Opportunities for Ocean-Climate Action in the United States

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CEA CONSULTING

About this report

CEA Consulting is an independent consultancy that provides research, analysis, and programmatic support to foundations, non-profits, businesses, multilateral agencies, and governments working on environmental issues. In 2020 we were commissioned by the David and Lucile Packard Foundation to conduct a non-partisan, fact-based, and objective assessment of the greenhouse gas mitigation potential of five ocean-based climate measures in the U.S.: offshore wind and marine renewable energy deployment; coastal blue carbon ecosystem protection, restoration, and cultivation; decarbonizing shipping; fisheries and aquaculture efficiency improvements and dietary shifts; and carbon storage in the seabed.

A similar analysis was recently conducted at a global level by the High Level Panel for a Sustainable Ocean Economy (HLP); these findings were summarized in a report: "The Ocean as a Solution to Climate Change: Five Opportunities for Action." The structure and methods of this report are based on that assessment, which includes five independent chapters that model greenhouse gas emissions reductions using ambitious but plausible assumptions for deployment of each solution. Each chapter in this report was written by an internal expert at CEA Consulting, and vetted externally by expert reviewers. In all cases, the full technical emissions reduction potential of each solution is much greater than what each author and the expert reviewers identify as ambitious but plausible.[1] Each chapter also includes a brief discussion of costs and benefits, current deployment status and future opportunities in U.S. coastal regions, and recommendations for policy, research, and technology required to fulfill these ambitious but feasible deployment scenarios. Detailed methodologies and assumptions are located in a supplementary Methodology Appendix.

Box 1. Comparing this report to High Level Panel for a Sustainable Ocean Economy

The High Level Panel for a Sustainable Ocean Economy (HLP) is an initiative of 14 serving world leaders building "momentum for a sustainable ocean economy, where effective protection, sustainable production and equitable prosperity go hand-in-hand." In 2019 the HLP released a report—"The Ocean as a Solution to Climate Change: Five Opportunities for Action"—that outlined the mitigation potential of five areas of ocean-based climate solutions: ocean-based renewable energy; ocean-based transport; coastal and marine ecosystems; fisheries, aquaculture, and shifting diets; and carbon dioxide storage in the seabed.

This report attempts to replicate that global analysis in the U.S. We assessed the same five areas of ocean-based climate action, although we opted to frame the report around the following specific actions: offshore wind and marine renewable energy deployment; decarbonizing shipping; coastal "blue carbon" ecosystem restoration, protection, and cultivation; fisheries and aquaculture efficiency improvements and dietary shifts; and carbon storage in the seabed. We used the same methods and approach in most cases, although the U.S. context presented some challenges in applying the methodology for all chapters in exactly the same way due to data limitations or different assumptions required for the U.S.

The U.S. context is quite different from the global context explored by the HLP, and as a result CEA's findings look different. The reasons for these differences include: the U.S. has a highly industrialized economy that results in the country being one of the world's most significant emitters of greenhouse gas emissions; the U.S. electricity grid is becoming less carbon-intensive as we shift toward natural gas and renewables (in comparison to other economies that still rely heavily on coal); the extent of existing and degraded blue-carbon ecosystems that can be restored in the U.S. is unique and different than global averages, and federal fisheries have made substantial gains toward improved fisheries management already. For full details on this study's methods, please see the supplementary Methodology Appendix.

The purpose of this report is to provide a quantitative, objective, and comparative assessment of the greenhouse gas mitigation potential of the five areas of ocean-based climate action in order to help policymakers and ocean advocates evaluate the mitigation opportunities of these solutions, and to weigh the associated costs, benefits, tradeoffs, and policy options to advance these solutions in efforts to address climate change at the federal and state levels.

This report has not conducted any original cost/benefit analyses of these solutions, which could further support discussions of tradeoffs, impacts, and implications, instead relying on literature review and expert interviews. The arguments, findings, and recommendations in this report represent the views of the authors and do not imply endorsement by CEA Consulting. Any errors or omissions are our own.

[1] Each author defined "ambitious" but plausible mitigation scenarios for each mitigation opportunity. The Paris Climate Agreement encourages "holding warming well below 2 degrees C, and pursuing efforts to limit warming to 1.5 degrees C." The U.S.'s emissions reductions efforts are currently rated "critically insufficient" by the Climate Action Tracker (an independent group that uses scientific analysis to track government climate action)—the lowest possible rating. For some mitigation opportunities, data was available to define a future scenario that is compatible with holding warming well below 2-degrees (e.g., offshore wind), but for others (e.g., blue carbon) data was not available to define a scenario that was compatible with well below 2-degrees of warming.

"Plausibility" varies by chapter and solution, and there is no universally accepted definition of a plausible deployment pathway for each of these measures. Each chapter outlines the key assumptions underpinning the analysis in the chapter, but reasonable individuals may disagree on these fundamental assumptions. These analyses should also be viewed as a snapshot in time. Market, policy, and social dynamics can affect the many assumptions that have gone into producing these analyses.

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Acronyms

AEO	Annual Energy Outlook
AFDF	Alaska Fisheries Development Foundation
AWWI	American Wind Wildlife Institute
BAU	business as usual
BC	blue carbon
BECCS	bioenergy with carbon capture and storage
BOEM	Bureau of Ocean Energy Management
CAT	Climate Action Tracker
CARB	California Air Resources Board
CCS	carbon capture and sequestration
CFCs	chlorofluorocarbons
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
DACCS	direct air carbon capture and storage
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
ECA	emission control area
EEDI	Energy Efficiency Design Index
EIA	U.S. Energy Information Administration
EOR	enhanced oil recovery
ETP	Energy Technology Perspectives
EPA	U.S. Environmental Protection Agency
ESI	Environmental Ship Index
EU	European Union
FERC	Federal Energy Regulatory Commission
GDP	gross domestic product
GHG	greenhouse gases
Gt	gigatonnes
GW	gigawatt
GWP	global warming potential
ha	hectare
HCFCs	hydrochlorofluorocarbons
HFCs	hydrofluorocarbons
HLP	High Level Panel for a Sustainable Ocean Economy
IEA	International Energy Agency
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
ITC	investment tax credit
LCFS	Low Carbon Fuel Standard
LCOE	levelized cost of energy
LNG	liquefied natural gas
McF	thousand cubic feet
MRE	marine renewable energy
Mt	million metric tonnes
MW	Megawatt
MWh	Megawatt-hour
NASEM	National Academies of Sciences, Engineering, and Medicine
NCS	natural climate solutions
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NOx	nitrous oxide compounds
NYSERDA	New York State Energy Research and Development Authority
OCAP	Ocean Climate Action Plan
OCS	Outer Continental Shelf
ODS	ozone depleting substances
OPEX	operational expenditures
OSW	offshore wind
PTC	production tax credit
R&D	research and development
RFS	Renewable Fuel Standard
SOx	sulfur oxides
USGCRP	U.S. Global Change Research Program
VSRP	vessel speed reduction program
WPTO	Water Power Technologies Office
ZEVs	zero-emission vessels

Executive summary

The U.S. is under direct threat from a changing climate, with this crisis playing out acutely along our coast and oceans. The U.S. coastline and oceans play a critical role in our economy and society—as a creator of jobs, as a hub of global and domestic commerce, and as an important part of American history and culture—while also performing an essential function regulating our climate. Climate change is a direct threat to the 127 million people, 61 million jobs, and 4.1 million businesses that make up our coastal and ocean economy (NOAA 2019). Sea-level rise, flooding, erosion, warmer temperatures, extreme weather, ocean acidification, and algal blooms are current threats to our infrastructure, ports, cities, fisheries, tourism, and communities (USGCRP 2018a). These impacts are not felt equally by all Americans, with the elderly, children, those living in poverty, those of ethnic and racial minorities, and those for whom English is a second language being especially vulnerable (U.S. Census Bureau 2016; 2018). The climate crisis is exacerbated by the COVID-19 pandemic and associated economic recession, with ocean-based industries such as fishing and aquaculture, maritime shipping, and tourism being particularly affected (ICP Hub for Action 2020).

Investments in ocean-based climate mitigation measures can reduce U.S. greenhouse gas (GHG) emissions by up to 13.7 percent annually by 2050. According to the Intergovernmental Panel on Climate Change (IPCC), direct action is needed within the next 10 years to manage the current climate crisis, and to prevent it from getting worse (Masson-Delmotte et al. 2018). Until recently, the ocean and coasts had received little consideration in policy proposals to reduce emissions despite their importance in regulating our climate and to the U.S. economy.[2] Yet investments in ocean-based climate measures studied in this report, such as offshore wind and other marine renewable energy (MRE) sources; coastal and marine ecosystem protection and restoration; shipping efficiency improvements; fisheries and aquaculture efficiency improvements and dietary shifts; and storage of GHGs in the seabed, could reduce annual U.S. GHG emissions by 704 Mt CO_2e annually—a full 13.7 percent of required emissions reductions to put the U.S. in line with limiting warming to of 2 degrees Celsius of global average temperature increase.

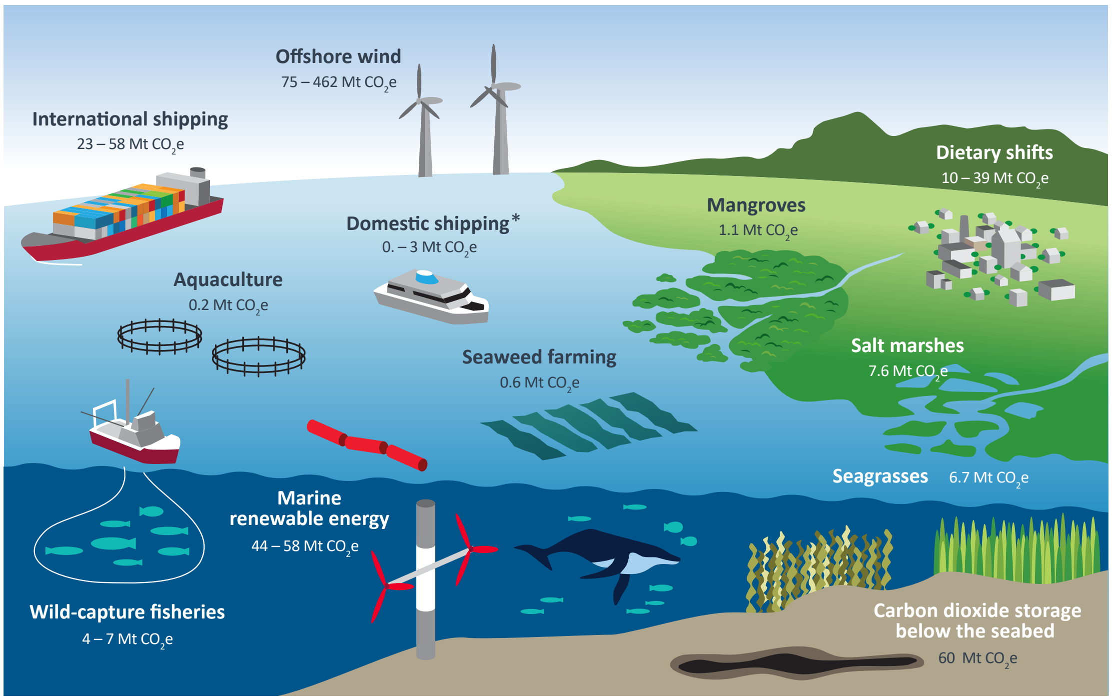
These mitigation measures have significant co-benefits for jobs, economic recovery and growth, American global competitiveness, public health, environmental justice, and the environment. By reducing air pollution, spurring economic activity in growing industries, and protecting our natural resources, all of these solutions can deliver positive co-benefits in the form of job creation, economic growth, and environmental justice—while also reducing GHG emissions. For example, building 30 GW of offshore wind installation in the U.S. by 2030 could create 83,000 jobs annually in construction, operations, supply chain, manufacturing, and supporting industries as well as $25 billion in annual economic output (Hensley and Wanner 2020).

