social impacts of unplanned growth in aquaculture and renewable energy installations. If deployed at scale, without scientific consensus or the appropriate governance, many marine carbon dioxide removal approaches explored in this report could alter chemical, physical and ecological processes in ways that contribute to ocean acidification and deoxygenation, and damage ocean ecosystems. Some of these risks can be adequately addressed through stakeholder engagement, inclusive management policies, careful monitoring, and effective marine planning. But others will require further research, and/or be evaluated unsuitable. Risks also include ethical issues. In some instances, governments may need to take action to reduce, resolve and erect safeguards against negative impacts. Concerted action is needed to understand global, regional and local risks to enhance net positive outcomes and minimise negative ones.

Policy design and implementation, such as through holistic planning tools like Sustainable Ocean Plans (SOPs) (Ocean Panel 2021) help determine how mitigation options affect social outcomes. Without stake- and rights-holder consultation and co-development of solutions, mitigation options aimed at rebuilding fish stocks and other ocean biomass could hamper efforts to create employment, alleviate poverty, and improve access to food. But with co-management, capacity support/development and community buy-in, stocks can be rebuilt for the long-term benefit of coastal communities and ecosystems. Lack of effective stakeholder engagement on 'blue carbon' restoration projects (including exclusion of local community representatives from key international decision-making events) can limit access to ocean spaces or resources (Schindler Murray et al. 2023). This can harm small-scale fishers who heavily rely on local ecosystems for jobs, nutritional needs and economic sustainability. Well-planned mitigation measures that engage communities, nongovernmental organisations (NGOs) and governments, and follow best governance practices, are essential to avoid worsening inequalities and creating new social injustices.

The results of the analysis are shown in Figure ES-4.

Figure ES-4. The wider impact of ocean-based interventions on sustainable development dimensions



*only adaptation

List of Sustainable Development Goals reviewed:

Note: The figure is an updated version of Figure ES.5 in Hoegh-Guldberg et al. (2019). New literature has been analysed to update this figure. Wider-impact dimensions cover various sustainable development dimension indicators as well as 2030 Sustainable Development Goals (SDGs). 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 mit*igation options in that area.*

Source: Authors.

Opportunities for action

Achieving the potential outlined in this report will require both concerted national action and appropriate financing mechanisms. Table ES-5 summarises short-term priorities (by 2025) for each ocean-based solution that are required to accelerate implementation and put all sectors on a pathway to realise the potential identified. For some sectors, this will mean catching up on opportunities missed over the past four years. Additional priorities for the medium term (by 2030) and long term (2050 to end-century) are explored in more detail in each chapter.

Utilising Sustainable Ocean Plans or equivalent holistic ocean governance mechanisms can support the acceleration of many of these ocean-based climate solutions in a manner that is equitable, inclusive and nature-positive (Ocean Panel 2021).

Table ES-5. Short-term priorities and opportunities to deliver on mitigation potential of ocean-based climate action areas

MARINE CONSERVATION AND RESTORATION	
Government	▪ Assess national blue carbon opportunities (Schindler Murray et al. 2023). ▪ Analyse national and international legal and policy frameworks to include blue carbon in sustainable development, climate change, forestry, biodiversity and marine resource management regulations, including national GHG inventories and NDCs by implementing the IPCC Wetlands Supplement from the Intergovernmental Panel on Climate Change (IPCC).[a] ▪ Enact regulation and policies to halt ecosystem losses and promote restoration. Set appropriate conditions based on global standards (clarity on land tenures, policy predictability, when possible public funding to de-risk investments) to attract private capital. ▪ Designate marine protected areas (MPAs) as an integral part of marine spatial planning (MSP) to enhance conservation, maximise climate and biodiversity benefits. ▪ Use non-market-based approaches, including community-based natural resource management and civil society cooperation aimed at the conservation of biodiversity (Target 19, CBD 2022). ▪ Recognise the wider ecosystem services and benefits for water quality, biodiversity, fisheries, aquaculture, coastal protection and climate change adaptation to develop appropriate financial and regulatory incentive tools. ▪ Increase investments in R&D and citizen science programs to fill priority knowledge gaps. ▪ Explore robust global or regional carbon pricing structures.
Private sector	▪ Set targets and/or pledges for ecosystem protection and restoration (as relevant to land ownership, operations or supply chains) (CBD 2022). ▪ Increase investments in coastal nature-based solution (NbS) projects (e.g. in project development, regulatory approvals, financial management, project implementation, research and development), including through impact funds and other instruments (Target 19, CBD 2022). ▪ Increase investment in conservation and restoration of blue carbon ecosystems through innovative finance (insurance, debt swaps, taxes, and carbon credits), carbon pricing mechanisms, and public-private partnerships (Target 19, CBD 2022). ▪ Partner with local communities to deliver all aspects of projects (including verification) (Target 19, CBD 2022). ▪ Implement the International Union for Conservation of Nature's NbS standard guidelines and the High Quality Blue Carbon Principles (Conservation International et al. 2022) for investments (e.g. equitable benefit sharing). ▪ Examine supply chains and eliminate components that lead to degradation of coastal and marine ecosystems and work towards positive impact on ecosystems.

Table ES-5. Short-term priorities and opportunities to deliver on mitigation potential of ocean-based climate action areas (Continued)

MARINE CONSERVATION AND RESTORATION (CONTINUED)	
Research community	▪ Develop robust, low-cost monitoring technologies (e.g. using remote sensing) for monitoring success of blue carbon projects. ▪ Improve seagrass and seaweed restoration techniques for large-scale implementation. Link management of offsite factors, e.g. improvement of catchment water quality, to restoration outcomes. ▪ Improve documentation and understanding of seaweed carbon fluxes and sequestration in relation to management action. ▪ Increase accuracy and knowledge of spatial and temporal variability of estimates of mitigation by blue carbon ecosystems, including impacts of climate change. ▪ Identify new opportunities for blue carbon projects (develop frameworks to aid identification of sites for blue carbon projects and co-benefits for communities). ▪ Characterise co-benefits of NbS projects, including social outcomes. Develop robust, standardised guidelines for projects. ▪ Develop knowledge on wider impact both at project scale and economy-wide as well as at global scale to better inform policy and action. ▪ Collaborate with the government, the private sector and communities to support projects and policy development.
OCEAN-BASED RENEWABLE ENERGY	
Government	▪ Utilise area-based management frameworks and marine spatial planning, including Sustainable Ocean Plans, to guide development and minimise conflict amongst ocean users. ▪ Provide a stable economic and regulatory framework to stimulate investment in required infrastructure for an accelerated deployment of ocean-based energy systems. ▪ Improve the transparency of siting and permitting processes. ▪ Introduce attractive financial support and guarantee schemes. ▪ Establish processes to resolve cross-border regulatory issues. ▪ Offer education and capacity building to create a skilled workforce and capacities for manufacturing repair, and installation.
Private sector	▪ Strengthen and expand supply chains, including where to site suppliers. ▪ Develop efficiency of technology deployment and supply chain to reduce costs. ▪ Identify alternative materials and material resources to avoid supply chain constraints and reduce costs. ▪ Enhance social responsibility and acceptability. ▪ Establish targets and/or pledges related to biodiversity protection and restoration associated with ocean-based renewable energy deployment and operation.

Table ES-5. Short-term priorities and opportunities to deliver on mitigation potential of ocean-based climate action areas (Continued)

OCEAN-BASED RENEWABLE ENERGY (CONTINUED)	
Research community	▪ Increase research on environmental and social impacts of large-scale offshore wind (OSW) energy and multi-use of ocean space. ▪ Develop technology components that reduce cost and dependency on critical materials. ▪ Further investigate the potential for installing large-scale floating solar installations at sea. ▪ Understand the potential benefits of co-location with other ocean-based industries (e.g. desalination plants and aquaculture).
OCEAN-BASED TRANSPORT	
Government	▪ Develop and communicate national targets and pledges for the decarbonisation of domestic vessel fleets and associated national infrastructure. ▪ Develop national and/or regional plans on the role and carbon intensity of trade. ▪ Commit to decarbonisation of national energy systems faster or as fast as the low-carbon transition in the international vessel fleet. ▪ Support the revision of the IMO's short-term measure policies—improving stringency, enforcement and effectiveness of the existing regulations such as Carbon Intensity Indicators (CIIs) and the Energy Efficiency eXisting ship Index (EEXI) and the development and adoption of new IMO mid-term measures. ▪ Refine the IMO Life Cycle Assessment (LCA) guidelines and use in policy. ▪ Adopt basket of goal-based IMO mid-term measures, enabling equitable transition. ▪ Provide support and incentives for early adopters of zero emission technologies. ▪ Revise the IMO Data Collection System (DCS) to include cargo carried.
Private sector	▪ Sign up for voluntary initiatives that robustly and transparently measure alignment to limit global warming to 1.5°C. ▪ Form value-chain clubs around early adoption zero emission opportunities. ▪ Include decarbonisation opportunity and risk efficiently into contracting
Research community	▪ Evaluate options to reduce cost, address safety, and increase efficiency of renewable-based fuels both in the form of electricity in combination with batteries, low-carbon fuel made from renewables and carbon capture and storage (CCS) on board. ▪ Assess performance of complementary efficiency technologies, including wind. ▪ Identify and rectify market and nonmarket barriers and failures to enable larger uptake of more energy-efficient technologies and cooperation patterns.

Table ES-5. Short-term priorities and opportunities to deliver on mitigation potential of ocean-based climate action areas (Continued)

OCEAN-BASED TOURISM	
Government	▪ Monitor and track GHG emissions (scope 1–3) from global cruise tourism to devise and revise climate policies for the sector. ▪ Implement voluntary disclosure of per passenger emission levels following the example of aviation industry to empower users in their decision making. ▪ Blend-in obligations for sustainable biofuels in jurisdictions such as the European Union. ▪ Set standard CIIs to track progress; the CII must reflect actual operations. ▪ Adopt stringent and effective IMO mid-term policy measures (GHG levy and GHG fuel standard).
Private sector	▪ Sign up for voluntary initiatives that robustly and transparently measure alignment to limit global warming to 1.5°C. ▪ Implement structured fees at port for cruise ships that imply a significantly higher cost for ship owners. ▪ Invest in research, development, and design of energy-efficient and low-carbon cruise ship technology. ▪ Design, order and build cruise vessels with low energy consumption and zero GHG emission fuels.
Research community	▪ Research options for utilising a standard connection for shore power to increase utilisation. ▪ Further research design of energy-efficient components and activities (such as hull cleaning).
OCEAN-BASED FOOD	
Government	▪ Enhance sustainable management and enforcement of ocean fisheries globally, with a focus on the use of MPAs and implementing rebuilding plans for depleted stocks. ▪ Promote electrification and decarbonisation of all aquaculture site energy inputs. ▪ Promote efficient licensing processes and strategic marine spatial planning for ocean aquaculture to avoid unplanned growth and maximise synergies with other ocean users and technologies (including ocean-based renewable energy). ▪ Utilise area-based management frameworks, including Sustainable Ocean Plans, to guide development and minimise conflict between ocean users. ▪ Review national regulatory and incentive structure to align with efforts to decarbonise ocean based food.
Private sector	▪ Scale best practices for fisheries management and marine aquaculture, including adaptative fisheries management to promote adaptation to climate change. ▪ Investment in species-targeted aquaculture strategies (e.g. improved genetics, husbandry practices) to reduce feed conversion ratio in fed aquaculture.
Research community	▪ Enhance development of monitoring, evaluation and enforcement tools that enhance sustainable fisheries and aquaculture management. ▪ Improve assessment and monitoring of data-poor fish stocks to facilitate management and rebuilding. ▪ Expand analyses on diet influences on human health to seek more options that are good for people and the planet. ▪ Make assessment of limits to sustainable ocean-based dietary protein sourcing.

Table ES-5. Short-term priorities and opportunities to deliver on mitigation potential of ocean-based climate action areas (Continued)

OFFSHORE OIL AND GAS	
Government	▪ Initiate processes to withdraw fossil fuel subsidies in countries which currently provide them. ▪ Establish governance to stop the granting of new licenses for offshore oil and gas extraction. ▪ Review offshore oil and gas leases that are not yet operational with a view to withdraw such leases. ▪ Invest public finance in energy security and access for economically vulnerable communities. ▪ Plan retraining, skill diversification and social protection. ▪ Enact legislation and/or regulation to ban routine flaring.
Private sector	▪ Invest in technology and practices to reduce methane leaks and end routine flaring in countries where it is still allowed. ▪ Increase energy efficiency in offshore oil and gas operations. ▪ Operators work with governments to develop and enact decommissioning plans. ▪ Operators reduce average reservoir depletion rates from ~8 percent per year to ~4 percent per year. ▪ Investors and financial institutions signal that new oil and gas exploration and new infrastructure is not worthwhile and reprioritise investment in renewable energy infrastructure.
Research community	▪ Investigate impacts of decommissioning of structures and materials on the health of surrounding coastal communities and marine environments. ▪ Identify gaps and opportunities for investment in training and skills development to ensure opportunities for transitioning the work force.

Table ES-5. Short-term priorities and opportunities to deliver on mitigation potential of ocean-based climate action areas (Continued)

MARINE CARBON DIOXIDE REMOVAL AND CARBON CAPTURE AND STORAGE	
Government	▪ Develop a model international governance framework to establish suitable guardrails for future research, field testing and potential deployment. ▪ Develop domestic legal frameworks specific to mCDR which set regulatory standards. ▪ Harness mCDR projects as an opportunity to increase equity and justice initiatives. ▪ Sponsor research including supporting incremental testing and monitoring programs. ▪ Support research on the environmental and societal implications of mCDR.
Private sector	▪ Coordinate with government and research sectors to sustain a transparent research infrastructure. ▪ Co-design research objectives with indigenous and coastal communities. ▪ Construct robust monitoring, reporting, and verification plans, which include life cycle emissions accounting for net removal estimates. ▪ Develop and follow a mCDR code of conduct. ▪ Provide early investments to catalyse innovation in the mCDR landscape.
Research community	▪ Conduct cross-sectoral research on the social and environmental impacts of mCDR strategies. ▪ Conduct field and pilot studies to understand the efficacy and impacts of mCDR. Incorporate mCDR methods into integrated assessment models and consider interactions with Sustainable Development Goals. ▪ Push forward innovative sensor and model designs to allow for more robust monitoring, reporting and verification. ▪ Improve the resolution of ocean chemistry baseline measurements.

Source: a. IPCC 2013b.

Financing the transition

Financing the solutions identified in this report is an urgent, time-sensitive challenge that world leaders must grapple with now. The nature of this challenge differs by sector and region. For instance, funding available from public and private sources for mature sectors in stable jurisdictions may exceed their absorptive capacity. In contrast, less mature sectors in regions with institutional bottlenecks and higher perceived risks to investment may be starved for finance. Where finance is available it needs to be fully aligned with the Kunming-Montreal Global Biodiversity Framework and goals of the Paris Agreement, and providing funding where it is now scant may require de-risking, guarantees and blended finance.

Since the 2019 Report was issued there has been an increase in public and private finance to deliver ocean-climate mitigation solutions. As an example, in Europe €41 billion was invested into offshore wind in 2021 (Wind Europe 2023), though the level of investment in 2022 was significantly lower.

While larger ocean sectors in particular have access to commercial finance and the capital markets to fund the required transition, this report suggests that at least $1 trillion of additional finance is needed between now and 2030 to facilitate a rapid transition to achieve the ocean-climate solutions outlined, supporting sectors at various stages of development, including research and technology, as well as delivery of adequate risk management and environmental impact assessment, governance and regulatory structures, with a particular emphasis on creating opportunities in the Global South. Innovative finance mechanisms including blended finance approaches to a sustainable blue economy will be key, with increased engagement of public finance institutions to facilitate flows based on blue finance guidelines (IFC 2022). It is expected that more ocean-climate solutions will be mainstreamed and have access to commercial finance beyond 2030.

This report suggests that an estimated $2 trillion[5] needs to flow into ocean solutions between 2030 and 2050 to support the achievement of the mitigation potential suggested in this report (GIH 2018; Krishnan et al. 2022; Morgan Stanley 2023).

Below are some of the priorities for reaching this trajectory:

By 2025

- Governments and the private sector to re-align frameworks and approaches to achieve nature positive net zero.
- Governments to provide additional finance to support early-stage companies develop zero carbon solutions.
- Governments, NGOs and the private sector to launch collaborative finance partnerships and solid standards for a rapid transition.
- Governments to agree on and outline targets and associated pathways for ocean sectors that are Paris-aligned to ensure consistent policy signals for investing.

By 2030

- All actors scale up working solutions, overcoming bottlenecks to finance a wider range of ocean technology solutions.
- All actors focus on delivering ocean climate benefits everywhere, including in those parts of the Global South that lack some of the preconditions for sufficient finance flow.
- Deliver NbS finance with emphasis on co-benefits, adaptation, resilience and biodiversity.
- Show significant progress across all sectors.

…an estimated $2 trillion needs to flow into ocean solutions between 2030 and 2050 to support the achievement of the mitigation potential suggested in this report.

- $1 trillion of additional finance by 2030 to facilitate a rapid transition to the ocean-climate solutions outlined in this report.

Under this approach, by 2050

- $2 trillion needs to flow into ocean solutions between 2030 and 2050. Depending on the success of mainstreaming and aligning investments in ocean solutions with commercial finance flows, not all of this is an additional financing need.
- Transformation of the sectors is complete so that there is no more need for transition finance and all funding goes to fully net zero climate approaches.
- All finance is ocean- and nature-positive, with a robust monitoring and management framework based on near-real time data at the site and asset level, both in national waters and in the high seas.

This report analyses each sector individually. It finds that global flows into nature-based solutions need to quadruple per year by 2050 (UNEP 2021). The State of Finance for Nature 2021 report (UNEP 2021) puts the cost of mangrove restoration finance at a total of $15 billion for the period from 2021 to 2050, of which $4 billion invested by 2030 is the target of the mangrove Breakthrough (Climate Champions 2022). Other systems such as seagrasses, salt marshes and potentially kelp are likely to require investments at a similar or smaller scale. Most traditional finance has limited traction, but bundled approaches and larger capital market transactions can steer international capital markets towards blue carbon. Options include structured finance, blue bonds and integrating nature-based solutions into broader blue infrastructure approaches. Carbon markets are increasingly being considered as financing mechanisms for nature-based solutions such as blue carbon, but the amount of carbon sequestered through those transactions and corresponding finance will remain small in the 2030 time frame (Sumaila et al. 2021; Schindler Murray et al. 2023).

Growing investment is expected to make offshore wind energy the leading ocean-climate mitigation solution by 2030 (IRENA 2023). Providing sufficiently accessible finance for this sector, however, will require action by finance sources, such as capital markets and public (government) finance, to reform lending practices, strengthen instruments such as blue bonds, and change procurement processes to channel finance to needed infrastructure such as transmission lines. Developing countries will also need assistance putting robust strategies and regulatory frameworks in place for offshore wind deployment. For other ocean renewable technologies that are not at the same level of maturity as offshore wind, funding should focus on research and development before large-scale commercial finance becomes available.

Estimates based on IMO Initial Strategy ambitions put the total additional capital needed for reducing carbon emissions from shipping by at least 50 percent by 2050 at $1–1.4 trillion, noting that over 80 percent of this total relates to infrastructure investment on land (Global Maritime Forum 2020). If shipping was to fully decarbonise by 2050, this would require extra investments of approximately $400 billion over 20 years (Global Maritime Forum 2020). Reaching this target will require around $40 billion annually in finance by 2030 (Baresic and Palmer 2022). The sector has access to a wide range of traditional finance mechanisms offering multiple pathways to deliver appropriate funding structures. However, there is limited financing appetite for zero carbon ocean transport solutions, such as wind-only cargo ships, or for investments into early-stage technology businesses that can help transform the sector. These opportunities to decarbonise shipping require targeted, knowledgeable impact and venture capital finance to scale.

Similarly, the cruise tourism sector has good access to traditional marine finance. Achieving zero carbon cruising, however, requires new technologies and approaches and appropriate finance mechanisms. These could include commercially funded investments in land-based renewables and port logistics to shrink the sector's carbon footprint.

Finance for ocean-based food should be re-aligned to fully integrate both climate and nature considerations into funding decisions. Remaining subsidies for fishing and food crops should be redirected away from non-sustainable activities. Investment needs for the sector reach $55 billion by 2050 (Elwin et al. 2023).

Introduction

Securing the long-term health of the ocean and achieving the potential benefits of a sustainable ocean economy will only be possible if atmospheric concentrations of greenhouse gases urgently begin to decline. The ocean offers a series of opportunities for reducing greenhouse gas emissions. It is a vital component of the global carbon cycle, and can be a significant part of the solution set in the fight against climate change.

1.1 Context

Covering over 70 percent of the Earth's surface, the ocean acts as a vast storehouse for both carbon dioxide (CO_2) and heat, playing a crucial part in shaping global climate patterns. Regrettably, human endeavours, such as burning fossil fuels, overfishing, disturbing the seafloor, and releasing various chemicals like fertilisers, sediments and pesticides are altering our planet. These activities have led to unprecedented acidification and warming of ocean waters, causing rapid and deep-seated changes throughout many aspects of the marine ecosystem.

…the ocean is increasingly seen as a potential solution to climate change.

The traditional narrative is that the ocean is a victim of climate change instead of being part of the solution. In many ways, however, the ocean is increasingly seen as a potential solution to climate change. Recognising this, the High Level Panel for a Sustainable Ocean Economy, comprising 17 world leaders, commissioned *The Ocean as a Solution to Climate Change: Five Opportunities for Action* in 2019 (the 2019 Report). This report presented a compelling case for the crucial role the ocean can play in mitigating climate change and provides a comprehensive roadmap for leveraging ocean-based solutions to combat the global climate crisis (Hoegh-Guldberg et al. 2019). It underscored the urgent need to prioritise the ocean in climate action and adopt transformative solutions that harness its mitigation potential. This report updates the previous report with a revised analysis of the initial five opportunities for ocean-based action, and covers additional sectors not included in the 2019 Report: offshore oil and gas and ocean-based tourism (Table 1).

Much has happened in the past years, not least of which includes the global pandemic, the war in Europe, and the intensifying and more frequent occurrences of extreme weather events. The pandemic created supply chain problems and pushed up prices through inflation so that things cost more now; e.g. offshore wind is now more expensive. The war has created market dislocations for fossil fuels and food products so that nations are leasing more offshore areas to access oil and gas in the future assuming we will still need these fuels, adding to a range of geopolitical challenges. And the environmental crises - heat waves, droughts, wild fires, floods, and rising sea levels - have increased energy usage, to say nothing of their devastating impact on lives and communities. Also, ocean warming, deoxygenation and acidification have negatively affected marine life, impacting fisheries and aquaculture as well as ocean flora that could act as part of the transition to more environmentally-friendly diets incorporating proportions of food from the ocean. In terms of positive developments, we have seen an almost doubling of national targets and pledges to increase offshore wind production, and most recently a more ambitious GHG strategy from the IMO to reduce emissions from international shipping.

The purpose of this updated report is to consider how this progress and associated challenges have changed the mitigation potential of ocean-based climate solutions. For each sector and ocean-based mitigation option, this update reflects progress to date, provides new data, and identifies both priorities and ongoing implementation challenges. It evaluates sectors as a key sink or source of CO_2 and explores both the mitigation potential and associated impacts (co-benefits and trade-offs). It recognises that the sectors are not completely independent of each other or of action on land. For example, marine transport is dependent on ports and connected to land transport.

Table 1. Seven ocean-based sectors and associated mitigation opportunities

OCEAN-BASED -SECTOR	MITIGATION OPTIONS	DESCRIPTION
Marine conservation and restoration	Restoration of coastal wetlands	Restoration of degraded coastal ecosystems towards natural state.
	Increased protection of coastal wetlands	Protection of coastal wetland systems, including mangroves, tidal marshes, seagrasses and seaweeds, aiming to avoid further degradation (and release of sequestered carbon) from these systems.
	Scaling up wild macroalgal protection and restoration	Protection of wild macroalgal habitats and related carbon sinks, and restoration of degraded macroalgal forests.
Ocean-based renewable energy	Scaling up offshore wind	Installing new fixed and floating offshore wind and solar farms.
	Scaling up other ocean energy	Installing new equipment to convert and harvest energy carried by ocean waves, tides, salinity and temperature differences.
Ocean-based transport	Reducing emissions from domestic shipping and marine transport	Reducing emissions from shipping between ports of the same country.
	Reducing emissions from international shipping	Reducing emissions from shipping between ports of different countries, including emissions associated with product tankers, chemical tankers, crude oil tankers, liquid natural gas carriers, liquid petroleum gas carriers, dry bulk, general cargo and open hatch, car carriers, roll-on/roll-off and roll-on/roll-off passenger. International shipping excludes military, fishing vessels, and cruise ships.
Ocean-based tourism	Reducing emissions associated with cruise tourism	Reducing emissions from a form of tourism where tourists are accommodated on and transported by ships.
Ocean-based food	Emissions reductions through rebuilding depleted wild stocks	Reduction in fuel use intensity to harvest fish and shellfish that results from rebuilding depleted stocks.
		Avoided emissions if the increased harvest achieved via rebuilding stocks is consumed in place of higher-emission land-based animal products.
	Reducing emissions from aquaculture	Improved feed conversion ratios (10% reduction in economic feed conversion ratios across all fed species).
		Complete avoidance of deforestation in the supply chains of feed ingredients from soy, palm, and other crops as well as in the feeds of poultry and livestock systems providing by-products.
		Shifting all energy inputs to farms are derived from electricity generated from renewable sources, rather than fossil fuels onsite or in electricity grids.
	Increasing share of ocean-based proteins in diets	Potential emissions avoided by behavioural shifts away from high-emission land-based proteins and towards lower-emission seafood systems.
Offshore oil and gas	Stopping the expansion of offshore oil and gas extraction along with a demand-led phase-down of current production	Potential emissions avoided via reduction in the production and consumption of offshore oil and gas.
Marine carbon dioxide removal and carbon capture and storage	CO_2 storage below the seabed	Storage of CO_2 below the seabed in geological formations.
	CO_2 removal approaches	Ocean alkalinity enhancement.
		Direct ocean removal.
		Ocean nutrient fertilisation.
		Seaweed cultivation and carbon sequestration (including both active sinking and passive sequestration associated with seaweed farming for harvest).

1.2 Global progress on ocean-based climate action

Since 2019, new initiatives have helped accelerate progress (Northrop et al. 2022). Updated Nationally Determined Contributions (NDCs) have set more ambitious targets. An analysis of 106 new and updated NDCs finds that 77 (73 percent) include at least one target, policy or measure aimed at ocean-based climate actions (Khan and Northrop 2022).

Governments and industry stakeholders have recognised the enormous potential of offshore wind farms to meet a significant share of the world's electricity needs while reducing reliance on fossil fuels. Notable pledges and initiatives have been launched since 2019 to bolster offshore wind capacity, including the North Sea Wind Power Hub, announced in 2021, which is a collaboration between European countries to develop a vast interconnected offshore wind farm. Moreover, several coastal nations have committed to ambitious domestic targets for offshore wind deployment since 2019, driving innovation in turbine technology, grid integration, and environmental impact assessments. These efforts reflect a strong commitment to harnessing the power of wind energy to achieve decarbonisation goals.

Marine and coastal conservation and restoration are expected to accelerate because of the targets agreed to under the Kunming-Montreal Global Biodiversity Framework in December 2022.

Shipping has also garnered growing attention. The IMO's revised and more ambitious GHG Reduction Strategy is now nearing the sector's maximum abatement potential (IMO 2023c). The Getting to Zero Coalition, launched in 2019, brings together over 160 stakeholders from across the maritime sector to facilitate the development and deployment of zero emission vessels. Over 200 zero emission pilot and demonstration projects are currently in the pipeline, an increase of almost 100 percent since 2019. The Pacific Blue Shipping Partnership aims to transition domestic maritime transport in the Pacific towards sustainable and low-carbon practices as well. Co-chaired by the Governments of Fiji and the Republic of the Marshall Islands and joined by five other Pacific Island nations, it seeks to reduce domestic emissions by 40 percent by 2030 and reach zero emissions by 2050. In October 2021 the UN Climate Change High Level Champions, UMAS, Getting to Zero Coalition and the Lloyd's Register published an action plan to reach zero emission fuels for 5 percent of international shipping and 15 percent of domestic shipping by 2030. This target would put the sector on track to decarbonise by 2050 and sets out the specific near-term actions and milestones around which businesses and governments can unite (Baresic and Palmer 2022).

The EU has developed a package of policy measures, national governments have stepped up support for research and development (R&D) in new technology, and frameworks (such as the *Poseidon Principles*) have been developed to monitor what the companies financing, insuring, and chartering ocean transport are doing to support decarbonisation. In November 2022, the Science-Based Target initiative's (SBTi) published guidance titled *Science-Based Target Setting for the Maritime Transport Sector*, designed for shipping companies that own and operate ocean-going vessels and for those setting targets for supply chain emissions from maritime trade. There has been less progress addressing climate change by shifting to foods harvested sustainably from the ocean. Initiatives are emerging at the company level to promote sustainable fishing and aquaculture practices. For example, the Norwegian fishing organisation, Fiskebåt, has pledged to reduce emissions from its fishing fleet by 40 percent by 2030, and Austral Fisheries, one of Australia's largest commercial fishing companies, promises to ultimately reach carbon neutrality across all operations. However, at the international level, this sector needs greater political attention and policy action to help it accelerate the achievement of its emissions reduction potential.

The role of global tourism and its potential to decarbonise has been brought into the spotlight by the Glasgow Declaration on Climate Action in Tourism. Signatories to the Declaration commit to act now and accelerate climate action to cut global tourism emissions by at least a half over the next decade and reach net zero emissions as soon as possible. Cruise companies have started coming forward with pledges to reduce emissions intensity, achieving net zero by 2050 (e.g., MSC Cruises) and advancing plans for zero emission ships (e.g. Royal Caribbean Group has promised to launch its first zero emission ship by 2040) (Northrop et al. 2022).

1.3 Ongoing challenges

Despite the significant attention that ocean-based climate solutions have received since the 2019 Report, and initiatives and pledges across all ocean-based sectors, the global climate crisis and the need for action are only growing more urgent and more unresolved.

The most recent Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR6) suggests that NDCs announced by October 2021 are unlikely to limit warming to 1.5°C during the 21st century and that even keeping warming below 2°C will be difficult. There is a significant gap between the emissions pathways of implemented policies and those from NDCs. Current financing falls far short of what is needed to meet climate goals across all sectors and regions.

The AR6 report indicates that the updated national pledges made after the 2021 United Nations Framework Convention on Climate Change Conference of Parties (COP 26, in Glasgow, UK), have not had a consequential impact on the projected emissions for 2030. Globally, governments are significantly deviating from the objective outlined in the Paris Agreement, which aims to restrict global warming to a level well below 2°C, preferably below 1.5°C. Current policies suggest a temperature increase of 2.8°C by the century's conclusion (UNEP 2022). However, if the existing pledges are implemented, this escalation would be reduced to a range of 2.4–2.6°C, depending on whether the pledges are conditional or unconditional. To follow a trajectory leading to a 1.5°C increase, emissions need to be cut 45 percent below what they are projected to be under existing policies. Even to reach a 2°C target, a 30 percent reduction is required.

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

This information shows that we are running out of time. Comparing the emissions reduction options laid out in the 2019 Report, with the ones available to us in 2023, brings this into stark relief. Some key actions that the 2019 Report identified as having the potential to cut emissions by 2030 have now dropped off that list. The lack of implementation, as well as investment in the necessary infrastructure, research and enabling environment means some of those opportunities have been lost, and emissions reduction potential today is much less than it was in 2019. The global pandemic has stalled domestic efforts to decarbonise maritime transport, scale offshore renewable energy and limit emissions from fisheries and aquaculture.

The present report emphasises that only an immediate and comprehensive transformation at a systemic level can achieve the substantial reductions required to curtail GHG emissions in line with the Paris Agreement by 2030. Its objective is to catalyse change by offering a pathway towards ambition and broadening opportunities for action that countries should consider as we rapidly move towards 2030 and 2050.

1.4 Methodology

This report follows the same methodology as the 2019 Report and is a bottom-up approach that does not holistically consider the global energy system. Each ocean-based climate solution is assessed in the context of its 2030 and 2050 annual 'mitigation potential' in line with the mitigation goals of average 1.5°C and 2.0°C pathways. This assessment is based on publicly available scientific and research literature, considering geophysical, technical, economic, and socio-political considerations that may affect feasibility. Based on this assessment, a conservative lower (minimum) and theoretical higher (maximum) range was estimated.

As in the 2019 Report, this report collates multiple analyses for each ocean-based sector. Underlying assumptions of these analyses may differ, and interactions amongst sectors are not explicitly considered. 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 greater detail in the relevant sections of the report. The following approach was applied to each ocean intervention area to ensure consistency and comparability:

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

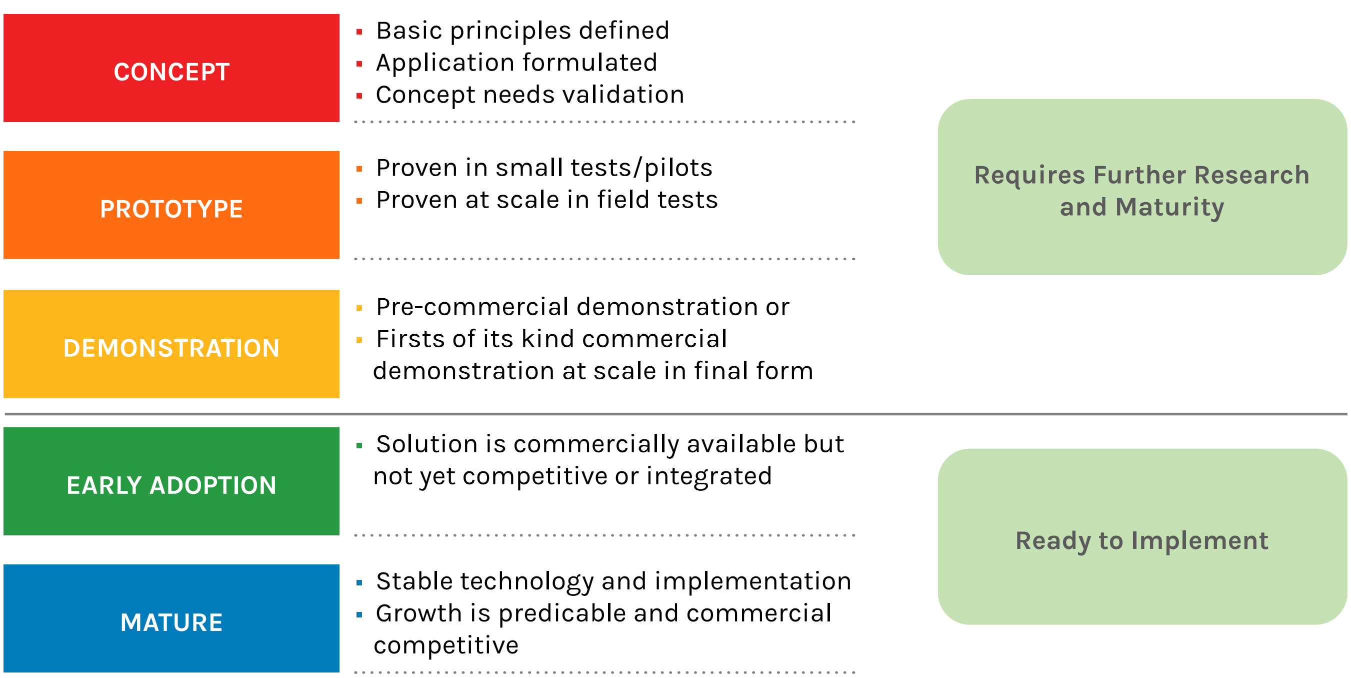
The UNEP Current Policy scenario (reflecting all adopted and implemented policies) (UNEP 2022) was used as the baseline to estimate the contribution made by the solutions identified to closing the emissions gap in 2030 and 2050 between Current Policy (UNEP 2022) emissions pathway and pathways consistent with achieving the 1.5°C and 2.0°C goals of the Paris Agreement (United Nations 2015; IPCC 2023).

A more detailed methodology for each sector is contained in Appendix A. Methodology, including assumptions, risks and limitations. These methodologies are important to consider in conjunction with the findings of each section. This report also explores the technology readiness of solutions (IMO 2022, 2023b; Odenweller et al. 2022). Our assessment suggests that the high rates of transition needed over the next decades are feasible. However, they are not likely without unprecedented levels of action, cooperation and collaboration. Development and deployment of the identified solutions will require rapidly scaling up of global supply chains, learning and sharing lessons on best practices to increase the speed of deployment, reduce costs and minimise technology incompatibilities and other problems.

Figure 1 is applied to the relevant technologies needed to implement the mitigation solutions quantified for each sector to present a consistent and uniform assessment of readiness, with the results summarised in Table 2.

This readiness framework should help guide prioritisation for implementing those approaches, which are ready to implement now as opposed to those that will require greater investment or carry more uncertainty in terms of viability (e.g. marine carbon dioxide removal). It can also serve as a basis to inform investment in research, piloting and capacity building to support the achievement of the mitigation potentials identified for each sector.