[2] The ocean plays an important role in regulating the climate by absorbing and redistributing heat and carbon dioxide, and producing oxygen—through ocean currents and wind patterns, stratification (the contrast in density between surface and deeper waters), and the biological productivity of coastal and marine ecosystems. The ocean has absorbed more than 90 percent of the excess heat resulting from increased temperatures due to climate change since 1900, while also absorbing 25 to 30 percent of human-caused carbon dioxide emissions. Warming, acidification, and deoxygenation resulting from climate change are reducing the ocean's ability to perform these essential functions (USGCRP 2018b).

This report considers five areas of ocean-based action to mitigate climate change:[3]

- **Offshore wind and other MRE deployment** such as wave and tidal power, and ocean salinity energy technology
- **Coastal "blue carbon" (BC) ecosystem protection, restoration, and cultivation**[4]
- **Decarbonizing U.S. shipping,** which includes efforts to reduce emissions from domestic shipping between U.S. ports as well as international shipping between U.S. ports and foreign ports on American vessels through zero-emission vessels (ZEVs) and operational measures
- **Fisheries and aquaculture efficiency improvements**—such as improved fisheries management, vessel and refrigeration efficiency technology, low-emissions aquaculture operations and feeds—as well as **dietary shifts** toward seafood and away from meat consumption
- **Carbon dioxide storage below the seabed** through a range of technologies that capture, transport, and store carbon dioxide captured from heavy polluting sources (such as power plants)

Figure 1. Opportunities for ocean-climate action and associated annual mitigation potential in 2050



Graphic reproduced from Hoegh-Guldberg. O., et al. 2019 with permission from the World Resources Institute.

*Low-end mitigation potential from domestic shipping is greater than 0, but according to EIA, domestic shipping emissions have already fallen significantly, from 17.5 Mt CO_2 in 2008 to 6.2 Mt CO_2 in 2019. This is likely the result of a change in accounting methodology rather than major emission reductions in the last 11 years.

Several possible ocean-based solutions were considered but ultimately not included in the scope of this report. Additional possible ocean-based climate change solutions such as adaptation, limits on offshore oil and gas production, other geologically based approaches, and ecosystem engineering are briefly discussed in the report, but are not addressed in depth due to this report's focus on mitigation, as well as the significant uncertainty around those measures' viability and ultimate impact.[5,6] Offshore oil and gas is the most notable exclusion, as combustion of fossil fuels is the leading source of U.S. emissions and the U.S. is one of the top five leading offshore oil and gas producers globally (EIA 2018; 2020). Proposed moratoria on offshore oil and gas drilling are one of many supply-side strategies that could limit the continued burning of fossil fuels, which is widely believed to be necessary to reduce emissions in line with globally accepted targets (Heede and Oreskes 2016). These and other considerations are discussed in Box 2 in the Introduction.

[3] These five areas were chosen in order to replicate a global-level analysis at the U.S. level. The High Level Panel for a Sustainable Ocean Economy released a report in 2019—*The Ocean as a Solution to Climate Change: Five Opportunities for Action*—that outlined the mitigation potential of these same five ocean-based climate solutions. The HLP is an initiative of 14 serving world leaders to "build momentum for a sustainable ocean economy, where effective protection, sustainable production and equitable prosperity go hand-in-hand."

[4] "Blue carbon" ecosystems refer to coastal and marine ecosystems—mangrove forests, tidal salt marshes, subtidal seagrass meadows, and seaweed—that naturally remove CO_2 from the atmosphere, similar to trees on land. These ecosystems sequester more than 10 times as much carbon per unit of area as terrestrial ecosystems.

[5] Measures to address climate change largely fall into two categories: mitigation and adaptation. Mitigation refers to measures that reduce GHG emissions and solve the underlying causes of climate change. Adaptation refers to measures that help people adapt to the current and future effects of a changing climate.

[6] Geoengineering approaches include solutions that aim to enhance the ocean's capacity to store carbon dioxide through engineered interventions on a massive scale, such as enhancing ocean alkalinity. Ecosystem engineering approaches refer to efforts to manage the life cycles of living marine organisms to maximize their potential to sequester carbon dioxide.

Within each of these mitigation areas, this report provides a common set of analyses. These analyses include a description of the set of options that could be undertaken; quantification of the emissions reduction (mitigation) potential of each option; a high-level discussion of costs and benefits; an assessment of where within U.S. states and territories these options are currently deployed or most relevant; and a set of policy, research, and technology recommendations that are required to make these actions a reality. Each mitigation area also includes a detailed technical and methodology appendix, as well as a discussion of data limitations and caveats.

This assessment of mitigation potential is intended to be non-partisan, fact-based, and objective. Each chapter is authored by an independent expert and vetted externally. The mitigation scenarios modeled use ambitious but realistic assumptions, with a focus on efforts that are technically viable today. Our expectation is that this report will help support policymakers in prioritizing climate mitigation solutions that have been suggested by ocean policy advocates. The inclusion of any of these options does not imply endorsement by CEA Consulting.

Mitigation potential

Expanding offshore wind production has the greatest mitigation potential of all of the measures modeled, with the potential to reduce power system emissions by 75 - 462 Mt CO_2e annually, out to 2050. Offshore wind is commercially viable today, with nearly 28,000 MW of offshore wind capacity installed globally, compared to just 42 MW in the U.S. (AWEA 2020). The U.S. will need to set national targets, invest in market development, streamline the permitting and development process, assess and address cumulative impacts to the marine environment and marine species, and figure out a way to address competing interests and needs in order to scale offshore wind deployment up to 164,000 MW—the capacity that is needed to achieve the high-end of the mitigation potential range. The Bureau of Ocean Energy Management has already issued 14 leases off the U.S. East Coast that represent a pipeline of 9,000 MW in development that is expected to be online by 2026 (AWEA 2020). There is great technical potential for other ocean-based sources of renewable energy (such as waves, tides, currents, salinity, and temperature), and investments in research and development (R&D) today have significant emissions reductions potentia—44 - 58 MT CO_2e annually by 2050.

The U.S. shipping sector is a major contributor to U.S. and global emissions and local air pollution, and it has the potential for full decarbonization by 2050—but will require substantial policy support, research, and new technology development. Eliminating emissions in the U.S. shipping sector could achieve up to 61 Mt CO_2e of annual mitigation by 2050, but the rate of progress will depend on how aggressively the shipping industry and supportive policies and investments encourage retrofits of existing infrastructure and transition to zero-carbon technologies. The International Maritime Organization (IMO) has already set a target of at least 50 percent GHG emission reductions below 2008 levels by 2050 (IMO 2018). To achieve or exceed these reductions the U.S. will have to set ambitious federal emissions reduction targets for the sector, implement mandatory vessel speed reductions, mandate zero emissions in port, and support zero-carbon fuel and ship infrastructure through federal subsidies. Because ships are long-lived assets, the development and deployment of zero-emission vessels by 2030 will be critical to achieving targeted reductions. Reducing emissions associated with ports would also reduce local air pollution, preventing the cardiovascular and respiratory diseases that disproportionately affect communities near ports, which are predominantly low-income and communities of color (Bailey et al. 2004).

Protection and restoration of coastal "blue carbon" ecosystems and efforts to secure sound fisheries management are near-term opportunities for ocean-based climate mitigation in the U.S. and also offer major co-benefits. Protection of coastal ecosystems represents a full 91 percent of the estimated blue carbon mitigation potential of 16 Mt CO_2e by 2050, by preventing the release of immense amounts of carbon stored in these habitats through conversion or destruction. Standardized mapping, data collection, accounting, and reporting practices are needed to fully and accurately account for BC mitigation potential. Coastal ecosystem protection, in addition to serving as a carbon sink, has numerous other co-benefits such as shoreline protection from flooding and storms, recreation opportunities, public access to the shoreline, improved fisheries habitat, and improved water quality. Fishing and aquaculture are highly carbon-efficient forms of animal protein production, and ensuring effective fisheries management reforms through defending and strengthening the Magnuson-Stevens Act is the most effective way to keep emissions from the sector low and further reduce emissions. The Act should be modified to help support climate-adaptive management of U.S. fisheries, given that fish stocks are already migrating, population dynamics are changing, and ecosystems are shifting due to a changing climate. Climate-friendly refrigeration technology and hybrid or zero-emission vessels would further reduce emissions and improve the efficiency of production. These efficiency improvements (such as refrigerants with low or no global warming potential) are already being implemented on fishing vessels, but policy action (such as ratification of the Kigali Amendment to the Montreal Protocol, or zero-emission vessel subsidies) could accelerate adoption.[7]

[7] The Kigali Amendment to the Montreal Protocol requires ratifying countries to phase down their consumption of hydrofluorocarbon gases (HFCs) that affect the ozone layer and contribute to climate change. HFCs are commonly used as refrigerants in cooling equipment. The Kigali Amendment has been ratified by over 100 countries—the U.S. is not one of them.

Capturing emissions from point sources (such as power plants) and storing those emissions in undersea geological formations is technologically feasible and could result in major emissions reductions at its full technical potential—2.6 Gt CO_2e/year—and it may be the only option for some emitters. Capturing, using, and storing carbon dioxide from point source polluters such as power plants, refineries, and heavy industry is a proven technology, most often used to augment oil production via a process known as enhanced oil recovery.[8] Large-scale carbon capture and sequestration (CCS) could realistically reduce up to 300 Mt CO_2e/year by 2050, but we estimate that a smaller portion of that (60 Mt CO_2e/year by 2050) will occur offshore, due to less expensive storage site availability on land. Investments in CCS could create jobs—especially for workers in the offshore oil and gas industry (an estimated 60,000 job-years within a 10-year timeframe)—while also serving as the only economical emissions reduction option for stationary heavy polluters that provide essential goods (such as cement manufacturing, steel, fossil fuel-based electric power generation, chemical production, and glass) (King et al. 2020). Achieving this mitigation potential from CCS would require significant investments in tax credits to enable this solution to compete with cheaper mitigation alternatives, such as reforestation.

Table 1. Summary of U.S. mitigation potential offered by each area of ocean-based climate action

Action area	2030 Mitigation potential (Mt CO_2e/year)	2050 Mitigation potential (Mt CO_2e/year)
1. Offshore wind and other marine renewable energy deployment	27 – 96	119 – 520
2. Coastal "blue carbon" ecosystem protection, restoration, and cultivation	15	16
3. Decarbonizing U.S. shipping	8 - 21	23 - 61
4a. Fisheries and aquaculture efficiency improvements	4 - 6	4 - 7
4b. Seafood dietary shifts	8 - 33	10 - 39
5. Carbon dioxide storage below the seabed	10	60
Total	**72 - 182**	**232- 704**
Total percentage contribution to equal emissions reductions (1.5°C pathway)	**2.3 - 5.8%**	**4.2 - 12.6%**
Total percentage contribution to equal emissions reductions (2°C pathway)	**2.9 - 7.2%**	**4.5 - 13.7%**

Across all five of these ocean-based climate action areas, we estimate the maximum GHG mitigation potential as 182 Mt CO_2e in 2030 and 704 Mt CO_2e in 2050, which represents 7.2 percent and 13.7 percent of equal per capita emissions reductions required for the U.S. to achieve its contribution to the 2 degree pathway.[9] Offshore wind is the most decisive investment that could be made today, with significant emissions reduction potential by 2030 and 2050. Blue carbon protection and restoration and fisheries management and efficiency improvements represent immediately actionable mitigation opportunities with significant co-benefits. Decarbonizing the U.S. shipping sector and expanding other sources of marine renewable energy could be major sources of mitigation with co-benefits for local air pollution, but will require substantial investments today in order to yield impacts by 2050. Shifting diets, while possible, may be challenging as a consumer-driven strategy requiring tax, policy, and behavioral incentives. CCS has substantial technical potential and will be an important component of future emissions mitigation, but it faces ongoing questions about viability without major federal support and in the face of competition from cheaper land-based storage sites.

[8] Enhanced oil recovery is a process by which carbon dioxide and water can be used to flush residual oil from oil wells underground.

[9] By "equal per capita emissions reductions" we mean emissions reductions in line with the Climate Action Tracker's Equality scenario, which projects needed U.S. emissions reductions to be reduced equally across all nations globally. Pursuing equal per capita emissions reductions is in line with past public statements the U.S. has made in international climate negotiations.

We have assigned these different ocean-based solutions to four policy clusters: decisive, low regret, unproven, and risky (Gattuso 2019). These assignments are based on a mix of factors including implementation status, effectiveness in reducing emissions, co-benefits, and current understanding of uncertainties and risks.

Figure 2. Contribution of ocean-based climate measures to mitigating U.S. emissions in 2030 (maximum Mt CO_2e)

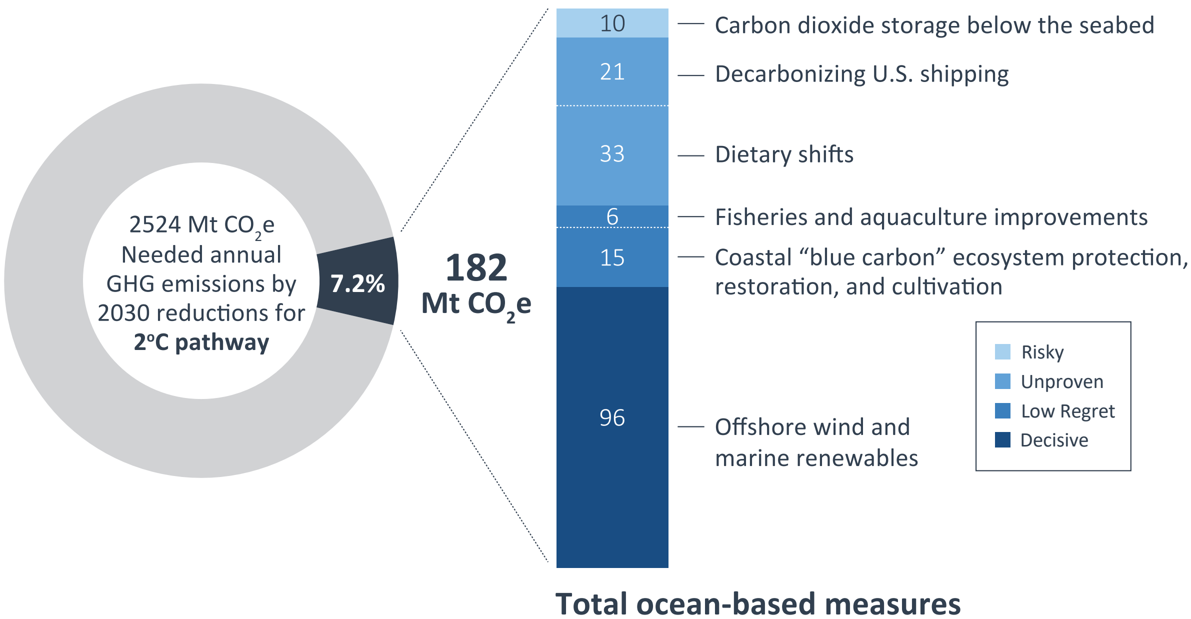
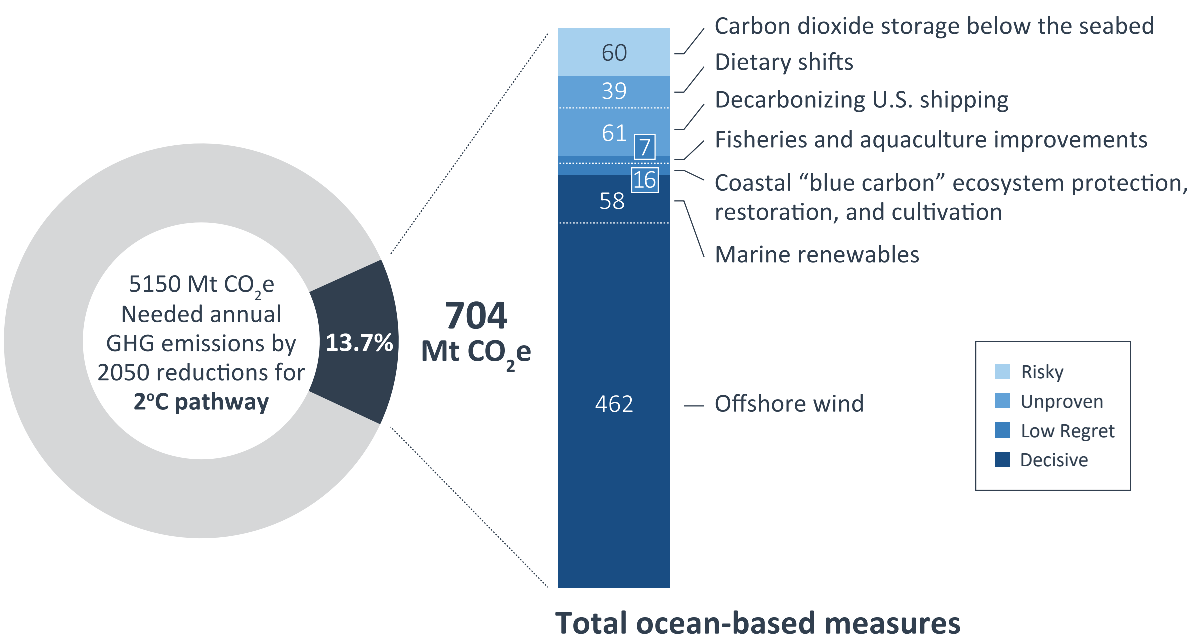


Figure 3. Contribution of ocean-based climate measures to mitigating U.S. emissions in 2050 (maximum Mt CO_2e)



Policy, research, and technology needs to achieve mitigation potential

Experts estimate that the U.S. has 10 years to shift our current emissions trajectory toward one that will not result in large-scale economic and social disruption. This effort will require ambitious and coordinated solutions from all sectors of the U.S. economy. Leaders and experts globally have aligned on a 1.5 degree Celsius trajectory for warming by 2100 as the scenario that presents a reasonable chance of managing climate impacts, with the 2 degrees Celsius scenario presenting a less desirable option (UNFCCC 2015). Currently, the U.S.'s efforts to restrain its emissions are rated "Critically Insufficient" by the Climate Action Tracker—the lowest possible rating, which would suggest global average warming of 4 degrees Celsius by 2050.[10] The impacts of 4 degrees of warming on the U.S. are hard to predict, but even under a 1.5 degrees Celsius scenario the U.S. can expect to see greater temperature extremes in hot months—an expected 7.2 degrees Fahrenheit on average—as well as increased coastal flooding, beach erosion, and salinization of water supplies due to an average sea-level rise of 0.33-0.66 feet, for example (NASA 2019). Some of the human and economic impacts would include an increase in heat-related morbidity and mortality, as well as an estimated loss of 2.3 percent of U.S. GDP for each degree of increase in global average temperatures, primarily due to the impacts of extreme weather events (Kahn et al. 2019).

Offshore wind and decarbonizing shipping offer the most significant emissions reductions potential in the near term and long term; all of the solutions modeled offer substantial co-benefits for the economy, pollution reduction, and climate adaptation. Scaling up offshore wind offers the most climate mitigation potential of all of the solutions modeled, with significant co-benefits in terms of job creation—an estimated 80,000 annually. Decarbonizing the shipping sector could also offer significant emissions benefits, while reducing local air pollution and supporting environmental justice. Other solutions provide important climate adaptation and other co-benefits, such as shoreline protection through coastal BC ecosystem protection and restoration, as well as improved fisheries management that helps to reduce risk to fisheries from a changing climate. Carbon dioxide storage in the seabed has the potential to reduce emissions at a large scale—if there is significant policy support and subsidies.