Figure 1. Technology readiness framework



Source: Authors, adapted from the technology readiness level scale applied by the IEA (2020).

Table 2. Readiness assessment of ocean-based solutions

OCEAN-BASED -SECTOR	TECHNOLOGY REQUIREMENTS TO IMPLEMENT OCEAN-BASED SOLUTIONS	READINESS ASSESSMENT
Marine conservation and restoration	Sequestration from restoration and protection of coastal wetlands (mangroves, tidal marshes, and seagrasses)	Mature
	Avoided anthropogenic degradation/impacts on coastal wetlands (mangroves, tidal marshes, and seagrasses)	Mature
	Sequestration and storage from protection and restoration of wild macroalgae (kelp forests and other seaweeds)	Prototype
Ocean-based renewable energy	Scaling offshore wind	Mature
	Scaling tidal barrage	Mature
	Floating solar	Early adoption
	Scaling ocean wave energy	Demonstration
	Scaling tidal stream energy	Demonstration
	Scaling energy capture of ocean temperature differences (thermal gradient)	Demonstration
	Scaling salinity gradient	Concept
Ocean-based transport	Reducing emissions from domestic shipping and marine transport through efficiency measures	Mature
	Reducing emissions from international shipping through energy efficiency measures	Mature
	Reducing emissions from international shipping through retrofitting to accommodate alternative lower-carbon fuels	Mature
	Zero emission vessels	Early adoption
Ocean-based tourism	Reducing emissions associated with cruise tourism	Early adoption

Table 2. Readiness assessment of ocean-based solutions (Continued)

OCEAN-BASED -SECTOR	TECHNOLOGY REQUIREMENTS TO IMPLEMENT OCEAN-BASED SOLUTIONS	READINESS ASSESSMENT
Ocean-based food	Reduction in fuel use intensity to harvest fish and shellfish that results from rebuilding depleted stocks	Early adoption/mature
	Avoided emissions if increased harvest achieved via rebuilding stocks is consumed in place of higher emissions land-based animal products	Early adoption/mature
	Improved feed conversion ratios	Early adoption/mature
	Avoidance of deforestation in the supply chains of feed ingredients from soy, palm and other crops as well as in the feeds of poultry and livestock systems providing by-products	Early adoption/mature
	Ensuring all energy inputs to farms are derived from electricity generated from renewable sources, rather than onsite fossil fuels or in electricity grids	Early adoption/mature
	Increasing share of ocean-based proteins in diets	Early adoption/mature
Offshore oil and gas	Stopping the expansion of offshore oil and gas extraction along with a demand-led phase down of current production	Mature
Marine carbon dioxide removal and carbon capture and storage	CO_2 storage below the seabed	Early adoption/mature
	Ocean nutrient fertilisation	Concept/prototype
	Ocean alkalinity enhancement	Concept/prototype
	Direct ocean removal	Concept/prototype
	Seaweed cultivation and carbon sequestration (including both active sinking and passive sequestration associated with seaweed farming for harvest)	Concept/prototype

Note: Current deployment of these sectors will be unavailable to bring the global climate back to equilibrium without major emission reductions. Farmed seaweed can also contribute to emissions reduction by substituting products with higher CO_2 footprint or being used as feed supplement to reduce ruminant CH_4 production (see 2.5 Ocean-based food).

Source: Authors, adapted from the technology readiness level scale applied by the IEA (2020).

Ocean-based solutions

Whilst ocean ecosystems are imperilled by climate change, ocean-based sectors offer opportunities for reducing greenhouse gas emissions. This report outlines a diverse suite of options for how ocean-based sectors can be a part of the solution set in the fight against climate change. The technological readiness of different solutions is investigated to differentiate those that are ready to implement from emerging solutions that require further research and impact assessment.

2.1 Marine conservation and restoration

Nature-based solutions to climate change have gained significant attention from academic, private and public sectors over the past decade. In the last three years, blue carbon, which refers to the carbon sequestered, stored or released from coastal and marine ecosystems, has become a focus of international policy. Countries are increasing integrating blue carbon actions into NDCs to the Paris Agreement for both mitigation and adaptation. Private sector organisations like the Blue Carbon Buyers Alliance are implementing global standards, financing blue carbon conservation and restoration, and developing ways to use carbon markets and advance high-quality blue carbon crediting projects to do this (Conservation International et al. 2022; Schindler Murray et al. 2023). This report updates projections related to the protection, conservation and restoration of nature-based solutions from the ocean and coastal ecosystems and informs agenda setting for conservation, climate policy, carbon finance mechanisms and action planning to limit global warming to 1.5°C above pre-industrial levels.

The main focus is on blue carbon ecosystems that qualify as actionable mitigation pathways. These must demonstrate evidence of long-term carbon storage. Actions to conserve them must also have the potential to influence atmospheric greenhouse gases (GHG) as well as deliver co-benefits and meet international standards (IUCN 2020; Conservation International et al. 2022). Mounting interest in blue carbon stems in part from the important role that restoring and conserving blue carbon ecosystems can play in reaching multiple SDGs such as supporting adaptation to climate change, increasing protection from storms and coastal erosion, providing food from the ocean, enhancing livelihoods and providing decent work, protecting biodiversity and improving water quality (Sasmito et al. 2023; Schindler Murray et al. 2023).

Currently, the IPCC only recognises the management of mangroves, tidal marshes, and seagrass as actionable blue carbon pathways (IPCC 2013b). But evidence is coalescing to demonstrate that managing other coastal ecosystems such as kelp forests and other wild macroalgae (seaweeds) may also have significant mitigation potential and could be integrated within blue carbon strategies where appropriate. Documentation of their storage potential and permanence is limited, so further research is needed before these solutions are considered mature and therefore ready to implement (Ross et al. 2023; Pessarrodona et al. 2023).

Mitigation potential

The present report estimates the potential mitigation provided by combined protection and restoration of mangroves, seagrass, and tidal marshes to be between 0.05 and 0.29 Gt CO_2e year^{-1} in 2050. This computation, detailed in Table 3, is higher in magnitude to recent estimates by Jankowska et al. (2022) (0.04–0.12 Gt CO_2e year^{-1}) because of methodological differences (differences in conservation and restoration scenarios, use IPCC tier one emission factors), but similar to global estimates of carbon sequestration (0.11–0.26 Gt CO_2 yr^{-1} (Lovelock and Reef 2020)) and estimates of the GHG sink for coastal vegetation and estuaries (0.39 Gt CO_2e yr^{-1}, Rosentreter et al. 2023). For the present report update, assessment of the mitigation potential for these ecosystems is bound by:

- scientific consensus that carbon accounting methods for an ecosystem are robust enough to allow global estimates to be made;
- the potential for anthropogenic activities to increase or decrease carbon stocks or rates of sequestration that deviate from a baseline scenario; and
- data gaps concerning the current and future management of ecosystems.

Where data gaps mean that ecosystems may not currently meet the first two criteria but there is confidence that these gaps will be filled within a short enough time frame to allow these ecosystems to play a role in meeting 2030 or 2050 mitigation targets, the relevant ecosystems have been included in mitigation estimates. Since 2019, knowledge of the global cover of seagrass and tidal marshes has improved (Unsworth et al. 2019; McKenzie et al. 2020; Murray et al. 2022), leading to lower estimates of emissions reduction here than estimated in 2019. Additionally, estimates for seaweed farming are now included in sections 2.5 Ocean-based food and 2.7 Marine carbon dioxide removal and carbon capture and storage.

Mitigation from conservation and restoration of marine ecosystems could be between 0.028 and 0.135 Gt CO_2e year^{-1} in 2030 and up to 0.313 Gt CO_2e year^{-1} in 2050. The largest component of this mitigation potential comes from mangrove conservation and restoration (0.037 and 0.172 Gt CO_2e year^{-1} in 2050 respectively for conservation and restoration). Mitigation associated with restoration will increase towards 2050 as carbon stored in woody biomass increases. Tidal marshes offer smaller maximum mitigation potential than other ecosystems, reflecting their lower global cover and current low rates of loss (Murray et al. 2022), but restoration potential could increase with further knowledge of historical losses and restoration opportunities. Restoration and conservation of seagrass and seaweeds could offer up to 0.043 and 0.044 Gt CO_2e year^{-1} respectively in 2050, although the range of potential mitigation is high, given high levels of uncertainty in global cover and potential area available for restoration of these ecosystems.

Table 3. Potential for different marine conservation and restoration opportunities to mitigate carbon emission, 2030 and 2050

OCEAN-BASED SECTOR	MITIGATION OPTIONS	DESCRIPTION	ECOSYSTEM	2030 MITIGATION POTENTIAL (GT CO_2E/YEAR)	2050 MITIGATION POTENTIAL (GT CO_2E/YEAR)
Marine conservation and restoration	Restoration of coastal ecosystems	Restoration of degraded coastal ecosystems towards natural state.	Mangroves Tidal marshes Seagrass Seaweeds (kelp)	0.004–0.026 0.001–0.002 0.001–0.004 0–0.022	0.028–0.172 0.004–0.015 0.007–0.025 0–0.018
	Increased protection of coastal ecosystems	Protection of coastal ecosystems systems to avoid further degradation (and release of sequestered carbon) from these systems.	Mangroves Tidal marshes Seagrass Seaweeds (kelp)	0.018–0.040 0.001–0.003 0.003–0.034 0–0.0044	0.009–0.037 0–0.002 0.003–0.034 0–0.0103
Total				0.028–0.135	0.05–0.313

Note: There are no available mitigation estimates for conservation and restoration of marine fauna. Mitigation for reducing disturbance to the seabed is estimated to vary between 0.04 and 0.124 Gt CO_2e year^{-1} (Sala et al. 2021; Jankowska et al. 2022; Atwood et al. 2023) and for conservation and restoration of tidal mudflats estimates range between 0.003 and 0.008 Gt CO_2e year^{-1}. These activities are not included in the total potential mitigation because they are emerging activities with a high degree of associated uncertainty. Further development of these emerging mitigation pathways may be regionally significant to mitigation.

Source: See Appendix A for sources of data used to estimate mitigation opportunities.

COASTAL WETLANDS (MANGROVES, TIDAL MARSHES, SEAGRASS MEADOWS)

Conservation and restoration of coastal wetlands remains the most readily actionable nature-based solution in marine and coastal environments. Although losses have slowed in recent years, losses in coastal wetlands continue (Goldberg et al. 2020; Murray et al. 2022), and restoration practices are becoming more effective and practical on a larger scale (Duarte et al. 2020). Since 2019, more is known about the complexity of carbon movement within these systems (Rosentreter et al. 2023). Recent research on mangroves indicates that sequestration and emissions vary widely across mangrove ecosystems, driven by local biological and environmental factors (e.g., energy of coastline, topography, and soil types), land use, and disturbance histories (Sasmito et al. 2020). Conservative estimates can account for this variability in mitigation potential, however local project-level data can improve estimates and models.

Additional advances in mapping the extent of coastal wetlands and rates of change are enhancing the ability to track emission mitigation benefits at a global and regional scale (e.g., Arifanti et al. 2022) and to draw connections between national and global trends related to policy initiatives (Hagger et al. 2022). Specifically, the present report uses updated coastal wetland extent, loss and gain estimates (e.g. Murray et al. 2022) and advanced models based on remote sensing of mangrove tidal marsh and tidal mudflat distribution), which have not previously been available (Table 4). In the period 1999–2019, 5,561 km^2 of mangroves and 1,064 km^2 of tidal marshes were lost, giving rise to estimated CO_2 emissions and forgone sequestration of approximately 0.7 Gt. Changes in mangrove and tidal marsh (and tidal mudflat) extent are caused by direct anthropogenic activities (e.g. conversion to alternative land uses) but also by coastal processes associated with variation in climatic and oceanographic conditions, including sea level rise and extreme events, that interact with anthropogenic activities (Goldberg et al. 2020; Murray et al. 2022). Further research may distinguish between ecosystem changes attributed to various factors driving it. Seagrass extent and loss rates (Table 4), which previously relied on conservative estimates from a limited number of sites, have been updated based on estimates of ecosystem cover (Unsworth et al. 2019; McKenzie et al. 2020) and change (Buelow et al. 2022), which provides a range of plausible estimates of change to determine conservative and optimistic mitigation benefits for seagrass management.

Previous estimates of mitigation potential were calculated by percent net change, multiplied by standard emission factors. However, net loss combines losses and gains. For example, loss of coastal vegetation causes high levels of emissions, while levels of carbon sequestered when ecosystems recover are comparably lower (Adame et al. 2021). This present report revises the global estimates of emissions and removals from mangrove and tidal marshes, with adjustments to account for both losses and gains. Although mapping of seagrass and carbon stocks and sequestration in seagrass meadows has improved (resulting in lower emissions reduction estimates) further research is needed to create global maps of change (like that available for mangroves), increase knowledge of regional variation in GHG emissions and removals, and IPCC guidance on changes in carbon stocks with seagrass management, including restoration activities.

Table 4. Ecosystem extent and percentage change of mangroves, tidal marshes and tidal mudflats

ECOSYSTEM	EXTENT (2019) IN 1000S KM²	ANNUAL % LOSS (HIGH AND LOW ESTIMATE)	ANNUAL % GAIN (HIGH AND LOW ESTIMATE)	ANNUAL % NET CHANGE (HIGH AND LOW)
Mangrove	135.6	-0.122 to -0.251	0.109 to 0.034	-0.137 to -0.217
Tidal marshes	90.8	-0.035 to -0.072	0.103 to 0.032	0.069 to -0.039
Seagrass	160.4–325.2	NA	NA	-0.5 to -0.1
Tidal mudflats	127.9	-0.164 to -0.337	0.424 to 0.133	0.26 to -0.204

Note: NA = data not available.

Sources: Ecosystem extent and percentage change of mangroves, tidal marshes and tidal mudflats are from Murray et al. (2022); seagrass extent is from McKenzie et al. (2020) and Unsworth et al. 2019; rates of change are from Buelow et al. (2022).

Restoration scenarios used for mangroves, tidal marshes, and seagrass range from a recovery of 1.5 to 9 percent of current ecosystem cover by 2030. By 2050, recovery may reach a maximum of 30 percent of the current ecosystem cover for mangroves, 20 percent for tidal marshes, and 35 percent for seagrass (40,700, 18,200 and 56,000 – 114,000 km² of mangrove, tidal marsh and seagrass, respectively) to achieve maximum mitigation potential of 0.212 Gt CO_2e. These restoration scenarios reflect different conversion types of these ecosystems, where some losses are considered reversible (restorable), but others are difficult to reverse. Restoration estimates reflect conversion of mangroves to urban or industrial land uses (Worthington and Spalding 2018) as well as from significant social barriers linked to land tenure and livelihoods, from biophysical impediments such as poor water quality, which limits seagrass restoration, from the challenges of implementing successful restoration, and from the length of time it takes for ecosystems to recover or develop (Lee et al. 2019; Lovelock et al. 2022). For mangroves, a restoration target of 40,700 km² represents approximately 30 percent of the estimated global extent of mangroves that have been removed, consistent with the Kunming-Montreal Global Biodiversity Framework targets. Improvements in knowledge of the extent and location of degraded ecosystems, restoration techniques, policies, incentives for investment, and transparent monitoring and reporting, as well as showing how local communities can benefit, could accelerate restoration and raise ambition (Duarte et al. 2020; Schindler Murray et al. 2023). Climate change poses risks to restoration projects that will consequently need further research. Reducing local human stressors (such as pollution) and planning for coastal wetlands that allows migrate landward will help (Duarte et al. 2020).

Additional research is needed to assess methane and nitrous oxide emission from baseline land uses and coastal wetlands in blue carbon accounting (Rosentreter et al. 2023). For example, tidal marshes can vary greatly in the amount of methane they emit, partly because of differences in inundation and salinity, which inhibits methanogenesis. Emissions from intact coastal wetlands, however, are lower than those from converted coastal wetlands (Iram et al. 2022; Rosentreter et al. 2023). Also, carbon dioxide sequestration, or drawdown processes, are highly site- and location-specific, depending on factors like tidal inundation, sediment characteristics (e.g. grain size, nutrients) and plant community type (Sasmito et al. 2020), and methane and nitrous oxide gas emissions counteract some of the carbon dioxide uptake (Rosentreter et al. 2023). A suite of spatiotemporal, biogeochemical, biotic, hydrological, climatic, and anthropogenic drivers of methane emissions need further investigation but will likely modify estimates of emissions and emissions reductions from coastal wetland restorations. The complexities of accounting for methane emissions adds uncertainty to calculating trade-offs and identifying climate mitigation opportunities.

Additional mitigation options requiring further researching and piloting.

MACROALGAE

Since the 2019 Report, progress has been made on quantifying the mitigation potential of macroalgae (seaweeds), their extent and how much carbon they can assimilate and bury, reducing uncertainties in their role in the global carbon budget. No ready-to-implement mitigation solutions are yet available for macroalgae. Nevertheless, this report provides a coarse theoretical estimate of the potential climate change mitigation benefit of restoring and reducing kelp forest losses (the most studied type of seaweed bed) based on updated estimates of the global area and productivity of kelp (Duarte et al. 2022b), trends in kelp extent over the past 50 years (Krumhansl et al. 2016) and C-sequestration estimates (Krause-Jensen and Duarte 2016). The potential mitigation of CO_2 emissions from seaweed aquaculture is presented in section 2.5 Ocean-based food, and other aspects are included in section 2.7 Marine carbon dioxide removal and carbon capture and storage.

Naturally occurring macroalgal habitats are the largest and most productive of the coastal vegetated habitats, comparable in area and productivity to the Amazon forests (Duarte et al. 2022b). Globally, they cover between 6.07 and 7.22 million square kilometres and have a net primary production of 1.32 Gt C per year (Duarte et al. 2022b). Trends in the net change of macroalgae are unclear on a global scale (Duarte et al. 2022b), but for kelp forests, average loss rates have been estimated at 1.8 percent per year (compared to 0.13 percent loss of mangroves) with major regional variability in direction and magnitude of trends (Krumhansl et al. 2016). Over the past 50 years, this translates to lost CO_2 sequestration of 0.513 Gt CO_2 corresponding to an average loss of 0.0103 Gt CO_2 year^{-1}.

Naturally occurring macroalgal habitats are the largest and most productive of the coastal vegetated habitats, comparable in area and productivity to the Amazon forests…

The Kunming-Montreal Global Biodiversity Framework is an outcome of COP 15 (2022). Under it, countries agreed to a number of targets to help protect biodiversity, including 30 percent of land and ocean by 2030. A restoration scenario following the targets of the Framework aiming to recover 30 percent of the lost kelp area by 2030, would yield a restored sequestration capacity of 0.154 Gt CO_2e plus avoided emissions of 0.031 Gt CO_2e from gradually decreasing losses. This adds up to a total contribution of 0.185 Gt CO_2e over this seven-year period (annual contribution from restoration: 0.022 Gt CO_2e year^{-1}, annual contribution from protection: 0.0044 Gt CO_2e year^{-1}). Continued recovery of kelps to their full extent over the 2030–50 period would contribute a sequestration of 0.359 Gt CO_2e, and avoided emissions over the same period would yield an additional 0.205 Gt CO_2e, for a total contribution of 0.565 Gt CO_2e over those 20 years (annual contribution from restoration: 0.018 Gt CO_2e year^{-1}, annual contribution from protection: 0.0103 Gt CO_2e year^{-1}). For comparison, the 2018–60 scenarios for combined gained mitigation and emissions reduction by macroalgal protection and restoration by Jankowska et al. (2022) range from 1.20 to 4.9 to 6.8 Gt CO_2e in low, plausible and ambitious management scenarios, respectively. The estimates by Jankowska et al. exceed those in this report, probably because they address macroalgae in general (rather than solely kelp forests) and cover a longer period, but also because they are based on different assumptions regarding the area targeted by management. Moreover, both sets of estimates address the protection of macroalgae in general and therefore overestimate the mitigation potential, as only avoided losses from anthropogenic causes are relevant for mitigation.

Since our 2019 Report, restoration techniques for kelp forests have improved (Eger et al. 2022) brightening prospects for kelp restoration’s potential in the future. However, most examples are small scale. Kelp forest areas can vary greatly from decade to decade, driven for instance by herbivore outbreaks. This makes it difficult to document long-term restoration success and implies that restoration efforts must be sustained over time. Moreover, to protect and restore macroalgal mitigation potential, management activities must consider both the macroalgal habitats themselves, and the habitats where macroalgal-fixed carbon is ultimately sequestered (e.g. marine sediments) (Jacquemont et al. 2022;

Jankowska et al. 2022), see also section ‘avoiding the disturbance of marine sediments’. There is only one example (from Japan) where a framework has been used to certify carbon accumulated by macroalgal restoration (Kuwae et al. 2022; Pessarrodona et al. 2023). Further development of certification frameworks is required in other regions to support the scaling up of restoration activities.

Multiple barriers must be overcome to include macroalgae within climate change mitigation schemes. These include uncertainty regarding the long-term fate of seaweed transported away from where it grew, the difficulty of tracing and documenting how management affects carbon sequestration by these highly dynamic and naturally variable ecosystems, and a need to develop new carbon verification schemes (Krause-Jensen et al. 2018; Hurd et al. 2022; Ross et al. 2023). These challenges apply to C-sequestration related to protecting and restoring macroalgal habitats and their sink sites as discussed above, and to the passive export of macroalgae from sustainable seaweed farming before harvesting the seaweed for multiple uses (Duarte et al. 2023). On top of this, initiatives to actively grow and then sink macroalgal carbon into the deep ocean as a climate mitigation approach are being developed; see section ‘2.7 Marine carbon dioxide removal and carbon capture and storage’. These activities face societal, ethical, ecological, and technological hurdles and lack appropriate policy and legal frameworks (Webb et al. 2021; Hurd et al. 2022; Ricart et al. 2022; Troell et al. 2023).

CONSERVATION AND RESTORATION OF MARINE FAUNA

The role of marine fauna, and particularly for the ocean’s largest ‘mega-fauna’ in mitigation has been the focus of recent research. For example, the motions of whales and large fish may help stir up and mix nutrients into the shallow, photic zones of the ocean, thereby stimulating production of phytoplankton and enhancing their ability to act as carbon sinks, absorbing carbon from the atmosphere, incorporating it into their bodies, and carrying it down to the depths of the ocean when they die (Mariani et al. 2020; Pearson et al. 2023). Additionally, large marine grazers of seagrass (e.g. dugongs and turtles) influence carbon stocks and accumulation in seagrass meadows by grazing biomass and disturbing sediments and taking part in complex food web interactions that affect kelp production and biomass. Although fauna and their activities are fundamental to the processes that are supporting a healthy ocean, management of fauna and characterisation of mitigation benefits remain uncertain (Malhi et al. 2022; Meynecke et al. 2023).

AVOIDING THE DISTURBANCE OF MARINE SEDIMENTS

Marine sediments were not discussed in the 2019 Report. Recent years have seen growing interest in offshore carbon pools and regulating bottom trawling to better manage sediment carbon. Marine sediment is estimated to contain over 2 million Gt of carbon in the top metre alone (Atwood et al. 2020). Emerging mitigation opportunities centre around the sediment carbon pool’s vulnerability to disturbances caused by trawling of shallow continental shelves, which can cause it to re-enter the atmosphere. Globally, trawling takes place over 1.3 percent of the ocean floor (Sala et al. 2021). Organic carbon in the sediment that is churned up as fishing gear runs over the seabed may be respired by organisms, releasing CO_2 into the environment. Estimates of global emissions from seabed trawling range between 0.04–1.5 Gt CO_2e year^{-1} (range dependent on the model used) (Sala et al. 2021; Atwood et al. 2023) and estimates provided by Jankowska et al. (2022) for this activity are lower (0.025–0.124 Gt CO_2e year^{-1} for protection). Indeed, assumptions on emissions from seabed sediment carbon have been challenged (Hiddink et al. 2023) and trawling intensity varies globally (Pitcher et al. 2022), which contributes to the uncertainty. Better management of marine sediments may be a viable blue carbon pathway. But uncertainty persists because of inadequate knowledge of the effects of sediment characteristics, seasonal changes, differences between trawling gear and frequency, and seabed species, as well as other local and regional factors that collectively influence mitigation potential (Atwood et al. 2020). Nevertheless, repeated damage to the ocean floor is likely to alter the distribution of carbon (Legge et al. 2020) and investigations of risks posed by seabed trawling and potential mitigation are underway in the United Kingdom and elsewhere (Epstein and Roberts 2022).

Current data are insufficient to include the management of trawling as a nature-based solution (Epstein et al. 2022). There is also no IPCC guidance for this carbon pool, or activities which may cross national jurisdictional boundaries. The impacts of reducing seabed trawling on fisheries production and food from the ocean should also be evaluated, however, as should be strategies for investing in building knowledge and improving management practices in areas of high sediment disturbance and high carbon stocks.

MANAGEMENT OF TIDAL MUDFLATS

The global extent of tidal flats is estimated to be 127,921 km^2, with the largest proportion (44 percent) found in Asia (Murray et al. 2019). Unlike vegetated coastal habitats, shallow unvegetated tidal flats largely trap carbon deposited from adjacent ecosystems. Sediment and organic material are delivered to them by rivers driven by wave and wind forces. Tidal flats were not discussed in the 2019 Report, but recent studies show that despite the large variation in sequestration estimates (1.35–5.4 $MgCO_2e\ ha^{-1}yr^{-1}$), their wide distribution means they may in fact be significant carbon sinks (Chen and Lee 2022). Tidal flats are also rapidly disappearing as a result of coastal development and sea level rise (Murray et al. 2019). There are, however, management strategies to protect or enhance their carbon storage benefits through restoration. Emerging mitigation opportunities being explored are often associated with other conservation efforts. For example, Korea is exploring the role of protection and restoration of tidal mudflats in mitigation, as well as for their role as migratory bird habitat (Lee et al. 2021). Uncertainty hovers around the question of whether tidal flat conservation and restoration is additional, as sediment carbon may be stored elsewhere in the marine environments (e.g. deep ocean). Strategically protecting and restoring tidal flats can meet multiple conservation targets, prevent further degradation, enhance coastal protection, and avoid greenhouse gas emissions, resulting in a suite of benefits which may include climate mitigation (Hill et al. 2021).

Wider impact analysis

Various marine conservation and restoration mitigation options can not only reduce GHG emissions but generate many economic, social, environmental and governance co-benefits (Schindler Murray et al. 2023). Overall, co-benefits outweigh trade-offs and risks, but the latter cannot be ignored. With concerted action, it is possible to manage negative societal impacts such as short-term reductions in fish catches which can affect employment, nutrition, food security, and well-being. Social protection mechanisms and systems for sharing benefits need to be put in place. Data-driven governance and incentive designs can accelerate positive actions and social acceptance.

Delivering on the potential: priorities for action

The proliferation of blue carbon projects over the last five years has yielded a wealth of information about a wide range of factors that can help and hinder the implementation (Table 5) (Schindler Murray et al. 2023). There have been large and small-scale projects, projects with and without private investment, undertaken in different countries with different ecosystems, and external market-based mechanisms (Schindler Murray et al. 2023). Large-scale projects have mainly been implemented in mangrove ecosystems, often with government support (e.g. Kenya, Indonesia, Pakistan), but also with support from the private sector (e.g. Apple Corporation and the Cispata project in Colombia) (Schindler Murray et al. 2023). The recognition of the importance of safeguards for communities embarking on conservation and restoration for climate change mitigation have led to the development of high-quality blue carbon principles and guidance (Conservation International et al. 2022). Some of the main lessons learned since 2019 include the need to:

- Prioritise leadership and partnership with local communities and recognise formal and informal land tenure arrangements (e.g. Madagascar, Indonesia) (Conservation International et al. 2022; Schindler Murray et al. 2023).

POTENTIAL BENEFITS	▪ Marine conservation and restoration provide multiple co-benefits—habitat gain, biodiversity, carbon sequestration, higher fishery productivity, improved water quality and income from tourism, provision of food, medicine, fuel, wood and cultural benefits (IPCC 2019). ▪ Improved protection, conservation, and restoration of terrestrial, freshwater, coastal and ocean ecosystems not only increase carbon uptake and storage but also help stimulate biodiversity and ecosystem services, reduce coastal erosion and flooding, and storm protection (IPCC 2019, 2023). ▪ Blue carbon market projects in mangroves have delivered positive economic and social benefits for communities, although concerns around equitable benefit sharing from carbon projects with local communities have emerged (Conservation International et al. 2022; Dencer-Brown et al. 2022; Schindler Murray et al. 2023). ▪ Tourism in natural ecosystems contributes to local economies (Spalding et al. 2023).
POTENTIAL IMPACTS OR RISKS TO MITIGATE	▪ Land requirements can be high for wetland restoration, so unless barriers (e.g. seawalls, levees, bunds) are removed or modified, landward expansion of ecosystems will be challenging (IPCC 2019). ▪ Marine protection can have short-term negative implications for ending poverty and reducing inequalities. 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) and mangrove and tidal marsh restoration may reduce aquaculture and agricultural production. These trade-offs may be avoided through stakeholder consultation and implementation in areas with low productivity. ▪ Data gaps create difficulty in understanding the likely impact of protecting and restoring coastal ecosystems along gender dimensions. Attainment of SDG 14 is inextricably related to SDG 5 on gender equality (Le Blanc et al. 2017; Prakash et al. 2022). ▪ Inequitable benefit sharing from carbon projects with local communities (Dencer-Brown et al. 2022). ▪ In mangrove restoration projects, women's participation is often limited by a lack of access to information about adaptation projects (Omukuti 2020). Marine protected areas (MPAs) tend to reinforce existing gender disparities because of gender differences in leadership and power (Roy et al. 2022). ▪ 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).

- Understand that governments in most nations have limited capacity to implement policies that support NbS mitigation and adaptation projects. Networks of nations (e.g. International Partnership for Blue Carbon) can aid in building capacity (Schindler Murray et al. 2023).
- Realise that IPCC's lack of guidance on emissions inventories for climate mitigation resulting from protecting or restoring seagrass, seaweed, tidal mudflats, and other ecosystems limits policy development and implementation by governments, industry, and communities, which also limits private sector investment. New IPCC inventory guidance is needed, and guidance for seagrass could be expanded to cover restoration and other activities (Luisetti et al. 2020).
- Sort out questions of land ownership. Marine and intertidal ecosystems are often 'owned' (managed) by governments, limiting participation by private landholders (Sasmito et al. 2023), including indigenous peoples, in ecosystem management. This may exacerbate degradation and impede restoration.

Private landholders need assurances to participate in restoration, including rights to carbon, access for fishing, and equitable taxation arrangements.

- Recognise that regulations for coastal developments could impede coastal wetland restoration (Shumway et al. 2021) and limit the ability to launch larger restoration projects. Improvements in regulatory and policy settings could incentivise restoration (Schindler Murray et al. 2023).
- Engage the private sector (and civil society) as key actors that can stimulate conservation and restoration of coastal wetlands for mitigation, adaptation, and other ecosystem services. Activities could include partnerships, investments, research, capacity building, innovative financing, adoption of best practice standards, certifications, and management of supply chains to support conservation and restoration of coastal ecosystems (Schindler Murray et al. 2023).
- Develop appropriate technologies that are accessible and low cost (e.g. software, satellites, drones, cameras) to support monitoring and evaluation of blue carbon ecosystems and their ecosystem service benefits (Macreadie et al. 2022).

Table 5. Short-, medium-, and long-term priorities/milestones to advance blue carbon

GOVERNMENT		
SHORT TERM (BY 2025)	**MEDIUM TERM (BY 2030)**	**LONG TERM (2030–50)**
Assess national blue carbon opportunities including area extent, ecosystem health, threats, carbon stores, ecological importance, and socioeconomic dependence of local communities.[a]	Support creation of new IPCC guidance for estimating mitigation and associated benefits from management of seaweeds/kelps and other emerging blue carbon ecosystems and management activities.	Implement economy-wide greenhouse gas accounting for ocean ecosystems.
Analyse legal and policy frameworks to include blue carbon in sustainable development, climate change, forestry, biodiversity and marine resource management regulations; also consider providing for an explicit mandate for government agencies to engage in blue carbon (project) development on state land.[a]	Include coastal ecosystems in national Greenhouse Gas Inventories, Nationally Determined Contributions and other national commitments to adaptation and biodiversity conservation.	
Create supportive communities of practice, including awareness campaigns to build the social license for protecting and restoring blue carbon ecosystems and increase the number of stakeholders actively engaged in efforts and projects.	Include nature-based solutions (NbS) in national carbon finance mechanisms.	
Enact regulation and policies to halt ecosystem losses and support active or passive restoration, particularly for ecosystems that often have low levels of protection, e.g. seagrass and macroalgae (regulation, incentives, land tenure, carbon rights, biodiversity enhancements). Align actions across different agencies.	Develop mechanisms to align reporting on mitigation with reporting for Sustainable Development Goals, Convection on Biological Diversity commitments and others.	
Designate marine protected areas (MPAs) to enhance conservation and maximise climate benefits as well as biodiversity benefits and be an integral part of marine spatial planning (MSP).	Global development and implementation of policies to support restoration of coastal and marine ecosystems (e.g. community mangrove forestry, family forestry, fishers' seaweed repair).	

Table 5. Short-, medium-, and long-term priorities/milestones to advance blue carbon (Continued)

GOVERNMENT		
SHORT TERM (BY 2025)	**MEDIUM TERM (BY 2030)**	**LONG TERM (2030–50)**
Improve IPCC guidance for seagrass to include management of offsite factors that influence water quality, such that projects that improve water quality are recognised for mitigation.		
Explore robust global or regional carbon pricing structures (through carbon taxes, social costs of carbon, fuel taxes, or removal of fossil fuel subsidies or at a minimum develop a robust value of blue carbon sequestration services).		
Recognise the wider ecosystem services and benefits for water quality, biodiversity, fisheries, coastal protection, and adaptation to develop appropriate financial and regulatory incentive tools. Thereby ensure holistic management of blue carbon ecosystems.		
Increase investments in R&D and citizen science programs to fill priority knowledge gaps.		
Use non-market-based approaches including community-based natural resource management and civil society cooperation aimed at the conservation of biodiversity (Target 19, CBD 2022).		
Enact and/or clarify policies that both blue carbon market or non-market projects must go hand-in-hand with emission reductions at source (Schindler Murray et al. 2023).[a]		
PRIVATE SECTOR		
SHORT TERM (BY 2025)	**MEDIUM TERM (BY 2030)**	**LONG TERM (2030–50)**
Set targets and/or pledges for ecosystem protection and restoration (as relevant to land ownership, operations or supply chains) (CBD 2022).	Increase capacity of community partners to implement NbS projects.	Develop a portfolio of NbS projects/investments that deliver mitigation, adaptation and other co-benefits contributing to mitigation and environmental, social and governance targets.
Increase investments in coastal and marine conservation projects, including capacity building (e.g. in project development, regulatory approvals, financial management, project implementation, R&D), including through impact funds and other instruments (Target 19, CBD 2022).	Support development of new methods for NbS projects within voluntary carbon markets.	
Partner with local communities to deliver all aspects of projects (including verification) (Target 19, CBD 2022).	Develop NbS certification for products and services based on mitigation and co-benefits.	
Implement International Union for Conservation of Nature NbS standard guidelines and the High Quality Blue Carbon Principles (Conservation International et al. 2022) for investments (e.g. equitable benefit sharing).	Education programs on benefits of blue carbon mitigation and products and services with certification.	

Table 5. Short-, medium-, and long-term priorities/milestones to advance blue carbon (Continued)

PRIVATE SECTOR		
SHORT TERM (BY 2025)	**MEDIUM TERM (BY 2030)**	**LONG TERM (2030–50)**
Increase commitment to sustainable business models to avoid trade-offs with social dimensions.	Develop and implement verification and reporting processes that are transparent and verifiable that contribute to communities.	
Examine supply chains and eliminate components that lead to degradation of coastal and marine ecosystems.		
RESEARCH COMMUNITY (INCLUDING TECH AND INNOVATION)		
SHORT TERM (BY 2025)	**MEDIUM TERM (BY 2030)**	**LONG TERM (2030–50)**
Develop robust, low-cost monitoring technologies (e.g. remote sensing) for monitoring success of blue carbon actions. Improve seagrass and seaweed restoration techniques for large-scale implementation.	Develop fine scale temporal and spatial models of mitigation for protection and restoration of coastal and marine ecosystems.	Real time sensing of coastal ecosystem extent and condition that underpin predictive models of impacts of management actions and climate on mitigation in coastal ecosystems.
Improve seagrass and seaweed restoration techniques for large scale implementation. Link management of offsite factors, e.g. improvement of catchment water quality, to restoration outcomes.	Increase knowledge on effects of bottom trawling on marine sediment carbon dynamics.	
Improve documentation of seaweed carbon fluxes and sequestration in relation to management action.	Enhanced knowledge of lateral carbon fluxes among ecosystems.	
Link management of offsite factors, e.g. improvement of water quality, to restoration outcomes.	Enhanced models of impacts of climate change on coastal and marine ecosystems and their mitigation potential over time.	
Increase accuracy and knowledge on spatial and temporal variability of estimates of mitigation by blue carbon ecosystems, including those associated with climate change.[b]	Map all blue carbon ecosystems globally.	
Identify new opportunities for blue carbon projects (develop frameworks to aid identification of sites for blue carbon projects and co-benefits for communities).	Enhanced knowledge of social impacts of NbS projects.	
Characterise co-benefits of NbS projects. Develop robust, standardised methods.	Clarify drivers of community attitudes to NbS projects by developing clearer communication about the risks and opportunities.	
Develop knowledge on wider impact both at project scale and economy-wide as well as at global scale to better inform policy and action.		
Collaborate with the government, private sector and communities to support projects and policy development.		