Figure 4. Co-benefits of ocean-based climate mitigation measures

Measure	Co-benefit: Jobs	Economic benefits	Environmental justice and just transition	Hazard reduction	Pollution reduction	Health	Environmental benefits
Offshore wind and marine renewables	✓	✓	✓		✓	✓	
Coastal protection, restoration, and cultivation	✓	✓		✓	✓		✓
Decarbonizing U.S. shipping		✓	✓		✓	✓	
Fisheries and aquaculture efficiency and diets	✓	✓			✓	✓	✓
Carbon dioxide storage below the seabed	✓	✓	✓		✓		
Offshore oil and gas moratorium*				✓	✓	✓	✓

This table presents documented and estimated co-benefits of the five ocean-climate mitigation measures and an offshore oil and gas moratorium, based on a combination of literature review and expert interviews. Check marks indicate that co-benefits are present—described more in detail in each chatper. The lack of a check mark does not necessarily indicate a co-benefit is not present, but it did not arise in our review.

*A moratorium on offshore oil and gas was not modeled, but discussed in detail in the Introduction.

[10] The Climate Action Tracker is an independent scientific analysis that tracks government climate action and measures it against the Paris Climate Agreement goal of "holding warming well below 2 degrees C, and pursuing efforts to limit warming to 1.5 degrees C." The tracker quantifies and evaluates climate change mitigation commitments and assesses whether countries are on track to meet those commitments.

Policy action is critical to enable rapid deployment and development of these solutions to ensure they can deliver their emissions reduction potential on the timeline required to manage the worst impacts of climate change. The viability of the solutions modeled here will depend on a mix of economic, political, technological, and social drivers. Policymakers have it in their hands to decide how to weigh and influence these drivers, viewed in the context of the climate crisis and its impacts.

Table 2. Policy, research, and technology needs required to deliver on mitigation potential of U.S. ocean-based climate action areas

1. Offshore wind and other marine renewable energy deployment

Offshore wind

- **Establish national offshore wind deployment targets combined with direct financial support** (such as investment and production tax credits) to grow the market for offshore wind similar to how the federal government and states have supported solar and land-based wind.
- **Identify sufficient sea space for the development of offshore wind through ocean planning and efficient permitting.** The Bureau of Ocean Energy Management plays an essential role in offshore wind siting. Developing national guidelines for siting and a streamlined permitting process could expedite the siting process and address the need to protect ocean wildlife and minimize conflict with other human uses.
- **Support investments in supply chain and infrastructure** through regional planning goals and funding for transmission and port upgrades to service the offshore wind sector.
- **Reduce uncertainty by supporting targeted research** that proves and optimizes large-scale floating offshore wind installations; assesses the capacity value of offshore wind and its cost-effectiveness as part of electricity portfolio planning; and assesses and mitigates potential environmental or human-use impacts from turbine installations.
- **Direct funding to advance technology development.** Improvements to turbines, design standards, and integrating technology will help improve the value proposition of offshore wind as a decarbonization strategy.

Marine renewables

- **Continue research and development** to advance MRE technologies from small-scale prototype testing to large prototype testing, demonstration, and finally early commercial stage. Augmenting funding to existing programs such as the Pacific Marine Energy Center and the DOE's Water Power Technologies Office could support this goal.
- **Direct the DOE to identify the most promising markets for MRE** in order to right-size deployments to market needs, such as ocean observation and navigation, marine vehicle charging, aquaculture, algae farming, desalination, power for island communities, and disaster recovery efforts.
- **Apply the recommendations listed above for offshore wind once MRE technologies and markets are more mature.** Once MRE technology is more mature and an MRE industry is poised to launch, many of the policies we have recommended for offshore wind related to siting and permitting could be adapted to support scaling-up of MRE.

2. Coastal “blue carbon” ecosystem protection, restoration, and cultivation

Conservation and restoration

- **Strengthen policies to bring BC habitat loss rates to zero**, such as a “no net blue carbon loss” policy and implementing recommendations to strengthen the compensatory mitigation rule for unavoidable habitat loss under the Clean Water Act.
- **Integrate BC habitat protection and restoration into shoreline protection plans and policies** for coastal flooding and emissions benefits.
- **Identify and integrate climate change impacts in conservation and restoration** management plans to ensure BC ecosystems are able to protect carbon storage and sequestration in the face of sea-level rise, coastal erosion, and wetland migration.
- **Provide long-term funding for BC ecosystem conservation and restoration**, especially for continued monitoring of GHG emissions.
- **Establish national governance of BC to maintain a standardized inventory**, such as the proposed Interagency Working Group on Blue Carbon that will develop and maintain a national map and inventory of BC ecosystems, identify roadblocks to restoration, assess impacts of climate change on BC ecosystems, and ensure continuity of BC data.

Seaweed cultivation

- **Fund research and development** to evaluate the use of seaweed aquaculture for climate mitigation.

3. Decarbonizing U.S. shipping

- **Leverage EPA authority to set federal emissions reduction targets in line with or exceeding IMO targets** for rapid decarbonization of the U.S. shipping sector.
- **Implement national mandatory vessel speed reduction programs** within 200 nautical miles from shore.
- **Reduce localized emissions and promote environmental justice** by mandating zero at-berth emissions for ships in port.
- **Establish a centralized monitoring, reporting, and verification data collection system for U.S. shipping.**
- **Provide funding to the Maritime Environmental and Technical Assistance program** for research on zero-emission vessels and port technologies.

4. Fisheries and aquaculture efficiency improvements and dietary shifts

- **Maintain and strengthen fisheries** management by defending and strengthening the Magnuson-Stevens Act, incorporating climate adaptation into fisheries management, and managing fisheries to maximum economic yield.
- **Provide grants and loan guarantees for efficiency upgrades** and for low- or zero-emission fishing vessel technology.
- **Ratify the Kigali Amendment to the Montreal Protocol** and develop an implementation plan that includes refrigeration equipment for the fishing sector.
- **Streamline the regulatory process for offshore aquaculture** while providing protections for the environment and other ocean stakeholders.
- **Increase the recommended amount of seafood consumption in the U.S. dietary guidelines.**
- **Promote American-produced seafood.**

5. Carbon dioxide storage below the seabed

- **Enhance and extend the 45Q tax credit** by increasing the credit from $50 per ton of CO_2 that is captured and stored to above $65 per ton, and extend the timeframe beyond the current expiration in 2023.
- **Amend the Low Carbon Fuel Standard in California to include offshore storage** and adopt a similar standard in other states.
- **Conduct a national assessment of the carbon storage potential in deep seafloor environments.**
- **Streamline the permitting framework** for CO_2 storage to accelerate technology deployment.

Introduction

Background

America's coastlines, Great Lakes, and oceans are major contributors to the U.S.'s economic prosperity and global competitiveness. More than 127 million Americans live along this nation's 95,000 miles of coastline, representing nearly 40 percent of the U.S. population (NOAA 2019). The U.S. coastal and ocean economy accounts for nearly $9 trillion (43 percent) of GDP, employs 61 million people (40 percent of the nation's jobs), and supports 4.1 million businesses (NOAA 2019). Ocean-based industries such as tourism and recreation, marine transportation, offshore mineral extraction, ship and boat building, living resources (such as fisheries), and marine construction employ more people in the U.S. than the telecommunications, crop production, and building construction industries combined, while our seaports serve as gateways to the U.S. economy and as global hubs of commerce (NOAA 2019). Similarly, our nation's exclusive economic zone is one of the largest in the world, with an area larger than all 50 states combined and an estimated value of its living resources, ecosystems, and other economic benefits in the billions if not trillions of dollars (Ocean Science and Technology Subcommittee of the Ocean Policy Committee 2020).

The ocean also plays a critical role in the global climate system, by absorbing and redistributing heat and carbon dioxide, while also serving as habitat for many species and providing other services like shoreline protection from storms (USGCRP 2018a). The ocean has absorbed roughly 93 percent of excess heat energy since the 1970s, and also captures about a quarter of carbon dioxide emissions from human sources (USGCRP 2018a), demonstrating its critical role in the global climate system.

Climate change is already a direct threat to the U.S. as a whole, with acute effects on the coastal and ocean economy and way of life. These impacts will intensify unless emissions are reduced in line with global benchmarks. The Fourth National Climate Assessment documented the observed and anticipated impacts of a changing climate on the U.S.: more frequent and intense extreme weather and climate-related events, changes in average climate conditions, damage to infrastructure, ecosystems, and social systems, and increasing inequality (USGCRP 2018a). These impacts are acute along our ocean and coasts, including sea-level rise, high-tide and storm surge flooding, erosion, saltwater intrusion into groundwater, greater rainfall and river runoff, increasing water and surface air temperatures, ocean warming, ocean acidification, and deoxygenation (USGCRP 2018a).[11] Documented and anticipated increases in coastal flooding threaten the greater than $1.4 trillion in real estate and businesses along the coasts, the 60,000 miles of U.S. roads and bridges in coastal floodplains, critical energy infrastructure, and coastal seaports that handle 99 percent of overseas trade (USGCRP 2018a). Sea-level rise is resulting in significant losses in wetlands that support fisheries, reduce shoreline erosion, and create valuable recreation opportunities. The U.S. is losing over 80,000 acres of coastal wetlands annually (USGCRP 2018a). Hypoxic "dead zones" and harmful algal blooms that are exacerbated by warmer ocean and coastal waters are increasing in frequency and severity—with 500 percent more algal blooms reported in 2020 than 2010 (Environmental Working Group 2020). Algal blooms result in fish kills and fishery closures, toxic algae growth that affects public and animal health, and beach closures. Warmer waters are adding stressors to U.S. fisheries—driving changes in distribution, timing, and productivity.[12]

[11] The **National Climate Assessment** is a U.S. research assessment that evaluates the impacts of global climate change on the U.S.'s natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity no less than every four years as a report to Congress and the President. The report is produced by the U.S. Global Change Research Program as mandated by the Global Change Research Act of 1990. It is distinct from the **Intergovernmental Panel on Climate Change** Assessment Reports on the state of scientific, technical, and socio-economic knowledge about climate change for all UN member countries. IPCC reports are produced by scientific experts nominated by UN member governments.

[12] For example, two major marine "heat waves" occurred along the Northeast Coast in 2012 and along the West Coast from 2014 to 2016, warming ocean temperatures to a level that had not been expected until later this century. Changes included the appearance of warm-water fish species, increased mortality of marine mammals, and a harmful algal bloom that created intense economic stress in some of the nation's most valuable fisheries (USGCRP 2018a). The 2012 extreme marine heat event resulted in lobster catches peaking 3-4 weeks earlier than usual, which flooded the market and resulted in steep drops in prices. The 2015 "blob" event in the North Pacific resulted in a toxic algae bloom of *Pseudo-nitzschia* that led to mass die-offs of sea lions and whales, as well as the closure of the Dungeness crab fishery and reduced catch of Pacific cod.

Climate change does not affect all people on coastlines equally; certain groups are more vulnerable to negative health and economic impacts of coastal hazards, including children, the elderly, households where English is not the primary language, and those in poverty. Approximately 40 percent of Americans living in coastal counties fall into elevated coastal hazard risk categories, including children, the elderly, households where English is not the primary language, and those in poverty (U.S. Census Bureau 2016). Coastal counties are also more ethnically and racially diverse than America as a whole (51.5 percent of the population in coastal counties identifies as non-white vs. 38.7 percent in the U.S. as a whole) (U.S. Census Bureau 2018). The impacts of hurricanes Harvey, Maria, Sandy, and Irma illustrate what is at stake, with economic impacts of these events estimated in the hundreds of billions of dollars, and both acute and long-term health impacts including injury, illness, death, and mental health pathologies (Lane et al. 2013; NOAA's National Hurricane Center 2018).[13] These vulnerabilities are likely to intensify as more people migrate to coasts. Coastal populations are increasing both seasonally and permanently; from 1970 to 2010 the population in coastal counties increased 40 percent, by 34.8 million people—almost triple the national growth rate (NOAA's Office for Coastal Management 2016).

Climate change is colliding with one of the worst recession in American history to create unprecedented challenges and opportunities. Although still unfolding, the U.S. recession caused by the COVID-19 pandemic has resulted in tens of millions of lost jobs and sharp reductions in GDP and economic growth projections, ending the longest period of economic expansion in U.S. history and paralleling the Great Depression in terms of its economic impact (Center on Budget and Policy Priorities 2020). Some of these impacts are being felt acutely by ocean-based industries, particularly fishing and aquaculture, maritime shipping, and tourism (ICP Hub for Action 2020). In response, the federal government passed a series of three recovery packages that combined mark the largest economic rescue package in American history (Davis, Grisales, and Snell 2020). As the U.S. looks to recover from the economic crisis, additional aid packages are being considered.

This influx of investments—by the federal government, but also potentially states and municipalities—could be used to invest in "win-win" solutions for the economy and for climate change while reducing vulnerabilities among affected groups. For example, experts at the University of California, Berkeley estimate that given the rapidly declining costs of clean energy, the U.S. can deliver 90 percent of its electricity from carbon-free sources by 2035 (Goldman School of Public Policy, University of California, Berkeley 2020). They also argue that accelerating investments in clean energy could support economic recovery through significant job creation—at the level of 530,000 jobs annually.

The U.S. ocean and coastal economy can be part of the solution to climate change, with significant co-benefits for economic recovery, American global competitiveness, public health, and environmental justice. Offshore renewable energy; protection, restoration, and expansion of coastal ecosystems; fisheries management improvements; and shipping and port efficiency improvements can create jobs, support growth in sustainable new industries, and protect coastlines and communities from sea-level rise and extreme weather events, while helping reduce overall carbon dioxide emissions. A recent report by the High Level Panel for a Sustainable Ocean Economy estimated that every dollar invested in four ocean-based climate solutions delivered $5 in benefits (Konar and Ding 2020).[14] For example, experts estimate that every $1 million invested in coastal restoration generates 17 to 30 jobs, compared to 2.65 jobs in fossil fuel industries (P. E. T. Edwards, Sutton-Grier, and Coyle 2013; Garrett-Peltier 2017; Restore America's Estuaries 2011). Restoration jobs are also labor intensive, so they cannot be exported or automated, and they tend to be located in rural areas where unemployment levels may be higher than the national average (BenDor et al. 2015). Coastal protection and restoration have myriad benefits, including protecting communities from sea-level rise and flooding, halting erosion, storing carbon dioxide and pulling it out of the atmosphere, providing fishery habitat, and creating opportunities for coastal recreation.

[13] Hurricanes Harvey, Maria, Sandy, and Irma were four of the most economically destructive hurricanes in American history, causing $125 billion, $90 billion, $65 billion, and $50 billion in damage respectively—surpassed only by Hurricane Katrina in 2005 ($125 billion in damages). Four of the top five most destructive hurricanes occurred in the last eight years.

[14] The four investments included conserving and restoring mangrove habitats, scaling up offshore wind production, decarbonizing the international shipping sector, and increasing the production of sustainably sourced ocean-based proteins.

To help support prioritization of the most critical interventions to combat climate change, this report focuses on the greenhouse gas (GHG) mitigation potential—meaning the potential to reduce or remove GHGs from the atmosphere—of a series of ocean-based options to address climate change:[15]

- **Offshore wind and other marine renewable energy** such as wave and tidal power and ocean salinity energy technology, which have the potential to contribute significantly to a clean energy economy, primarily via offshore wind. That sector is expected to see rapid growth in the next decade and could contribute to nearly 25 GW of wind power by 2030, alongside 80,000 new jobs annually (Zhang, Cohen, and Barr 2020).
- **Coastal ecosystem protection, restoration, and cultivation,** specifically the protection, restoration, and cultivation of "blue carbon" ecosystems—seagrasses, salt marshes, mangrove and kelp forests, and macroalgae—that can sequester GHGs.[16] Coastal protection and restoration have numerous co-benefits beyond mitigation, including providing protection from storms and flooding, habitat for fisheries, opportunities for tourism and recreation, and well-paying jobs—an estimated 17 to 30 jobs per $1 million invested (P. E. T. Edwards, Sutton-Grier, and Coyle 2013; Restore America's Estuaries 2011).
- **Decarbonizing U.S. shipping**—including efforts to reduce emissions from domestic shipping between U.S. ports and international shipping (which refers to shipping between a U.S. port and foreign ports on ships that fly an American flag) through development and deployment of zero-emission vessels as well as operational measures. This report does not examine recreational boat emissions given their proportionally small contribution to total emissions. Decarbonizing shipping will require significant investments in research, technology, and deployment, but shipping represents a major source of emissions. Potential co-benefits include reducing local air pollution and improving health outcomes in communities near ports that are predominantly low-income and communities of color, as well as increasing demand for renewable energy and offshore wind.[17]
- **Fisheries and aquaculture efficiency improvements** as well as **dietary shifts.** This chapter assesses the emissions reduction potential of efforts to improve the efficiency of fishing vessels (engines, refrigeration), improvements to fisheries management—including adapting to climate change, aquaculture operations and feed improvements—and a shift toward more seafood consumption. Although fisheries are not a major source of emissions, sustainable fisheries management can yield numerous benefits for long-term fishery health, and well-managed, healthy fisheries are better able to adapt to climate change (Gaines et al. 2018). Efficiency improvements can reduce costs for producers, although they may require up-front investment. In addition to emissions benefits, shifting diets toward seafood has numerous potential health benefits, but may affect beef, chicken, and pork producers.
- **Carbon dioxide storage below the seabed** refers to a range of technologies that capture carbon dioxide from point sources and remove it from the global carbon cycle through storage in geological formations deep below the ocean floor—also known as carbon capture and sequestration (CCS). There is potential to store thousands of years of emissions in the seafloor. Technologies are largely proven but are at the early stages of deployment in marine environments. These technologies also offer one of the most viable emissions reductions options for heavy polluters such as oil refineries, pulp and paper production, chemical manufacturing, cement manufacturing, and iron and steel production.

[15] Solutions to climate change largely fall into two categories: **mitigation** and **adaptation**. Mitigation refers to solutions that reduce greenhouse gas emissions and solve the underlying causes of climate change. Adaptation refers to solutions that help people adapt to the current and future effects of a changing climate.

[16] The term "blue carbon" refers to greenhouse gases, specifically carbon dioxide, that are captured by the world's ocean and coastal ecosystems. Seagrasses, mangroves, salt marshes, and seaweed along coastlines capture and hold—"sequester"—carbon dioxide, acting as a natural mechanism to remove carbon from the atmosphere, similar to trees and forests on land. More details about blue carbon ecosystems are discussed in Chapter 2.

[17] Ports are major sources of local air and water pollution, rivaling or exceeding air pollution from power plants and refineries. For example, the Port of Los Angeles emits more air pollution than all of the power plants in Southern California combined. Pollution comes from a wide array of sources, including oceangoing ships, harbor tugs, passenger ferries, diesel truck traffic, rail traffic, chemical storage and handling, ship discharges, fueling, channel dredging, and many other sources. A range of pollutant types are emitted, such as particulate matter, volatile organic compounds, nitrous oxides, ozone, and sulfur oxides. Negative health outcomes include respiratory diseases, cardiovascular diseases, lung cancer, asthma and bronchitis, and premature death. Port workers and communities living near ports tend to be disproportionately low-income and communities of color (Bailey et al. 2004). In California alone the California Air Resources Board estimates that 3,700 premature deaths per year are directly attributable to ports and goods movement activities statewide, at an economic cost associated with deaths, medical care, and missed school and work days of $30 billion annually (Marquez and Vallianatos 2012).

These mitigation opportunities were identified through a combination of literature review, review of policy and advocacy proposals, and expert consultation. Specific details on what each option entails are described in Table 3 below. These mitigation options should not be viewed as the only ocean-based solutions to a changing climate. Excluded from this report are the following:

- **Adaptation solutions.** This category of solutions focuses on how to support communities in adapting to the impacts of a changing climate. Examples include support to low-income, vulnerable, and tribal coastal communities to retreat from unstable shorelines, reform of the National Flood Insurance Program, and stormwater management improvements to reduce coastal flooding. As far as the authors of this report are aware, the GHG emissions reduction potential of these adaptation solutions is not well known. Additionally, many of the mitigation options examined in this report may have adaptation benefits, which are discussed in more detail in each chapter.
- **Limits on offshore oil and gas production**. This is the most significant source of ocean-based GHG emissions, and achieving global emissions reduction goals to maintain a 1.5 degree or 2 degree future will require leaving significant fossil fuel resources in the ground to limit further combustion and associated emissions (EIA 2018; 2020; Heede and Oreskes 2016). Limiting offshore oil production has the added benefit of reducing the risk of catastrophic oil spills, such as the BP Deepwater Horizon disaster, and reductions in air pollution. It is challenging to assess the emissions impact of supply-side strategies (e.g., bans, limitations) targeting a specific mode of oil production of a single producing country. See Box 2 for a more detailed discussion of the implications of offshore oil and gas moratoria.
- **Marine sediment protection.** Similar to nearshore blue carbon ecosystems, marine sediments also store carbon, which is vulnerable to release from activities such as trawling or mining. Globally, these marine sediments are estimated to be the largest pool of soil carbon stocks in the world, 2.3 times greater than carbon stocks of terrestrial soils (Atwood et al. 2020). Safeguarding these soils from remineralization of their carbon back into the ocean is a critical goal to prevent further exacerbation of climate change. This is an emerging area of research and therefore was not included in this report.
- **Ocean geochemistry** solutions such as direct injection of carbon dioxide into the deep ocean, addition of alkalinity to seawater, and artificial fertilization as a means for ocean-based carbon dioxide removal. Apart from some discussion in the section on carbon storage below the seabed, these solutions are excluded from this report due to current knowledge gaps on viability and on societal and environmental impacts. Ocean-based carbon dioxide removal is an active and growing area of research.
- **Ecosystem engineering**, which refers to an emerging set of approaches exploring how to store carbon in marine life such as whales, sharks, and other living organisms. While these organisms—like all living organisms—are made up of carbon, some scientists and advocates are exploring conservation efforts that seek to maximize the carbon storage potential of these creatures' life-cycle. These approaches have only been discussed in theory, and have not been seriously considered by many ocean climate advocates (Thompson et al. 2017).