Sources:
A. Schindler Murray et al. 2023
B. Williamson and Gattuso 2022; Leiva-Dueñas et al. 2023

2.2 Ocean-based renewable energy

Ocean-based renewable energy includes a range of technologies that include offshore wind (OSW) energy, wave and tidal energy, floating solar photovoltaics, and thermal gradient (ocean thermal Energy Conversionec, OTEC), which generate energy from differences between cooler deep and warmer shallow or surface seawaters. Nascent salinity gradient, high-altitude wind, and biofuel renewable technologies are at very early stages and/or have more limited potential. Offshore wind is the most mature of the ocean-based renewables. Estimates of the technical potential of OSW energy range from 193,000 to 630,000 TWh/yr, at least twice the electricity needed to meet expected global demand of about 50,000 TWh (Bosch et al. 2018) to 90,000 TWh (IRENA 2023) by 2050.

Offshore wind reduces GHG emissions by replacing electricity generated by burning fossil fuel. Its mitigation potential depends on what the alternatives are. If ORE replaces conventional coal power plants, the mitigation is about 1.0 kg CO_2e/kWh, while if a current energy mix is replaced, the mitigation is about 0.46 kg CO_2e/kWh (Hoegh-Guldberg et al. 2019). The latter is assumed in this report.

Electric power from ocean-based renewable energy is mostly expected to go to the grid, but it can also be used off-grid, as can green hydrogen and ammonia production, to decarbonise hard to abate sectors such as heavy industry and long-distance transport. Ocean-based renewable power can also be converted to hydrogen to store energy when the weather makes it hard to generate wind or solar power. In some cases, ORE may also provide energy services directly, such as heating, cooling and desalinating seawater in combination with ocean thermal energy conversion.

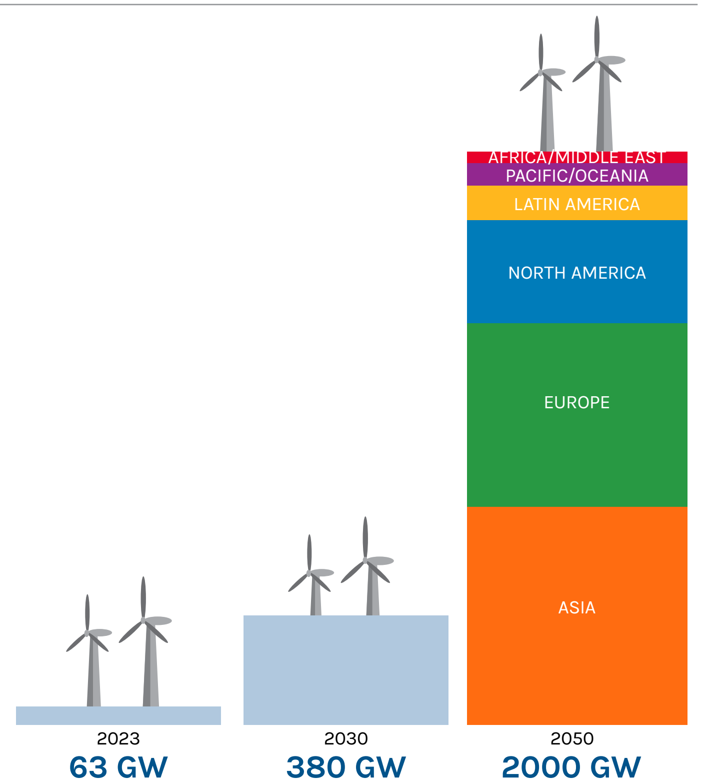
Since 2019 many countries have increased their ambitions for OSW. According to Bosch et al. (2018), about 70 percent of the global offshore wind resources are located at water depths greater than 60 metres. That is too deep for standard fixed-bottom turbines that must be deployed in shallow shelf waters. Tapping this resource requires floating wind turbines. Floating wind technologies are maturing rapidly into pre-commercial projects, removing constraints, and providing ample opportunity for growth in ambition.

The deployment rates for offshore wind energy in 2020, 2021 and 2022 were about 6, 21 and 9 GW/year, respectively (IEA 2021a; GWEC 2023). 2021 was a record year with a large number of offshore installations driven by special conditions in China (China ended an attractive support scheme that year).

By the end of 2022 a total of about 64 GW of offshore wind capacity was installed worldwide. To meet net zero goals in 2050, more than that needs to be installed every year. Between 2030 and 2050, the deployment rate needs to be 70–80 GW/year (IEA 2021a). This deployment rate would rival wind energy deployment onshore and offshore combined.

The Global Offshore Wind Alliance (GOWA) has set its sights on rapidly ramping up using offshore wind. Its 13 member countries want global offshore wind capacity to reach at least 380 GW by 2030 and aim to add a minimum of 70 GW each year from 2030 on. The largest contributions are expected to come from Asia, Europe and North America (Figure 2). These pledges for 2030 exceed what was projected in the 2019 Report (Hoegh-Guldberg et al. 2019). But implementation does not always follow stated political ambitions, and the current pace of OSW installations is too slow to reach the target of 2,000 GW of offshore wind that the IEA and IRENA set to reach carbon neutrality by 2050 (IRENA 2023).

Figure 2. Global Offshore Wind Alliance targets for 2030 and 2050



Source: Authors.

Costs for offshore wind have plummeted in recent decades. The global weighted average levelised cost of electricity (LCOE) of offshore wind declined by 60 percent between 2010 and 2021, from $0.188/kWh to $0.075/kWh. It dropped 13 percent in 2021 alone (IRENA 2022). However, during the last two years costs have increased by 38 percent (Ferris 2023). Russia's war in Ukraine has disrupted supply chains, stoked political divisions between trading partners, and thereby driven up the costs for materials for OSW (Vestas 2022). Both Europe and the US are facing the risk of supply chain shortfalls, and these could be worsened by policies aimed at reshoring manufacturing away from China and protecting local industry and jobs (GWEC 2023). Slow permitting, rising costs for raw materials and logistics, dependence on imports of raw materials, growing demand for larger turbines, and competition from China are causing shortages and bottlenecks. Energy markets have been rewarding fossil fuel companies with record profits, while renewable energy companies struggle (Janipour 2023). China has been insulated from some of these problems because of its over-supply of steel, domestic supply of rare earth minerals, and the fact that its supply chains are less vulnerable to the turmoil that has caused shortages and driven up prices of OSW elsewhere (Waite 2022).

For the other offshore renewable power generation technologies, relatively little has changed since the 2019 Report (Hoegh-Guldberg et al. 2019). Installed capacity has not surged (IEA and OES 2023). For wave energy and tidal stream, some research and development activities are ongoing, but the technologies have not converged on solutions suited for installation at industrial scale. Thus, we cannot expect these technologies to make significant contributions to global electrical energy production by 2030. If a technological breakthrough is made, some contribution may come by 2050. A newer technology that has shown promise is floating solar energy systems. Such systems are presently installed in lakes and in calm ocean areas with the development of these systems to more turbulent open ocean areas still to come. Our expectations for offshore generating technologies other than offshore wind are conservative, because of the nascent stage and multiple uncertainties surrounding these technologies.

Mitigation potential

The world's electrical energy production is expected to more than double from 2020 to 2050. The mitigation estimates associated with ORE are higher than stated in the 2019 Report (Table 6) (Hoegh-Guldberg et al. 2019). The estimates are uncertain and depend on what replaces traditional fossil fuels in, for example, the transport sector. The switch to renewable energy in the transport sector depends upon available and affordable electricity (Lindstad et al. 2023). Most of the ocean-based electrical energy production is expected to come from wind and solar energy. By 2031, offshore wind is anticipated to account for approximately 30 percent of global wind installations (up from 21 percent in 2021) (GWEC 2023).

The mitigation potential for ORE calculated in this report is between 3.25–4.47 Gt CO_2e/year in 2050. These numbers assume that what ORE is replacing or 'displacing' is the current global power generation mix, with emissions of 0.46 kg CO_2e/kWh (see Appendix A. Methodology for the full methodology). To complement

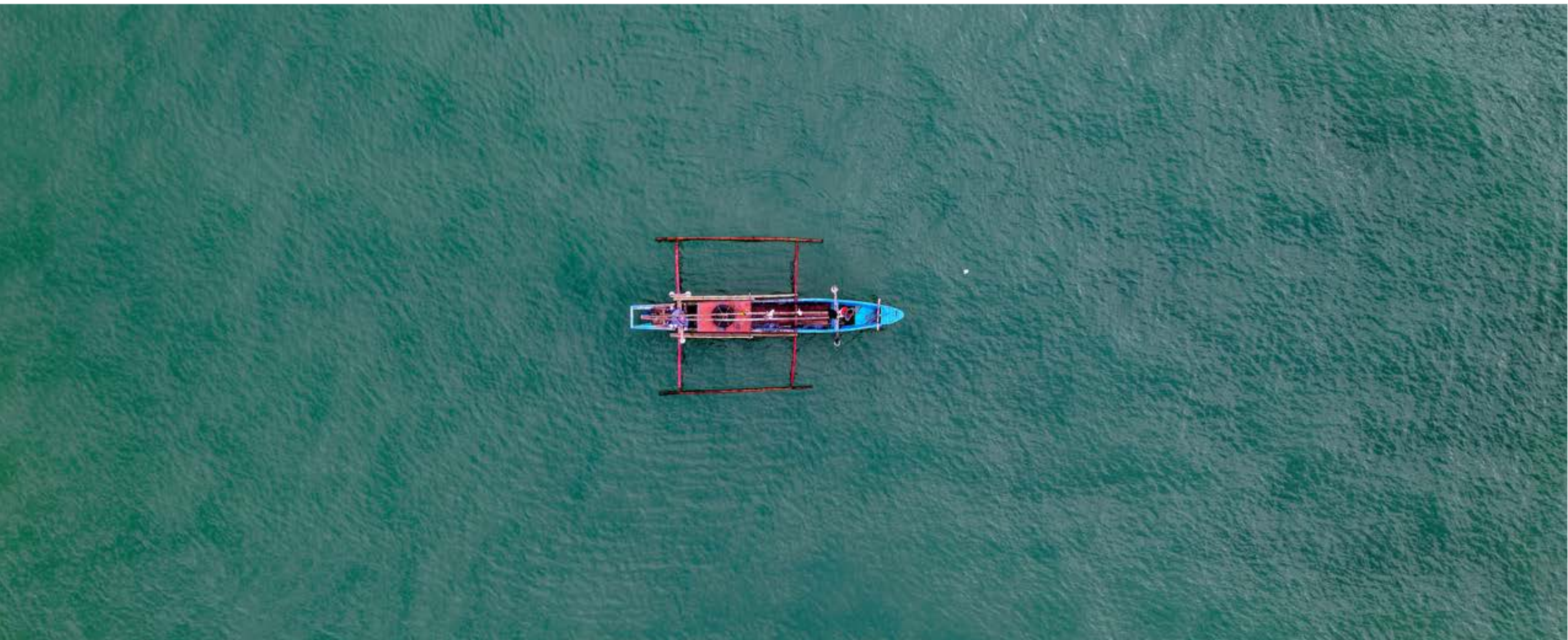


Table 6. Potential to mitigate carbon emission, by 2030 and 2050

OCEAN-BASED SECTOR	MITIGATION OPTIONS	DESCRIPTION	2030 INSTALLED CAPACITY (GW)	2030 MITIGATION POTENTIAL (GT CO_2E/YEAR)	2030 INSTALLED CAPACITY (GW)	2050 MITIGATION POTENTIAL (GT CO_2E/YEAR)
Ocean-based renewable energy	Scaling up offshore wind and solar	Installing new fixed and floating offshore wind and solar farms.	380	0.60–0.69	2000	3.20–3.60
	Scaling up ocean energy**	Installing new equipment to convert and harvest energy carried by ocean waves, tides, salinity, and temperature differences.	-	0.003–0.007	-	0.05–0.87
Total				0.603–0.697		3.25–4.47

Notes:
Assumptions:
Capacity factor for offshore wind (OSW) ~50%
OSW life cycle assessment (LCA) emissions 0.026-0.079 kg CO_2e/kW
Global current energy mix emissions 0.46 kg CO_2e/kWh (Hoegh-Guldberg et al. 2019)
Regional energy mix emissions taken from https://app.electricitymaps.com/map
Global and Regional OSW targets taken from 2021 UN OSW compact, https://www.un.org/sites/un2.un.org/files/2021/09/irena_and_gwec_offshore_wind_energy_compact_-_final_1.pdf
Mitigation potential for ocean energy remains the same as in the 2019 Report.

Source: Authors.

this global analysis, Table 7 presents the regional distribution of mitigation potential based on regional energy mixes and distributions of CO_2 intensity and regional ambitions for ORE deployment. The mitigation potential calculated from global averages is close to the sum of regional mitigation potentials, supporting the global analysis.

Over the last four years, in most countries, ambitions and plans for deploying OSW have gained momentum (Bouckaert et al. 2021). The IEA indicates that 2,000 GW offshore wind power should be installed by 2050. Achieving this capacity, the total mitigation from OSW alone in 2050 will amount to 3.2–3.6 Gt CO_2e/year if replacing the current mix of energy generation. This is equivalent to removing approximately 8,000 gas-fired power plants from the energy grid (EPA 2023), and about 8.2 percent of the global mitigation needed to close the gap to a 1.5°C scenario by 2050 (UNEP 2022).

Uncertainties surround other types of ORE because technologies have not converged, making it difficult to gauge their mitigation potential. Also, geophysical potential variations widely by location. The status of the ORE technologies are summarised as follows:

Wave energy: Installed capacity by 2020 was about 0.0023 GW (IRENA 2021). At optimal sites, the yearly average power potential in waves is in the range of 30–70 kW per metre of average wave height (Atan et al. 2018). The most favourable sites for deploying wave energy devices are generally along western coasts at latitudes between 40–60 degrees north and south, where waves are most powerful (Rusu and Rusu 2021). A site with potential for 50 kW generation per metre wave height, and a conversion efficiency of 30 percent, will thus require a coastal length of 7.6 km to produce 1 TWh per year (enough to fully power about 70,000 homes).

Tidal stream: Installed capacity by 2020 was about 0.01 GW (IRENA 2021). Tidal stream energy can be utilised where the stream velocity is high, typically in narrow straits in areas with a large tidal range. This implies that tidal stream energy has a limited potential as a share of global energy supply. A big advantage of tidal energy, however, is predictability.

Table 7. Regional mitigation potentials in 2050, current energy mix displacement

SCENARIO FOR EMISSIONS MITIGATION POTENTIAL OF OFFSHORE WIND	2050 INSTALLED CAPACITY (GW)	MITIGATION POTENTIAL AT 2050 (GT CO_2E $YEAR^{-1}$)
Asia	760	1.5–1.7
Europe	640	0.55–0.70
North America	360	0.49–0.57
Latin America	120	0.12–0.14
Pacific/Oceania	80	0.16–0.18
Africa/Middle East	40	0.10–0.11
Regional total	2,000	2.92–3.9

Tidal barrages are like dams built across tidal rivers, bays and estuaries to create tidal basins. Turbines inside these barrages turn when tides flow in and when they flow out, generating electricity in both directions. Installed capacity by 2020 was about 0.522 GW (IRENA 2021). Tidal barrages can be constructed where the tidal range is large, ideally with at least a 10 metres vertical difference between high and low tide levels. These are feasible only in limited locations and are often installed together with other coastal infrastructure such as roads or breakwaters. Like tidal streams, barrages offer the benefit of predictability.

Thermal gradient: This technology utilises the difference in temperature between the ocean surface and deep waters to generate electricity. OTEC systems use a temperature difference of at least 20°C to power a turbine and produce electricity. Warm surface waters are pumped through an evaporator containing a working fluid. The vapourised fluid is used to drive a turbine/generator and is turned back to a liquid in a condenser that is cooled with cold water pumped from deeper in the ocean (EIA 2022). The technology is feasible in tropical areas where the ocean surface temperature is high. The efficiency of these systems in converting thermal energy to electricity is low. Only experimental systems are in operation (IRENA 2021). The theoretical potential of ocean thermal systems is large though, and in principle could deliver a steady power supply.

Salinity gradient: This technology utilises a difference in salinity levels, for instance, between the ocean and in less saline rivers that flow into it, generating electricity. Two main technology types, reverse electrodialysis (RED) and pressure-retarded osmosis (PRO) make use of semi-permeable membranes which generate an osmotic potential between seawater and freshwater that can be used to generate electricity using turbines (Tethys n.d.). Salinity gradient technologies are at an experimental stage and must solve the requirement for large amounts of freshwater among other challenges.

Floating solar: Floating solar power plants are now being deployed in sheltered waters, that is, lakes and reservoirs. The difficulty with floating solar panels on the ocean is the roughness of the waves, which can damage solar panels. New research is being conducted to develop methods for keeping solar panels operative in the high seas. Plans for deploying such systems in the ocean exist but have not yet been implemented. Floating solar power has considerable technical potential in areas of high solar flux coupled with calm conditions. The technology readiness level (TRL) for the ORE technologies is summarised in Table 8.

Table 8. Technology readiness level for offshore renewable energy technologies

TECHNOLOGY	APPROXIMATELY GLOBALLY INSTALLED POWER (MW)	READINESS LEVEL	COMMENT
Offshore wind	64,000	Mature	Bottom fixed systems are mature and in a commercial phase. Floating systems are presently under installation at commercial scale.
Wave energy	2.3	Demonstration	Full scale prototypes. Several technologies. Precommercial.
Tidal stream	10	Demonstration	Pilot projects, demonstration phase.
Tidal barrage	522	Mature	A few systems in commercial operation (note that a number of these have been in operation for over 50 years).
Thermal gradient	0.23	Demonstration	Small systems tested at sea (Japan and Hawaii).
Salinity gradient	0.05	Concept	Tested at laboratory scale.
Floating solar	2,600	Early adoption	Commercial scale in sheltered lakes, experimental systems in the ocean. Plans for commercial deployments.

Source: Authors, adapted from Soukissian et al. (2023).

The readiness level of the various technologies suggests that only offshore wind and floating solar systems are poised to make significant contributions to global power generation by 2030, possibly joined by wave energy by 2050. Tidal energy may be important at certain locations.

The geophysical resources for ORE far exceed the estimated need for electrical energy by 2050. The limitations are related to technology, availability and costs. IRENA (2021) has summarised estimates on the resource potential for various ocean energies. The resource estimate for offshore wind has risen sharply as floating offshore wind turbines now are considered feasible at commercial scales.

Wider impact analysis

The possible negative environmental impacts of large-scale deployment of offshore energy generation facilities need to be understood. Large ocean areas are required. A 1 GW offshore wind farm requires an ocean area in the range 100 to 500 km^2. The distance between the turbines may span 1.5 to 3 km (European Maritime Spatial Planning Platform 2023). For bottom-fixed wind turbines, the foundations take up just a tenth of a percent of the wind farm area. Concerns have been raised over whether and how vibrational noise from the turbines could affect sea life, by interfering with sonic communication used by several species. Electromagnetic fields from the power cables have raised concern as well. Threats to birds makes understanding bird migration routes essential in siting wind farms. But these farms could possibly benefit sea life as well, by expanding areas free of bottom trawling and creating artificial reefs. The large ocean areas needed for ORE by 2050 also call for combining them with other uses. These areas could possibly be used for seaweed or fish farming or installing technology to harness wave power.

The need for OSW and other ocean-based renewable energy development is increasing the importance of marine spatial planning in reducing growing risks to marine life, benthic habitats, sea and migratory birds and other environmental impacts. Generating advanced national-level data can lay the groundwork and create the necessary enabling conditions. Data will be needed to examine this technology's potential wider impact and design incentives, manage regulations, build capacity and foster international collaboration.

POTENTIAL BENEFITS	▪ Expansion of ocean energy for job creation, economic growth and additional investment benefits the energy sector whilst enhancing energy security source diversity. Increasing the capacity using fossil fuels can be avoided and existing production phased out, with several positive impacts, such as on saving freshwater use in the fossil fuel sector. ▪ Co-development of offshore renewables with algae growing farms, offshore aquaculture farms and coastal municipal water supply through desalinisation provide cross-sector adaptation benefits (Hoegh-Guldberg et al. 2019); combinations of ocean-based renewables technologies can provide affordable solutions (Wang et al. 2022). ▪ Opportunities for innovation are expanding through pilot projects in developing country contexts also. For example, implementation of Searaser-based mini hydroelectric power plant (MHPP) technology on St. Martin's Island, Bangladesh proved to be profitable and eco-friendly through replacement of the existing stand-alone diesel generators (Shahriar et al. 2019). ▪ Expansion of ocean-based renewable energy that replaces fossil fuels reduces local pollution, improves health outcomes, reduces emissions and enhances tourism potential (Hoegh-Guldberg et al. 2019; Shahriar et al. 2019; Lathwal et al. 2021; *The Economist* 2023). ▪ Emerging ocean sectors have an opportunity to advance social equity and environmental sustainability if equity guidelines are prioritised and mandated so that business-as-usual practices do not become entrenched (Cisneros-Montemayor et al. 2022). ▪ The business case for Australia's first offshore wind farm, Star of the South, is heavily based on the closure of coal-generated power in the same region. Offshore wind provides a source of generation that can utilise the existing grid network that radiates from the previous power station.
POTENTIAL IMPACTS OR RISKS TO MITIGATE	▪ The rapidly expanding ocean energy sector is to date highly concentrated in a few regions, serving grids in urbanised areas, and economic benefit-sharing mechanisms with local residents are uncommon. There are examples of how local communities can be better included in planning and implementation, including negotiating subsequent economic benefits (Cisneros-Montemayor et al. 2022). ▪ Transitioning to ORE will incur high capital costs at the initial stage, which may hamper deployment rate. Eventually, it will lead to a cost-effective generation, transmission, environmental improvement, and stable energy supply to match demand when compared with the conventional mode of generation in West Africa (Adesanya et al. 2021). ▪ Noise from operating marine energy devices is most likely to affect marine animals near the spreading source. There is also some evidence that planktonic larvae of crustaceans may be affected by underwater noise. Pelagic animals, including marine mammals, fish, diving seabirds, and sea turtles who may swim close to or even aggregate around devices, are most likely to be affected (Hemery et al. 2021; IEA and OES 2023).

Delivering on the potential: Priorities for action

Achieving pledges for the deployment of ocean-based renewable energy will require timely and collaborative actions from government, private and research sectors. Near-term priorities for government include utilising marine spatial planning to minimise conflict with other ocean sectors; providing a stable economic and regulatory framework to promote investment; accelerating and improving site and permitting processes, with a focus on transparency; working to remove cross-border regulatory issues, for example, grid connections and public and private ownership; and capacity building to upskill the workforce. Priorities for the private sector include examining and refining supply chains and identifying alternative materials to avoid constraints; and establishing targets for biodiversity protection and restoration to limit the impacts of ocean-based renewable energy deployment and operation. Priorities for research include developing technology to reduce cost and dependency on critical materials, exploring the potential to co-locate offshore renewable energy generation with other ocean sectors; and developing large-scale floating solar installations (see Table 9 for additional details).

Table 9. Short -, medium-, and long-term priorities to advance research and development of ocean-based renewable energy

SECTOR: GOVERNMENT		
SHORT TERM (BY 2025)	**MEDIUM TERM (BY 2030)**	**LONG TERM (2030–50)**
Utilise area-based management frameworks and marine spatial planning, including Sustainable Ocean Plans, to guide development and minimise conflict between ocean users.	Make ocean areas available/minimise conflicts.	A transformed energy/power system that is decarbonised, reliable, and affordable and exploits techni-cal and societal implications.
Provide a stable economic and regulatory framework to stimulate investments in required infrastructure for an accelerated deployment of ocean-based energy systems.	Identify opportunities through inclusive policy development of combined use of ocean areas.	
Accelerate and improve site and permitting processes, including transparency and clarity.	Develop strategic national roadmaps and implementation action plans for zero carbon economy in 2050.	
Introduce efficient and foreseeable (stable) support schemes.		
Resolve cross-border regulatory issues for grid connections, public and private ownership.		
Offer education and capacity building to create a skilled workforce and capacities for manufacturing repair, and installation.		

Table 9. Short -, medium-, and long-term priorities to advance research and development of ocean-based renewable energy (Continued)

SECTOR: PRIVATE SECTOR		
SHORT TERM (BY 2025)	MEDIUM TERM (BY 2030)	LONG TERM (2030–50)
Identify where to build supply chains.	Incorporate alternative materials to avoid constraints, reduce costs and expand access to technology and deployment across all regions.	Implement solutions for multi-use of ocean areas such as combined energy and food production.
Construct major supply chain facilities.	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.	
Identify alternative materials and material resources to avoid constraints and reduce costs.		
Develop concepts for technologies, deployment and supply chain efficiencies to reduce costs.		
Establish targets and/or pledges related to biodiversity protection and restoration associated with ocean-based renewable energy deployment and operation.		
SECTOR: RESEARCH COMMUNITY (INCLUDING TECH AND INNOVATION)		
SHORT TERM (BY 2025)	MEDIUM TERM (BY 2030)	LONG TERM (2030–50)
Increase research on impacts of large-scale offshore wind.	Follow up installation of OSW to identify impacts and take action if needed.	Design the future decarbonised energy/power system which can provide energy reliability with reasonable energy costs (spanning economic, social and environmental factors), accommodate large fraction of intermittent power and be resilient in the face of a 2050 climate.
Develop technology components that reduce cost and dependency on critical materials.	Develop alternatives to critical materials.	
Understand the potential benefits of co-location with other ocean-based industries (e.g., desalination plants and aquaculture).	Scale research on impacts of large-scale ocean energy (prioritise based on readiness assessment).	
Explore the potential for installing large-scale floating solar installations at sea (under wave conditions).	Develop alternatives to critical materials.	
	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.	
	Quantify the potential of Ocean Thermal Energy Conversion (OTEC).	

2.3 Ocean-based transport

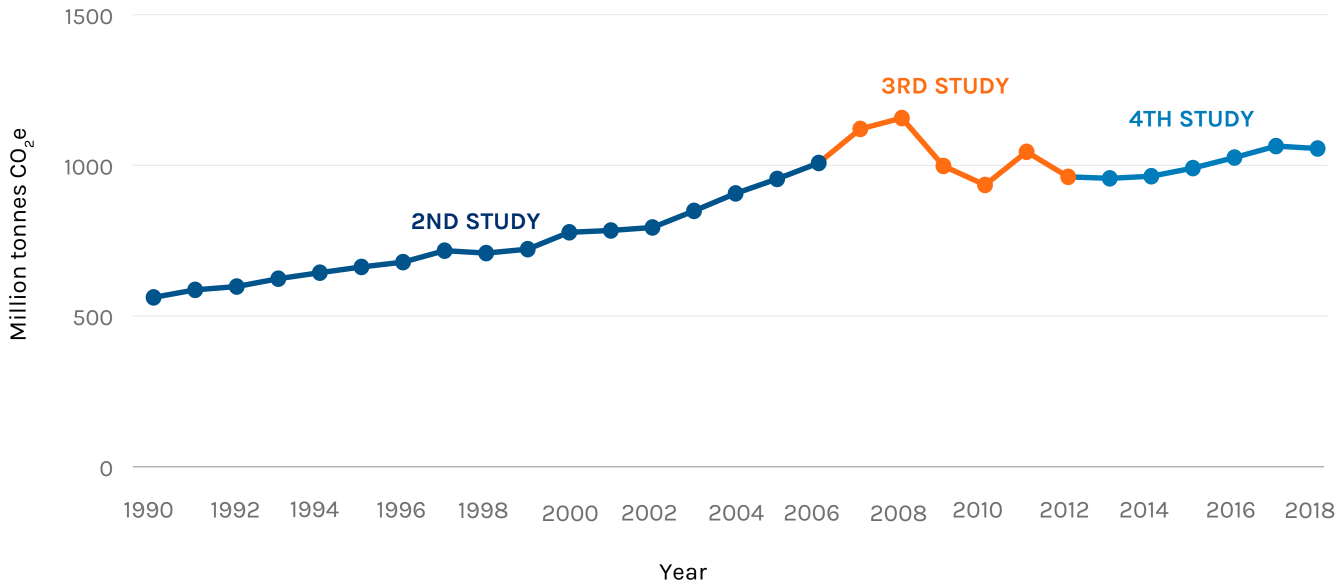
Significant progress has been made towards ocean-based transport's GHG mitigation since 2019, greatly enhancing the likelihood that this sector achieves the upper bound 2050 mitigation potential. In 2023, the IMO agreed to ratchet up the targets adopted in 2018 (40 percent carbon intensity in 2030) to 20 percent, striving for 30 percent absolute reduction by 2030, equivalent to approximately 55–60 percent GHG intensity reduction. The IMO has also moved from framing mitigation on CO_2 to the more comprehensive 'well-to-wake framing' which will increase the investment case for renewable energy. The IMO has also committed both to revising and improving its short-term measures and developing two new GHG policy measures (a GHG price and a GHG fuel standard applied to international shipping) by 2025. In regional regulatory developments, the EU has now included both international and domestic shipping into its Emission Trading Scheme. It has also implemented a fuel standard for shipping, including minimum volume requirements of fuels produced from renewable electricity. At the same time, the US has made a subsidy regime (through the Inflation Reduction Act) which has the potential to subsidise and support shipping's use of renewable fuels.

The timescales to 2030 and 2050 remain very short in practice, so whilst regulatory developments are now appearing, their conversion into final investment decisions aligned with the energy transition lag behind these policy developments. The poor energy efficiency in the global fleet remains an untapped opportunity for mitigation, primarily because the IMO's GHG mitigation policy, designed to the earlier and lower 2018 mitigation ambitions, is weak.

Ships carry about 80 percent of the volume and about 60 percent of the value of goods traded worldwide between nations.[6] Seaborne trade has grown at about 3 percent year-on-year for the last decades, roughly proportional to growth of global GDP, and this is expected to continue.[7] Container shipping has replaced some general cargo ships and, to an even larger degree, containers have replaced specialised refrigerated hold ('reefer') vessels. Fossil fuel products such as crude oil, refined oil products and coal currently make up nearly 40 percent of global sea-borne trade, so decarbonisation of the world economy will have profound implications for shipping. Some types of cargo will disappear, while others such as hydrogen, ammonia, methanol, biomass and biofuels are likely to grow. Carbon capture and storage may make CO_2 a commodity in need of transportation from industrial hubs to geological reservoirs.

The main source of ships' GHG emissions is exhaust gas from their internal combustion engines (ICE), estimated to be around 1 billion tonnes of CO_2e annually (Buhaug et al. 2009; Smith et al. 2015; Faber et al. 2020). Such estimates cover what happens on the ship only (Schuller et al. 2019); i.e. the tank-to-wake (TTW) emissions. When including the well-to-tank (WTT) emissions from producing the fuels (Lindstad et al. 2021), the total well-to-wake (WTW) emissions add up to 1.25–1.5 billion tonnes of CO_2e; equal to around 3 percent of the 50 billion tons of anthropogenic GHG emitted annually (BP 2021).

Figure 3. Total shipping emissions, 1990–2018



Source: The 1990–2007 figures are based on the second IMO GHG study (Buhaug et al. 2009), the 2007–12 figures are based on the third IMO GHG study (Smith et al. 2015), and the 2012–18 figures are based on the fourth IMO GHG study (Faber et al. 2020).

Figure 3 shows how total TTW CO_2 emissions from ocean-based transport have increased from 1990 to 2018.

Historically, global shipping emissions peaked in 2008, dipped in the following years because of the 2007–08 financial crisis, and have been growing slowly from 2013–14 onwards. For a range of plausible long-term economic and energy scenarios (based on IPCC's Shared Socioeconomic Pathways, SSPs), which assume no further policy action to reduce GHG emissions, the projections for 2050 emissions are between 90 percent to 130 percent of 2008 emission levels (Faber et al. 2020).

Since 2019, new data in the fourth IMO GHG study (Faber et al. 2020) has lowered projections for the growth of trade. These revise down a key driver of energy demand and emissions for shipping and could make GHG reduction objectives easier to reach. Major progress has been made in identifying transition pathways for the sector. Multiple studies have identified ammonia and methanol as the most likely successors to hydrocarbon molecules, leading to trials and pilot projects (Gielen et al. 2022; Rouwenhorst et al. 2022) and nations collaborating to de-risk options such as hydrogen-derived fuels (IEA 2022a). Investment and commitments in green hydrogen and ammonia since 2019 add up to roughly three exajoules (EJ). This equals approximately one-third of international shipping's energy demand. Despite this momentum, the volume of green hydrogen/ammonia projects passing key investment milestones has lagged behind what would be needed to reach the maximum mitigation potential identified in the 2019 Report of a nearly 100 percent reduction in operational net GHG emissions.

In July 2023, the IMO adopted its revised Strategy on the Reduction of GHG emissions from ships (Resolution MEPC.377(80) (IMO 2023a). This commits the IMO to achieve much stronger levels of absolute WTW GHG reduction than the initial GHG Reduction Strategy, requiring a minimum of 20 percent (striving for 30 percent) reduction in 2030 and a minimum of 70 percent (striving for 80 percent) reduction in 2040 (on a 2008 baseline). GHG emissions are required to reach net zero by or around 2050. Currently these targets are not legally binding, but the IMO also committed to adopting legally binding policy measures (a fuel standard and GHG pricing) designed to achieve the reductions by the end of 2025. This has made significant progress since 2019.

However, shortcomings and details in the IMO's key mid-term measures policy (e.g. uptake of alternative low-carbon and zero carbon fuels, direct carbon capture on board, wind-assisted propulsion and operational efficiencies) need to be worked out—there is still much to be done and little time in which to do it.

The following key options for mitigation remain:

- Reduce demand for ocean transport
- Increase efficiency
- Substitute energy generated from fossil fuels to renewable energy sources
- Capture emissions by using mobile (onboard) carbon capture and subsequent sequestration

Mitigation potential

Ocean transport has managed to reduce its carbon intensity by over 30 percent relative to 2008 (Faber et al. 2021). Practically all of this has been achieved by taking several technical and operational measures to boost efficiency, rather than by switching to alternative fuels. The estimation of further mitigation potential is presented in Table 10. The near-term opportunities (to 2030) of a 20–39 percent mitigation of emissions are constrained by the fuel compatibility of the existing fleet and the supply chain of renewable energy and fuel, which limits the potential to further energy efficiency improvements (Bouman et al. 2017; Hoegh-Guldberg et al. 2019). By 2050 however, there is the potential for a fundamental change in fleet and energy supply chain. At the upper bound, there is potential for a full (100 percent) substitution of the sector's use of fossil fuels with renewable fuels. The lower bound reduction potential at 2050 is set at 50 percent as in the previous report, taken as the minimum interpretation of the IMO's objectives in the initial GHG reduction strategy (Hoegh-Guldberg et al. 2019).

The main change to the mitigation quantifications for international shipping since 2019 comes from the development of new trajectories of the business-as-usual (BAU) emissions, detailed and explained in Faber et al. (2021). The lower demand growth rates in these scenarios are particularly important to the BAU emissions in 2050, and therefore the mitigation potential if the sector reaches zero GHG emissions in that year.

The changes to the 2030 mitigation potential are similar as the options for mitigation remain the same and are centred on existing technologies and operational improvements that there is still time to implement. Both the 2030 and 2050 mitigation potentials have an improved likelihood of achieving their upper bound values relative to the 2019 assessments, because of the development of more ambitious policy measures (short-term measures), and levels of ambition (2023 revised strategy), as discussed in this chapter.

The domestic fleet's potential for mitigating GHG emissions is in proportion to mitigation in international shipping, but as the total emission is estimated to be smaller, so is the mitigation potential. They remain similar to the 2019 potential because there is no further comprehensive analysis of their potential growth and therefore quantification of their mitigation potential.

For further reductions, optimising the logistics of the transport chain remains the natural place to start; the aim is to carry more cargo while moving less total tonnage. Maximising utilisation, reducing ballast, repositioning legs of trips to shorten distances, and minimising dead time anchored outside ports can all help to maximise efficiency and the transport work that can be done by the current fleet. Such measures lower carbon intensity and avoid expanding the fleet, reducing the use of energy and resources, emissions from shipbuilding, and environmental harm from ship recycling.

Reducing speed can have the opposite effect if stable or growing demand for transportation leads to increased shipbuilding activity. However, many ships now travel at reduced speeds relative to 2008, sail at optimum trim angles, carry less water ballast and find routes with favourable weather conditions to reduce fuel consumption. Periods of high fuel prices have popularised effective anti-fouling coatings (coating on the hull of a ship that reduces the growth of fouling organisms such as barnacles), along with robots and divers that remove fouling from hull and propellers to minimise frictional resistance, the main resistance component for almost all vessels.