[18] Carbon dioxide removal approaches aim to enhance the ocean's capacity to store carbon dioxide, both biologically (through increased photosynthesis) and abiotically (through efforts to shift the chemistry of seawater and the amount of carbon dioxide it can store). These are highly technical solutions that are described more concretely on **oceancdr.net**.

Table 3. Summary of mitigation options assessed

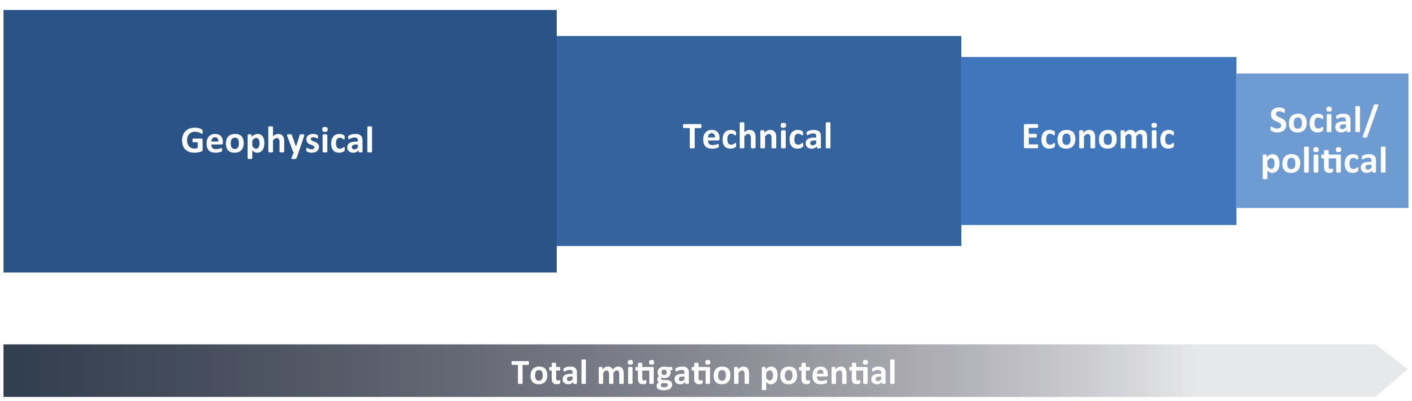
Action area	Mitigation action	Description
Offshore wind and other marine renewable energy deployment	• Expand offshore wind	• Fixed and floating offshore wind turbine installations
	• Develop renewable energy technology from other marine sources	• Energy extracted from ocean waves, tides, currents, salinity, and temperature differences
Coastal “blue carbon” ecosystem protection, restoration, and cultivation	• Conservation and protection to prevent habitat loss	• Preventing the release of high levels of already-sequestered carbon in soils and vegetation in coastal wetlands through protection and avoided degradation
	• Restoration of previously lost or degraded habitat	• Sequestration potential gained from restoration of salt marsh, seagrass, kelp, and mangrove habitat
	• Expansion of seaweed cultivation	• Capturing and storing carbon through seaweed aquaculture cultivation (kelp)
Decarbonizing U.S. shipping	• Reducing emissions from domestic shipping	• Efforts to reduce emissions from shipping between two or more U.S. ports, including inland waters and port emissions, and excluding recreational boating
	• Reducing emissions from international shipping	• Efforts to reduce emissions from shipping between a U.S. port and foreign port on vessels that fly an American flag, including emissions in ports
Fisheries and aquaculture efficiency improvements and dietary shifts	• Reducing emissions from wild-capture fishing	• Emissions reduction strategies include improving fisheries management; transitioning to more efficient, hybrid, or zero-emission vessels; favoring fuel-efficient fishing methods and gears; eliminating capacity-enhancing subsidies; and upgrading refrigeration to low GWP technologies
	• Reducing emissions from aquaculture	• Emissions reduction strategies include shifting to low-carbon feeds and unfed aquaculture; reducing farm energy use; minimizing fertilizer application; promoting seaweed farming; and prioritizing smart farm siting
	• Reducing emissions by shifting diets	• Creating incentives for more seafood consumption as a lower-carbon protein source, compared to ruminant meats
Carbon dioxide storage below the seabed	• Capturing emissions from stationary sources (e.g., factories, power plants) for subsequent transport and storage in sub-seabed geological formations	• A suite of technologies and related supply chains required to capture carbon dioxide emissions from stationary (point) sources, compress and transport the CO_2 to geological formations such as saline aquifers, and permanently store it in the porous rock under the seabed

Methods

This report comprises five chapters that calculate the mitigation potential of these options in 2030 and 2050. These numbers are calculated based on ambitious but plausible scenarios for emissions reductions, economic growth, and deployment that vary by solution.[19] The year 2030 was chosen to highlight potential near-term benefits of immediate climate action, while the year 2050 was chosen to highlight possible contributions of these solutions to long-term strategies of reducing emissions to net zero by mid-century, which is in line with accepted global targets.[20] These five separate chapters reflect five distinct analyses, but each covers several common areas of inquiry:

- **Context.** A brief description of why this mitigation option is relevant and what actions it entails.
- Mitigation potential. The estimated size of the GHG mitigation potential, considering geophysical, technical, economic, and socio-political dynamics relevant for each intervention.
- **Costs and benefits.** A high-level discussion of the cost and benefit implications of implementing each of the interventions modeled, with a focus on contributions to job growth, economic recovery, and environmental justice.
- **Geographic opportunities - status and future deployment potential.** A summary of what is known about the current state and future opportunities in all U.S. coastal regions: East Coast, West Coast, Gulf Coast, Great Lakes, Alaska, Hawaii, and U.S. territories, as well as tribal coastal interests.
- **Policy, research, and technology needs.** Deployment status of these solutions can vary significantly. Each chapter provides discrete recommendations for how to deploy each solution, building on recent policy, research, and technology reports unique to each solution area.
- **Key assumptions, data limitations, and caveats.** Authors describe any notable challenges with data or underlying assumptions that are covered in more detail in a separate **Methodology Appendix** for each chapter.

Figure 5. Determining mitigation potential



Reproduced from Hoegh-Guldberg. O., et al. 2019 with permission from the World Resources Institute.

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

[19] To project emissions into the future and help countries plan for the impacts of a changing climate, the Paris Climate Agreement suggests two scenarios for global average temperature increase due to climate change, each with a set of implicit assumptions and anticipated outcomes. These are known colloquially as the 1.5 degrees Celsius and the 2 degrees Celsius scenarios (1.5DS and 2DS, respectively).

[20] The Paris Climate Agreement encourages countries to develop targets that would reduce emissions in line with the 1.5DS. If the 1.5DS comes to pass, it is estimated that global carbon dioxide emissions would reach "net zero" by 2050. Net zero means that any human-caused GHG emissions are balanced out by removal of GHGs from the atmosphere via natural processes or enhanced sequestration.

Box 2. Assessing the greenhouse gas impact of offshore oil and gas production

Combustion of fossil fuels is the leading source of U.S. CO_2 emissions, responsible for 75 percent of U.S. anthropogenic GHG emissions in 2018.[1] U.S.-based offshore oil and gas drilling—which almost exclusively occurs in the Gulf of Mexico—made up approximately 15 percent of U.S. crude oil production and 3 percent of U.S. dry natural gas production in 2019.[2] The offshore oil and gas industry is also an important economic sector, supporting an estimated 315,000 jobs and contributing $30 billion to the U.S. economy—predominantly in Gulf Coast states.[3]

To limit global average temperature increases to 1.5 or 2 degrees Celsius, the world will need to keep proven oil and gas reserves in the ground. The Bureau of Ocean Energy Management estimates that the U.S. could economically recover 68.17 billion barrels of oil and up to 173.95 billion Mcf of natural gas from the Outer Continental Shelf—equivalent to approximately seven years of U.S. oil and gas production.[4] The U.S. was the top crude oil producer in 2018 and 2019, and it is also one of the top five leading offshore oil and gas producers globally, after Saudi Arabia, Brazil, Mexico, and Norway.[5] Climate experts have shown that to limit warming to less than 1.5 or even 2 degrees globally, a significant share of oil and gas reserves will have to stay in the ground.[6] Continued production and combustion of fossil fuels will not enable the world to meet climate goals.

A moratorium on new offshore oil and gas leases in U.S. waters has been an area of public policy debate for decades, with significant back and forth in policy proposals across federal administrations. Most recently, the Trump administration partially reversed course on its 2018 plan to expand offshore drilling off the U.S. Pacific and Atlantic coasts, the west coast of Florida, and Alaska by issuing a moratorium on new offshore oil and gas leases in the Gulf of Mexico.[7] The arguments for a moratorium on offshore oil and gas exploration have historically focused primarily on the potential economic and environmental risks from oil spills for coastal communities and wildlife, as evidenced by the BP Deepwater Horizon oil spill disaster. Public health risks are also a major concern, as an individual offshore oil platform is estimated to contribute to between $426,000 and $2.9 million in damages due to air pollution.[8]

Opposition to offshore drilling has broad bipartisan support. The Center for American Progress found that opposition to the Trump administration's offshore oil and gas drilling plan cuts across both the Republican and Democratic party, including governors from 17 coastal states; more than 330 municipalities; more than 2,100 local, state, and federal elected officials; the U.S. Department of Defense; the U.S. Air Force; the Florida Defense Support Task Force; NASA; and an alliance representing more than 43,000 businesses and 500,000 fishing families. Offshore drilling is also opposed by more than 60 percent of voters.[9]

There are several challenges associated with estimating the effects of constraining offshore oil supply on U.S. emissions. As oil is a global market driven by both supply and demand constraints, a moratorium on offshore oil and gas would constrain supply from this part of the market, but in response the market will look to alternative sources of production to meet demand, such as terrestrial production or imports.[10] The emissions profile of these alternative sources would be challenging to predict.[11,12]