Table 10. Potential of different opportunities to mitigate carbon emissions, 2030 and 2050

OCEAN-BASED SECTOR	MITIGATION OPTIONS	DESCRIPTION	2030 MITIGATION POTENTIAL (GT CO_2E/YEAR)	2050 MITIGATION POTENTIAL (GT CO_2E/YEAR)
Ocean-based transport	Reducing emissions from domestic shipping and marine transport[a]	Reducing emissions from shipping between ports of the same country.	0.04–0.07	0.15–0.3
	Reducing emissions from international shipping	Reducing emissions from shipping between ports of different countries, including emissions associated with product tankers, chemical tankers, crude oil tankers, liquid natural gas carriers, liquid petroleum gas carriers, dry bulk, general cargo and open hatch, car carriers, roll-on/roll-off and roll-on/roll-off passenger. International shipping excludes military, fishing vessels, and cruise ships.	0.21–0.53	0.65–1.70

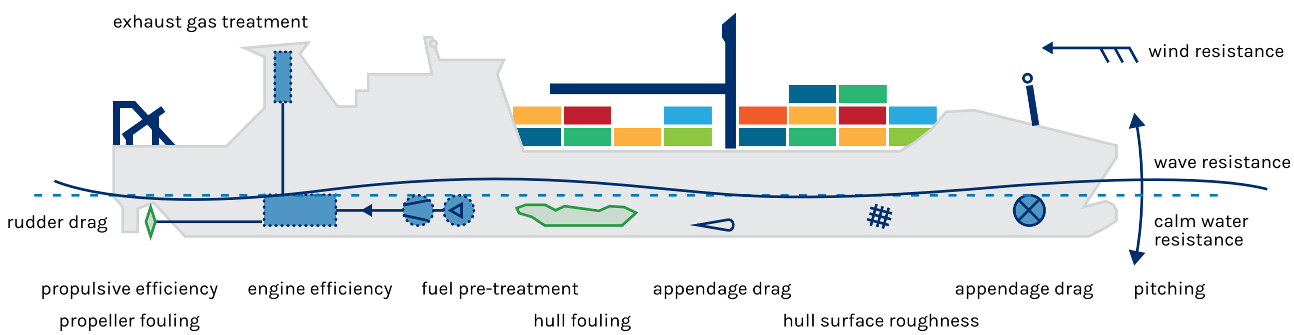
Note: a. The mitigation potential for domestic shipping remains the same as in the 2019 Report.
Source: Authors.

Most of the energy consumed by cargo ships goes to propulsion (Faber et al. 2020) (Figures 4 and 5). The shape and dimensions of vessels (especially the hull) should be optimised for minimum resistance and maximum propulsive efficiency, while still observing requirements for safety, noise and vibrations. Enhanced computer power and physical model testing remain essential optimisation tools. The focus of tests should be on realistic sea conditions in the intended route; this challenges the practice of standard designs and will make vessels more specialised to the trading area in which they were designed to operate.

For vessel engines, the thermal efficiency and emissions of the machinery depend on the engine fuel type, operation speed, dimensions of internal components and their condition. As engine emissions vary significantly with the load placed on the engine (i.e. the force it needs to generate to propel the vessel), it is important to run engines at optimal load.

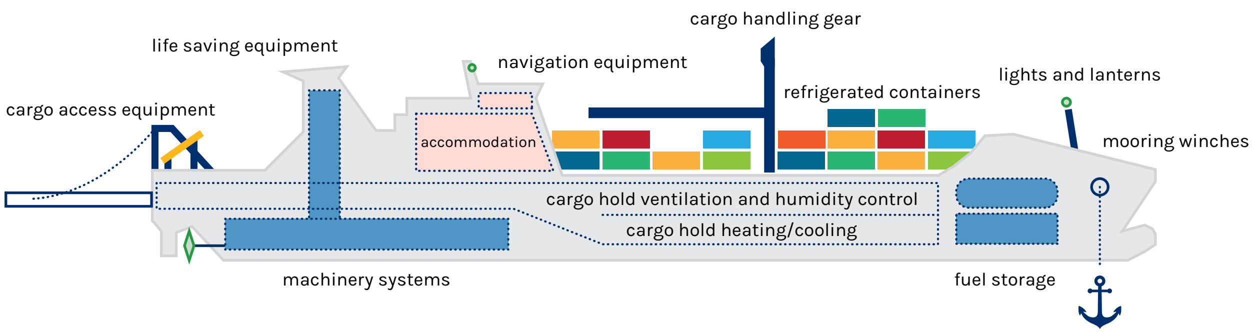
After reducing energy demand to a minimum, further emissions reductions require a transition away from fossil fuels to renewable energy/fuels, or carbon capture and storage (CCS). Carbon capture and storage can take place during the production of synthetic fuels, or onboard (mobile CCS).

Figure 4. Main resistance components and drivers of energy consumption when sailing



Source: Adapted from Gamlem (2023).

Figure 5. Energy consumed by ship's ancillary systems at sea and or in port



Source: Adapted from Gamlem (2023).

A return to wind power (a source of renewable energy available to shipping) after a century of coal and oil may be underway as different types of sails are being piloted on cargo vessels and passenger ferries. Sails are most suitable for slow vessels with a somewhat flexible schedule, good stability and course keeping and available deck space. Model tests indicate that sails can reduce the propulsion power by up to 30 percent even on mid-sized ocean-going transport, when combined with designing the hull form to be more slender to reduce resistance through water (Lindstad et al. 2022, 2023). Therefore, wind may not obviate the need for a source of stored energy (e.g., fuel) and associated propulsion system, but it can significantly reduce the demand for stored energy.

For some ships, there is also the potential to store the ship's demanded energy in batteries with an energy system like those used in road vehicles, and there are increasing numbers of small ships being designed and used in this way. Although this is a more efficient use of renewable electricity than the production and use of renewable fuels, the cost of batteries means that this is likely to remain a competitive and attractive technology pathway for ships on short voyages, and therefore primarily suited to domestic and not international shipping. Bioenergy presents another alternative option for shipping's GHG reduction, but its scalability and availability, along with sustainability risks of the significant production increase (depending on its source), make it likely to remain a small share of total energy use in the sector (Englert et al. 2021).

…the GHG reduction potentials of these fuels are dependent on the expansion of renewable energy supply…

This leaves a key role for renewable fuels to play in achieving shipping's mitigation potentials. Renewable fuels include hydrogen, ammonia, synthetic hydrocarbon fuels (e.g. synthetic methane) and synthetic alcohols (e.g. synthetic methanol). They can have high emissions in the production phase unless they are produced with renewable electricity and electrolysis. These fuels can also be made from hydrogen that has been reformed from fossil fuels, e.g. natural gas, but with effective carbon capture and storage integrated in the reformation process, also known as blue hydrogen. While not a renewable fuel if produced in this way, fuels derived from blue hydrogen can achieve significantly lower GHG emissions relative to crude oil-derived fuels currently used in international shipping.

These are all candidate fuels because they are relatively energy dense (e.g., they have similar or slightly lower energy density than the crude oil derived fuels currently used in shipping, so would take up similar amounts of space on board), and because they have the potential to be synthesised using renewable energy and industrial processes. The synthesis of all these fuels requires a source of hydrogen (which must have low or zero GHG hydrogen if they are to achieve any GHG mitigation), with other elements and industrial processes:

- Ammonia is made by an industrial process known as the Haber-Bosch process.
- Synthetic hydrocarbon fuels combine hydrogen with a source of carbon (e.g., methane can be made through the Sabatier process). The source of carbon needs to be biogenic or extracted from the atmosphere (e.g., through direct air capture) for there to be significant GHG mitigation potential.
- Synthetic alcohols require a source of oxygen and carbon to be combined with hydrogen.

Both hydrogen production and industrial processes require significant amounts of energy. Noting that recently only 14 percent of the global primary energy is renewable (IEA 2021a), the GHG reduction potentials of these fuels are dependent on the expansion of renewable energy supply to meet the renewable energy demands of both shipping fuel production and of wider energy system decarbonisation.

Overall, the appropriateness of different mitigation options, including their GHG reduction potential, can depend both on the type and size of ships and on whether ships trade locally, regionally or worldwide, or sail in fixed or nearly fixed routes and schedules (liner service), or criss-cross the ocean unpredictably (tramp service).

Wider impact analysis

Maritime transport and its governance require global collaboration. R&D and uptake of new technology depends on cooperation between researchers and investors. Accelerating emissions reductions and achieving wider benefits is possible. But nations will need to work with one another and the IMO to accomplish this.

POTENTIAL BENEFITS	▪ Shipping has an important role in maritime transport and globalisation with current strong dependency on fossil fuels. Consequently, any reduction in emissions by changing fuels, along with increasing the energy efficiency, optimising operations, and ship design can have very wide range of benefits (Jaramillo et al. 2022). ▪ Shipping efficiency, logistics optimisation, increase in the share of renewable energy, new innovations through the 'internet of things', new fuels can generate GHG emission benefits, coastal air quality improvements and health benefits especially from reduction of sulphur emission and emissions of fine particulate matter (PM2.5), reduce premature death, create jobs associated with the supply chain of new fuels, reduce life cycle emissions to build and operate the associated infrastructure (Hoegh-Guldberg et al. 2019; Viana et al. 2020; Zou et al. 2020; Al-Douri et al. 2022; Denton et al. 2022). ▪ Reducing emissions from shipping vessels will help mitigate hotspots of ocean acidification on ocean species and ecosystems (Hassellöv et al. 2013) and can generate a variety of adaptation benefits. ▪ Most countries are examining opportunities for combined mitigation adaptation efforts, using the need to mitigate climate change through transport related GHG emissions reductions and reduction of pollutants as the basis for adaptation action (Jaramillo et al. 2022).
POTENTIAL IMPACTS OR RISKS TO MITIGATE	▪ Achieving the International Maritime Organisation (IMO) revised targets (striving for 30% and 80% GHG reductions in 2030 and 2040) needs further international cooperation to convert these into legally binding policy measures that incentivise and enforce their achievement. Geopolitical debate regarding national and international level regulations and policies, maritime infrastructure to support Arctic shipping development are on the rise (Jaramillo et al. 2022). ▪ Impact of decarbonisation targets and actions on international trade needs better understanding, to ensure that the efforts to reduce GHG emissions do not have avoidable negative impacts on developing economies, and to ensure broad consensus in the development of further IMO policy measure adoption (UNCTAD 2023). ▪ There remains a risk that the production of renewable energy and renewable liquid fuels does not increase at the rates needed to achieve the GHG emissions reductions of international shipping (Campbell et al. 2023). This can be best mitigated by further policy action to stimulate supply of new fuels, both at national, regional and multilateral levels.

Delivering on the potential: Priorities for action

Although major progress has been made in recent years, and the IMO has committed (in the revised GHG strategy adopted in 2023) to take strong further policy action, urgent priorities remain. More specific policies need to be developed to maximise the mitigation potential identified in this chapter, especially those that align with the IMO's revised ambitions and targets. Specifically, this now includes (by the end of 2025):

- The revision of the IMO's short-term measure policies (improving stringency, enforcement, and effectiveness of the existing regulations CII and EEXI)
- The development and adoption of new IMO mid-term measures (a goal-based fuel standard and a GHG price and fund policy)

Further narrowing and ultimately closing the gap between the IMO's targets and a clearly 1.5°C-aligned pathway of emissions reduction will take vigorous action from national and regional government and industry.

Immediate objectives between now and 2030 must include maximising efficiency in this decade. The pathway of GHG reductions between 2030 and 2050 must include maximising the rate of energy transition and ensuring that shipping's demands from a decarbonised energy system are met, while avoiding unintended consequence risks and impacts.

LOGISTICS EFFICIENCY PRIORITIES

Longstanding market barriers and failures preventing greater energy efficiency in the shipping sector include that the ship owner is often not responsible for paying for fuel costs, and the use of rigid contracts (charterparties) which do not allow logistics efficiency optimisation. These barriers and failures create a recognised split-incentive (Rehmatulla and Smith 2020). Changes to these aspects should be top priorities for action. IMO regulation could help address this by revising the way efficiency is regulated and incentivised (e.g., revise the carbon intensity indicators—CIIs—to include the mass of cargo carried so that policy can minimise the emissions per unit of transport work (cargo mass x distance), which then ensures greater incentivisation of cross-value-chain collaboration to find efficiencies. In parallel, national and regional governments can produce regulations to increase the transparency of data being used at port-operator interfaces (to enable both the ship operator and port to find mutually beneficial optimisations for time slots at berth and voyage speed), Governments and private sector actors (shipowners, charterers, ship financiers, port owners, insurers, fuel producers etc.) can form stakeholder communities for sharing best practices and developing data standards that can make it easier to share information that can help optimise logistics efficiency.

Another priority is for governments and companies to consider the contribution of supply chain emissions as part of overall consumption/product emissions. Increasing use of policies such as the EU's Carbon Border Adjustment Mechanism (CBAM), as well as scope 3 (i.e. supply chain) reporting requirements, will shine a light on the portion of emissions associated with the distances and transport involved in producing goods. This will encourage more holistic decision-making that trades off the costs and benefits of long and complicated supply chains. For some goods, this may increase the value of near-shoring (outsourcing of operations or services to an area that is geographically close by), even if for many goods there remains value in long-distance trade. Both governments and private sector actors will benefit from evaluating the potential changes in trade operations that could result in a reduced demand for transport, as well as increased logistics efficiency.

OPERATIONAL EFFICIENCY PRIORITIES

Take-up of technology and operational improvements for efficiency remains far lower than its potential even though it is the key no-regrets solution for maximising shipping's mitigation potential. Changes can be made now and are not dependent on a broader energy transition, and in many cases they can be cost-neutral since increasing efficiency reduces fuel use and saves money. Making efficiency improvements will also increase the viability of a transition to low-carbon fuels by reducing the demand for them.

However, there remains a large legacy fleet of highly inefficient ships built before 2013 (the year that IMO's EEDI regulation that specifies minimum design efficiency entered into force), that continue to be viable to operate given periods of high freight rate and revenues that offset their high running costs. There remains a widespread lack of uptake of wind power, air lubrication and other technologies, and continued general use of 'sail fast then wait' practices that waste energy through unnecessary high speeds to no benefit in logistics efficiency.

The adoption by the IMO of short-term measure policy, entering into force in January 2023, was a missed opportunity to create a strong and clear incentive to maximise efficiency within this decade. The adopted policy exhibits multiple key shortcomings (Smith et al. 2023):

- The policy uses the Annual Efficiency Ratio (AER), which assumes that vessels are always operating at maximal capacity, overestimating their energy efficiency.
- The policy lacks a meaningful enforcement mechanism; the only sanction is to submit an action plan if the policy is underperforming.
- The policy is misaligned to the 1.5°C target and provides negligible incentive for efficiency improvement beyond what could occur through market forces (BAU). There is no clarity of stringency beyond 2027.

- The policy considers only TTW CO_2 emissions (i.e. those from vessels themselves), as opposed to WTW emissions (which consider emissions from the broader supply chain), and so perversely incentivises certain fuels—certainly liquefied natural gas (LNG), possibly biofuels—depending on LCA guidelines.

A key priority is therefore the urgent and effective revision and improvement of IMO's short-term measures to address these key shortcomings. However, the slow pace of IMO's revision of CII (by 2026) and the complexity of multilateral agreement means that there is a role for national governments and companies to respond in the interim. National and regional governments can leverage the IMO's CII architecture and apply minimum requirements for port-calls in their countries (e.g. accepting port calls only by the most efficient ships) (Smith et al. 2023).

There is increasing pressure on companies to be transparent to customers and shareholders about their alignment with the 1.5°C target. There is therefore a priority for enabling widespread adoption of standards for the measurement and reporting of carbon emissions. This would incentivise cross-value chain efforts to maximise efficiency by use efficiency improvements to secure market advantage (e.g. Science-Based Targets initiative, Poseidon Principles, Sea Cargo Charter) (Table 11).

ENERGY TRANSITION PRIORITIES

Shipping's energy transition is highly dependent on the land-side infrastructure and transition in energy systems. The sector will not be able to operate on new low-carbon fuels if they are not widely available and appropriately incentivised (Campbell et al. 2023).

A priority during this phase of the transition is to maximise rigour in policy relevant to carbon neutral technology and WTW emissions, converting the IMO's revised strategy targets (specified for reductions of all GHG and on a WTW basis), into effective policy measures. A policy focus on carbon-neutral technology and WTW emissions might help stimulate innovation by rewarding all potential solutions. This would also manage a significant risk to shipping's decarbonisation, which is that high GHG emissions from a ship's exhausts are not reduced, but merely displaced to land-side energy production, or that infrastructure and vessels are built to minimise TTW emissions as opposed to WTW emissions.

These risks would divert investment away from long-term solutions and ultimately result in stranded assets, adding unnecessary costs to the transition. The most important way to address this lies in finalising IMO's LCA guidelines, and the design of IMO mid-term measures (Table 11).

Although there is now a commitment for an IMO mid-term measure 'basket' to have been adopted before the end of 2025, because the timescales for entry into force would not be until at least 2027, the initiation of shipping's energy transition remains a key priority to address in the near-term (Smith et al. 2021). Until this has been adopted there are no specific criteria against which companies can formulate an investment strategy to manage their risks and opportunities. More developed countries need to address calls for an equitable transition, recognising the disproportionate negative impacts of climate change on developing countries. Addressing this will help ensure that a multilateral solution can be reached as soon as possible and avoid a protracted and polarised debate that may hinder the transition.

National and regional governments need to compensate for the timescales of IMO policy development. They can use national strategies to align shipping's decarbonisation as specified by the targets and objects of the IMO's revised strategy, with their energy transitions across both renewable energy and CO_2 sequestration ambitions to stimulate early adopter and first mover opportunities. This can be done either through clear regulatory measures or economic stimulus, but evidence to date (including IPCC's AR6 report and climate action tracker) shows that most governments are not yet incentivising a 1.5°C transition and instead are placing too much faith in the ability of private sector actors to overcome the large cost differentials by themselves, in turn delaying and adding risk to shipping's energy transition.

Private companies can form stakeholder communities around initiatives such as green corridors, to develop early mover opportunities, as well as work on transparency of measurement and standards related to energy transition. Mechanisms like 'book and claim' (a system often based on blockchain technology that decouples a consumer from the physical flow of goods while still allowing them to claim any CO_2 reduction benefit associated with the goods) can help spread cost and risk, and thereby develop aggregate demand as a means to ensure there is a business case that enables investment in shipping's decarbonisation as early as possible.

Table 11. Short-, medium-, and long-term priorities/milestones to advance research and development of zero emissions fuels and vessels for maritime transport

SECTOR: GOVERNMENT		
SHORT TERM (BY 2025)	**MEDIUM TERM (BY 2030)**	**LONG TERM (2030–50)**
Develop and communicate national targets and pledges for the decarbonisation of domestic fleets and associated national infrastructure.	Adopt revision of short-term measures significantly increasing stringency.	Monitor impacts and tracking of greenhouse gas reductions to revise and improve policy cost-effectiveness.
Develop national and/or regional plans on the role and carbon intensity of trade.	Adopt national action plans for implementing shipping's energy transition	
Develop national and/or regional plans to support action on energy efficiency.	Adopt national incentives for decarbonising domestic transportation.	
Support the revision of the IMO's short-term measure policies (improving stringency, enforcement and effectiveness of the existing regulations CII and EEXI and the development and adoption of new IMO mid-term measures (a goal-based fuel standard and a GHG price and fund policy).		
Commit to decarbonisation of national energy systems faster or as fast as the transition in the international fleet.		
Refine IMO life cycle assessment guidelines and use in policy.		
Adopt basket of goal-based IMO mid-term measures, enabling equitable transition.		
Provide support and incentives for early adopters of zero emissions.		
Develop national/regional plans on the role and carbon intensity of trade.		
Develop national/regional action on energy efficiency.		
Revise the IMO Data Collection System to include cargo carried.		
SECTOR: PRIVATE SECTOR		
SHORT TERM (BY 2025)	**MEDIUM TERM (BY 2030)**	**LONG TERM (2030–50)**
Sign up for voluntary initiatives that robustly and transparently measure alignment to 1.5°C.	Develop company-level strategies adopted for managing risk and opportunity through a 1.5°C-aligned transition	Continue scaling up of 1.5°C-aligned investment.
Form value-chain clubs around early adoption zero emission opportunities.	Scaling private sector investment in energy transition.	Monitor and revise strategy.
Include decarbonisation opportunity and risk efficiently into contracting.		

Table 11. Short-, medium-, and long-term priorities/milestones to advance research and development of zero emissions fuels and vessels for maritime transport (Continued)

SECTOR: RESEARCH COMMUNITY (INCLUDING TECH AND INNOVATION)		
SHORT TERM (BY 2025)	MEDIUM TERM (BY 2030)	LONG TERM (2030–50)
Evaluate options to reduce cost, address safety, increase efficiency of hydrogen-derived fuel supply and use technology.	Advance research on cost reduction, safety and efficiency work on hydrogen-derived energy technology, and other zero emission technologies.	Research into optimisation of retrofit, and greater multi-sector integration and efficiency in the energy transition.
Assess performance of complementary efficiency technologies including wind		
Identify and rectify market and non-market barriers and failures to enable larger uptake of more energy-efficient technologies and cooperation patterns.		

Source: Authors.

2.4 Ocean-based tourism

Cruise tourism is a particularly carbon-intensive form of tourism that often also involves air travel to and from the port of departure (Scott et al. 2008). Yet there are no comprehensive assessments of the sector's contribution to climate change. As the cruise sector has an oligopolistic structure with three major players, Carnival, Royal Caribbean, and Norwegian (Chang et al. 2017), data from annual reports from these three cruise lines can be used to determine the sector's carbon intensity (Humpe et al. 2023). In 2019, the three largest cruise lines carried 22 million people, or 80 percent of the global passenger volume and emitted direct emissions of 18 Mt CO_2e (scope 1 and 2).[8] Available data thus suggests that between 2012 and 2018, direct GHG emissions from global cruises increased from 25–30 Mt CO_2e/year, even though the sector improved its carbon efficiency by about 20 percent (Faber et al. 2021). The estimate does not include scope 3 emissions, which annual reports from cruise lines suggest are as high as scope 1 and 2 combined (Royal Caribbean Group 2021; Hurtigruten Group 2022). Overall, the global cruise sector may thus have emitted 60 Mt CO_2e in 2018; comparable to the annual emissions of countries such as Austria, Greece, Morocco or Peru.

Data for the three most extensive cruise lines also suggests that in 2019, the average trip length was 7.2 days, with average emissions of 115 kg CO_2e per passenger per day (scope 1 and 2; Humpe et al. 2023). Including scope 3 emissions brings the total to 230 kg CO_2e per passenger per day. For the average cruise at 7.2 days, this amounts to 1.7 t CO_2e per passenger, or one-third of the average global carbon footprint of 5 t CO_2 per year (Ritchie et al. 2020).

Only 0.4 percent of the world's population participated in cruises in 2019. Should the sector continue its historical growth of more than 6 percent per year (1990–2019), there will be 40 million passengers in 2030, causing emissions of 40 Mt CO_2e (scope 1 and 2 in the BAU scenario with recovery in 2024, considering 2 percent annual improvement in carbon intensity (Hurtigruten Group 2022). Including scope 3 emissions there will be 80 Mt CO_2e emitted in 2030 by cruises. This is in stark contrast to global ambitions to halve emissions by 2030. Under the same assumptions, the sector will carry 155 million passengers in 2050, causing scope 1 and 2 emissions of 100 Mt CO_2e, or more than 195Mt CO_2e including scope 3 emissions.

The sector also emits other pollutants. Emissions of sulphur oxides (SO_x), nitrous oxides (NO_x) and particulate matter (PM) are a concern as cruise ships operate in pristine waters as well as in populated areas near ports (e.g. Dragović et al. 2018). Extrapolation of data in sustainability reports by Carnival and Royal Caribbean suggest that the cruise sector accounted for emissions of 544,600t SO_x, 383,500t NO_x and 32,200t PM in 2019 (Royal Caribbean Group 2021; Carnival Corporation & PLC 2022).

The cruise industry will need to confront these and other environmental challenges. These include the production of potable water, handling of grey and black water, food and other wastes, single use plastic, and the degradation of habitats that store carbon (Carić and Mackelworth 2014; MacNeill and Wozniak 2018). Noise and vibrations disturb marine organisms, and tourists are not always considered welcome in the coastal destinations they visit.

Rising traffic in the Arctic as sea ice diminishes poses risks to Arctic marine ecosystems and coastal communities. These include local pollution and the arrival of invasive species (Jaramillo et al. 2022). Black carbon or soot from burning fossil fuel contains fine particulates that absorb light, hasten the melting of snow and ice, and are particularly effective at warming polar waters (Lindstad et al. 2016).

In addition to cruise ships, ferries that carry cars and passengers also support ocean-based tourism. Jet skis, recreational boats, yachts and super yachts all contribute to fuel use at a scale that potentially exceeds emissions from cruise lines. For example, ferries for passengers and cars alone generated emissions exceeding 48 Mt CO_2 in 2018 (scope 1; Faber et al. 2021). Super yachts owned by affluent individuals can be the size of cruise ships and emit tens of thousands of tons of CO_2 per year (Barros and Wilk 2021). To date, there is no comprehensive assessment of the fuel use by these different leisure boat sectors.

To decarbonise the cruise sector, it is important to consider its structure, management, technology, and ship design. Above all, energy consumption is influenced by design choices such as the average floor space of cabins or the space given to provide other amenities, including restaurants and activities. All of these determine passenger capacity in relation to ship size. Management decisions affect fuel use as they set the destinations and distances sailed, sailing speeds and port of departure choices that require air transport for passengers and staff. Menu designs determine the carbon-intensity of foods as well as food waste. This suggests that energy consumption can be reduced significantly throughout scopes 1–3, even though it remains unclear which individual contributions these measures might make, and under which policy scenarios the sector will adopt them.

In general, efforts to reduce emissions should start with cutting energy consumption. This is necessary because low-carbon energy is and will likely continue to be scarce and expensive (IEA 2021a). Also, a shift to other fuels will increase the complexity of construction as well as operations, and hinge on technology and infrastructure developments.

Cruise vessels demand so much energy, both at sea and in port, that drawing power from the onshore grid makes more sense for them than for other large vessels such as cargo ships. Turning off shipboard generators means these ships pollute less, though the climate effect is only as good as the footprint of the electricity grid. For example, while Norway's hydropower gives electricity at only 10 g CO_2e/kWh, the European average is 265 g CO_2e/kWh and American electricity emits closer to 400 g CO_2e/kWh (Ember n.d.). Renewable electricity is still a scarce resource; globally, only about 14 percent of the primary energy and 25 percent of the electricity is renewable (IEA 2021a). Also, the high power requirements need infrastructure, and regions with seasonal activity, may find it hard to justify the large shoreside investments needed. New EU regulation (FuelEU Maritime) makes shore power mandatory for cruise vessels operating in Europe from 2030.

Cruise ships have transport and hotel functions, and hence require substantial energy for propulsion and passenger facilities. There are numerous systems to work with, from heat, ventilation, and air conditioning of passenger facilities to hydrodynamic and aerodynamic resistance. These are discussed in detail in the previous ocean transport sector.

Propulsion power, constituting about 60 percent of total power demand of cruise ships (Faber et al. 2020; NCLH

2022) can be reduced by optimising the hull shape below and above the waterline for minimum hydrodynamic and aerodynamic resistance. Friction between hull and water is the dominating resistance component for most vessels and can be reduced by non-toxic anti-fouling paint and hull cleaning. Air lubrication of the flat bottom portions of ships appears to be promising for cruise vessels. Cruise ships have multiple transverse thrusters to help them manoeuvre in port, and efficient designs can minimise the drag around these. Above the waterline wind resistance is a concern, and larger cruise ships require more energy for propulsion.

The engine rooms of cruise vessels contain diesel-electric machinery, dominated by several generators. This allows flexibility to run the propulsion engines on optimal load to minimise fuel consumption and specific emission levels while also having power reserves for safety. The use of batteries to store electrical energy can avoid low-load running of diesel generators. Azimuthing thrusters (propellers that can be rotated left or right to turn the ship) are used to improve vessel manoeuvrability, but their efficiency can be improved, for example by using contra rotating propellers.

In operation, route choices that consider prevailing weather conditions, use of optimum vessel tilt angles and speed and frequent cleaning of the hull can help to ensure fuel efficiency is as high as possible. In calculating the energy costs and benefits of slow steaming, it is important to factor in the effect of auxiliary power demand at sea and energy demand in port.

The only way to know the effectiveness of these mitigation measures is to collect, analyse, and present data on operational performance. New carbon intensity indicator (CII) regulations from IMO are a good step forward, but these should be amended further to reflect actual vessel utilisation rather than vessel capacity (see Ocean-based transport).

Hydrogen (H_2), ammonia (NH_3) and methanol are under consideration as future fuels to substitute the sector's use of fossil fuels. The technical challenges and regulatory incentivisation for much of cruise shipping are similar to the ocean transport sector more generally; for a discussion on these options, see section '2.3 Ocean-based transport.'

Batteries can power the smallest vessels, but only if the sailing time between ports with charging facilities is very short. Batteries can also serve as energy-saving devices for large vessels with complex diesel electric machinery. The manufacturing of batteries, including sourcing of metals such as cobalt and lithium, raise new sustainability and logistical challenges.

Considering growth and the importance of scope 3 emissions in particular, it is likely that total emissions from cruises will continue to rise.

Mitigation potential

It is hard to quantify the total potential mitigation effect, as it all depends on a vessel's starting point and operating profile. Two of the major cruise liners report 2 percent annual improvements in carbon intensity in recent years and aim to continue this going forward (Royal Caribbean Group 2021; Hurtigruten Group 2022). These figures refer to scope 1 and 2 emissions only. Unfortunately, 2 percent improvement in carbon intensity is cancelled out many times over by the expected 6–7 percent passenger growth, so the cruise liners must at least triple their ambitions to successfully reduce greenhouse gas emissions. Cruise vessels have numerous systems onboard, and thus reducing energy consumption requires implementing an array of technologies. Efficiency gains of between 20 and 39 percent by 2030, and between 50 and 100 percent by 2050 (in line with estimates developed in this report for ocean-based transport) may mitigate emissions by between 8–15.6 Mt CO_2e/year by 2030 and by between 50–100 Mt CO_2e/year by 2050. However, whether absolute emissions reductions from current levels (scope 1) are a realistic assumption remains to be seen, as the IEA (2021a) in its Net Zero Emissions (NZE) scenario expects only 15 percent of total energy demand in shipping to be constituted by low-carbon fuels. Considering growth and the importance of scope 3 emissions in particular, it is likely that total emissions from cruises will continue to rise.

Regulations in some environmentally sensitive and busy coastal areas are tightening. There are already requirements for zero GHG emissions in some areas, such as the Norwegian requirements for zero emissions in UNESCO World Heritage fjords. At best, such regulations can motivate zero emissions technology, such as use of battery power and electric motors. At worst, such regulations will displace the most polluting vessels to other waters and ports. Also, charging batteries with fossil energy enroute to such zero emission areas will simply shift GHG emissions from one place to another, and possibly contribute to greater global inequalities, since some developing nations that need the revenue may encourage such ships.

The cruise ship fleet can be divided into nearly two equal halves; smaller vessels up to 10,000 gross tonnes (GT) make up about 45 percent of vessels and emit only 10 percent of the total GHG emissions. The other 55 percent of the ships (greater than 10,000 GT in size) emit 90 percent of GHG emissions (Faber et al. 2021). Finding solutions for the larger half of the cruise ship fleet is thus essential for the sector to decarbonise. Nevertheless, developing solutions for the smaller half will still be meaningful, because switching to new technologies and alternative fuels will be easier on a smaller scale; work here can pave the way for the larger emitters.

Cruise vessels have features that make them ideal candidates for spearheading the transition to alternative fuels. First, cruise vessels tend to have a predictable itinerary and operate in one or a few regions, so a few supply agreements can be enough. The cost of fuel is also very minor in comparison to their overall costs, so an increase in fuel costs would mean less to the overall cruise prices. Studies nevertheless show that switching from fossil fuels to biofuels would increase fuel costs from 7 to 18 percent of total costs, under current biofuel cost structures, reducing profitability from 15 to 4 percent (Humpe et al. 2023) unless the operators are able to increase ticket prices.

Operational measures, such as accounting for prevailing weather conditions, using optimal vessel tilt angles and speed and frequently cleaning the hull, can lower emissions from existing ships. But deploying new technology is generally easier when building new vessels. The lead time for new cruise vessels is long because of their complicated design and construction, and thus fundamental changes in future cruise vessels must be researched, developed and decided upon now.

New policies are necessary at the global, regional, and national level to change the course of the cruise sector and can be expected by 2025 given the recent outcome of the IMO's revised GHG reduction strategy (see discussion of Ocean-based transport). A global study of marine policies on air pollution concluded that ports currently have the greatest influence on the sector's development, as vessels need to reduce pollution levels to enter specific jurisdictions (Gössling et al. 2021). Related policies may include banning excessively polluting ships from entering ports, imposing higher port fees on inefficient ships, or reducing fees for the cleanest ships.

The EU's new FuelEU Maritime regulation aims to cut down on pollution and GHG emissions by making shore power mandatory for passenger vessels in Europe from 2030 on. It also promotes uptake of alternative fuels to power vessels. More policies need to be developed at the national level as well, to force the sector to align its development with global climate goals.

As noted, a 6 percent annual rise in passenger numbers will dwarf the impact of the industry's promised 2 percent cuts in carbon intensity. This particularly carbon-intense type of vacation, enjoyed mainly by a very small minority of people, often in pristine waters, brings an opportunity to act more decisively and make sharper cuts in the sector's energy use and its environmental footprint than the industry's sustainability reports promise.

The necessary pathway to limit temperature increase to between 1.5°C and 2°C severely restricts carbon budgets and suggests that these should be allocated to essential ocean activities such as providing food, sustainable energy, medicines, transport of essential goods and other necessary services. Leisure activities like cruises must quickly become carbon neutral to justify their continued existence. Pressure to reduce the industry's carbon footprint and other environmental impacts is likely to mount.

Wider impact analysis

Ocean-based tourism has a broad impact because its rapid growth has driven a rising demand for access to environmentally sensitive areas, air and water pollution from vessels, and pollution and user-generated waste. Current technology and regulatory mechanisms are inadequate to manage these pressures. Regulating the sector requires participation from various stakeholders, including users. As in aviation, growing awareness of per-passenger emissions might accelerate action and lead to better governance.

POTENTIAL BENEFITS	▪ Decarbonising and increasing the efficiency of cruise ships and port-side activities can result in the creation of jobs associated with the supply chain of new fuels and associated infrastructure, coastal air and water quality improvements, and health benefits, especially those associated with a reduction of sulphur and PM2.5 emissions (Viana et al. 2020; Zou et al. 2020; Al-Douri et al. 2022; Denton et al. 2022). ▪ Decarbonising ships will help mitigate hotspots of ocean acidification on ocean species and ecosystems (Hassellöv et al. 2013) and improved waste management can reduce negative impacts on marine life and coastal environments.
POTENTIAL IMPACTS OR RISKS TO MITIGATE	▪ Cruise ships, in defiance of tourism sector regulations, intentionally travel off regular shipping corridors. There is a need for region-specific governance regimes, specialised infrastructure, and focused policy attention (IPCC 2019). ▪ Summertime Arctic ship-based transportation (including tourism) increases with sea ice reductions and poses risks to Arctic marine ecosystems and coastal communities, such as from invasive species and local pollution (Jaramillo et al. 2022). ▪ Besides water pollution, use of fossil fuel cruise ships in Ísafjörður, Iceland, often pollute ocean water with wastewater, garbage and food waste, and ballast water. Many cruise vessels carry out illegal activities, including violation cases (Wang and Chambers 2023).

Delivering on the potential: Priorities for action

Decarbonising ocean-based tourism, and in particular cruise tourism, will require broadscale changes in government, private and research sectors. Near-term priorities for government include gaining a more detailed picture of scope 1–3 emissions for the sector to help devise and revise climate policies; promoting voluntary disclosure of per passenger emissions from cruise vessels; and supporting revisions to the IMO's short-term measure policies and promoting the development of more stringent IMO mid-term measures. Priorities for the private sector include transparently communicating alignment with measures to limit warming to 1.5°C; and investing in research and development of energy-efficient and low-carbon cruise ship technology and construction. Priorities for research include developing a standard connection for shore power for cruise vessels; and researching the design of energy-efficient components and activities (such as hull cleaning). Please see Table 12 for additional detail.

Table 12. Short-, medium-, and long-term priorities/milestones to advance research and development of low and zero emissions ocean-based tourism

SECTOR: GOVERNMENT		
SHORT TERM (BY 2025)	MEDIUM TERM (BY 2030)	LONG TERM (2030–50)
Monitor and track GHG emissions (scope 1–3) from global cruise tourism to devise and revise climate policies for the sector.		Implement quota for net zero fuels that fully replace fossil fuels.
Implement voluntary disclosure of per passenger emission levels following the example of aviation industry to empower users in their decision making.		
Blend-in obligations for sustainable biofuels.		
Set standard carbon intensity indicators to track progress; the carbon intensity indicators must reflect actual operations.		
Support the revision of the IMO's short-term measure policies—improving stringency, enforcement, and effectiveness of the existing regulations CII and EEXI and the development and adoption of new stringent IMO mid-term measures (a goal-based fuel standard and a GHG price and fund policy).		
SECTOR: PRIVATE SECTOR		
SHORT TERM (BY 2025)	MEDIUM TERM (BY 2030)	LONG TERM (2030–50)
Sign up for voluntary initiatives that robustly and transparently measure alignment to limit warming to 1.5°C.	Provide shore power in key cruise ports with renewable electricity.	Accept and support policies that bring the entire sector on track to net zero.
Implement structured fees at port for cruise ships that imply a significantly higher cost for ship owners.	Retrofit, convert and build new cruise vessels with low energy consumption and zero GHG emission fuels.	
Invest in research, develop and design energy efficient and low carbon cruise ship technology.		
Design, order and build cruise vessels with low energy consumption and zero GHG emission fuels.		
SECTOR: RESEARCH COMMUNITY (INCLUDING TECH AND INNOVATION)		
SHORT TERM (BY 2025)	MEDIUM TERM (BY 2030)	LONG TERM (2030–50)
Explore options for utilising a standard connection for shore power to increase utilisation.	Advance research on net zero fuels and efficiency technologies for the sector.	Continue research as outlined for 2030, under consideration of technology developments and mitigation achievements.
Assess the effect of air lubrication on ship resistance.	Investigate transition barriers to net zero technology introductions.	
Research effect of hull cleaning on ship resistance and avoidance of introducing invasive species in hull fouling.	Study implications of demand management with lower growth rates or sectoral de-growth.	

Source: Authors.

2.5 Ocean-based food

Global food systems account for up to a third of anthropogenic GHG emissions from production through processing, distribution and point of sale, driven particularly by animal protein production (Poore and Nemecek 2018; Crippa et al. 2022). 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). Changing the composition of global diets and the potential to shift away from the most GHG-intensive food production, while feeding more people adequately, has been modelled to be the most impactful way to cut GHG emissions from food provisioning (Poore and Nemecek 2018; Springmann et al. 2018; Searchinger et al. 2019).

Total emissions from marine fisheries and marine and freshwater aquaculture currently make a small contribution to the overall emissions from the global food system (each previously estimated at about 4 percent). However, they play a larger role in the overall food-related emissions of those countries that are more dependent on seafood for nutrition, livelihoods and trade, and may be particularly relevant to emissions reduction efforts for some coastal and island nations (Parker et al. 2018). The more minor contribution to emissions reflects both the smaller scale of these sectors relative to cropping and livestock farming, along with their lower emissions intensity—total emissions per tonne of fish or shellfish produced—compared to many other protein sources (Bianchi et al. 2022). However, the intensity of emissions varies substantially according to species, production method, fishing gear and locale. Both fished and farmed seafood products range from very climate-friendly to very climate and GHG intensive (Parker et al. 2018; Bianchi et al. 2022). Emissions associated with the production of seaweeds and aquatic plants, meanwhile, have been critically understudied, despite representing over half of global mariculture and producing 35 million tonnes of wet weight product in 2020 (FAO 2022). Importantly, to date little effort has been expended on any meaningful scale to systematically reduce GHG emissions from seafood systems, and efforts to measure and characterise emissions have overwhelmingly focused on systems either located in or serving markets to rich nations.

There are two principal ways that ocean-based foods can contribute significantly to climate change mitigation.

The first pathway is by directly reducing emissions from seafood production, for example, lowering the emissions intensity of fisheries. For fisheries, this could be done by rebuilding fish stocks, switching to fishing gear that uses less fuel, and decarbonising fuel that powers fishing fleets. Aquaculture farms could, for example, use more renewable electricity, or feed ingredients from fisheries, crops, and other upstream systems that generate lower emissions. Four key interventions could contribute most meaningfully towards climate change mitigation in the sector are:

- **Rebuilding fisheries** through large-scale and coordinated improvements to fisheries management to optimise production volumes and minimise effort—and fuel—requirements to fish;
- **Reducing emissions** associated with feed for farmed fed species (e.g. fish and shrimps) and increasing aquaculture of extractive species (e.g. seaweeds and invertebrates);
- **Avoiding deforestation** in the production of crop inputs (e.g. soy, palm oil) to aquaculture feeds;
- **Sourcing all on-farm energy inputs** to aquaculture from renewable or other non-fossil fuel sources, effectively decarbonising on-farm energy use.

The second pathway is to increase production more rapidly, as well as the consumption of low-emissions seafood products and concurrently, encouraging a wide-scale shift in global diets away from more GHG-intensive animal proteins like beef and lamb towards more climate-friendly seafood options (in addition to vegetarian and other lower-emissions dietary choices). This latter pathway, which we refer to here as dietary shifting, assumes the ability to adequately scale production of low-emissions seafood sources while not exceeding the ecological capacity to do so. For fisheries, even including the potential increased production that could arise from vastly improved management systems, such expansion is likely to be minimal because of caps on maximum sustainable harvesting. Rather, aquaculture of both seaweeds/plants and animals will continue to account for most of any major increase in seafood availability, as it has for the past two decades (FAO 2022). Ideally, a combined approach which seeks to maximise production of low-emissions seafood systems, while avoiding those systems and practices that drive seafood emissions upwards, would ensure that the industry contributes meaningfully to climate mitigation.

Emissions associated with the production of seaweeds and aquatic plants have been critically understudied, despite representing over 50 percent of global mariculture, producing 35 million tonnes of wet weight product in 2020 (FAO 2022). Gephart et al. (2021) found the GHG intensity of aquatic plant production to be very low in comparison to other seafood sectors, but they had a limited dataset of aquatic plant assessments to draw from. Throughout this chapter, we refer qualitatively to potential opportunities related to expanding seaweed and aquatic plant production, but we have not included such expansion directly into the modelling estimates, which are instead primarily concerned with the production of fishes, crustaceans, and molluscs.

Although both pathways for ocean-related food systems provide considerable scope for emissions reductions, achieving them will require substantial, sustained and collaborative public and private sector effort to transform energy systems, fisheries management, feeding practices, siting decision-making, etc., coupled with broad-scale public behaviour change. The lack of a meaningful and coordinated public and private sector action to reduce GHG emissions from fisheries and aquaculture operations since the 2019 Report was published has meant that our emissions reduction estimates to 2030 have been reduced, highlighting the challenges ahead if those emissions reduction potentials are to be achieved. Current practices in fisheries and aquaculture are deeply entrenched and rely on many tens of thousands of individual decision-makers globally who own and operate the vessels and farm sites (FAO 2022). Many of these individuals have a poor understanding of the significant sources of GHG emissions from their operations or lack control over those high emission activities (e.g. many fed aquaculture operators are unaware that inputs to aquafeeds purchased from separate companies are typically the largest source of emissions that arise from their products), or are effectively locked into higher emissions practices through substantial sunk costs in vessels and gear or management restrictions (e.g. many fishing operations are restricted in the fishing gear that they can use through their licenses).

At the same time, the primacy of protein derived from high emission sources of animal protein in many wealthy diets suggests that these meat products will be difficult to displace with lower emission sources of seafood (Graça et al. 2019). Together with the potential that fisheries and aquaculture operations may continue to resist or face barriers to change or be excluded from policies and programmes to reduce their emissions, we have set the low estimate of mitigation potential in both 2030 and 2050 at zero.

Sustaining any projected increase in production of food from the ocean will necessarily demand substantial improvements to coastal management, governance effectiveness, and understanding of environmental capacity to support operations within the constraints of local ecosystems, along with investments to coastal infrastructure and cold chains for storage and distribution (Costello et al. 2016; Worm 2016). These developments will be difficult to achieve at scale and in a meaningful time frame, particularly given the large producing role of remote and less developed regions.

Mitigation potential

Though we set the low estimate for emissions reductions from fisheries and aquaculture to 2030 to zero, we estimate that seafood industries could contribute up to 0.035 Gt CO_2e in potential emissions reductions by 2030 through improvements in efficiencies, inputs and practices (Table 13). These direct emissions reductions would arise, in part, from reductions in the volume of fuel combusted to land fish and shellfish as a result of stock rebuilding efforts in fisheries; in aquaculture operations through the electrification and decarbonisation of direct energy inputs to farm sites; through a 10 percent across the board improvement in the feed conversion efficiency; and the complete avoidance of feed inputs derived from deforested landscapes (Table 13). Another 0.2–0.8 Gt CO_2e reduction could be achieved through the more rapid transition of diets to shift away from more GHG-intensive land-based animal production (Table 13). Extending to 2050, these potential contributions from the seafood sector increase to 0.14 and 1.0 Gt CO_2e, respectively, providing a total potential mitigation value in 2050 of 1.5 Gt CO_2e, relative to a BAU scenario. The basis for these estimates is explained more fully in Appendix A: Methodology. This mitigation potential reflects just those interventions identified here as globally meaningful actions with sufficient data to support modelling. Further interventions ranging from the rebuilding of mangroves and other coastal habitats to the contributions of seaweed aquaculture and novel sectors of the industry are either considered in other chapters of this report or do not have sufficient data and literature available to quantify potential contributions.

Table 13. Potential GHG emissions reductions from ocean-related food systems, by 2030 and 2050

OCEAN-BASED SECTOR	MITIGATION OPTIONS	DESCRIPTION	2030 MITIGATION POTENTIAL (GT CO_2E/YEAR)	2050 MITIGATION POTENTIAL (GT CO_2E/YEAR)
Ocean-based food	Rebuilding wild fish stocks	Reduction in fuel use intensity to harvest fish and shellfish that results from rebuilding depleted stocks	0–0.021	0–0.081
		Avoided emissions if the increased harvest achieved via rebuilding stocks is consumed in place of higher emissions land-based animal products[a]	0–0.015	0–0.056
	Reducing emissions from aquaculture[b]	Improved feed conversion ratios (10 percent reduction in economic feed conversion ratios across all fed species)	0–0.004	0–0.025
		Complete avoidance of deforestation in the supply chains of feed ingredients from soy, palm, and other crops as well as in the feeds of poultry and livestock systems providing by-products	0–0.028	0–0.161
		Shifting all energy inputs to farms are derived from electricity generated from renewable sources, rather than fossil fuels onsite or in electricity grids	0–0.015	0–0.088
	Increasing share of ocean-based proteins in diets	Potential emissions avoided by behavioural shifts away from high emissions land-based proteins and towards lower emissions seafood systems	0.24–0.84	0.30–1.06
Total			**0.24–0.92**	**0.30–1.47**

Notes:
a. We indicate this value separately from the dietary shifting values as the increase in production is directly linked to rebuilding of fishing stocks, rather than any societal shift in demand for products.

b. The cumulative emissions reduction potentials from aquaculture interventions are lower than the sum of each individually because of the shared reduction potentials between feed conversion ratio improvements and avoiding deforestation in feeds.

Source: Authors.

REDUCING EMISSIONS FROM WILD CAPTURE FISHERIES

The best available data suggest that global emissions from marine fisheries are roughly 180 Mt CO_2e annually, or 2.2 kg CO_2e per live weight kg of landed fish and shellfish (Parker et al. 2018, as modelled for 2011). Global fishing thus accounted for roughly 4 percent of the global food system production emissions in 2011. This includes both direct and upstream supply chain emissions from combustion of fuel on fishing vessels as well as assumptions related to non-fuel emissions, such as those that arise from gear manufacture and refrigerant use but excludes post-landing emissions from processing and distribution.

Following the oil price shocks of the 1970s, efforts to limit fuel use in wild capture fisheries focused mainly on technological advances in engine efficiency or hull design, or changes in skipper behaviour, such willingness to reduce speed or fish in poor conditions when fish may be more available. However, the effects of energy-saving technological and behavioural changes at the fleet level are unclear and can be overshadowed by variation in stock abundance or structural changes to the fishery (Pascoe et al. 2012; Farmery et al. 2014; Ziegler and Hornborg 2014).

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 (Ziegler et al. 2016; Parker et al. 2017). Therefore, while acknowledging technological and behavioural factors, our estimate of mitigation potential focuses on the flexibility for future changes in effort and landings. The World Bank (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 emissions model based on landings in 2011 (Parker et al. 2018), this increase in efficiency could reduce GHG emissions by a total of 81 Mt CO_2e, equivalent to roughly half of current fishing emissions (Table 13). Achieving these efficiency gains only requires improved fisheries management rather than technological advances in fleet efficiency or the widespread adoption of fuel-saving behaviours by skippers. However, climate change could seriously constrain potential gains (Gaines et al. 2018; Free et al. 2020, 2022).

REDUCING EMISSIONS FROM AQUACULTURE

Since the first version of this report was released in 2019, several global analyses have been published that improve understanding of GHG emissions from aquaculture on a global scale. These include the global emissions estimates by MacLeod et al. (2020), a comprehensive methodological review of aquaculture life cycle assessments by Bohnes et al. (2019), the environmental performance of Blue Foods analysis by Gephart et al. (2021), and analyses of emissions from globally relevant seafood products along with their nutritional value by Bianchi et al. (2022). These broad syntheses and aggregation studies confirmed patterns of GHG emissions between and within aquaculture production systems previously identified by species- and system-specific life cycle assessments, and data from numerous individual studies were scaled up to globally relevant levels. These results provide a more robust basis for identifying the most widely applicable and effective emissions reduction opportunities within different forms of seafood aquaculture based on the primary drivers of those emissions.

MacLeod and colleagues (2020) estimated global GHG emissions from aquaculture production in 2017 at roughly 260 MT, or approximately 4 percent of emissions from global food production systems. Included in this estimate were emissions from the production and processing of aquafeeds (sourced from crops, fisheries and other feed inputs), energy inputs to farm systems, use of fertilisers, and an estimate of nitrous oxide emissions. While constrained in scope and limited by data availability, the analysis by MacLeod and colleagues provides a starting baseline against which we can calculate the potential emissions reduction potential of interventions in the aquaculture sector.

Gephart and colleagues (2021) assessed the GHG emissions intensity of a wide range of cultivated aquatic species (alongside wild-caught fisheries products) and undertook sensitivity and scenario analyses that provide a clear indication of the relative efficacy of strategies to reduce GHG emission intensities per tonne of production across a wide range of fed and unfed aquaculture systems, such as shrimp and bivalves. This provides a robust basis for identifying the most meaningful emissions reduction opportunities for aquaculture systems that can be applied to the total emissions of the sector. Of these, the interventions identified as most impactful across fed aquaculture systems were any strategies that durably reduce feed conversion ratios (FCRs—ration of calories in feed to calories in product, e.g. improved genetics, husbandry practices, feed formulations, etc.), and avoid deforestation in production of soy and other crop inputs to feeds. This reflects the common conclusion in assessments of fed aquaculture systems that targeting feed-related emissions provides the most significant opportunities for emissions reductions. To address non-feed related emissions and include mitigation strategies that also apply to unfed aquaculture systems, we can include the decarbonisation of all farm-site energy use. This means that all aquaculture systems would derive all energy inputs from electricity, as opposed to diesel and other fuels, and that that electricity would be sourced from either renewable or nuclear generation resulting in negligible emissions.

A significant source of emissions in marine aquaculture production, which is not included in our analysis here, is the GHG impact of mangrove deforestation and other land use change, driven by production of shrimp and other tropical species. Mangrove destruction causes not only lost carbon sequestration potential from coastal habitats, but often, biogenic emissions of methane and carbon dioxide from decomposing organic matter in converted ponds. Limited early research suggests that mangrove deforestation can dramatically increase emissions from shrimp production. Substantial uncertainty surrounds current estimates and the assumptions they rely on (Jonell and Henriksson 2015; Järviö et al. 2018). However, historically, this can be identified as an important source of emissions for marine aquaculture, and can be prevented by avoiding siting farms in mangrove ecosystems. We cannot confidently quantify the emissions that could potentially be avoided.

We expect production of marine and freshwater aquaculture to increase in coming decades, regardless of whether additional production is also needed to support a shift in diet away from protein grown on land and towards food from the sea (FAO 2022). As a result, we can expect increased production of aquafeeds to support much of this growth. The composition of aquafeeds varies greatly across herbivorous, omnivorous and carnivorous species, and within species as feed formulators strive to achieve lowest cost formulations from hundreds of globally available potential feed inputs. Two of the key components of many feeds for omnivorous and carnivorous species have historically been fish meal and fish oil, which are products derived primarily from industrial fisheries and increasingly from processing co-products from species landed for direct human consumption. These components are typically highly digestible and improve the palatability of feeds, which improves fish growth compared to all plant diets. Incorporation of fish oils into feed provides some key nutrients (e.g. Omega-3 fatty acids) and resulting aquaculture products have been 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, surging demand for fishmeal has driven the global supply to an all-time high and possibly near biological limits (Costello et al. 2012), leading to steep price increases and incentivising reductions in the fishmeal and fish oil content of many aquaculture feeds (Rana et al. 2009; McGrath et al. 2015).

Increased demand for aquafeeds, and limited availability of traditional sources for fishmeal and oil, point to the need to identify alternative sources for protein, amino acids and fats in the diets for fish and invertebrates. Soy has quickly risen as a choice ingredient to satisfy these demands. As much of the world's soy is produced in regions of South America that have been or are being actively deforested, this reliance links fed aquaculture with the high rates of GHG emissions from deforestation. But inputs other than soy pose their own problems. Some aquaculture species have historically been fed a range of livestock-derived inputs (e.g., blood, meat, and feather meal) as a substitute for fishmeal. Using some types of livestock to derive these co-product meals can cause more GHG emissions than relying on many fish meals (Pelletier et al. 2009; Parker 2018). Yet many substitute ingredients, particularly those derived from some crops, present palatability and digestibility challenges that can reduce fish and crustacean growth and health, especially for farmed predators. Consequently, efforts are now underway to identify new, highly digestible, nutritious, and ideally low climate impact feed inputs. 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). Substitutions with macroalgae (Chopin 2019) have shown no negative effects on growth parameters such as growth rate, weight gain, feeding efficiency, or muscle protein at a substitution rate of up to 5 percent seaweeds, and in some cases at rates as high as 10–15 percent. Other effects included improved lipid metabolism, increased red blood cell numbers, and increased disease resistance without impairing overall growth. Although the motivation for this innovation was to provide better quality feeds, one potential co-benefit is that some alternative feed inputs could have significantly lower GHG emission intensities than soy-based protein (Couture et al. 2018). However, other emerging feed alternatives can have substantially higher emissions with few benefits relative to soy protein (Couture et al. 2018).

REDUCING EMISSIONS BY SHIFTING DIETS

As other major sectors (transportation, space heating, etc.) decarbonise, food will account for a larger portion of global anthropogenic GHG emissions and play an increasingly large role in future climate change mitigation efforts (Tilman et al. 2001, 2011; Poore and Nemecek 2018; Springmann et al. 2018; Searchinger et al. 2019). GHG emissions from food systems are high, particularly with respect to methane emissions associated with ruminant 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 life cycle GHG emissions per unit of protein (Poore and Nemecek 2018), changes in the composition of future diets could greatly affect the emissions consequences of global growth in demand (González et al. 2011).

Considering only food system emissions of methane and nitrous oxides, which will not be affected by advances in low-emission energy sources, the BAU scenario projects that GHG emissions from food production will grow from 5.2 Gt CO_2e in 2010 to 9.7 Gt CO_2e in 2050 (Springmann et al. 2018). Of that, over 75 percent will come from projected growth in animal products. In a global analysis of strategies to bring food system impacts in line with planetary boundaries by 2050, Springmann and colleagues (2018) found that shifting diets away from livestock consumption and towards protein sources with lower climate impacts had a major impact on climate change mitigation, one far greater than either substantially reducing food loss and waste or making across the board improvements in technological efficiency (e.g. feed conversion ratios, and growth periods for livestock, etc.).

Changing behaviour to shift diets enough to materially affect projected GHG emissions is an immense challenge. One promising strategy is to incentivise lower consumption of foods with particularly large carbon footprints (i.e. most animal-based products) (Poore and Nemecek 2018; Springmann et al. 2018) through education, but also through market mechanisms that increase the relative 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 fortunately a strong alignment between dietary changes that would improve human health and those that would benefit the environment (Tilman and Clark 2014).

Changing behaviour to shift diets enough to materially affect projected GHG emissions is an immense challenge.

Sustainable growth in seafood production and consumption, particularly from aquaculture, lies at the core of these potential benefits. Such growth would necessitate improvements in ocean and coastal management to ensure that harvests cannot only be increased but also sustained. Increased aquaculture production of non-fed/extractive seaweeds and invertebrates, which are less carbon-intensive than terrestrial sources of food, are likely to provide the largest emissions benefits (Gephart et al. 2021). Their cultivation within Integrated Multi-Trophic Aquaculture (IMTA—integrated production of aquaculture species of different trophic levels) systems would also provide other ecosystem services (Chopin and Tacon 2021).

Springmann et al. (2018) suggests that an aggressive dietary shift at a global scale could reduce annual emissions by 4.7 Gt CO_2e—more than offsetting projected growth of emissions from food production under a BAU scenario. Pathways to achieve this scale of behaviour change are not clear. More conservatively, we estimate that two practical scenarios could achieve significant emissions reductions: a carbon tax and aggressive health campaigns focusing on diets. These could lead to emissions reductions of 0.24–0.84 Gt CO_2e per year in 2030 and 0.30–1.06 Gt CO_2e per year in 2050 (Table 13). Both scenarios would see the ocean playing a significantly larger and beneficial role within global food systems.

ADDITIONAL MITIGATION OPTIONS REQUIRING FURTHER RESEARCH/PILOTING.

Reducing emissions of wild capture fisheries through technological improvements

Our projection of future production and emissions from the fishing sector following an optimistic stock rebuilding scenario suggests a potential reduction of emissions from marine fisheries of roughly 50 percent to 2050. Additional potential reductions could come from technological and behavioural change. Technological improvements to vessels, engines and gears have often been promoted as opportunities to reduce fuel inputs, costs and emissions in fisheries. However, there is a lack of evidence that these changes have, to date, achieved any fleetwide reductions in emissions. In fact, in some cases, technological advances may even increase fuel consumption if they facilitate vessels traveling farther to fishing grounds or fishing in less ideal conditions

(Bastardie et al. 2022; Ziegler and Hornborg 2023). Estimated global emissions from marine fisheries increased during the 1990s and early 2000s despite implementation of technological improvements to vessels (Parker et al. 2018).

A recent study by Ziegler and Hornborg reviewed potential pathways to fleet decarbonisation up through 2050, including lowering fuel intensities and shifting to alternative non-fossil fuels for vessel propulsion and operation. They projected a potential pathway to decarbonise fishing fleets by switching to alternative fuels including hydrogen, liquid ammonia and methanol, but caution that such a transition would require making substantial investments in infrastructure, updating fleets, and gaining more understanding of fishery-specific needs to determine which fuels may be suitable for different fisheries (Ziegler and Hornborg 2023). In theory, alternative fuels and new technologies could allow fisheries to avoid most emissions that remain in the stock rebuilding scenario. However, the lack of implementation to date on a global scale, and inconsistent evidence on the effects of individual technological changes, make it difficult to predict that such reductions would be achieved by 2030 or 2050. Further, given the pattern of lower emissions from wild fisheries compared to land-based animal protein sources, policies aimed at transitioning away from the use of fossil fuels in fisheries, such as the removal of fuel subsidies or adoption of taxes or fees, may be costly to the fishing sector and could actually be counterproductive if they lead to the decreased production of lower emissions fishery products and non-competitive market price increases as a result.

Decarbonising global fishing fleets on any meaningful scale will require substantial investment into technologies suitable to individual fisheries as well as infrastructure and supply chains to provide alternative energy sources. Substantial research will be needed to determine how such a transition could feasibly be implemented across a wide variety of global fishing fleets, jurisdictions and management systems. These pathways to decarbonisation are receiving increased attention and recent studies have helped identify some of the barriers and challenges expected. Whether those can be overcome for a substantial portion of the global fleet will determine if adoption of alternative fuels and the transition away from fossil fuels in marine fisheries is feasible in any time frame.

SEAWEED AS A FEED SUPPLEMENT TO REDUCE EMISSIONS FROM CATTLE

The tropical red seaweed *Asparagopsis* Montagne, 1840 has exceptional capacity to reduce emissions from beef cattle. At 0.1 and 0.2 percent of feed dry weight, it reduced methane emissions from cattle by 40 and 98 percent, respectively, without reducing feed efficiency (Kinley et al. 2020). For dairy cows, more *Asparagopsis* was needed and was less effective. It reduced methane emissions by just 26 percent when added as 0.5 percent of organic matter in the feed. A higher share caused the cows to eat less (Roque et al. 2019). Some other seaweed species also contain methane-reducing bioactives, but they are much less efficient than those in *Asparagopsis* (Nørskov et al. 2021). There are several important barriers to the large-scale application of seaweed in ruminant feed as a GHG mitigation tactic (Nielsen et al. 2022; De Bhowmick and Hayes 2023). The bioactive components of Asparagopsis are halomethanes such as bromoforms, some of which are ozone degrading and carcinogenic. In addition, high concentrations of heavy metals and iodine in seaweeds may also restrict their use as feed additives. There is no large-scale production of *Asparagopsis* yet, and costs of production are very high. Perhaps most importantly, however, most cattle in the world are not held in confinement where diets can include a daily dose of *Asparagopsis*. Bringing all cattle, including those in cow-calf operations, into production settings where GHG emission-reducing diets can be controlled is a formidable challenge.

Wider impact analysis

Unless well managed and planned, shifting dietary choices from land based protein to ocean-based proteins could negatively impact all dimensions of sustainable development: economic, social and environmental. Aquaculture can present numerous societal and ecological challenges. Unplanned aquaculture expansion in some regions has degraded or destroyed other coastal and terrestrial ecosystems. Care should also be taken when sourcing sustainable ocean-based protein. Because of the emissions and environmental harm, they can cause unsustainable aquaculture feeds and should be disincentivised through national regulations and international cooperation.

POTENTIAL BENEFITS	▪ Even moderate dietary shifts from high meat consumption to ocean-based protein has well-documented human health benefits (Tilman and Clark 2014). ▪ Moving to diets that are less dependent on terrestrial 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) (OECD 2016). ▪ Replacing fishmeal of future feeds with crops (including crops of the sea) instead of animal by-products requires less water; reducing feed conversion ratio in aquaculture production reduces upstream water usage (Parker 2018). ▪ Structural changes to fisheries that reduce fuel consumption will be economically beneficial (World Bank 2017). ▪ Increased inclusion of seaweed- and aquatic plant-based ingredients in fish feed for a growing aquaculture industry could address the issues of land competition, crop irrigation, fertilisers and agrochemicals, and social and environmental conflicts. ▪ Reducing land-based meat production for consumption through substitution by sustainable balanced diet and ocean-based protein has mitigation and multiple positive wider benefits including 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 (Hoegh-Guldberg et al. 2019; Creutzig et al. 2022). ▪ Seaweeds provide source of nutritious human food with low lipid content, high minerals, fibres, polyunsaturated fatty acids, polysaccharides, vitamins, and bioactive compounds, offer unique properties to develop various functional foods for the food processing industries, raw materials for biofuel and bioplastics production and livestock feed (Sultana et al. 2023). ▪ Seaweed farming systems also help in climate change adaptation by absorbing wave energy, safeguarding shorelines, raising the pH of the surrounding water, and oxygenating the waters to minimise the impacts of ocean acidification and hypoxia on a localised scale. Moreover, it contributes substantially to the sustainable development of the economic condition of coastal women by providing livelihood opportunities and ensuring financial solvency (Sultana et al. 2023).
POTENTIAL IMPACTS OR RISKS TO MITIGATE	▪ Marine aquaculture is associated with multiple environmental challenges (such as eutrophication, disease, and risk of invasive species). These risks are also associated with land-based farming. ▪ The poorly planned expansion of aquaculture in some regions has negatively impacted other coastal and terrestrial ecosystems and has multiple negative impacts especially shrimp aquaculture which remove mangroves and other important habitat species (Ahmed and Thompson 2019). ▪ Unless adequately managed through spatial planning and monitoring, seaweed farming at large scale can generate risks of spreading disease, changing population genetics, altering the wider local physiochemical environment, seagrass beds, and thereby disturb important flows of ecological goods and services (Hoegh-Guldberg et al. 2019; Spillias et al. 2023a). ▪ Gender inequity is exacerbated because most commercial-scale aquaculture projects are gender-blind especially in countries with sustainable aquaculture practices involving women (Galappaththi et al. 2020; Prakash et al. 2022). ▪ Globally, most seafood products are more nutritious and emit less greenhouse gases in production than terrestrial animal-source foods. However, seafood consumption is influenced by price and consumer preference, so it is unclear whether low-emissions nutritious seafood will dominate or not. Farmed salmon, for example, were produced in large volumes because of high demand and relatively higher prices than other seafood, whereas highly nutritious, low-emissions farmed mussels had limited production volumes. (Robinson et al. 2022).

Delivering on the potential: Priorities for action

Achieving a level of efficiency gains in wild fisheries that would drive emissions reductions requires more effective management of fisheries around the world (Table 14). Several global analyses highlight where fisheries are working well and where there are needs for significant reforms (e.g. World Bank and FAO 2009; Sumaila et al. 2012; Costello et al. 2016) and help identify which management practices are linked to success or failure in fisheries management (World Bank and FAO 2009; Evans et al. 2011; Allison et al. 2012; Barner et al. 2015; Costello et al. 2016; Lubchenco 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 (e.g. climate change driven reductions in fisheries potential yields [Gaines et al. 2018; Free et al. 2020]). Achieving this goal requires national recognition of the nature of each country's fisheries challenges and the benefits of improved management, and a concerted effort to draw on the lessons of others to drive more rapid change.

Significantly altering the behaviour of a broad section of society, even for actions that are both in the interest of the planet and its 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.

Unlike other categories in this assessment, the largest gains from changes in the global food system do not depend heavily on developing new technologies. Rather, the benefits depend on scaling solutions globally that have been already demonstrated in specific places and a shift towards long-term profitability through circular approaches (e.g. the development of Integrated Multi-Trophic Aquaculture systems). Although this requires new innovative approaches, new market solutions, and new campaigns, it is not exclusively dependent on new technological advances.

Achieving a level of efficiency gains in wild fisheries that would drive emissions reductions requires more effective management of fisheries around the world.

Table 14: Short-, medium-, and long-term priorities/milestones to advance research and development of low carbon ocean-based food

SECTOR: GOVERNMENT		
SHORT TERM (BY 2025)	**MEDIUM TERM (BY 2030)**	**LONG TERM (2030–50)**
Enhance sustainable management and enforcement of ocean fisheries globally, with a focus on implementing rebuilding plans for depleted stocks.	Financially incentivise sustainable food production and consumption with far lower GHG emissions.	Monitor transition of all fisheries to maximise biological output.
Promote efficient licensing processes for sustainable ocean aquaculture.	Promote aquaculture licensing practices that minimise costs, or produce benefits, to wild fisheries.	Support equitable investments in aquaculture for countries projected to experience large fisheries losses as a result of climate change.
Promote electrification and decarbonisation of all aquafarm site energy inputs.		Implement regulatory and financial incentives towards the development of sustainable food production systems (e.g. Integrated Multi-Trophic Aquaculture, or IMTA).
Utilise area-based management frameworks, including Sustainable Ocean Plans, to guide development and minimise conflict between ocean users.		
Review national regulatory and incentive structure to align with efforts to decarbonise ocean based food.		
SECTOR: PRIVATE SECTOR (INDUSTRY AND NON-PROFITS)		
SHORT TERM (BY 2025)	**MEDIUM TERM (BY 2030)**	**LONG TERM (2030–50)**
Scale best practices for fisheries management and marine aquaculture.	Aggressively promote diet choices that result in demonstrably lower greenhouse gas emissions.	
Invest in species-targeted strategies (e.g. improved genetics, husbandry practices, etc) to reduce feed conversion ratio in fed aquaculture systems.		
SECTOR: RESEARCH COMMUNITY (INCLUDING TECH AND INNOVATION)		
SHORT TERM (BY 2025)	**MEDIUM TERM (BY 2030)**	**LONG TERM (2030–50)**
Enhance development of monitoring and evaluation tools that enhance sustainable fisheries management.	Seek continued innovations on fish feed with lower GHG emissions.	
Improve assessment and monitoring of data-poor stocks to facilitate. management and rebuilding.	Research climate resilient aquaculture products to offset climate change driven losses in wild fisheries.	
Expand analyses on diet influences on human health to seek more options that are good for people and the planet.	Explore potential benefits of co-locating aquaculture with other emerging ocean uses (e.g. renewable energy).	
Make assessment of limits to sustainable ocean-based dietary protein sourcing.	Develop robust valuing tools for the ecosystem services provided by low-trophic aquaculture species (seaweeds and invertebrates) and sustainable food production systems (e.g. IMTA).	

Source: Authors.

2.6 Offshore oil and gas

Reducing oil and gas consumption is critical for meeting global climate commitments. Currently, nearly 30 percent of all oil and gas production comes from offshore areas (EIA 2016; IEA 2019), with most of the offshore production and investment concentrated in just a few regions (Rystad Energy 2023). Both onshore and offshore drilling generates GHG emissions throughout the entire process, starting with exploration and extraction of oil and gas from below the seafloor; through onshore emissions during energy-intensive processing and transportation; and finally, and most significantly, when the fuels are burned (Wolvovsky and Anderson 2016; Ayasse et al. 2022). The intentional burning of excess gas during oil extraction, known as flaring, is also a significant source of CO_2 emissions globally (estimated at 500 million tonnes CO_2e in 2022 [IEA n.d.]), and natural gas venting and leakage from infrastructure releases large amounts of methane, an especially powerful GHG (Elvidge et al. 2009; Nara et al. 2014; Foulds et al. 2022; Negron et al. 2023). The latest IPCC report suggests that in order to remain consistent with a 1.5°C warming pathway, governments and industry should not pursue additional oil and gas operations, whether offshore or onshore (IPCC 2023). The UN Secretary General called for an 'Acceleration Agenda' that includes 'ceasing all licensing or funding of new oil and gas' and 'stopping any expansion of existing oil and gas reserves' (United Nations 2023).

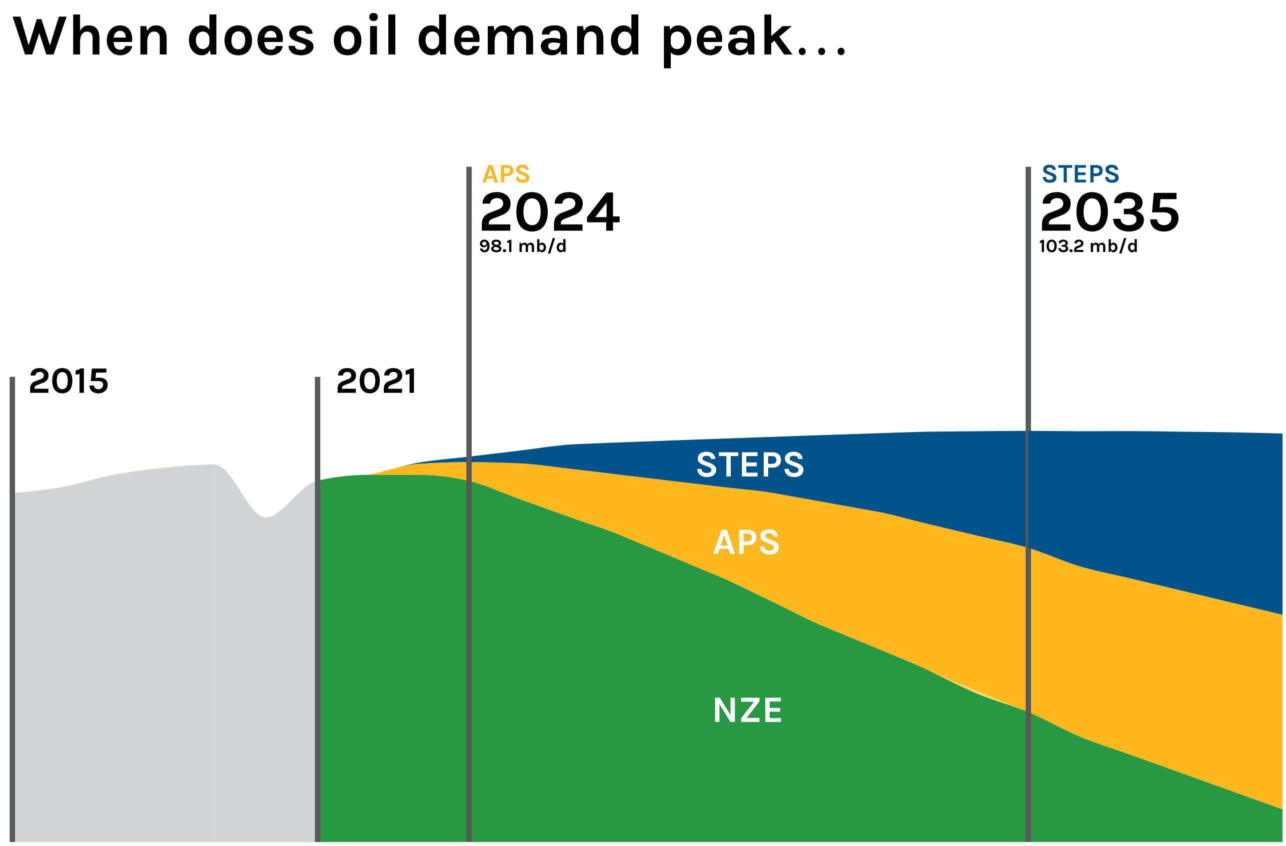
The latest World Energy Outlook (IEA 2022b) from the International Energy Agency (IEA) projects a peak in global energy-related CO_2 emissions in 2025. It makes this projection in its Stated Policies Scenario (STEPS), where governments around the world advance their existing energy policy measures without the development of additional energy targets in subsequent years (IEA 2022b). However, in this scenario, the energy sector emissions subside far too slowly to avert most catastrophic impacts of climate change. Between 2021 and 2050, annual CO_2 emissions from the energy sector decline by only 13 percent, projecting a rise of about 2.5°C in global average temperatures above pre-industrial levels by 2100. Conversely, stopping the expansion of oil and gas exploration and production, and accompanying this with policies to support deep and rapid reductions in hydrocarbon demand, will dramatically reduce emissions. The IEA maps out a way to achieve 1.5°C stabilisation by 2050 in its NZE scenario (IEA 2021a, 2022b). In this demand-led framework, future fossil fuel demand, from both onshore and offshore sources, could be met 'without approving the development of any new long lead-time upstream conventional oil and gas projects' (IEA 2021a, 2022b).