While there is no question that fossil fuel combustion and associated emissions must decrease as part of any solution to climate change, the impacts of an offshore oil moratorium will depend on assumptions about the market dynamics for oil, which is a highly globalized and volatile market. **Because there is no clear assessment in the literature on the likely GHG impacts of an offshore oil moratorium in the U.S., we have not quantified the emissions reduction potential of this area of action.**

[1] U.S. Energy Information Administration. **"Where greenhouse gases come from."** Aug. 11, 2020.
[2] U.S. Energy Information Administration. **"Oil and petroleum products explained: Where our oil comes from."** June 26, 2020. **https://www.eia.gov/energyexplained/oil-and-petroleum-products/offshore-oil-and-gas-in-depth.php**
[3] Bureau of Ocean Energy Management. **"Offshore Oil and Gas Economic Contributions."** 2016.
[4] Bureau of Ocean Energy Management. **"2019-2024 National Outer Continental Shelf Oil and Gas Leasing: Draft Proposed Program."** Jan. 2018.
[5] U.S. Energy Information Administration. **"Oil and petroleum products explained: Where our oil comes from."** June 26, 2020.
[6] Richard Heede and Naomi Oreskes. "Potential emissions of CO2 and methane from proved reserves of fossil fuels: An alternative analysis." 2015.
[7] USA Today. **"Donald Trump extends moratorium on offshore drilling in Gulf of Mexico as he visits Florida."** Sept. 8, 2020.
[8] Muller, Nicholas Z. Air Pollution Damages from Offshore Energy Production. The Energy Journal. 2014.
[9] Cooney, Margaret and Mary Ellen Kustin. **"Trump's Offshore Drilling Plan Would Be an Environmental Disaster."** Oct. 23, 2019.
[10] Samantha Gross. **"Big Ideas: The United States can take climate change seriously while leading the world in oil and gas production."** Brookings Institute. Jan. 27, 2020.
[11] U.S. Department of Interior Bureau of Ocean Energy Management. "OCS Oil and Natural Gas: Potential Lifecycle Greenhouse Gas Emissions and Social Cost of Carbon." 2016.
[12] Foehn, et al. "Climate policies in a fossil fuel producing country – demand versus supply side policies." The Energy Journal. Volume 38. 2017.

Potential contributions to U.S. emissions reductions

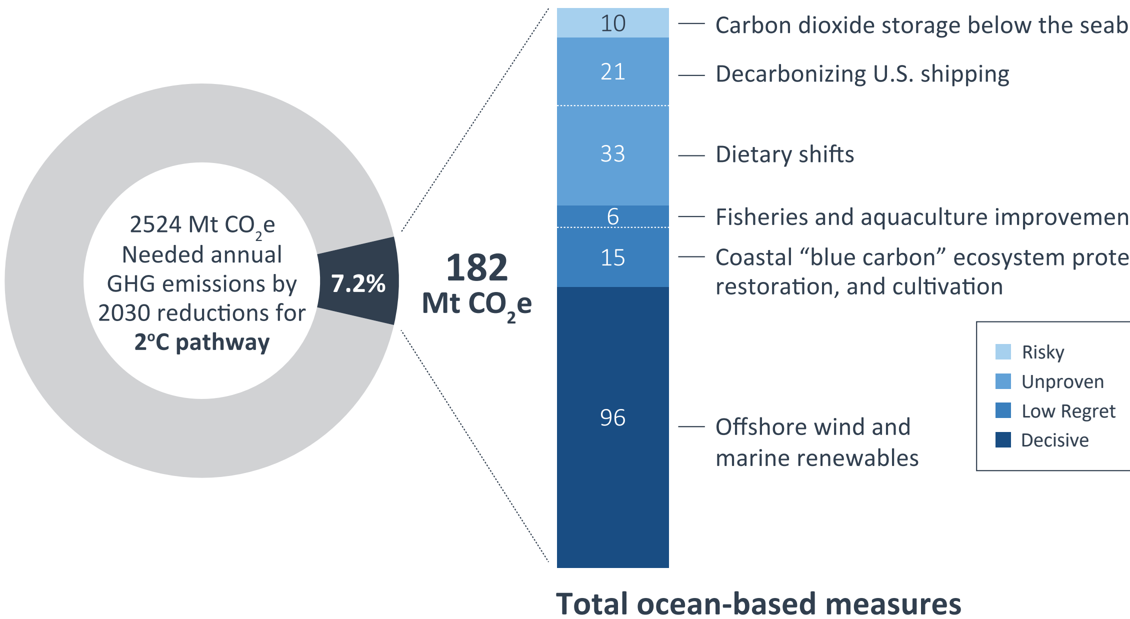
To achieve the required emissions reductions and put the U.S. on a lower-risk climate trajectory, mitigation and adaptation measures are needed from all sectors of the U.S. economy—including the ocean and coastal economy. Leaders and experts globally have aligned on a 1.5 degree Celsius trajectory as the scenario that presents a reasonable chance of managing climate impacts, with the 2 degrees Celsius scenario presenting a less desirable option (UNFCCC 2015). The 1.5 degree scenario will only be feasible if significant mitigation action is taken in the next 10 years.[21] To date, emissions mitigation efforts have focused largely on reducing emissions from land-based fossil fuel combustion (such as from electric power generation, transport, industry, and buildings), since fossil fuel combustion accounts for 77 percent of total U.S. GHG emissions (USGCRP 2018c). Adaptation efforts are also needed in tandem, and ocean-based solutions have significant co-benefits that can protect coastlines, reduce reliance on fossil fuels, help fisheries adapt to changing climate, and reduce localized air and water pollution. *This report highlights the emissions mitigation potential—and the adaptation co-benefits—of a new class of measures that have largely not been included in large-scale efforts to promote GHG mitigation in the U.S.*

Not all ocean-based mitigation measures are at the same stage of implementation or have the same level of technical or economic viability, risk, and certainty. While some are well-established and could be rapidly scaled up today, several approaches will require significantly more research, technology development, planning, and policy support. Offshore wind, blue carbon protection and restoration, and fisheries and aquaculture management and efficiency improvements are interventions that could be deployed today, with immediate impacts in protecting carbon sinks and reducing GHG emissions. Decarbonizing the U.S. shipping sector has high GHG mitigation potential and air pollution reduction co-benefits. Measures can be deployed today to reduce emissions from the sector, but achieving deep decarbonization requires significant investments in technology and infrastructure. Shifts in seafood consumption also have significant potential, but as consumer-driven strategies these efforts may be hard to predict and implement and may be less politically feasible. CCS has more technical potential than all of the other solutions combined at 2.6 Gt CO_2e, but the economic viability of offshore CCS is much more limited than its land-based counterparts.

We have assigned these different ocean-based solutions to four policy clusters: decisive, low regret, unproven, and risky (Gattuso 2019). These assignments are based on a mix of factors including implementation status, effectiveness in reducing emissions, co-benefits, and current understanding of uncertainties and risks.

Ocean-based climate solutions studied could help address 7.2 percent of the gap to the U.S. meeting equal per capita emissions reductions by 2030, or 182 Mt CO_2e.[22] If all countries globally were to reduce their emissions by the same amount per capita, the U.S. would need to mitigate 2,524 Mt CO_2e annually by 2030.[23] Offshore wind, decarbonizing shipping, and blue carbon ecosystem protection and restoration represent the most immediate and sizeable opportunities to support climate mitigation from ocean-based solutions.

Figure 6. Contribution of ocean-based climate measures to mitigating U.S. emissions in 2030 (maximum Mt CO_2e)



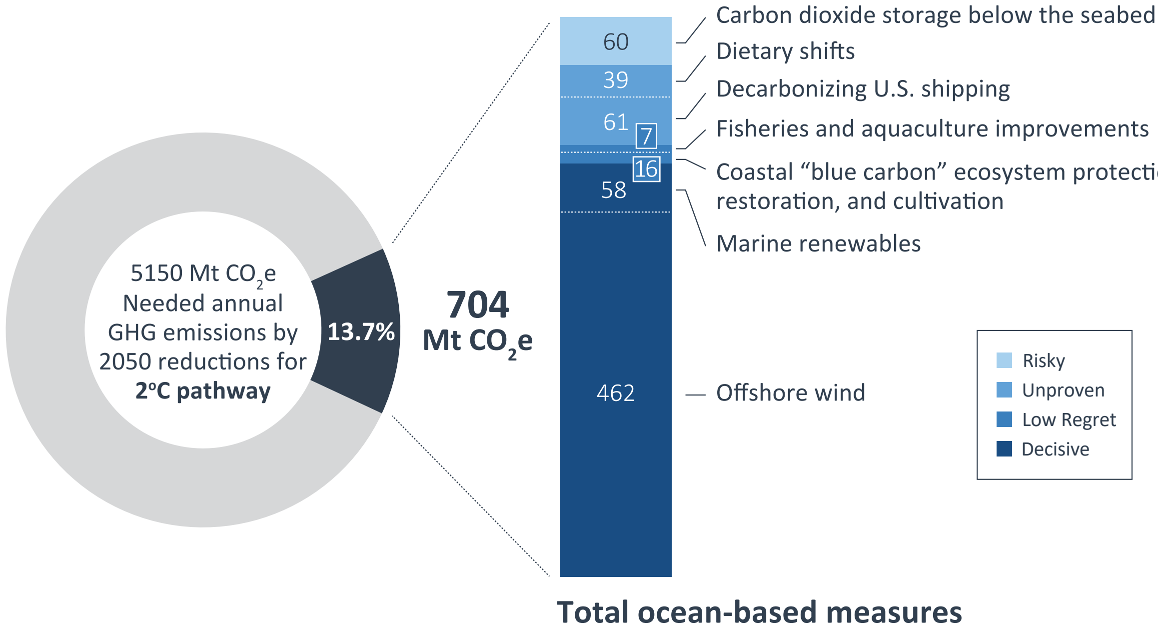
[21] In 2018 the IPCC released a report outlining what it would take to achieve the 1.5 degree Celsius goal outlined in the Paris Climate Agreement. To achieve this goal, countries would have to cut emissions to net zero (described in the text above) by 2050, and emissions would need to fall by 45 percent by 2030, which was 12 years away at the time. U.S. emissions have fallen by 10 percent since 2005, even as the economy grew by 25 percent (EPA 2020).

[22] The required annual GHG emissions reductions by 2030 were calculated based on the difference between Climate Action Tracker (CAT) business-as-usual projections for U.S. emissions to 2030 and the CAT Equality Scenario to support a 2 degree Celsius trajectory to 2030, which assumes equal per capita emissions reductions across all countries globally. For more detail on the CAT methodology and comparability of effort, see its **Methodology**.