This analysis quantifies, based on scenarios from the IEA, how emissions would be reduced by stopping the expansion of offshore oil and gas drilling, as well as through the measured phasing down of production from existing offshore wells resulting from policies and changes in consumer behaviour that decrease fossil fuel demand. The analysis addresses only offshore oil and gas since it is a sector of the ocean economy. Neither the challenges with reducing global demand for oil and gas nor the specifics of which operations should phase down first, are addressed here.

Mitigation potential

The oil and gas industry, from production, transport, and refinement to combustion of those fuels, accounts for 35 percent of GHG emissions worldwide (UNEP 2022; IEA 2023c), and about 30 percent of that production is offshore. The World Energy Outlook (IEA 2022b) presents multiple scenarios for future oil and gas production and demand, including STEPS and NZE (Figure 6). In STEPS, oil demand would continue increasing slightly up until the mid-2030s (from 94.5 mb/d—million barrels per day—in 2021 to 103.2 mb/d in 2035), making it impossible to meet emissions reductions targets set out in the Paris Agreement.

Figure 6. Future oil and gas production (million barrels equivalent per day) according to different scenarios



Note: APS = 'Announced Pledges Scenario'; STEPS = 'Stated Policies Scenario'; 'NZE = Net Zero Emissions'.".
Source: IEA 2022b.

The NZE scenario shows what is necessary for the global energy sector to achieve net zero CO_2 emissions by 2050: no new oil and gas development and a contraction in production from existing wells driven by a sharp decline in fossil fuel demand (IEA 2021a).[9] For the offshore oil and gas sector, this will reduce production from 47 million barrels of oil equivalent per day (mboe/day) in 2021 to 12 mboe/d by 2050 (values derived from IEA 2022, Tables 7.1 and 8.1)—in line with a 1.5°C emissions reduction pathway. In this scenario, reduced demand is driven by a range of decarbonisation levers, such as energy efficiency measures, renewables expansion, greater electrification, and the use of green hydrogen. Many of these low-carbon technologies are passing key economic tipping points and are already more attractive than their hydrocarbon counterparts. For example, wind and solar are already the cheapest forms of new energy globally, and cost reductions are anticipated to continue (IRENA 2022; Lazard 2022; Systemiq 2023). However, as illustrated in section 2.2 Ocean-based renewable energy, scaling up requires many technical and non-technical factors including regulations to be developed to realise the technical and economic potential.

For this analysis, which focuses on ocean-based solutions to climate change, we assume that the gap in energy demand generated by the reduction in offshore oil and gas production is met by onshore sources of low-carbon energy to avoid double-counting with other ocean-based energy solutions highlighted in this report. The assumption of compensating growth in onshore low-carbon energy shows that phasing down offshore oil and gas depends on land-based action, not only action in the ocean. Conversely, we can assume the offshore renewable energy mitigation scenario for 2050 would displace electricity generation capacity that has the same emissions profile as currently exists, which carries a small offshore oil and gas component. However, the potential overlap between the two components is expected to be less than 5 percent of the offshore renewable energy associated estimates and within the bounds of uncertainty of the assumptions taken in each section.

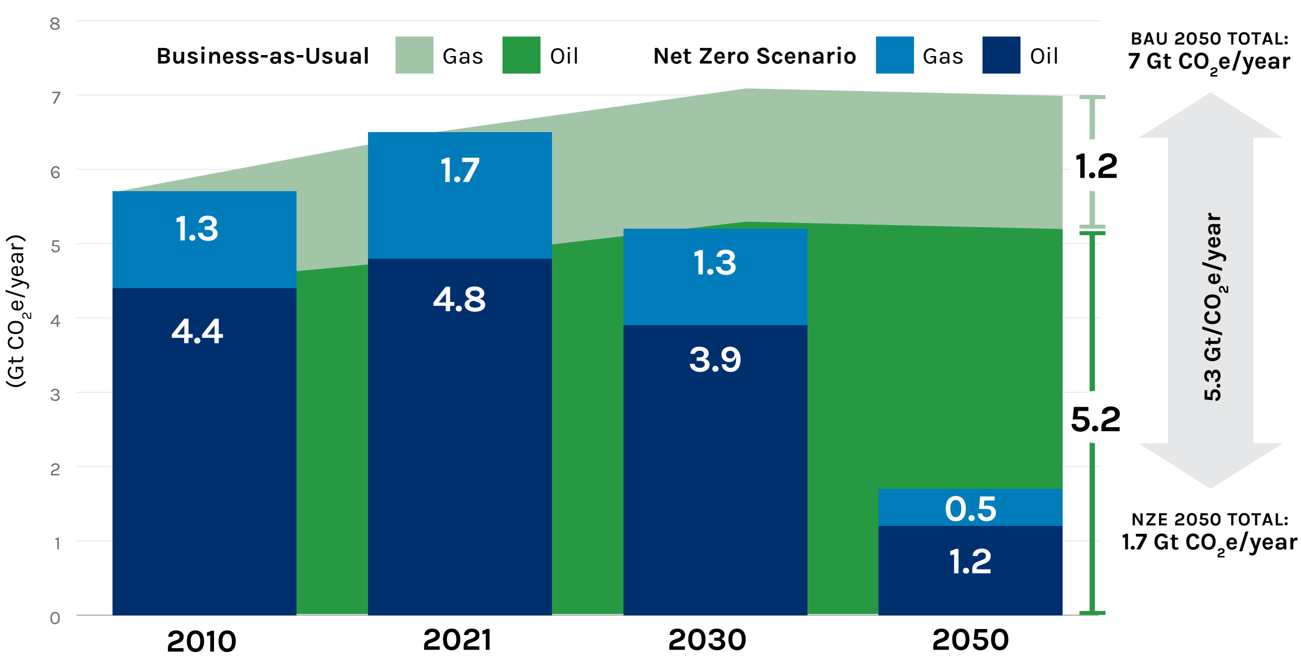
Compared to the current policies scenario STEPS, IEA's updated NZE scenario from 2022 would result in a reduction of 5.3 Gt CO_2e in 2050 (values derived from IEA 2022b, Tables 7.1 and 8.1) (Figure 7). In 2030, the mitigation potential versus STEPS is 1.8 Gt CO_2e per year (Table 15). In summary, this represents the net life-cycle emissions reductions possible if exploration for and development of new offshore oil and gas fields is halted, and production from existing fields is ramped down.

Table 15. Potential for different opportunities to mitigate carbon emissions, 2030 and 2050

OCEAN-BASED SECTOR	MITIGATION OPTIONS	DESCRIPTION	2030 MITIGATION POTENTIAL (GT CO_2E/YEAR)	2050 MITIGATION POTENTIAL (GT CO_2E/YEAR)
Offshore oil and gas	Stopping the expansion of offshore oil and gas extraction along with a demand-led phase-down of current production	Potential emissions avoided via reduction in the production and consumption of offshore oil and gas.	0–1.8	0–5.3

Source: Authors.

Figure 7. Emissions reduction that could be delivered by stopping the expansion of offshore drilling and phasing down production from existing wells in 2030 and 2050, compared with a BAU scenario of 7 Gt Co_2e/year



Source: Geers et al. 2022.

Wider impact analysis

Beyond the direct climate impact of extracted hydrocarbons, the offshore oil and gas sector also poses significant risks to the environment and marine biodiversity, which is a challenge for sustainable blue growth. Offshore operations pose the danger of accidental oil spills into the marine environment. Globally, the number of spills from offshore and coastal pipelines has multiplied from an average of 47 per year during 1968–77 to 350 per year by the 1990s (GESAMP 2007; Jernelöv 2010). On the U.S. outer continental shelf alone, between 1971 and 2010, there were 23 large offshore spills of more than 1,000 barrels of oil, or an average of one every 21 months (Anderson et al. 2012). Spills were so common in the Gulf of Guinea, that between 2002 and 2012 an ocean area averaging 574 square km was covered with oil slicks originating from offshore rig operations (Najoui et al. 2022). Operating conditions can be more complex for deepwater and ultra-deepwater offshore assets, and accidents, though less frequent, can have severe consequences as in the case of the Deepwater Horizon disaster (Beyer et al. 2016). Moreover, climate change impacts such as sea-level rise and more severe coastal storms may increase the risk of damage to offshore oil infrastructure and thus the risk of oil spills (Dong et al. 2022).

Phasing down fossil fuel usage to meet mid-century net zero goals will have a broad impact because it requires a planned retirement of existing facilities, and efforts to avoid the creation of new stranded assets. To overcome economic repercussions such as job losses, there is need for planned action including retraining and social protection for displaced workers. While this mitigation option extends many more comprehensive benefits, there is a need for consensus among various stakeholders for the planned phasing down and substituting alternative low-carbon energy installations to avoid disruption in access to affordable energy, minimise trade-offs and enhance social acceptance.

POTENTIAL BENEFITS	▪ **Wider benefits** of moving away from fossil fuel production and replacement by low-carbon energy is well established in the literature and in global assessments along most of the dimensions of sustainable development if diversification and social protection and retraining facilities are appropriately managed to take care of revenue loss, job loss and distributional impacts (IPCC 2018). ▪ **Social benefit can come from lower fatality rates**. Some country-specific case studies during 2003–10 showed that oil and gas extraction (onshore and offshore, combined) had a fatality rate seven times higher than all national workers (27.1 versus 3.8 deaths per 100,000 workers) (Gunter et al. 2013). ▪ **Halting new offshore oil and gas** extraction and burning will in turn avoid and reduce environmental contamination risks associated with operational by-products, discharges and leaks. For instance, produced water is the most significant by-product of offshore oil and gas extraction, and when unmonitored or unregulated is one of the largest operational sources of oil pollution to the sea that can potentially harm marine life and ecosystems (Neff et al. 2011; Beyer et al. 2020). ▪ **Social tension between groups** advocating for environmental protection and those pushing for expansion of offshore oil and gas can be avoided (Kapoor et al. 2021). ▪ **Reduced risk of oil spills and related** ecological, social and economic impacts to coastal environments and communities (Jernelöv 2010; Pascoe and Innes 2018; Najoui et al. 2022).
POTENTIAL IMPACTS OR RISKS TO MITIGATE	▪ Economic impact on coastal communities reliant on offshore industry for jobs. ▪ Environmental impacts in decommissioning sites.

Delivering on the potential: Priorities for action

The low-carbon energy transition, including stopping new offshore oil and gas and phasing down existing operations, relies on many changes across sectors, not just oil and gas (Table 16). To achieve the mitigation potential demonstrated by this analysis of the NZE scenario, any additional low-carbon demand beyond current extraction will have to be met by clean energy sources. The Section 2.2 on ocean-based renewable energy shows some of the complexities and challenges associated with scaling up capacity of offshore wind even if it is now a mature and cost-effective technology. The build-up of low-carbon energy onshore and offshore is key if phasing down offshore oil and gas is to contribute to solving the climate challenge. The authors acknowledge that if offshore production is phased down too quickly, new sources of conventional onshore oil and gas would need to come online in the near term to replace that fuel, diverting investment away from renewables and other low-carbon technologies and potentially increasing overall emissions. The emphasis therefore needs to be on reducing demand for fossil-fuel based energy sources through a variety of levers, in part by making it a less attractive option for consumers. In addition to halting the expansion of oil and gas production, the ramping down of existing fields should prioritise decommissioning the dirtiest extractive operations first, coupled with continued efforts to improve emissions efficiency and the environmental footprint of remaining operations. While this transition must be swift, it must not be done recklessly to avoid repeating the environmental, social and human harms unleashed by fossil fuel exploitation.

GOVERNMENT

To achieve the mitigation potential identified in this sector, governments can prioritise halting the expansion of offshore drilling, while at the same time promoting low-carbon energy policies and incentives (see 'Ocean-based renewable energy' for priorities for scaling ocean-based renewable energy), and drive a controlled phasedown of oil and gas demand and production worldwide (Table 16). Between 2021 and 2025, 355 major offshore crude oil and gas projects are expected to start operations in 48 countries (GlobalData 2021). A more recent analysis by Oil Change International found that new oil and gas production approved and likely to be approved between 2022 and 2025 could consume 17 percent of the world's remaining 1.5°C carbon budget (Tong et al. 2022). Under IEA's NZE scenario, none of these projects where the final investment decision was taken after 2021 are needed for energy security, even if exploration and development leases have already been awarded.

The first step that governments can take is to stop granting new licenses for oil and gas exploration in parallel with phasing in new carbon neutral energy sources. When a license for exploration is granted, it takes 20 years, on average, for an offshore asset to start producing (IEA 2022b). For already discovered reserves, the average time to start-up offshore operations is about 13 years (IEA 2022b). Under scenarios focused on reducing GHG emissions enough to prevent the worst impacts of climate change, pursuing new offshore oil and gas reserves is not viable. Indeed, a number of countries have either proposed or taken steps to halt or limit future offshore oil and gas exploration (Ambrose 2020; Danish Energy Agency 2020; Agencia Estatal de España 2021; Government of Ireland 2021).

Second, leases that have been granted but are not yet operational could be withdrawn. Some countries have leased areas of the seabed to drilling or suggested opening areas to exploration while also making net zero commitments[10]—these positions appear incompatible. Indeed, policies may be vulnerable to changes in government leadership and to global shocks such as the COVID-19 pandemic (Norouzi 2021), leading some governments that previously committed to halting offshore exploration to grant new licenses in recent years (New Zealand Parliament 2018; BOEM n.d.).

Third, stop subsidising offshore oil and gas development, which only encourages more production and disincentivises industry from investing in renewable energy or improving energy efficiency. From 2020–21, production subsidies almost doubled, reaching nearly $700 billion (OECD 2022). Consumption subsidies reached $1 trillion in 2022 (IEA 2023c). Under the NZE scenario, reduced demand for fossil fuels results from improving energy efficiency to lower overall energy demand, and from growing demand for renewable energy. Continued government subsidies for fossil fuel consumption distort the market and impede the private

…governments should invest in energy security and access for economically vulnerable communities.

sector and consumers from responding appropriately to signals, such as the increasing cost competitiveness of renewables. Providing incentives towards offshore wind may be particularly relevant since it relies on related technologies and operations and is sometimes co-located with present offshore oil and gas. Subsidies are not the only way governments are fuelling artificial demand for oil and gas. International public financing underwrites fossil fuel expansion, and this should be shifted towards incentivising and supporting the rapid scaling of renewable energy.

Fourth, countries that have significant offshore and coastal oil and gas infrastructure should—if they do not already—ban routine flaring and require decommissioning plans to ensure that remaining structures and materials do not jeopardise the health of surrounding coastal communities and marine environments. Additionally, economies that are heavily reliant on offshore oil and gas exports for foreign currency and income must proactively diversify their economies.

Finally, governments should invest in energy security and access for economically vulnerable communities. The energy transition can cause short-term fluctuations in energy prices as the global market adjusts to demand shifts, creating challenges for some consumers trying to meet their basic energy needs for heating, cooling, refrigeration and cooking. However, with foresight and planning, these are mitigatable challenges. In general, the fastest way to build local energy security is to rapidly deploy low-carbon energy technologies such as wind and solar (ETC 2022).

PRIVATE SECTOR

In the NZE scenario, whilst the extraction of oil and gas continues, global demand for oil and gas, including offshore, declines and no new fields are developed (IEA 2022b). To meet the demand levels modelled in the NZE with existing fields, operators must reduce average reservoir depletion rates from about 8 percent per year to about 4 percent per year, and therefore continue to invest in existing operations (Geers et al. 2022, appendix). As mentioned in section 2.2 Ocean-based renewable energy, the offshore wind industry, and the pace of scaling up offshore wind is affected by the level of activity in offshore oil and gas. In periods of low oil and gas prices, the offshore industry has turned to offshore wind and can be expected to do so the if demand for oil and gas is reduced.

Investors and financial institutions can play an important role in this shift. The Net Zero Asset Owners Alliance (NZAOA), a coalition of investors worth $11 trillion, recently published its position paper on oil and gas, in which it states an expectation that members adopt policies excluding investment in new upstream oil and gas projects (Peura et al. 2023). In 2022, HSBC, a global bank, also published an updated energy policy saying it will no longer directly finance new upstream oil and gas projects (HSBC 2022).

For operations remaining by 2030 and 2050 under the NZE scenario, well-to-tank emissions reductions and efficiency improvements are a priority. Most urgently, oil and gas operators should end routine flaring and invest in technology and practices to reduce methane leaks. These steps offer the dual benefit of helping to meet short-term demand shortfalls while reducing emissions. Indeed, in its latest World Energy Outlook, the IEA estimates that reduced flaring, venting and leakage could economically bring nearly 210 billion cubic metres of otherwise wasted gas to market, roughly 5 percent of current global demand (IEA 2022b). Additional opportunities to increase energy efficiency in operations (e.g., site transportation and power) also remain.

Along with governments, operators need to start making technical and financial plans for rig decommissioning. The private sector bears responsibility for ensuring that hazardous materials and infrastructure are properly dealt with while minimising environmental and safety risks and conflicts with other marine resource users.

Table 16. Short-, medium-, and long-term priorities/milestones to stop new offshore oil and gas development and phase down current production

SECTOR: GOVERNMENT		
SHORT TERM (BY 2025)	MEDIUM TERM (BY 2030)	LONG TERM (2030–50)
Initiate processes to withdraw fossil fuel subsidies in countries that currently provide them.	Shift government subsidies from offshore oil and gas development to renewable energy sources.	Treasuries reliant on offshore oil and gas for revenue should diversify economies.
Establish governance to stop the granting of new licenses for offshore oil and gas extraction.	End public financing for offshore oil and gas development.	Develop and enact decommissioning plans for offshore oil and gas infrastructure that ensure that remaining structures and materials do not jeopardise the health of surrounding coastal communities and marine environments.
Review offshore oil and gas leases that are not yet operational with a view to withdraw such leases.	Invest in energy security for economically vulnerable communities.	
Enact legislation and/or regulation to ban routine flaring.	Avoid encouraging investment in stranded assets.	
	Plan retraining, skill diversification and social protection.	
SECTOR: PRIVATE SECTOR		
SHORT TERM (BY 2025)	MEDIUM TERM (BY 2030)	LONG TERM (2030–50)
Invest in technology and practices to reduce methane leaks and end routine flaring in countries where it is still allowed.	Increase energy efficiency in offshore oil and gas operations.	Operators work with governments to develop and enact decommissioning plans.
Operators reduce average reservoir depletion rates from ~8% per year to ~4% per year.		
Investors and financial institutions need to signal that new oil and gas exploration and new infrastructure is not worthwhile and reprioritise investment in renewable energy infrastructure.		
SECTOR: RESEARCH COMMUNITY		
SHORT TERM (BY 2025)	MEDIUM TERM (BY 2030)	LONG TERM (2030–50)
Understand impacts of decommissioning of structures and materials on the health of surrounding coastal communities and marine environments.		
Identify gaps and opportunities for investment in training and skills development to ensure opportunities for transitioning the work force.	N/A	N/A

Source: Authors.

2.7 Marine carbon dioxide removal and carbon capture and storage

Carbon dioxide removal—or 'anthropogenic activities that remove CO_2 from the atmosphere and durably store it in geological, terrestrial, or ocean reservoirs, or products'—will be needed to help constrain global temperature increases to 1.5°C (IPCC 2018). Estimates of required total CDR (not marine pathways alone) in the 21st century vary from 100 to 1,000 gigatons of CO_2. The wide range of estimates results from differing assumptions about rates of emissions reduction. Marine carbon dioxide removal is a subset of activities within carbon dioxide removal that use the ocean to draw down and/or store CO_2 from the atmosphere (Table 17).

At present, research into mCDR is largely nascent. Scaling the industry in an equitable and responsible manner first requires large investment and coordination at the R&D level between governing bodies, researchers and industry. While this chapter focuses on the promise of mCDR techniques it also outlines the next steps to enable responsible mCDR research and implementation such as stringent monitoring of mCDR techniques and environmental impacts, as well as products that critically evaluate the efficacy of various approaches.

Table 17. mCDR approaches

TECHNIQUE	DESCRIPTION	WHERE DOES CO_2 DRAWDOWN OCCUR?	WHERE IS THE CARBON DURABLY SEQUESTERED?
Ocean alkalinity enhancement	Addition of alkaline materials into the ocean to increase ocean carbon uptake. Materials can be synthesised from rocks or produced electrochemically with seawater.	Surface ocean	In the surface and deep ocean as bicarbonate and carbonate ions
Direct ocean removal	Removal of dissolved CO_2 from seawater using physical and chemical approaches coupled with the return of CO_2-depleted seawater to the ocean for uptake of additional CO_2.	In enclosed facilities, likely in the nearshore, to leverage existing infrastructure required to move seawater	End products include: ▪ CO_2 gas, which can be durably sequestered in geologic reservoirs ▪ Carbonate minerals, which can be used as building materials
Ocean nutrient fertilisation	Application of macronutrients (e.g. nitrogen, phosphorus) and/or micronutrients (e.g. iron) to stimulate phytoplankton blooms or fertilise large-scale seaweed farms. Nutrients may come from surface addition or artificial upwelling.	Surface ocean	Deep ocean, as either biomass or dissolved CO_2
Seaweed cultivation and carbon sequestration[a]	Large-scale cultivation of seaweeds[c], often in new habitats and in deeper water. May require new nutrients, including via artificial upwelling or fertilisation.	Surface ocean	Active sequestration: Deep ocean if sinking seaweed or harvest and bring onshore for transformation, substitution and sequestration (e.g. biochar from seaweeds)[b] Passive sequestration: Regardless of where active sequestration occurs, all seaweed cultivation operations will passively export to the underlying sediments (whether in the shallow or deep ocean)[c]

Notes:

a. Protection and restoration of coastal habitats (marshes, mangroves, seagrasses, and natural seaweed beds), as well as restoration of marine animal populations, is covered in section 2.1 Marine conservation and restoration.

b. Farmed seaweed can also contribute to emissions reduction by substituting products with higher CO_2 footprints or being used as feed supplements to reduce ruminant CH_4 reduction (see '2.5 Ocean-based food'). Note that CO_2 drawdown and durable storage are also relevant for management of nuisance algal blooms, such as sargassum in the Atlantic Ocean.

c. Most seaweed cultivation relies on excess nutrients from land. Some projects suggest increasing nutrient supply via, e.g., artificial upwelling.

Source: Authors

There are three principal reasons why mCDR may be able to contribute between 100 and 1,000 gigatons of CDR by 2100. First, the ocean occupies over 70 percent of the surface area of the planet, which offers enormous pathways for scalability. Its vastness may also permit a wider array of mCDR activities, some with lower rates of CDR per unit area than would be feasible for land-based techniques when considering the competition for space with existing uses. Second, mCDR activities have the potential for fewer conflicts over space than do land-based activities, which must compete with a myriad of other land, energy and water uses. Relatedly, the more overall approaches of CDR that are applied in the earth system, the lighter the resource demands from any one method may be (Fuhrman et al. 2023). However, it should be noted that marine spatial planning also poses unique challenges (e.g. Spijkerboer et al. 2020). Third, the ocean is already the largest reservoir of carbon on the planet. With 38,000 gigatons of carbon, the ocean contains 50 times more carbon than the atmosphere (Canadell et al. 2018). The ocean carbon reservoir is so large that all anthropogenic carbon in the atmosphere constitutes less than 1 percent of the oceanic carbon reservoir.

In the years since the release of the 2019 Report, interest in and attention paid to mCDR activities has surged (GESAMP 2019; Moniz et al. 2020; National Academies of Sciences, Engineering, and Medicine 2021; Lebling et al. 2022; Ocean Visions n.d.). Yet mCDR measures remain at early stages of technological readiness, and none have been put through fit-for-purpose field testing repeatedly in ocean environments. A number of the mCDR approaches outlined in Table 18 have potential ecological and/or ethical impacts that need to be thoroughly considered and evaluated.

Carefully controlled and managed field testing is therefore critical for making evidence-based assessments of carbon removal efficacy and impacts to marine ecosystems. Marine CDR's substantial potential for achieving needed CDR and the technology's early stage of development highlights the need for further research and investment of resources (time, energy and people) to advance the science, engineering, policy, and governance strategies for addressing the socio-ecological and justice issues involved. Making informed decisions about any potential future deployments demands it.

Mitigation potential

Implementation of mCDR approaches may have the potential to help remove multiple gigatons of carbon dioxide from the atmosphere per year by 2050. This potential remains uncertain given the lack of research, pilots and field testing to date and the associated environmental and ethical risks raised by these approaches.

The mitigation potential estimates provided in Table 18 therefore represent plausible upper bounds of each technology's mitigation potential. Realising this potential is highly dependent on the research and development steps that should be taken right now to improve the knowledge base and de-risk these technologies. These mitigation potentials must be explored and considered in light of the possible risks and impacts associated with each option.

Box 1. Differentiating CCS from mCDR

Carbon capture and storage (CCS) is distinct from marine carbon dioxide removal (mCDR) approaches. CCS refers to the capture of carbon dioxide (CO_2) emissions from large point sources, such as power plants or industrial facilities, and then storing it in geological formations or other storage sites, including within the seafloor, to prevent it from entering the atmosphere.[a] In contrast, CDR involves removing CO_2 that is already in the atmosphere and upper ocean. Both CCS and CDR have the potential to contribute to mitigating climate change, but only CDR can address the warming from legacy emissions. CCS was covered extensively in the 2019 Report. Updates on mitigation potential of CCS are provided here, but the primary focus of this chapter is mCDR approaches which were not covered in the 2019 Report. Note that if CCS is used as part of a strategy for enhanced oil recovery (i.e. to push more oil and gas out of depleted reservoirs), it results in additional emissions of CO_2 to the atmosphere and exacerbates the climate crisis.

Source: a. IPCC 2005.

Table 18. Potential of different opportunities to mitigate carbon emission, 2030 and 2050

OCEAN-BASED SECTOR	MITIGATION OPTIONS	DESCRIPTION	DURABILITY OF CARBON REMOVAL (YEARS)	2030 MITIGATION POTENTIAL (GT CO_2E/ YEAR)	2050 MITIGATION POTENTIAL (GT CO_2E/ YEAR)
Marine carbon dioxide removal and carbon capture and storage	CO_2 storage below the seabed	Storage of CO_2 below the seabed in geological formations (total operational, under construction, and planned carbon capture and storage projects)	-	0–0.32	0–1
	Carbon dioxide removal approaches	Ocean alkalinity enhancement	>1,000	<0.1–>1	0.1–3
		Direct ocean removal	>100	<0.1–<0.5	0.1–1
		Ocean nutrient fertilisation	Unknown	<0.1–>1	0.1–3
		Seaweed cultivation and carbon sequestration (including both active sinking and passive sequestrationa)	Potential > 100 (deeper waters generally provide greater durability)	<0.1–<0.5	0.1–1
Total				**0.10–1.82**	**0.40–9.00**

Notes: See Appendix A. Estimates provided in this table represent gross mitigation potential and need accompanying life cycle analyses to develop net mitigation potential estimates.

For passive seaweed sequestration, 2030 ranges are 0.43×10^{-3} Gt CO_2e year-1 to 0.82×10^{-3} Gt CO_2e $year^{-1}$, and 2050 ranges are 1.44×10^{-3} Gt CO_2e $year^{-1}$ to 7.90×10^{-3} Gt CO_2e $year^{-1}$.

In addition, carbon capture and storage projects (Box 1) may avoid an additional gigaton of emissions annually in 2050 if the pace of current and planned projects continues to grow. These 2050 projections are based on a linear extrapolation of available data from the IEA (2023a).

ADDITIONAL OPTIONS REQUIRING MORE RESEARCH TO DETERMINE MITIGATION POTENTIAL

Terrestrial biomass sequestration

An additional mCDR option includes aggregating and sinking terrestrial biomass in the ocean. This would take place in either the deep ocean or shallow anoxic basins. Either biomass or dissolved CO_2 could affect deep ocean ecosystems and potentially expand anoxic zones. Further research is needed to gauge the mitigation potential and possible impacts of deploying this approach.

These mitigation potentials must be explored and considered in light of the possible risks and impacts associated with each option.

Wider impact analysis

The impacts on ecosystems from marine CDR are under-researched (National Academies of Sciences, Engineering, and Medicine 2021; Collins et al. 2022; Ocean Visions .n.d.) (Table 19).

Potential benefits, if demonstrated at scale, could offer critical services for climate mitigation that hold their market value. However, negative impacts could have substantial consequences on marine ecosystems, including economically important species. All ecosystem impacts should be evaluated in a comparative risk assessment framework that balances the risks of mCDR approaches against the risks to marine ecosystems from climate change along the present trajectory.

While sustainable seaweed farming and related products may support several sustainable development goals (Duarte et al. 2022a), there are social/ethical issues (e.g. conflicts in use of seaweeds for food as opposed to climate mitigation) in addition to ecological issues related with sinking such valuable products (Chopin 2021; Ricart et al. 2022).

Table 19. Environmental impacts of mCDR approaches

TECHNIQUE	POTENTIAL POSITIVE ECOSYSTEM IMPACT	POTENTIAL NEGATIVE ECOSYSTEM IMPACT
Ocean alkalinity enhancement[a]	Localised mitigation of ocean acidification	▪ Environmental impacts of mining (for mineral sources) (e.g. PM2.5) ▪ Heavy metal toxicity ▪ Secondary precipitation of carbonate minerals ▪ Changing phytoplankton functional groups and succession ('white ocean' effects)[b]
Direct ocean removal	Localised mitigation of ocean acidification	▪ Bycatch of marine life during intake pumping ▪ Secondary precipitation of carbonate minerals
Ocean nutrient fertilisation	Localised mitigation of ocean acidification	▪ Midwater column and deep-sea acidification and deoxygenation ▪ Changes in supply of food and energy to benthic ecosystems ▪ Use of nutrients that would otherwise support local and downstream marine ecosystems (nutrient robbing) ▪ Changes in plankton community structure, including risk of harmful algal blooms[c] ▪ (if using upwelling), introduction of substantial material into open ocean ecosystems
Seaweed cultivation and carbon sequestration	Localised mitigation of ocean acidification Increased refugia for marine organisms	▪ *Alterations to the deep-sea environment if cultivated seaweed is sunk in deep waters (>200 metres)*: acidification; oxygen depletion as seaweeds decompose and mineralisation of C (and other nutrients) becoming available again; changes in supply of food and energy ▪ *Alterations to the local physiochemical environment:* Use of nutrients that would otherwise support marine ecosystems ('nutrient robbing') in case nutrient requirements exceed excess nutrient supply from land; changes in supply of food and energy to benthic ecosystems ▪ *Biotic issues:* Alteration of population genetics, facilitation of disease

Notes: This table includes commonly considered environmental impacts but is not comprehensive.
a. Bach et al. 2019.
b. Bach et al. 2019.
c. Trick et al. 2010.

Source: Authors.

The positive and negative social impacts of mCDR approaches are understudied and need to be investigated. Resources will need to be invested to better understand the social challenges and opportunities of mCDR (National Academies of Sciences, Engineering, and Medicine 2021; Collins et al. 2022; Cooley et al. 2023).

Marine CDR approaches require input products such as fertiliser, crushed rock, and electricity. At research and development stages, these materials can be procured without substantial disruption to existing supply chains and social systems. Should these technologies be ready for deployment after scaled research and development, their impacts on human livelihoods, well-being and sustainable development goals will need to be analysed, and risks mitigated.

Research is needed to understand the opportunities and challenges associated with any scaling from research-stage activities to deployment-stage activities. For example, 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).

Community input is a critical part of responsible mCDR research projects (Nawaz et al. 2023). In future scenarios where they are sufficiently de-risked and scaled, mCDR approaches would likely impact coastal communities and labour markets. Individuals in technical and non-technical fields will need training to succeed in any potential new industry. Governance will be needed to ensure that the risks and benefits of the mCDR industry are equitably distributed.

Delivering on the potential: Priorities for action

Harnessing the potential of mCDR as a climate solution will require scaling quickly, equitably and sustainably. Yet the current research landscape is inadequately resourced to resolve the scientific, technological and ecological uncertainties at hand. There is insufficient funding for the research necessary to resolve uncertainties (Lebling et al. 2022).

Existing international and national governance frameworks for activities in the ocean are not sufficient to comprehensively and proactively regulate mCDR approaches as they are being developed and deployed (Lebling at al. 2022). Existing international law frameworks, although designed to minimise and regulate environmental harm, predate the development of novel mCDR approaches. There are thus limited and often conflicting assessments of how these frameworks would apply to mCDR approaches, creating a great deal of uncertainty. Inadequate regulation could potentially allow unsuitable or excessively risky projects to proceed without necessary safeguards or monitoring. It could also potentially delay research or test projects unnecessarily (Brent et al. 2019; Webb et al. 2021). Governance of mCDR must not only involve regulation but should include public policy participation, equitable benefit sharing and transparent access to information (Lebling et al. 2022).

Government, industry and researchers must work together in order to successfully execute mCDR research strategies and set up robust governance structures to support responsibly scaled operation. Table 20 synthesises mCDR approach-neutral priorities outlined in various reports and other published mCDR studies (Mace et al. 2021; Gagern et al. 2022; Lebling at al. 2022; Loomis et al. 2022; Boyd et al. 2023; Fuhrman et al. 2023; Webb and Silverman-Roati 2023).

Short-term priorities are centred on generating knowledge and enabling governance frameworks to allow for pilot projects and robust monitoring of carbon removal. With adequate mobilisation of resources, many short-term milestones can be accomplished by 2025. Medium-term priorities focus on creating market standards, cultivating diversity in an expanding industry, and managing large pilot projects. Lastly, long-term priorities focus on transition of mCDR to a fully operational scale.

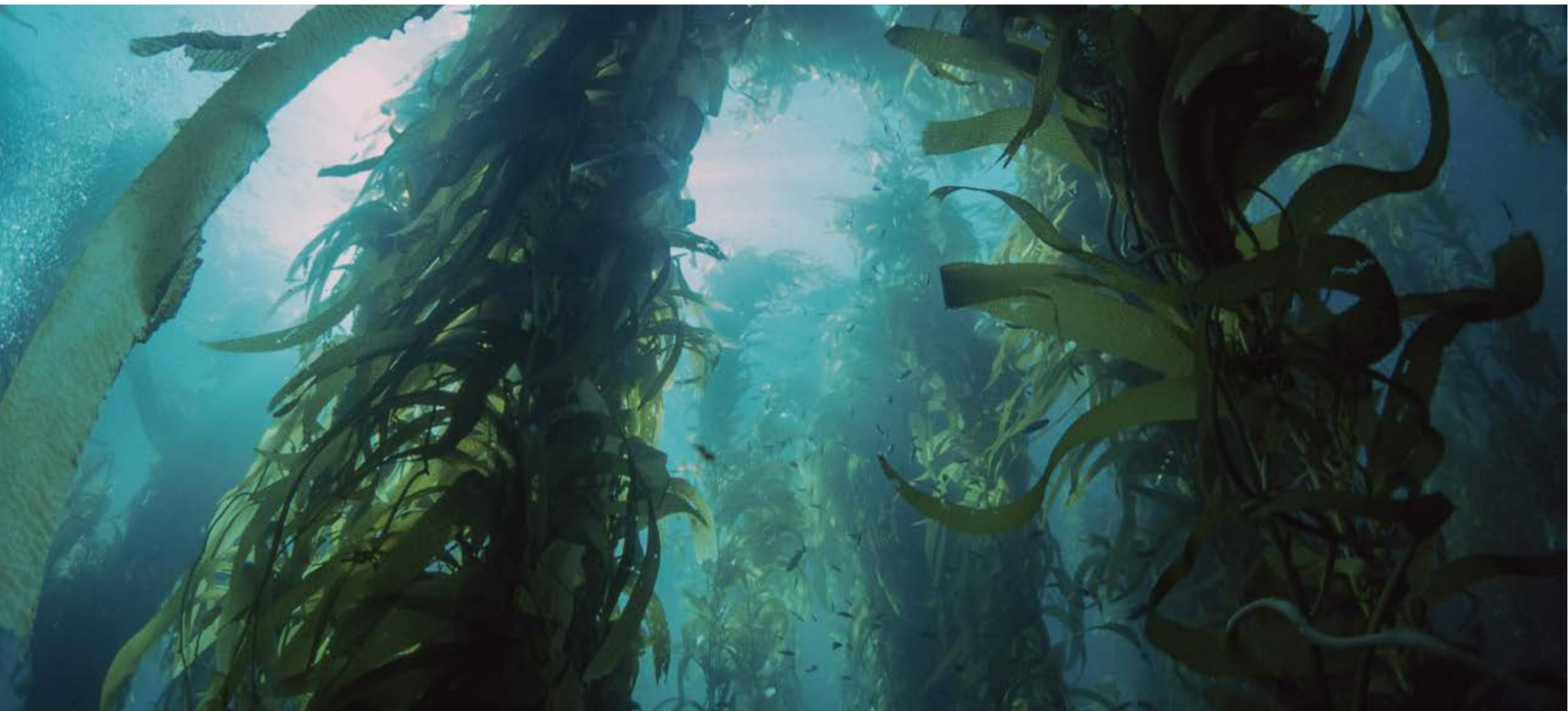
Table 20. Short-, medium-, and long-term priorities/milestones to advance research and development of mCDR approaches

SECTOR: GOVERNMENT		
SHORT TERM (BY 2025)	**MEDIUM TERM (BY 2030)**	**LONG TERM (2030–50)**
Develop model governance frameworks and/or codes of conduct (internationally and domestically).	Develop products that document the efficacy and trade-offs of mCDR for deployment decisions.	Support responsible deployment of promising mCDR methods.
Establish domestic and international legal frameworks specific to mCDR which set regulatory standards.	Create standards for ocean-based carbon accounting including standards for monitoring, reporting, and verification (MRV).	Continue to advocate for a just transition to a growing mCDR sector.
Harness mCDR projects as an opportunity to increase equity and justice initiatives.	Sustain an accurate and substantial in situ observing program that reflects MRV and transparent environmental monitoring needs.	Robust international governance of deployments.
Sponsor research, including supporting incremental testing and monitoring programs.	Support a publicly accessible system for monitoring mCDR impacts.	
Support research on the environmental and societal implications of mCDR.		
SECTOR: PRIVATE SECTOR (INDUSTRY AND NON-PROFITS)		
SHORT TERM (BY 2025)	**MEDIUM TERM (BY 2030)**	**LONG TERM (2030–50)**
Coordinate with government and research sectors to sustain a transparent research infrastructure.	Deploy various pilots with robust monitoring, reporting and verification to verify the efficacy of mCDR approaches.	Execute field deployments.
Co-design research objectives with indigenous and coastal communities.	Streamline processes for monitoring, reporting and verification through automation and modelling.	Scale from pilot projects to commercial operation.
Construct and share robust monitoring, reporting and verification plans, which include life cycle emissions accounting for net removal estimates.		Hire and retain a diverse and highly trained workforce.
Co-develop with other stakeholders, and follow a mCDR code of conduct.		
Provide early investments to catalyse innovation in the mCDR landscape.		

Table 20. Short-, medium-, and long-term priorities/milestones to advance research and development of mCDR approaches (Continued)

SECTOR: PRIVATE SECTOR (INDUSTRY AND NON-PROFITS)		
SHORT TERM (BY 2025)	**MEDIUM TERM (BY 2030)**	**LONG TERM (2030–50)**
Conduct cross-sectoral research on the social and environmental impacts of mCDR strategies and develop best practice guides for mCDR research.	Understand how users view and use monitoring data and certification.	Support a transition to autonomous and interpolated monitoring, reporting and verification through continuous ocean observing, innovation and modelling efforts.
Conduct field and pilot studies to understand the efficacy and impacts of mCDR.	Integrate regional field data into integrated assessment models.	Continue to train and mentor a diverse and highly trained mCDR workforce.
Incorporate mCDR methods into integrated assessment models and consider interactions with Sustainable Development Goals.	Deploy next generation of ocean sensors.	
Push forward innovative sensor and model designs to allow for more robust monitoring, reporting and verification.	Increase baseline ocean chemistry measurements in regionally under-monitored areas.	
Improve the resolution of ocean chemistry baseline measurements.	Translate mCDR literature into other languages and incorporate indigenous knowledge into mCDR learning.	
	Mentor and support early career ocean professionals and researchers, including from the Global South, that will fuel the mCDR workforce.	
	Grow ocean science programs to provide adequate training for the growing mCDR sector.	

Source: Authors.



Research and large-scale field testing of mCDR approaches could accelerate through integration with existing coastal and offshore industries. Direct ocean removal and electrochemical ocean alkalinity enhancement both require large quantities of pumped and filtered seawater, as well as stable sources of electricity. Existing coastal industries, such as desalination and power plants, may be well positioned to meet these requirements. In addition, existing and planned offshore infrastructure, such as offshore wind farms and decommissioned oil platforms, may provide unique opportunities to co-locate mCDR approaches, such as seaweed cultivation and direct ocean removal. As an example, a recently announced pilot 10-hectare seaweed farm within an offshore wind park in the North Sea may serve as a model for these multi-use integrations.

Should mCDR approaches prove effective and safe during research and development phases, as determined through an internationally coordinated, inclusive and transparent sharing of findings and results, these approaches will need large quantities of stable, renewable energy for large-scale demonstration and potential deployment. All CDR approaches must account for emissions within their value chain as part of a life cycle assessment, so minimising carbon emissions as part of mCDR operations is a key part of maximising these approaches' climate mitigation potential. Meeting the energy needs of any future large-scale operations in the open ocean is a challenge because of the current high cost and difficulty of transporting conventional sources of energy. New marine renewable energy technologies, such as wave energy, ocean thermal energy and floating solar may meet the energy needs, especially for mCDR projects far from shore. As mCDR and marine renewable energy continue to develop, there is an opportunity to align development needs of these two nascent fields to ensure that future mCDR testing, and any future deployments, are powered by local renewable energy.

Investment of time, energy and resources to conduct controlled field trials of mCDR approaches is most critical to advancing knowledge. Governments, civil society, academia and the private sector will need to collaborate to conduct the multiple field trials that are needed for each mCDR approach. These field trials must be designed in a manner that allows for transparent assessments of additionality, durability, environmental impacts and social impacts. They will need to occur in the near-to-medium term (between now and 2030). Field trials can start at smaller scales and grow. It is likely that large-scale (greater than one square kilometre) field trials in the open ocean will each cost 10s to 100s of millions of US dollars (National Academies of Sciences, Engineering, and Medicine 2021; Ocean Visions and MBARI 2022). Sub-national, national and international policies that facilitate responsible research, transparency, outside review of field trial results, co-design and knowledge sharing are all key to creating an enabling environment for conducting controlled field trials.

Investment of time, energy and resources to conduct controlled field trials of mCDR approaches is most critical to advancing knowledge.

Financing the transition

The potential climate benefits of the opportunities detailed in this report can only be realised with sufficient financial investment to support needed technology and infrastructure development, alongside capacity building. Each ocean-based sector investigated has distinct possible financial sources, needs, and challenges. Where finance is currently available it needs to be fully aligned with zero carbon pathways; where funding is currently scarce, de-risking, guarantees and blended finance can help.

Financing the sustainable ocean economy is daunting (Sumaila et al. 2021) with each ocean-based climate solution facing its own array of challenges. One way to facilitate finance flows is to remove subsidies from competing activities, thereby making investments into alternatives more attractive. Funding available from public and private sources for mature technologies in stable jurisdictions probably already exceeds their absorptive capacity. Yet less mature approaches in regions with institutional bottlenecks and higher perceived risks have limited access to finance at any significant scale. Where finance is available it needs to be fully aligned with zero carbon pathways; where funding is scarce, de-risking, guarantees and blended finance can help. In practice, institutions need to address three distinct topics:

1. The development of new and robust funding pathways based on the diverse benefits ocean-based climate solutions support. In particular, the finance of NbS and sustainable blue foods —sectors which have been difficult historically to adequately address by traditional finance. In practice this means , for instance, that public development finance institutions need to proactively engage in supporting sustainable ocean economy investments and integrate NbS and biodiversity finance into infrastructure finance; for example, offering de-risking tools to facilitate access to international capital markets and to longer-term large private capital asset owners.

2. Allowing rapid disbursement and adequate refinancing to large-scale ocean-based climate opportunities that are mature, such as offshore wind, where finance bottlenecks no longer apply to the projects themselves but may still result from a lack of regulatory frameworks and supply-chain aspects in certain countries.

3. Implementing a robust transition finance disbursement criteria for those sectors that have sufficient access to traditional finance but need to rapidly reduce their climate and biodiversity impacts, such as shipping, fishing and cruise tourism. These sectors will also need access to new technologies and processes which themselves face finance constraints because of their lack of maturity.

All three topics can benefit from increased scale and common standards, based on the development of a robust ocean finance architecture. Common standards can lead to lower transaction costs and increased secondary market activity. As the overall scale of the sector increases, performance metrics should become more robust and attract additional investment, and thereby support wider market and finance development. This will support the delivery of an overall additional investment of at least $2 trillion[11] during the 2030–50 period to reach scale across the sectors (GIH 2018; Krishnan et al. 2022; Morgan Stanley 2023). Whilst the finance available for ocean-based climate solutions probably already exceeds the identified SDG14 financing gap of $175 billion per annum (Johansen and Vestvik 2020), it is not efficiently targeted at this goal. In any case, this amount is dwarfed by what governments and international financial institutions are currently spending on funding for activities that can cause damage to the natural environment, which ranges from $500 billion to $1,100 billion per year. That sum is three to seven times larger than current investments in NbS overall (UNEP 2021). Philanthropies, foundations, NGOs and civil society will also need to play an active role in helping to promote and de-risk ocean-climate solutions.

An important recent development in providing additional sources of finance is the IMO's commitment to implement GHG pricing. Various studies have estimated the magnitude of the annual revenues this could raise as $40–$80 billion per annum, and cumulatively reaching $1–$2 trillion, which could be committed into an IMO 'fund' (Baresic et al. 2022). Several states have made proposals within the IMO's process for finalising the design of this policy. The Summit for a new Global Financing Pact, led by President Macron and held in June 2023, saw 23 countries, both high and low income, supported the concept of an IMO levy/price on GHG emissions. The countries agreed that any levy should contribute to a 'just and equitable transition,' language which is also deployed in the IMO's Revised Strategy (IMO 2023a; Présidence de la République 2023). One specific proposal is for the spend to be on ocean transport decarbonisation to accelerate this ocean mitigation opportunity. Other proposals suggested that the majority of monies be spent on wider GHG mitigation and adaptation opportunities, with prioritisation towards the most climate-vulnerable countries (IMO

2021). The range of options for the use of IMO GHG pricing revenues has been explored by the World Bank (World Bank 2023), classifying a range of uses. These debates are a key opportunity for shaping a new source of finance. The IMO has committed to completing the specification of how much revenue will be raised and where and how it will be deployed by the end of 2025. Leading up to this, key debates are scheduled throughout 2024 (IMO MEPC 81 and 82).

3.1 Overarching goal to finance 2030 and 2050 mitigation potential

Global investment in the low-carbon energy transition amounted to $1.1 trillion in 2022 (BNEF 2023). The Global Gateway programme alone aims to mobilise €300 billion in investments into climate action, low-carbon energy and connectivity between 2021 and 2027 with a mix of grants, concessional loans and guarantees to de-risk private sector investments. EIB Global, the development arm of the European Investment Bank, will mobilise at least €100 billion of this target to partner countries in the Global South in support of their resilience and sustainable development. Other relevant pathways include Just Energy Transition Partnerships with deals so far in South Africa ($8.5 billion), Indonesia ($20 billion) and Vietnam ($15.5 billion). These approaches offer opportunities to revamp national development prospectives, using large-scale renewables production both for export-led green hydrogen and to develop in-country manufacturing and services, integrating ocean-climate mitigation solutions cost-effectively at scale, from offshore wind to port logistics and zero carbon shipping to a domestic services industry around coastal tourism and blue well-being.

Some countries will be able to rapidly access significant funding sources whilst others may struggle given the need for appropriate investment formats (such as public-private partnership structures), regulatory frameworks and capacities. Furthermore, unless these mitigation opportunities are fully embedded into wider development plans that take into account ocean health overall and address the concurrent challenges of adaptation, biodiversity loss and pollution, such as Sustainable Ocean Plans developed under appropriate guidance (Ocean Panel 2021), these finance approaches may on their own not be sufficient to deliver a nature-positive and just transition. A broader-based funding narrative is thus required.

Nature-based solutions, fully integrated into coastal development plans and embedded into blue infrastructure concepts, can play a critical role in delivering wider environmental and economic benefits. This requires appropriate accounting approaches to support the development of natural capital asset classes, which facilitate access to large-scale institutional finance. Likewise, large, efficient finance sources such as capital markets need to fully engage through the issuance of specific instruments such as blue bonds but also by developing appropriate regulatory bodies, disclosure and reporting requirements and other needs to provide investment opportunities for large-scale long-term investors such as pension funds and other such asset owners (Schindler Murray et al. 2023). The World Bank's Global Program on Sustainability, for example, supports the development of cutting-edge data and analytical products on natural capital, supporting decision makers in over 20 countries to apply and implement natural capital accounting across the public and private sector.

The full range of financial approaches needs to be brought to bear to ocean solutions to help deliver not only immediate financial returns to investors but also long-term social returns to society if conscious decisions are made to avoid unintended trade-offs. $1 trillion of additional finance is required by 2030 to facilitate a rapid transition to the ocean-climate solutions outlined in this report.

3.2 Sector-by-sector analysis

Marine conservation and restoration

Global flows into NbS overall need to quadruple per year by 2050 (UNEP 2021), but there are key barriers to accessing finance for and investing in nature-based solutions. Most traditional finance has limited traction in the NbS space. Project companies have had limited use of basic commercial finance tools such as loans, factoring or asset finance. Whilst there has been some activity from a limited number of impact investors, the lack of track record and exit opportunities means that the equity segment is also at an early stage. Ecosystem protection rarely offers direct payment streams, whilst ecosystem restoration, where deliverable in the marine space, can have significant challenges and costs. As a result of the lack of direct financing options, bundled approaches through larger capital market transactions, including structured finance and blue bonds, are required to bring international capital markets into blue ecosystem restoration. The recent Galapagos debt for nature transaction is one such example. Similarly, the work of multilateral development finance institutions in integrating NbS into broader blue infrastructure approaches will be critical to develop this area.

This sector analysis covers the financing of the blue carbon ecosystems discussed in the relevant chapter. The State of Finance for Nature 2021 report (UNEP 2021) puts the cost of mangrove restoration finance at a total of $15 billion for the 2021–2050 period, of which $4 billion invested by 2030 is the target of the mangrove Breakthrough (Climate Champions 2022). Other systems such as seagrasses, salt marshes and potentially kelp are likely to require investments at a similar or smaller scale.

Whilst markets are increasingly proposed as financing mechanisms for nature, both in the form of specific credits (e.g. carbon, biodiversity) or in the form of broader nature asset markets, so far only blue carbon for mangrove restoration has found methodologies to provide some investment flows (Schindler Murray et al. 2023). The amount of carbon sequestered through those transactions and corresponding finance is likely to remain small by 2030, unless jurisdictional approaches under Art. 6 of the Paris Agreement can be put in place (Schindler Murray et al. 2023).

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

A wider range of nature-based ocean-climate efforts gaining access to significant finance will require solid assessment/accounting methodologies with granular and robust data for analysing sustainability risks, opportunities and impacts at the local level, as well as adequate asset disclosure and reporting frameworks, including via NDCs under the Paris Agreement (Schindler Murray et al. 2023).

Ocean-based renewable energy

The global offshore wind market grew by 8.8 GW in 2022, attracting $31 billion of investment, and is expected to add 35.5 GW in 2027 (GWEC 2023). Cumulative investments will make the sector the most important ocean-climate mitigation solution by 2030 (IRENA 2023). Offshore wind will install more than 25 GW in a single year for the first time in 2025, requiring investment into new industrial capacity, training and skills. For finance to be sufficiently accessible, it will require:

- Reform of the lending practices of development finance institutions, including being able to deploy concessional funding for projects in countries that may be in debt distress (IEG 2023).
- Strengthening instruments and procurement processes to channel public finance to key infrastructure such as transmission lines, including through equity and direct ownership of assets.
- Assisting developing countries to put in place a robust strategy and regulatory framework for offshore wind deployment (such as put in place by Brazil, Egypt, India and Morocco), including in terms of marine spatial planning and marine biodiversity protection.

Other marine energy sectors have not reached the maturity required for attracting traditional finance and are likely to continue to deliver energy that is more expensive, except for very specific applications, given limited economies of scale and technical challenges (IRENA and CPI 2023).

Ocean-based transport

The shipping sector has identified several pathways for the transition to net zero, including the Clydebank Declaration for Green Shipping Corridors, the IMO Initial Strategy of 2018 and other low-carbon shipping initiatives. Estimates based on IMO Initial Strategy ambitions put the total additional capital needed for reducing carbon emissions from shipping by at least 50 percent by 2050 at $1–$1.4 trillion, with over 80 percent going to infrastructure investment on land (Global Maritime Forum 2020). Based on these estimates, if shipping was to fully decarbonise by 2050, this would require extra investments of approximately $400 billion over 20 years, making the total investments needed between $1.4–1.9 trillion overall (Global Maritime Forum 2020). This includes the capital required to construct land-based bunkering infrastructure of zero carbon emission fuels, and related investment into research, which will require around $40 billion annually by 2030 (Baresic and Palmer 2022). The primary challenge is to align shipping fully with the Paris Agreement. For example, the global fleet running on LNG risks financial losses in stranded assets of $850 billion by 2030 (Fricaudet et al. 2022). The full value of this risk would not be realised if the LNG-fuelled vessels were retrofitted to run on zero emissions fuels, such as ammonia. In this scenario, the financial loss is estimated at around 15–25 percent of the vessel's value, between $129–$210 billion (Gerretsen 2022).

The key mechanism for unlocking Paris-aligned mitigation finance for ocean transport (and cruise tourism) is the development of clear and effective policy. The outcome of the IMO's Revised Strategy (IMO 2023c), committing the IMO to stringent GHG reduction targets, the revision of existing GHG policy measures, and the development of new GHG policy measures can create a business case for investment and significant alignment for new and existing private finance, with 'public' finance for ocean transport GHG mitigation generated through IMO GHG pricing, as well as in national and regional policy. This will need to rapidly develop as there is still limited evidence of final commitment to zero emissions technology investment for the sector, as well as limited evidence for investments into early-stage technology businesses that can help transform the sector. These areas require targeted, knowledgeable impact and venture finance to initiate investment, but ultimately, to achieve the scaling needed for this sector's transition, there is likely a need for the lower cost capital from institutional investors. The sector has access to a wide range of traditional finance mechanisms offering multiple pathways to deliver appropriate funding structures.

Ocean-based tourism

The cruise tourism sector faces similar challenges to ocean-based transport. It has good access to traditional marine finance, but transitioning rapidly to zero carbon cruising requires new technologies, approaches and appropriate finance mechanisms. Incentivising therefore requires strict regulation, such as the requirement some through ports have introduced requiring cruise ships to use (renewables-based) shore power. Investments into land-based renewables as well as into port logistics can be commercially funded and would help improve the carbon impact of cruise ships.

Ocean-based food

To deliver the drastic emissions cuts required from food systems, finance for the sector must be re-aligned to fully integrate both climate and nature considerations into funding decisions. This means targeted funding for regenerative aquaculture, including seaweeds and invertebrates, and mariculture that can contribute to ecosystem restoration and climate mitigation. Investment on the order of $55 billion total will likely be needed between now and 2050 (Elwin et al. 2023). At the same time all aquatic food production needs to be strictly managed to improve compatibility with biodiversity considerations, and any remaining subsidies need to be redirected away from non-sustainable activities.

Offshore oil and gas

Offshore oil and gas was not included in the sector by sector analysis because no public financing is required to halt the expansion of new offshore oil and gas extraction. However, redirecting subsidies that currently go towards fossil fuel exploration and production could provide valuable financing for the other ocean-based climate solutions outlined in this report (OECD 2022).

Marine carbon dioxide removal and carbon capture and storage

Given the complexities surrounding marine carbon dioxide removal and carbon capture and storage outlined in this report, it is critical that funding in this area be directed towards science, research and governance to provide a solid knowledge base before any future finance approach. Predictable carbon sequestration technologies are of significant interest to hard-to-abate industries and are likely to attract commercial finance over time.

3.3 Priorities for financing ocean-based climate solutions

Direct finance for mature ocean climate solutions such as offshore wind is available at scale and on commercial terms. Here the finance emphasis needs to be on supporting value chains, training and on delivery to the widest possible range of countries (Figure 8). For other renewables technologies (such as floating solar, wave and tidal) that have not reached the same level of maturity and may only be cost-competitive in selective locations, funding must focus on R&D before large-scale commercial finance will become available.

A different finance challenge is faced by those sectors where the climate mitigation benefits are primarily additional, even if significant, to the other benefits provided. For instance, blue foods serve direct human needs and coastal ecosystems provide protection and resilience to local communities. Both need to be managed to protect biodiversity and investments need to critically address adaptation and transition challenges, so emphasising purely carbon benefits is inadequate. The finance sector should prioritise reflecting this reality.

On 16 April 2023, the G7 in Sapporo reiterated their ‘commitment made in the G7 2030 Nature Compact, to increase our finance contributions for NbS through to 2025. We also commit to promoting better measurement and monitoring, management and restoration of the marine and coastal ecosystems which store carbon, enable resilience and provide habitat for marine species’. Multilateral Development Banks (MDBs), development finance institutions (DFIs), and private financial institutions will need to better integrate adaptation and resilience impact into their investment portfolios and scale up their ambition for future investments (HM Government 2023). Countries particularly affected by climate change need fast access to funding, such as through the Global Shield Financing Facility and increasing the volume of private finance for adaptation and resilience.

As an example, the European Commission through its Blue.invest initiative (van Aalst et al. 2018) supports an emerging group of blue impact funds. Under NextGenerationEU, the 27 national recovery and resilience plans funded by the Recovery and Resilience Facility (RRF) already make available €250 billion for green measures, including investments supporting the decarbonisation of industry. Horizon Europe dedicates €40 billion to Green Deal research and innovation (European Commission 2023). Cohesion policies make around €100 billion available for green transition, including the Just Transition Fund (European Commission 2023). All of these measures can help support ocean-climate solutions.

Supporting countries to capitalise on nature’s ability to tackle climate change through its ecosystem services, whilst also making ecosystems more resilient, will be key, including through the UNDP Climate Promise, which supports countries to integrate nature into their NDCs.

Countries particularly affected by climate change need fast access to funding, such as through the Global Shield Financing Facility and increasing the volume of private finance for adaptation and resilience.

Figure 8. Priorities for finance by 2025 and 2030, to achieve objectives in 2050

2025

- Re-align frameworks and approaches to achieve nature-positive net zero.
- Provide additional finance for early stage companies with zero carbon solutions.
- Launch collaborative finance partnerships and solid standards for a rapid transition.
- Agree on targets and pathways for ocean sectors that are Paris-aligned to ensure consistent policy signals for investing.

2030

- Scale up working solutions, overcoming bottlenecks to finance a wider range of ocean technology solutions.
- Focus on delivering ocean climate benefits everywhere, including in those parts of the Global South that to date lack some of the preconditions for sufficient finance flow.
- Deliver NbS finance, with emphasis on co-benefits, adaptation, resilience and biodiversity, backed by an emerging nature assets call.
- Show significant progress in all sectors.
- $1 trillion of additional finance by 2030 to facilitate a rapid transition to the ocean-climate solutions outlined in this report.

2050

- $2 trillion needs to flow into ocean solutions between 2030 and 2050.
- Transformation of the sectors is complete, so that there is no more need for transition finance, and all funding goes to fully net zero climate approaches.
- All finance is ocean- and nature-positive, with a robust monitoring and management framework based on near-real time data at site and asset level, both in national waters and in the high seas.

Source: Authors.

Conclusion

Our ocean has an essential role in mitigating and adapting to climate change. Ready-to-implement ocean-based solutions can close up to 35 percent of the emissions gap in 2050 between a pathway based on "Current Policy" and a pathway that would hold global warming to 1.5°C above preindustrial levels. However, time is running out to explore, test and invest in these options to realise their full potential. Decisive action is required on multiple fronts and must be accompanied by deep cuts in emissions across all terrestrial sources of greenhouse gasses.

The ocean and its economy are essential players in mitigating and adapting to climate change, but progress in adopting ocean-based climate solutions has not matched their potential. This report emphasises the significant role the ocean can play in offering sustainable and effective solutions to the global climate and biodiversity crises. However, time is running out to explore, test and invest in these options to realise their full potential. The solutions presented in this report are also not a silver bullet and must be accompanied by deep cuts in emissions across all terrestrial sources of GHGs.

The updated findings from this report (as compared to the 2019 Report) reveal that ocean-based solutions that are ready to implement could contribute 11–35 percent of the annual emissions reductions needed in 2050 to limit global warming to 1.5°C above pre-industrial levels. Promising advances in offshore renewables and the possibility of shifting away from offshore oil and gas in the global energy mix have expanded emissions reduction potential. Nature-based solutions, such as protecting coastal ecosystems, are no-regrets approaches, aligning with the Kunming-Montreal Global Biodiversity Framework.

To achieve meaningful results, we must also address coastal ecosystem degradation at its source and engage in proactive meaningful protection and conservation of coastal ecosystems. Once ecosystems are lost and soil carbon is emitted into the atmosphere, it can take decades to centuries for restored ecosystems to recover the soil carbon (Lee et al. 2019; Lovelock et al. 2022).

Additionally, comprehensive analysis of ocean-based interventions can minimise risks and trade-offs while enhancing climate benefits. To fund these solutions, world leaders must engage with time-critical challenges and harness opportunities for the private sector to align finance flows towards at least $2 trillion of investment flowing into ocean solutions over the 2030–50 period.

Ultimately, action can only be achieved through ambitious, inclusive and collaborative partnerships to address ocean challenges, including reducing pollution, improving governance and enhancing international cooperation. Recognising the ocean as a valuable ally in the fight against climate change, we invite urgent action from governments, businesses, civil society and individuals to protect and restore the ocean's health while embracing sustainable ocean-based solutions. Together, we can secure a greener, more resilient and equitable future for our planet and all its inhabitants. Considering the comprehensive analysis provided in this report, it is evident that the ocean and ocean-based solutions hold immense potential for addressing climate change and its far-reaching consequences. As with the 2019 Report, we are seeing that the ocean does not need always to be the victim. Despite this, the current pace of progress does not align with the urgency of the climate change challenges that confront us. To fully harness the ocean's potential and secure a sustainable and resilient future, we must take decisive action on multiple fronts.

Here are 10 key actions we should take without delay:

1. **Translate pledges into action.** Prioritise the implementation of existing pledges and targets across all ocean-based sectors, to translate their potential into verifiable and measurable action.
2. **Foster collaboration and research into emerging solutions.** Engage in ambitious, inclusive and collaborative partnerships to address ocean-related challenges and fill the knowledge gaps in emerging ocean-based climate solutions that are not yet ready for implementation. Prioritise research and knowledge-sharing across all ocean-based climate sectors to implement solutions in a synergistic and nature-positive manner, ensuring a contribution to achieving the Kunming-Montreal Global Biodiversity Framework.

3. **Prioritise nature-based solutions.** Protect and restore coastal ecosystems, such as mangroves, seagrasses and tidal marshes, recognising their no-regrets approach in climate mitigation and alignment with the Kunming-Montreal Global Biodiversity Framework.

4. **Initiate steps to replace offshore oil and gas in global energy supply with renewable energy.** Initiate conversations and establish governance to halt new oil and gas exploration and phase down current production through demand-led mechanisms. At the same time, align efforts with respect to the scaling of renewable energy, ensuring a just and equitable transition to maximise social and environmental benefits.

5. **Make the necessary capital investments to decarbonise maritime transport.** Take urgent measures to reduce emissions from shipping and cruise tourism, capitalising on the potential and urgency of these vital sectors and assisting in their rapid transition to zero carbon.

6. **Strengthen ocean-based climate finance.** Prioritise a more coherent approach to ocean-climate finance, aligning finance towards nature positive and net zero pathways, so that $2 trillion is directed towards ocean-based climate solutions between 2030 and 2050. Explore innovative financing models, including blended finance, to support nature-based solutions and other ocean-based initiatives.

7. **Monitor, evaluate and correct.** Implement robust monitoring, evaluation and adaptive management mechanisms across all ocean-based mitigation options to measure progress and correct any unintended consequences, ensuring that solutions remain on track.

8. **Encourage and provide incentives for international cooperation.** Enhance international cooperation, improve governance, and establish effective policies to address ocean challenges effectively.

9. **Align ocean-based and terrestrial solutions.** Recognise that ocean-based climate solutions are not standalone measures and hence must be accompanied by deep cuts in emissions from terrestrial sources of GHGs; this includes rapidly phasing down fossil fuels, expanding sustainable food systems, and increasing carbon sequestration in forests and terrestrial ecosystems.

10. **Embrace urgency, inclusivity and fairness.** Emphasise the need for immediate and coordinated action from governments, businesses, civil society and individuals to protect and restore the ocean's health while adopting sustainable ocean-based solutions.

Appendix A.

Methodology

Background data and assumptions for the report

Collecting data and understanding the key drivers and their variability has been a been central component of this study. The study has also benefited from the expert capacity of 28 specialists who have worked together to develop consensus on an array of issues of how the ocean may be able to increase its role in mitigating climate change. These efforts included discussions within each sector that focused on political will, technological advancements, economic considerations, public awareness and international collaboration, shaping the potential success of the scenarios.

Table A-1. Approaches taken to produce mitigation estimates, by sector

MARINE CONSERVATION AND RESTORATION	
SUMMARY OF RELEVANT UN ENVIRONMENT PROGRAMME (UNEP) CURRENT POLICY SCENARIO	Most countries do not yet include marine conservation and restoration within their Nationally Determined Contributions (NDCs). Some countries include mangroves conservation and restoration within their forestry sector. These emissions/removals may be included in the UNEP (2022) baseline.
DESCRIPTION OF REPORT BASELINE FROM BOTTOM-UP METHODOLOGY	Current estimates of rates of change of ecosystem extent continue through the century. Trends in change taken from: 1. Mangrove and tidal marshes—Murray et al. (2022) 2. Seagrass— Buelow et al. (2022). 3. Kelp—Krumhansl et al. (2016). 4. Mudflats— Murray et al. (2022). 5. Seabed trawling—Sala et al. (2021), Jankowska et al. (2022) and Atwood et al. (2023).
KEY DRIVERS FOR LEVEL OF AMBITION	Expectation of halting further losses and degradation of ecosystems. For mangroves a plausible restoration target of 10,000 km2 by 2030 is based on the extent of recent conversions that are considered readily reversible (Worthington and Spalding 2018). Improvement of restoration techniques. Method development to certify carbon accumulated by macroalgal restoration. For tidal mudflats ambition was low (2–4% by 2030) because of high uncertainty in the potential to reverse reclaimed areas to tidal mudflats.
KEY ASSUMPTIONS	Revised estimates of mangrove, tidal marsh and tidal flat emissions globally were adjusted to account for both losses and gains (Murray et al. 2022), since loss of coastal vegetation results in high levels of emissions, while the level of carbon sequestered during ecosystem recovery is comparably lower. Emission factors were derived from Intergovernmental Panel on Climate Change publications (IPCC 2013b, 2019) or from published studies. Restoration scenarios for coastal wetlands are conservative based on known limitations of restoration (Buelow et al. 2022). Potential mitigation benefit of restoration and reducing losses of kelp forests were based on updated estimates of the global area and productivity of kelps (Duarte et al. 2022), trends in kelp extent over the past 50 years (Krumhansl et al. 2016) and C-sequestration estimates (Krause-Jensen and Duarte 2016).
DESCRIPTION OF WHAT LOW AND HIGH SCENARIOS REPRESENT	Range (low and high estimate) is based on published uncertainty in baseline values of business as usual changes in the extent of these ecosystems over time. High and low restoration scenarios are based on published targets (Worthington and Spalding 2018) and literature values (Duarte et al. 2020, Buelow et al. 2022).

Table A-1. Approaches taken to produce mitigation estimates, by sector (Continued)

KEY UNCERTAINTIES	High levels of spatial variation in emissions from ecosystem losses and removals with ecosystem restoration that are not incorporated within estimates. Impacts of different management actions on emissions and removals. Uncertainty in the plausibility of restoration scenarios and the impacts of accelerating climate change. Role of methane emission from baseline land uses and coastal wetlands in blue carbon accounting. Large decadal variability characteristic of kelp forests. Uncertainty in long-term fate of submerged seaweed biomass and debris. Uncertainty in seaweed manageability, existing policy, legal frameworks, economic frameworks, lack of robustly calculated incentives, and societal and ethical issues. Trawling intensity and context varies globally, and assumptions on the lability of seabed sediment carbon have been challenged. Uncertainty as to whether tidal flat conservation and restoration is additional, as sediment carbon may be stored elsewhere in the marine environments.
BACKGROUND NOTES AND CAVEATS	Estimated climate mitigation benefits under the scenarios are conservative for tidal marshes because they are less than the 30% goal (the Kunming-Montreal Global Biodiversity Framework), and avoided CH_4 emissions from alternative land uses for mangroves and tidal marshes, such as agriculture (e.g. rice production, grazing, drained landscapes for cropping) and aquaculture are not included, but would increase the avoided emissions associated with restoration. Climate change is likely to have variable impacts on coastal marine ecosystems and their CO_2 mitigation potential but this is not included in this analysis. **Seagrasses, tidal marshes and mangroves** Carbon emissions and removals were calculated using recent global data of the extent of these ecosystems, and rates of change of this extent (i.e. loss or restoration). We assessed avoided emissions and lost potential for sequestration from halting further losses and degradation of ecosystems. We assessed potential carbon removal (sequestration) from the restoration of these ecosystems based on plausible values in the literature (Buelow et al. 2022). We provided a minimum and maximum estimate based on published uncertainty in anticipated values of changes in the extent of these ecosystems. Estimated climate mitigation benefits under our scenarios reflect uncertainty in area of degraded ecosystems that can be restored and spatial variation in emission factors. For example, 30 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 N2O and CH4 emissions (IPCC 2006, 2013b, 2019). Marine heatwaves 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 (Lovejoy and Hannah 2019), which may cause challenges for restoration in those regions. Warming and loss of sea ice may support increases in the distribution of coastal ecosystems at the polar edge of the distribution range (Krause-Jensen et al. 2020; Assis et al. 2022). Sea level rise will affect habitat areas for all coastal vegetated ecosystems and thus their mitigation potential (Saunders et al. 2013; Lovelock et al. 2015; Rogers et al. 2019; Schuerch et al. 2019). The impact of sea level rise on these ecosystems will be strongly influenced by human activities (e.g. sediment supply, land use changes, population and seawall defences) and the effects of climate change on adjacent ecosystems such as coral reefs (Saunders et al. 2013), mudflats or barrier islands; and emissions from freshwater wetlands (Luo et al. 2019). Extreme weather events could also reduce the effectiveness of habitat restoration. **Kelps** We used global estimates of kelp area and net primary production (NPP) (1.86 million km^2, 3,362 Gt $CO_2e\ yr^{-1}$) (Duarte et al. 2022a) combined with C-sequestration estimates (11% of NPP for macroalgae in general) (Krause-Jensen and Duarte 2016) and knowledge of past trends in kelp area (average global loss rate of 1.8% per year over the past 50 years with major variability between locations) (Krumhansl et al. 2016) to estimate the climate change mitigation effect associated with the restoration and protection of kelps. Restoration targets were aligned with the goals of the Kunming-Montreal Global Biodiversity Framework, and this restoration trend was continued for the 2030–50 period until full recovery of the historic kelp area (Krumhansl et al. 2016). Losses of annual carbon sequestration capacity related to kelp loss over the past 50 years was estimated at 0.513 Gt CO_2, corresponding to an average annual loss of 0.0103 Gt $CO_2e\ yr^{-1}$ over the 50-year period. Recovering 30% of the lost annual sequestration capacity by 2030 corresponds to 0.154 Gt CO_2 and the remaining restoration to full extent over the 2030–50 period corresponds to 0.359 (0.513–0.154) Gt CO_2. Total avoided emissions from gradually decreasing losses were estimated to be 0.0308 Gt CO_2 by 2030 and continued avoided emissions in 2030–50 was estimated to be 0.205 (20 x 0.0103) Gt CO_2. In total, the restoration and protection efforts would contribute 0.1848 Gt CO_2 by 2030 and 0.565 Gt CO_2 from 2030 to 2050. Annual rates by 2030 were computed by dividing the 2023–30 totals by seven and annual rates by 2050 were computed by dividing the 2030–50 totals by 20.

Table A-1. Approaches taken to produce mitigation estimates, by sector (Continued)

OCEAN-BASED RENEWABLE ENERGY	
SUMMARY OF RELEVANT UN ENVIRONMENT PROGRAMME (UNEP) CURRENT POLICY SCENARIO	Ocean based renewables are not discussed in detail. Relevant policy includes removing barriers to expansion of renewables and adapting market rules of electricity system for high shares of renewables.
DESCRIPTION OF REPORT BASELINE FROM BOTTOM-UP METHODOLOGY	Current energy generation mix with emissions of about 0.46 kg CO_2e/kWh (Hoegh-Guldberg et al. 2019).
KEY DRIVERS FOR LEVEL OF AMBITION	Rapid maturation of floating wind technologies. Global Offshore Wind Alliance aims to contribute to achieving total global offshore wind capacity of minimum 380 GW by 2030, and minimum 70 GW each year from 2030. Target of 2,000 GW of offshore wind that the IEA and IRENA has set for carbon neutrality by 2050. We take a conservative approach assuming that no significant contributions to the global electrical energy production are expected from wave and tidal technologies in a 2030 perspective. If a technology breakthrough is made, some contribution may come by 2050.
KEY ASSUMPTIONS	0.012 CO_2e/kWh for offshore wind. The limiting factors for the mitigation potential in 2030 and 2050 is mainly factors determining deployment rate. Emissions for these offshore renewable technologies are at least one order of magnitude less than the emissions from coal power plants. Capacity densities in the range 2–10 MW/km2 may be expected.
DESCRIPTION OF WHAT LOW AND HIGH SCENARIOS REPRESENT	Range reflects uncertainty in deployment rate of technologies investigated.
KEY UNCERTAINTIES	Relationship between implementation and stated political ambitions. Estimates of electrical energy production needed to achieve net zero emissions in 2050 are uncertain, and depend on e.g. how use of traditional fossil fuels is phased out, and degree of use of 'green' hydrogen and ammonia. Geophysical potential has large geographical variations, for example tidal stream resources are constrained to particular locations and ocean thermal conversion systems (OTEC) are feasible in tropical areas only.
BACKGROUND NOTES AND CAVEATS	The main assumptions and hence methodology related to mitigation potential as used in the 2019 Report have not changed (Hoegh-Guldberg et al. 2019). The emission in CO_2e/kWh for OSW has not changed (about 0.012 CO_2e/kWh). The limiting factors for the mitigation potential in 2030 and 2050 is mainly factors determining deployment rate. For ORE the emissions in CO_2e/kWh cannot be realistically estimated as the technological solutions have not converged. However, it may be assumed that the emissions for these technologies are at least one order of magnitude less the emissions from coal power plants. The potential for OSW is clearly dependent on the assumed maximum water depth for installation as well as distance to shore. The deployment rate is critical, relying upon, licensing, manufacturing capacity, financing, and availability of critical materials. Conflict may arise in the use of vast ocean areas for offshore wind farms, both with respect to ecological and societal implications. Capacity densities in the range 2–10 MW/km^2 may be expected. Installation of 2,000 GW offshore wind will thus require an area in the range 200,000 to 1 million km^2 (the area of the Mediterranean Sea is about 2.5 million km^2). Combined use of wind farm areas should thus be considered. This may involve e.g. other energy sources as wave power, fish farming, growing seaweed. Among the ORE technologies, floating solar and wave power are supposed to have the greatest potential on a global scale. The two technologies are complementary with respect to localisation. To realise the mitigation potential from these technologies will need a considerably increased effort in developing them to industrial options.

Table A-1. Approaches taken to produce mitigation estimates, by sector (Continued)

OCEAN-BASED TRANSPORT	
SUMMARY OF RELEVANT UN ENVIRONMENT PROGRAMME (UNEP) CURRENT POLICY SCENARIO	Develop regulations and supporting scalable policies to transition to 100 per cent low-carbon fuels for aviation and marine sectors by 2050, including advanced biofuels, green hydrogen, renewable electricity, and e-fuels generated with addition to renewable electricity' (UNEP 2022).
DESCRIPTION OF REPORT BASELINE FROM BOTTOM-UP METHODOLOGY	BAU emissions trajectory to 2050 based on fourth IMO GHG study.
KEY DRIVERS FOR LEVEL OF AMBITION	IMO ambitions were recently revealed in policy announcements (July 5, 2023): that the 'Member States of the International Maritime Organization (IMO), meeting at the Marine Environment Protection Committee (MEPC 80), have adopted the 2023 IMO Strategy on Reduction of GHG Emissions from Ships, with enhanced targets to tackle harmful emissions'.
KEY ASSUMPTIONS	Clear policies incentivising shipping's decarbonisation are in place by 2025. The wider energy system has fully decarbonised by 2050 and that renewable hydrogen (zero carbon in production) is available in sufficient volumes.
DESCRIPTION OF WHAT LOW AND HIGH SCENARIOS REPRESENT	The near-term opportunities (to 2030) of a 20–39% mitigation of emissions are constrained by the fuel compatibility of the existing fleet and the supply chain of renewable energy and fuel, which limits the potential primarily to further energy efficiency improvements (Bouman et al. 2017; Hoegh-Guldberg et al. 2019). By 2050 there is the potential for a fundamental change in fleet and energy supply chain. At the upper bound, there is potential for a full (100%) substitution of the sector's use of fossil fuels to renewable fuels. The lower bound reduction potential at 2050 is set at 50% as in the 2019 Report, taken as the minimum interpretation of the IMO's Objectives in the Initial GHG Reduction Strategy (Hoegh-Guldberg et al. 2019).
KEY UNCERTAINTIES	Rate of adopting policies to incentivise decarbonisation of shipping. 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. Demand growth could be significantly higher or lower than current IMO projections.
BACKGROUND NOTES AND CAVEATS	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 is taken from the fourth IMO GHG study, which is an update from the third IMO GHG study used in the 2019 Report. This BAU scenario applies existing IMO policy and estimates total GHG emissions from international shipping in 2030 and 2050. The group of technologies that can mitigate domestic and international shipping emissions are similar to that in 2019. The estimate of mitigation potential is thus based on a number of assumptions: A. The speed of policy implementation to enable or require the shipping industry to invest in the necessary changes to fleet and infrastructure (particularly 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. B. The 2030 GHG reduction potential is estimated by aggregating savings across a large number of technological and operational efficiency interventions. 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 is a key uncertainty. 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 emissions reductions. C. Demand growth could be significantly higher or lower than current IMO projections, with direct consequences for the BAU emissions and therefore (in proportion) the GHG mitigation potential of a fully decarbonised ocean transport industry.

Table A-1. Approaches taken to produce mitigation estimates, by sector (Continued)

OCEAN-BASED TOURISM	
SUMMARY OF RELEVANT UN ENVIRONMENT PROGRAMME (UNEP) CURRENT POLICY SCENARIO	Develop regulations and supporting scalable policies to transition to 100 per cent low-carbon fuels for aviation and marine sectors by 2050, including advanced biofuels, green hydrogen, renewable electricity, and e-fuels generated with addition to renewable electricity (UNEP 2022).
DESCRIPTION OF REPORT BASELINE FROM BOTTOM-UP METHODOLOGY	Business as usual—6 percent growth in passenger numbers and emissions per year, 2 percent annual improvement in carbon intensity.
KEY DRIVERS FOR LEVEL OF AMBITION	EU's FuelEU Maritime regulation will make shore power mandatory from 2030 for passenger vessels in Europe and advocate uptake of alternative fuels. FuelEU is a likely initiative of the European Union, considering its ongoing efforts to reduce carbon emissions and enhance sustainability.
KEY ASSUMPTIONS	6 percent growth in passenger numbers and emissions per year.
DESCRIPTION OF WHAT LOW AND HIGH SCENARIOS REPRESENT	As for ocean-based transport.
KEY UNCERTAINTIES	Availability and accessibility of low-emission fuels and technologies at ports around the world can be limited. While energy use and emissions can be reduced significantly through operational measures, it is generally easier to implement new technology when building new vessels. The lead time for new cruise vessels is long because of complicated design and construction and thus fundamental changes in future cruise vessels must be researched, developed and decided upon now if they shall have effect from 2030. The costs associated with these technological changes for cruise tourism decarbonisation can be a significant barrier for cruise operators, particularly for smaller companies. Balancing the need for emissions reduction with the economic viability and customer expectations of the cruise experience presents a substantial hurdle in the transition to low-emission cruise-based tourism.
BACKGROUND NOTES AND CAVEATS	The costs associated with technological changes for cruise tourism decarbonisation can be a significant barrier for cruise operators, particularly for smaller companies. The availability and accessibility of low-emission fuels and technologies at ports around the world can be limited, making it challenging for cruise ships to consistently operate with lower emissions in various regions. Finding innovative solutions to enhance energy efficiency in these vessels while maintaining their functionality and luxurious amenities is a complex task. Additionally, the construction of new low-emission cruise ships or the retrofitting of existing ones requires careful planning and investment, further adding to the financial and logistical challenges faced by the industry. Balancing the need for emissions reduction with the economic viability and customer expectations of the cruise experience presents a substantial hurdle in the transition to low-emission cruise-based tourism. Addressing these challenges requires collaboration among cruise operators, government bodies, and technology providers. It involves not only developing and implementing low-emission technologies but also establishing supportive policies and regulations that incentivise and facilitate the transition. Encouraging research and development, providing financial support or tax incentives, and fostering international cooperation are crucial for overcoming the barriers to low-emission cruise-based tourism. By addressing these challenges head-on, the cruise industry can make significant strides towards reducing its carbon footprint and contributing to a more sustainable and environmentally friendly tourism sector.

Table A-1. Approaches taken to produce mitigation estimates, by sector (Continued)

OCEAN-BASED FOOD	
SUMMARY OF RELEVANT UN ENVIRONMENT PROGRAMME (UNEP) CURRENT POLICY SCENARIO	Highlights the importance of transforming the food system: 'A range of transformation domains with several mitigation measures have been identified where food systems can contribute to bridging the emissions gap (UNEP 2022). They include 1) demand-side changes, including dietary changes towards sustainable and nutritionally balanced diets, and reductions in food loss and waste, protection of natural ecosystems, including reductions in deforestation for agriculture and degradation of agricultural land, 2) improvements in food production at the farm level, including changes in the composition of animal feeds, better rice management, better manure management, and improvements in crop nutrient management, and 3) decarbonising the food supply chain, including in retail, transport, fuel use, industrial processes, waste management and packaging. Notably, the emphasis is on land-based food systems; ocean-based strategies will be an important addition to emissions reductions.
DESCRIPTION OF REPORT BASELINE FROM BOTTOM-UP METHODOLOGY	Broken down into three sections: 1) **Fisheries**— Parker et al. (2018) global fishing emissions baseline for year 2011 and projections from *Sunken Billions* report 2) **Aquaculture**—FAO projections of aquaculture growth + MacLeod et al. (2020) global emissions estimates 3) **Dietary Shifts**—BAU scenario from Springman et al. (2018), GHG emissions reduction grow from 5.2 Gt CO_2e in 2010 to 9.7 Gt CO_2e in 2050.
KEY DRIVERS FOR LEVEL OF AMBITION	Scenarios for fisheries and aquaculture determined based on demonstrated means to reduce emissions in each sector, considering the feasibility and practicality for each. Lower emissions intensity compared to other protein sources. Shifting global diets has been modelled as the most impactful way of reducing future GHG emissions from food provisioning.
KEY ASSUMPTIONS	**Fisheries**—Assume that fuel use correlated with effort and equal reductions in fuel use and effort to estimate the fuel use (and associated emissions) required to catch that future optimal harvest. Also assumed optimal effort to catch ratios (World Bank 2017), and 100% substitution of available fish protein for average animal-based protein sources. Excluded possible emissions from bottom trawling because of uncertainty and overlap with other sections (possible double-counting). **Aquaculture**—assumes that no progress towards the listed interventions was achieved between MacLeod's estimated in 2017 and today, and that the intervention can be achieved in its entirety. **Dietary shifts**—looks at only methane and nitrous oxide emissions and assumes the ability to adequately scale production of low-emissions seafood sources while not exceeding ecological capacity to do so.
DESCRIPTION OF WHAT LOW AND HIGH SCENARIOS REPRESENT	**Fisheries** Low - 0, assuming fisheries management and vessel performance follow the current trend; the authors were not confident in a method to allow projecting ranges of improvement and developed a 'possible scenario' instead High - This is the projected reduction in emissions that the marine fishing industry could optimistically achieve if global fisheries management improved in accordance with the stock rebuilding and fisheries yields projected by the Sunken Billions report by the World Bank (2017). **Aquaculture** Low - 0, similar to fisheries the authors focused on potential scenarios as data and methods are insufficient for projecting ranges or suggested confidence levels. High - cumulative impact of three intervention scenarios: a reduction in average feed conversion ratios of 10 percent, complete avoidance of deforestation in the crop production supply chains for feeds, and complete decarbonisation of farm-level energy inputs; data on current emissions by sector and source from Gephart et al. (2021) and MacLeod et al. (2020). **Dietary Shifts** Low - Carbon Tax: methane emissions tax on livestock of \$15/t CO_2e reducing methane emissions to 2.8% + forecast production of animal proteins. Media Campaigns: Apply the median (11%) of past campaigns to the projected benefits a less-GHG intensive diet (4.7 Gt CO_2e estimated by Springmann et al. 2018) High - Carbon Tax: methane emissions tax on livestock of \$100/t CO_2e reducing methane emissions to 9.9% + forecast production of animal proteins. Media Campaigns: upper bound (15 percent) of past campaigns to the projected benefits a less-GHG intensive diet (4.7 Gt CO_2e estimated by Springmann et al. 2018).

Table A-1. Approaches taken to produce mitigation estimates, by sector (Continued)

OCEAN-BASED FOOD	
KEY UNCERTAINTIES	Our method fails to address technological and behavioural changes that may accompany changes in effort and landings, whether positive or negative. The World Bank scenario for global fisheries (World Bank 2017) would not only achieve emissions reductions through reductions in effort required to catch fish and shellfish but would also increase the availability of harvested fish and shellfish for consumers, allowing for potential replacement in markets of alternative more GHG-intensive animal protein products. We estimated the additional protein provided in this optimal scenario by assuming an average flesh yield from live weight of 50% and protein content of 20%. This results in an additional 863 million kg of protein produced annually once stocks are rebuilt. The degree to which that additional protein would be available to offset alternative animal protein sources would rely on numerous factors, and we calculated here the total potential assuming that all additional protein from fisheries replaces (does not add to) more emissions-intensive land-based protein sources.
BACKGROUND NOTES AND CAVEATS	Precautionary note: the models we built for fisheries and aquaculture are optimistic scenarios to demonstrate the total potential of the industry to reduce emissions from production. There is no indication that current trajectory will reach those potential reductions, and substantial transition in management and technology will be required to possibly achieve them. We used the economic scenario for global fisheries outlined in the *Sunken Billions* report (World Bank 2017). In this scenario, stocks are rebuilt to levels allowing for optimised production, resulting in (relative to 2012) 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, we assumed equal reductions in fuel use and effort to estimate the fuel use (and associated emissions) required to catch that future optimal harvest using the Parker et al. (2018) model. We assumed a uniform change in landings and fuel use across all species groups and gear types, re-modelled from Parker et al. (2018). This is likely an overly optimistic scenario, given the challenges to fisheries management globally, and the uneven and insufficient implementation of effective management techniques. 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 Mt CO_2e to 98 Mt CO_2e, a reduction of 81 Mt CO_2e. We used pork to represent an average land-based protein (Poore and Nemecek 2018), as it has a middle-range emissions profile. Assuming 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 invertebrates, we derived potential emissions offset of 6.5 kg CO_2e for every 100 g of additional fishery-sourced protein, or a total annual emissions reduction potential of 56.1 Mt CO_2e by 2050. The combined emissions reduction potential of global fisheries, assuming optimal effort to catch ratios (World Bank 2017), and 100 percent substitution of available fish protein for average animal-based protein sources, is 137.1 Mt CO_2e. FAO projects that global aquaculture production will grow at an annual rate of 2 percent from 2020 to 2030 (FAO 2022), with annual production reaching almost 110 Mt by 2030. FAO does not currently project to 2050, but if we assume a similar annual growth rate from 2031 to 2050, total aquaculture production (excluding seaweeds and aquatic plants) would reach approximately 163 Mt live weight in 2050—equal to approximately double the 2017 production at an additional 80 Mt live weight. Using the global emissions estimates from MacLeod and colleagues (2020) as a starting point and projecting to 2030 and 2050 based on the FAO growth rates above, the business-as-usual scenario would see emissions from aquaculture double as production doubles, meaning that the emissions intensity (per tonne of aquaculture production) would be unchanged. We applied three scenarios to these future emissions estimates reflecting potentially meaningful interventions: a reduction in average feed conversion ratios of 10 percent, complete avoidance of deforestation in the crop production supply chains for feeds, and complete decarbonisation of farm-level energy inputs (i.e., deriving all farm energy inputs from renewable or non-fossil electricity generation). For each of these scenarios, we assumed gradual phasing in over the course of 27 years beginning today and expanding linearly until the full intervention is achieved in 2050. This assumes that no progress towards the listed interventions was achieved between MacLeod's estimated in 2017 and today, and that the intervention can be achieved in its entirety, which may be overly optimistic. The combined effects of the three interventions were assessed taking a cumulative approach, recognising that the effect of avoiding deforestation in crop production would be diminished somewhat with a more efficient feed conversion ratio. When all three interventions are fully achieved, the total annual emissions are reduced to the extent that they are roughly equal to today's emissions despite the doubling of global production, avoiding annual emissions of 267 million tonnes of CO_2e GHG.

Table A-1. Approaches taken to produce mitigation estimates, by sector (Continued)

OCEAN-BASED FOOD	
BACKGROUND NOTES AND CAVEATS	To estimate the mitigation potential of shifting diets, we examined 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. Modelling suggests that a global price on methane emissions from livestock ranging from \$15/t CO_2e to \$100/t CO_2e would significantly reduce methane emissions by 2.8 percent and 9.9 percent, respectively (Tallard 2011). 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 237–840 Mt CO_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 Gt CO_2e/year. The projected health benefits of reducing meat consumption are so large (Willett et al. 2019) that GHG emissions mitigation could potentially be achieved as a co-benefit of behaviour change motivated by people's interest in their personal health. 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 Maibach 2008) on campaigns on seat belt use, smoking, cancer screening, alcohol use, and many other topics, observed effects were only moderate—typically 15 percent or fewer people changed targeted behaviours even when there were significant health benefits. 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 Gt CO_2e estimated by Springmann et al. 2018), suggests that effective campaigns focusing on health benefits of dietary change could potentially yield reductions up to 0.52–0.71 Gt CO_2e by 2050.

Table A-1. Approaches taken to produce mitigation estimates, by sector (Continued)

OFF-SHORE OIL AND GAS	
SUMMARY OF RELEVANT UN ENVIRONMENT PROGRAMME (UNEP) CURRENT POLICY SCENARIO	Relevant policy includes international cooperation on a fossil fuel phase-down; supporting initiatives on emissions-free electricity, power system flexibility and interconnection solutions (UNEP 2022)
DESCRIPTION OF REPORT BASELINE FROM BOTTOM-UP METHODOLOGY	BAU Stated Policies Scenario (STEPS) from the latest World Energy Outlook (IEA 2022b)—governments around the world advance policy measures as of September 2022 without additional energy targets, Accounts for unconditional NDC's under Paris Agreement.
KEY DRIVERS FOR LEVEL OF AMBITION	IPCC report (2023) which states no new oil and gas operations be pursued if we are to stay in line with 1.5°C warming. IEA Net Zero Emissions Scenario (NZE)—shows how to achieve 1.5°C stabilisation and meet fossil fuel demands without approval of new long-term projects. Marine environmental and biodiversity risks—potential for accidental oil spills.
KEY ASSUMPTIONS	World Energy Outlook calculates oil and gas both on and offshore—assumed 30% comes from offshore. The NZE scenario assumes that average oil demand falls by more than 4 percent per year between 2020 and 2050. Emissions factors were calculated as the weighted average of field-level data from the RMI Oil Climate Index plus gas (OCI+) model (Geers et al. 2022). Data covers 50 percent of world's oil and gas fields.
DESCRIPTION OF WHAT LOW AND HIGH SCENARIOS REPRESENT	Low—business as usual. High—NZE scenario.
KEY UNCERTAINTIES	NZE scenario assumes that any additional energy demand beyond current extraction will be met by low-carbon energy sources. Relationship between implementation and political ambitions of states. Economies that are heavily reliant on oil and gas will be willing to proactively diversify.
BACKGROUND NOTES AND CAVEATS	All offshore oil and gas production scenarios are based on analysis from the IEA World Energy Model (IEA 2022b). We treat IEA's Stated Policies Scenario (STEPS), which shows the trajectory implied by today's policy settings, as our BAU scenario and compare the STEPS production curve and associated emissions with that of the NZE by 2050 Scenario. The NZE maps out a way to achieve a 1.5°C stabilisation in the rise in global average temperatures, alongside universal access to energy by 2030. Further details on these scenarios can be found in the World Energy Outlook 2022 (IEA 2022b). The World Energy Outlook (WEO) 2022 estimates production for all oil and gas, not just offshore. To estimate offshore volumes only, we assume that 30% of oil and gas production comes from offshore sources. These estimates were derived from historical data in the World Energy Outlook Special Report Offshore Energy Outlook 2018 (IEA 2018) and are supported by more recent and projected data in WEO 2022 (see IEA 2022b). We calculated cradle-to-grave emissions of these production volumes using emissions factors of 498 kg CO_2e/barrel oil equivalent (boe) for oil and 223 kg CO_2e/boe for gas, including both direct and indirect life-cycle emissions. A conversion factor of six was used to convert gas production (billion cubic metres, or bcm) to barrels of oil equivalents. Emissions factors were calculated as the weighted average of field-level data from the RMI Oil Climate Index plus gas (OCI+) model (RMI 2022). The data available from OCI+ cover approximately 50% of the world's oil and gas fields, with 87 offshore oil fields and 48 offshore gas fields included in the dataset (RMI 2022). For additional details on the methodology and details behind this analysis, see Geers et al. (2022) and the associated appendix. These high-level estimates could be better refined with more accurate estimates of the offshore component of oil and gas production currently and projected, such as was done in IEA (2018). However, given the significant changes in energy production and demand that have occurred since 2018, we chose to use the updated data and projections from WEO 2022 (IEA 2022b).

Table A-1. Approaches taken to produce mitigation estimates, by sector (Continued)

MARINE CARBON DIOXIDE REMOVAL AND CARBON CAPTURE AND STORAGE	
SUMMARY OF RELEVANT UN ENVIRONMENT PROGRAMME (UNEP) CURRENT POLICY SCENARIO	Not included in UNEP current policy scenario.
DESCRIPTION OF REPORT BASELINE FROM BOTTOM-UP METHODOLOGY	No mCDR, no CCS under the seabed.
KEY DRIVERS FOR LEVEL OF AMBITION	IPCC reports (SR 1.5°C and AR6) which call for gigaton-scale CDR as a requirement to stop continued warming
KEY ASSUMPTIONS	Estimates of scalable mCDR for the various pathways provided in the 2022 US NASEM report can be achieved by 2050 4–8 percent growth rates are reasonable expectations for mCDR growth between 2030 and 2050. Current and planned CCS projects continue to grow in line with predictions (IEA 2023a).
DESCRIPTION OF WHAT LOW AND HIGH SCENARIOS REPRESENT	Bounded estimates that try to account for the deep uncertainty in the ultimate scale of contribution from mCDR because current levels of mCDR are in the range of hundreds, or thousands, of tons per year, and these systems need to ultimately scale to billions of tons per year
KEY UNCERTAINTIES	Large-scale scientific uncertainties remain regarding carbon sequestration efficacy, and environmental and social impacts Multi-billion dollar global support for research and development needs to be acquired and distributed Deep social, political, and governance challenges that need to be overcome in order to enable research and development, and if successful, any paths to full-scale deployment
BACKGROUND NOTES AND CAVEATS	Mitigation potential estimates for the year 2050 for mCDR approaches were derived from a study by the US National Academies of Science, Engineering, and Medicine (2021). This report was chosen as the foundational information for these mitigation potential estimates because the values provided in the report represent the synthesis of published peer reviewed studies on these topics. When the report only listed an upper bound of greater than one gigaton of CDR annually as opposed to a definite upper bound, we chose an upper bound of three gigatons of CDR annually. This is consistent with past studies for some of the technologies, which we believe represents a feasible upper bound for the approach by the middle of the century. The peer-reviewed scientific literature regarding the mitigation potential of mCDR approaches continues to grow and will continue to refine the estimates provided in this report. Mitigation potential estimates for 2030 were calculated by hindcasting mitigation potential estimates for 2050 using annual growth rates of 4–8 percent. These growth rate estimates bound the often-cited 6 percent growth rate for CDR technologies (Minx et al. 2018). Note that all estimates were made independent of one another, meaning that they do not consider interactive effects of multiple mCDR activities co-located in space and/or time. Integration of mCDR approaches into integrated assessment models will continue to refine mitigation potential estimates by explicitly quantifying how one or more mCDR approaches may contribute to a portfolio of CDR activities in a model scenario. Estimates for the durability of CDR provided by various mCDR approaches were derived from the US National Academies of Science, Engineering, and Medicine, with additional context for specific pathways provided by relevant studies (Renforth and Henderson 2017; National Academies of Sciences, Engineering, and Medicine 2021; Siegel et al. 2021). Seaweed farming for carbon capture, storage and utilisation- passive export of unharvested production to sediments below farms

Table A-1. Approaches taken to produce mitigation estimates, by sector (Continued)

MARINE CARBON DIOXIDE REMOVAL AND CARBON CAPTURE AND STORAGE	
BACKGROUND NOTES AND CAVEATS	The area of seaweed farming was projected to 2030 and 2050 based on the current growth rate in the industry (6.2 percent per year) and a doubling of this rate (12 percent) to provide a span (Duarte et al. 2022b). Quantification of the export of 'unharvested' seaweed production to the seafloor below the farm was based on a global study encompassing 20 farms worldwide (Duarte et al. 2023). For farms located over depositional seafloor, organic C burial rates in the farm sediments averaged (± SE) 1.87 ± 0.73 tonnes CO_2e ha^{-1} $year^{-1}$ (median 0.83, range 0.10–8.99 tonnes CO_2e ha^{-1} $year^{-1}$). The contribution of the seaweed farm to carbon burial was calculated by subtracting the average (± SE) C burial rate in reference sediments (0.90 ± 0.27, median 0.64, range 0.10-3.00 tonnes CO_2e ha^{-1} $year^{-1}$), so that the excess organic C burial attributable to the seaweed farms averaged 1.06 ± 0.74 tonnes CO_2e ha^{-1} $year^{-1}$ (median 0.09, range -0.13–8.10 tonnes CO_2e ha^{-1} $year^{-1}$) (Duarte et al. 2023). We then multiplied the projected farm area by the average excess burial estimates. In addition to the passive carbon burial under farms, there are potential climate change mitigation benefits associated with the substitution of traditional products with seaweed products having a smaller CO_2 footprint (e.g. Duarte et al. 2022b, Spillias et al. 2023a). The use of seaweed as feed supplement to ruminants to reduce their methane emission also has a potentially large CO_2 emissions reduction capacity although negative effects on animal health of bromoforms produced by certain seaweed species needs consideration (Kinley et al. 2020; Roque et al. 2019). A full estimate of the CO_2 mitigation/emissions reduction potential of this use of seaweed would require a life cycle analysis of the farms including the fate of the harvested biomass and derived products, and this was not performed here. Carbon capture and storage projects may avoid an additional gigaton of emissions annually in 2050 if the pace of current and planned projects continues to grow. 2050 projections are based on a linear extrapolation of available data from the IEA (IEA 2023a).

Wider impact dimensions

The IPCC Special Report on 1.5°C scenarios (IPCC 2018) integrated wider impacts into its assessment of mitigation options; however, the ocean received relatively little attention. The 2019 Report (Hoegh-Guldberg et al. 2019) addressed this major knowledge gap by focusing on 4 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 A-2.

Table A-2. Wider impact dimensions explored in the report

WIDER IMPACT DIMENSIONS	ASSOCIATED IMPACT CATEGORIES	LINKS WITH NEAR-TERM SUSTAINABLE DEVELOPMENT GOAL (SDG) TARGETS AND INDICATORS
Environment	Impact on marine and terrestrial biodiversity, water quality, coastal resilience, land use, and adaptability of ecosystems and human settlements to climate change, impact on adaptive capacity and mitigation-adaptation synergies	SDG 6, 12, 13, 14, 15
Economy	Impact on employment, household incomes, profits and/or revenues of firms, innovation, supply of low-carbon energy, and economic growth	SDG 7, 8, 9, 11, 14
Society	Impact on human health outcomes, poverty reduction and food security targets, regional income inequality, quality of education, and gender equity	SDG 1, 2, 3, 4, 5, 10, 14
Governance	Impact on national and local institutions, participation in global governance, global partnership for sustainable development, and capacity building	SDG 14, 16, 17

Source: Authors.

Following the publication of the IPCC Special Report on 1.5°C there have been many assessments which have further integrated the information on wider impacts for ocean sectors, and hence we updated the analysis contained within the 2019 Report (Hoegh-Guldberg et al. 2019) with this new information.

Evidence reviewed during the wider impact analysis (current report and 2019 Report)

Wider impacts were 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 (IPCC 2018), and the 2019 Report (Hoegh-Guldberg et al. 2019). A two-step procedure was followed as part of a review of the literature on wider impacts. 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 an expert review process. The types of evidence and number of studies are summarised in Table A-3.

Table A-3. Types of evidence included, and number of studies examined (current report and 2019 Report)

TYPE OF LITERATURE	DESCRIPTION	NUMBER
Case study	Case studies specific to countries or region	19
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	54
Review paper	Studies that exclusively mention 'review' in their objective or methods	22
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	36
Qualitative	Academic papers and reports that present qualitative discussion of the impact of policies and international agreements	5
Total number		**168**

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

Source: Authors.

Second, based on the review of existing literature and expert judgment the performance of each ocean-based mitigation option was scored within each of the wider-impact dimensions following Nilsson et al. (2016) (Table A-2). 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.

- 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). High and low scores are shown by shades of the colour in Figure ES-4.

Appendix B.

Updated mitigation potential of five sectors included in the 2019 Report

This Appendix provides opportunity to compare the results of this updated report with the estimates developed in the 2019 Report for the five sectors included in that report. Table B-1 provides the mitigation potential estimates of the 2019 Report, whilst updated equivalent mitigation potential estimates are provided in Table B-2.

Table B-1. Original estimates of five sectors included in 2019 Report towards closing the emission gap in 2030 and 2050—ocean-based renewable energy; ocean-based transport; marine conservation and restoration; ocean-based food; and carbon capture and storage below the seabed

	ANNUAL GLOBAL EMISSIONS (GT CO_2E)			GAP TO PATHWAY, BASED ON UNEP CURRENT POLICY SCENARIO (GT CO_2E)		TOTAL GHG MITIGATION POTENTIAL (GT CO_2E)		% GAP CLOSED: 1.5°C PATHWAY		% GAP CLOSED: 2°C PATHWAY	
	Current policy	1.5°C pathway	2°C pathway	1.5°C pathway	2°C pathway	Min	Max	Min	Max	Min	Max
2019	52	52	52	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

Notes: Estimates were based on comparing multiple scenarios for annual emissions in 2020, 2030 and 2050. For those years, the authors compared '1.5°C', '2°C' and the 'current policy' scenarios from UNEP 2018 and calculated the mitigation needed to fill the 'gaps' between the 'current policy' and the '1.5°C' and '2°C', respectively. Min refers to conservative ocean-based mitigation potential, while Max represents higher (more ambitious) theoretical potential projected in the report. The total ocean-based mitigation was compared to the gap at 2030, and that at 2050, generating the percentage of the gap (in each case) mitigated by ocean-based mitigation of GHG emissions. GHG = greenhouse gas; UNEP = United Nations Environment Programme.

Source: Authors.

Table B-2. Updated contribution of five sectors included in 2019 Report towards closing the emission gap in 2030 and 2050—ocean-based renewable energy; ocean-based transport; marine conservation and restoration; ocean-based food; and carbon capture and storage below the seabed

a. Mitigation potential of ready to implement solutions, within the five sectors, identified in this report, according to Table 2

	ANNUAL GLOBAL EMISSIONS (GT CO_2E)			GAP TO PATHWAY, BASED ON UNEP CURRENT POLICY SCENARIO (GT CO_2E)		TOTAL GHG MITIGATION POTENTIAL (GT CO_2E)		% GAP CLOSED: 1.5°C PATHWAY		% GAP CLOSED: 2°C PATHWAY	
	Current policy	1.5°C pathway	2°C pathway	1.5°C pathway	2°C pathway	Min	Max	Min	Max	Min	Max
Today	58	58	58	0	0	0	0	0	0	0	0
2030	58	33	41	25	17	1	3	4	11	7	16
2050	49	10	20	39	29	4	8	11	21	15	29

Table B-2. Updated contribution of five sectors included in 2019 Report towards closing the emission gap in 2030 and 2050—ocean-based renewable energy; ocean-based transport; marine conservation and restoration; ocean-based food; and carbon capture and storage below the seabed (Continued)

b. Mitigation potential of all solutions, within the five sectors, identified in this report, according to Table 2

	ANNUAL GLOBAL EMISSIONS (GT CO_2E)			GAP TO PATHWAY, BASED ON UNEP CURRENT POLICY SCENARIO (GT CO_2E)		TOTAL GHG MITIGATION POTENTIAL (GT CO_2E)		% GAP CLOSED: 1.5°C PATHWAY		% GAP CLOSED: 2°C PATHWAY	
	Current policy	1.5°C pathway	2°C pathway	1.5°C pathway	2°C pathway	Min	Max	Min	Max	Min	Max
Today	58	58	58	0	0	0	0	0	0	0	0
2030	58	33	41	25	17	1	3	4	11	7	16
2050	49	10	20	39	29	4	9	11	24	15	32

Notes: Estimates are based on comparing multiple scenarios for annual emissions in 2023, 2030 and 2050. For those years, we compare '1.5°C', '2°C' and the 'current policy' scenarios from UNEP (2022) and calculate the mitigation needed to fill the 'gaps' between the 'current policy' and the '1.5°C' and '2°C', respectively. *Min* refers to conservative ocean-based mitigation potential, while *Max* represents higher (more ambitious) theoretical potential projected in this report. The total ocean-based mitigation was compared to the gap at 2030, and that at 2050, generating the percentage of the gap (in each case) mitigated by ocean-based mitigation of GHG emissions. GHG = greenhouse gas; UNEP = United Nations Environment Programme.

Source: Authors.

List of abbreviations

AR6	IPCC's Sixth Assessment Report
BAU	business-as-usual
CCS	carbon capture and storage
CII	carbon intensity indicator
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
COP	United Nations Climate Change Conference
DCS	Data Collection System
DFI	development finance institution
EJ	exajoule
GHG	greenhouse gas
GT	gross tonne
IEA	International Energy Agency
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LNG	liquefied natural gas
mCDR	marine carbon dioxide removal
MPA	marine protected area
MRV	monitoring reporting and verification
MSP	marine spatial planning
NbS	nature-based solution
NDC	Nationally Determined Contribution
NGO	nongovernmental organisation
NZE	Net Zero Emissions
ORE	offshore renewable energy
OSW	offshore wind
OTEC	ocean thermal energy conversion
PM2.5	fine particulate matter
R&D	research and development
SDG	Sustainable Development Goal
SOP	Sustainable Ocean Plan
STEPS	Stated Policies Scenario
TTW	tank-to-wake
WTW	well-to-wake

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Endnotes

1 On behalf of the Lead Experts, J. Kildow served as report arbiter, overseeing the independent peer review and approval of the final report, while P. Haugan was co-author and contributor.

2 Based on combined annual emissions of 3.47 Gt CO_2e for 27 EU member states (EEA 2023).

3 Based on average annual emissions of 4.49 t CO_2 per gasoline-powered car (EPA 2023).

4 Forecast amounts provided in this report are referenced. Numbers provided by the authors are in current 2023 US$.

5 Forecast amounts provided in this report are referenced. Numbers provided by the authors are in current 2023 US$.

6 See the United Nations Conference on Trade and Development, www.unctad.org, and International Chamber of Shipping, https://www.ics-shipping.org/.

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8 Scope 1 emissions are direct emissions such as, from operating ships. Scope 2 emissions are indirect emissions created, for example, in the process of fuel production for ship operations. Scope 3 emissions are the indirect emissions associated with the inputs and outputs of an organisation, for example in the supply chain or the use of the products it makes (see the Greenhouse Gas Protocol, https://ghgprotocol.org).

9 Offshore oil and gas production from existing wells will continue over the course of the NZE transition, with measured year-over-year declines. The NZE scenario requires this managed phasedown, where production volumes fall but not as quickly as they would naturally, through continued maintenance investment in existing production assets. If offshore production is phased out too quickly, new sources of conventional onshore oil and gas would need to come online in the near term to replace that fuel, diverting investment away from renewables and other low-carbon technologies.

10 Belize confirms intentions for seismic testing (Cavcic 2022); Rishi Sunak supports oil drilling expansion (Scott 2023).

11 Forecast amounts provided in this report are referenced. Numbers provided by the authors are in current 2023 US$.

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