[23] There is no global consensus on what would constitute a "fair share" contribution to global efforts to reduce GHG emissions. The Paris Agreement provides narrative language describing how to determine a "fair share," including the notion that countries should pursue the "highest possible ambition" and "common but differentiated responsibilities and respective capabilities, in the light of different national circumstances" (Paris Agreement, Article 4.3). The CAT proposes a range of different "fair share" estimates for the U.S. We chose the "Equality" estimate in line with a 1.5 degree Celsius emissions pathway, which proposes equal per capita emissions reductions across all countries. This estimate of equal per capita emissions reductions is in line with past stances the U.S. has taken in international climate negotiations.

Ocean-based climate solutions could help address 13.7 percent of the gap to the U.S. meeting equal per capita emissions reductions by 2050, or 704 Mt CO_2e.[24] Given the current lack of aggressive climate action or decarbonization in the U.S., we project the gap between U.S. emissions and what is a “fair share” of the 2 degree pathway to grow to 5,150 Mt CO_2e by 2050. The 13.7 percent reduction is a significantly higher proportion of emissions reductions than in 2030 because the 2050 “fair share” estimates reflect a more significant expansion of offshore wind, as well as the results of investments in solutions that we assigned as currently “unproven” or “risky,” such as decarbonizing shipping, other marine renewable energy, and CCS. The increasing role of these solutions is notable given the major expected growth in the emissions gap.

Figure 7. Contribution of ocean-based climate solutions to mitigating U.S. emissions in 2050 (maximum Mt CO_2e)



Ocean-based climate mitigation measures can play both near-term and long-term roles for emissions reductions and deep decarbonization of the U.S. economy. Offshore wind, coastal blue carbon protection and restoration, and improvements to fisheries management are critical investments that can be made now to lock in immediate sources of emissions reductions (blue carbon protection, fisheries management) while setting the U.S. ocean and coastal economy on a clean energy trajectory (offshore wind). These solutions have significant co-benefits for adaptation, economic competitiveness, jobs, air and water pollution reduction, public health, and environmental justice. These solutions can be complemented by efforts to decarbonize the U.S. shipping sector, other sources of marine renewable energy, and CCS, which face near-term barriers to immediate deployment but could substantially contribute to decarbonizing the economy, far beyond what is modeled here.

[24] For the 2050 business-as-usual emissions projections, we used the U.S. Reference Case from **Pathways to 2050: Alternative Scenarios for Decarbonizing the U.S. Economy from the Center for Climate and Energy Solutions**.

These measures also have significant co-benefits: for jobs, public health, economic growth and prosperity, hazard protection, reducing pollution, and the environment. In addition to their potential to reduce emissions, each of these mitigation measures can contribute positively to the American economy and environment—creating new opportunities for workers, helping to facilitate a just transition, contributing to the American economy, and helping to protect and restore our natural resources.[25]

Table 4. Co-benefits of ocean-based climate action measures

Measure	Co-benefits
Offshore wind and marine renewables	• **Job creation** – an estimated 83,000 jobs annually in construction, operations, supply chain, manufacturing, and supporting industry (for 30 GW of production) • **Economic growth** – an estimated $25 billion in annual economic output • **Air pollution reduction** – the potential to replace fossil fuel power plants and to reduce associated criteria pollutants • **Public health** – reducing criteria pollutants by displacing fossil fuel power plants could yield public health benefits of $75 million to $690 million annually for the East Coast alone • **Tax revenue** – 86 GW of offshore wind could provide $440 million in annual lease payments and $680 million in annual property taxes to the federal government • **High-capacity value for the electric power system** – high annual production; produces consistently throughout the afternoon and evening; seasonal complementarity to solar • **Just transition** – can be an option for workers employed in offshore oil and gas with experience in offshore construction operations
Coastal "blue carbon" ecosystem protection, restoration, and cultivation	• **Hazard reduction** – through reduced susceptibility to erosion, flooding, sea-level rise, and extreme weather events for coastal communities • **Job creation** – restoration can create 17 - 30 jobs for every $1 million invested, which is more cost-effective than infrastructure or fossil fuels • **Job creation** – farms could employ thousands of people permanently and seasonally, given the high labor intensity—an estimated 5 employees per 10 hectares, not including seasonal harvesting jobs • **Coastal recreation** – new opportunities for coastal recreation and tourism through the protection and restoration of coastal wetlands • **Improved water quality** – seagrasses and coastal ecosystems can act as filters and remove nutrients and other sources of water quality impairment while also increasing oxygen content • **Increased aquaculture yields** – Seaweed cultivation can be used in polyculture with farmed fish and shellfish (e.g., regenerative ocean farming) and boost production as a result of nutrient recycling and water oxygenation. • **Habitat creation** – seaweed farms create new three-dimensional habitat that could also improve local marine biodiversity and fisheries • **Pollution reduction** – constructed wetlands can act as "green infrastructure" and serve as important stormwater and sewage treatment infrastructure when properly designed and maintained

[25] The term "just transition" emerged out of the organized labor movement as a way to describe the economic and social changes required to protect workers and communities and provide for more socially equitable distribution of benefits and risks in the transition toward a clean energy economy.

Measure	Co-benefits
Decarbonizing shipping	• **Air pollution reduction** – reductions in criteria pollutants PM2.5, NOx and SOx that come from combustion of shipping fuel near the coast and while idling in port • **Public health** – the North American Emissions Control Area contributed economic benefits (primarily in terms of avoided premature morbidity and mortality) of $110 billion in 2020; it is projected to reduce premature deaths by 14,000 and to reduce respiratory symptoms for 5 million Americans annually due to reduced air pollution • **Environmental justice** – reducing port emissions will reduce health burdens from air pollution and respiratory diseases in communities near ports, who are predominantly low-income and Black, Indigenous, or people of color • **Fuel savings** – Speed reduction for ships (such as an average 10 percent speed decrease) could reduce fuel consumption • **Economic competitiveness** – Alaska and Hawaii could become re-charging stops for transpacific zero-carbon vessels
Fisheries and aquaculture efficiency improvements and dietary shifts	• **Improved fish stock health** – sound fisheries management can maintain stocks and help depleted stocks recover • **Increased economic value** – well-managed fisheries can increase the economic value of fishing • **Reduced fuel costs** – through energy-efficiency improvements such as hybrid vessels, hull maintenance, and propeller upgrades • **Jobs and economic growth** – expanding U.S. aquaculture production to 2.5 times its current level in 10 years could create 109,500 - 133,400 jobs and add $10.7 - 12.8 billion to the U.S. economy • **Climate adaptation** – well-managed fisheries and aquaculture systems can be more resilient to a changing climate • **Create fishery habitat** – bivalve and seaweed aquaculture can create fishery habitat and improve marine biodiversity • **Reduce pollution** – bivalve and seaweed aquaculture utilize and store excess nutrients that pollute coastal and marine environments and cause harmful algal blooms (HABs) and eutrophied “dead zones” • **Health impacts** – shifting to diets with less red meat can reduce the risk of cardiovascular diseases and improve the micronutrient profile of protein consumed
Carbon dioxide storage below the seabed	• **Job creation** – an estimated 60 jobs per million tonnes of CO_2 sequestered per year, or an estimated 38,000 job-years between 2020-2050 under the scenario modeled here • **Reduced local air pollution** (SOx, NOx, mercury, and particulates) from heavy emitters if captured and stored • E**xtended lifetime for oil and gas infrastructure** by repurposing for CO_2 transport and storage • **Just transition** – often supported by unions of power workers given ease of applicability of current skills to CCS requirements
Offshore oil and gas moratorium*	• **Reduced risk of oil spills** and associated coastal pollution and environmental impacts • **Bipartisan agreement and broad-based support** from local, state, and federal officials, U.S. agencies, the business community, and the fishing industry • **Public health** – An average oil rig in the Gulf of Mexico contributes between $426,000 to $2.9 million in public health damages due to air pollution annually

This table presents a summary of the documented and estimated co-benefits of the five ocean-climate mitigation measures and an offshore oil and gas moratorium, based on a combination of literature review and expert interviews. More detail and specific references can be found in each chapter.

*A moratorium on offshore oil and gas was not modeled, but discussed in detail in this section.

Mitigation opportunities





1. Offshore wind and other marine renewable energy deployment

This section estimates the climate mitigation potential of offshore wind (OSW) from fixed and floating platforms, as well as other marine renewable energy (MRE) deployment such as wave, tidal, current, salinity, and thermal energy technology.

Highlights

Mitigation potential

- Total mitigation potential from OSW is 75 - 462 million tonnes CO_2e annually in 2050, or up to 8 percent of estimated U.S. emissions. This is the single largest ocean-based mitigation measure.
- OSW is a commercially mature technology with over 28 GW installed globally. U.S. installations represent less than 1 percent of this total capacity today (42 MW), but OSW leases, state targets, and solicitations are driving a pipeline of over 9 GW, primarily on the East Coast.
- MRE technologies are at an early stage of development, with only 0.53 GW installed globally. Estimated mitigation potential for MRE technologies is 58 Mt CO_2e annually by 2050.
- OSW offers substantial economic development opportunities as well as energy capacity value in a low-carbon grid. The potential environmental and human-use impacts of OSW should be considered relative to the impacts of fossil fuel and land-based renewable generation and balanced with socio-economic and environmental benefits.

Costs and benefits

- OSW prices are competitive with fossil fuel prices without subsidies in the EU. In the U.S., cost parity between OSW and land-based renewables is expected in the next two decades based on projected cost declines, although it is currently up to four times more expensive than land-based wind and solar. Cost parity for floating OSW, which is a newer technology necessary for Pacific markets and deeper water, will occur later than for fixed-bottom OSW, but cost declines are expected to be more rapid.
- OSW provides significant capacity value in the electric power system, meaning it has high annual production and produces energy relatively consistently throughout the late afternoon and night, while also providing seasonal complementarity to other renewable energy sources (such as solar).
- Proximity to coastal populations offers the opportunity to replace fossil fuel power plants that pollute nearby communities.
- Co-benefits of OSW include job creation and economic growth. By 2030, 30 GW of OSW could create 83,000 jobs in construction, operations, supply chain, manufacturing, and supporting industries and $25 billion in annual economic output. It can also help transition workers employed in oil and gas with experience in offshore construction and operations and allow workers to leverage their experience.
- OSW may have impacts on wildlife, habitats, and human uses such as commercial and recreational fishing, the U.S. Navy, navigation, tribal heritage and cultural practices, and aesthetic changes. The impacts of OSW should be considered in light of the relative impacts of fossil fuel based power generation and the impacts of land-based wind.

Policy recommendations

Offshore wind

- **Establish national offshore wind deployment targets combined with direct financial support** (such as investment and production tax credits) to grow the market for offshore wind similar to how the federal government and states have supported solar and land-based wind.
- **Identify sufficient sea space for the development of offshore wind through ocean planning and efficient permitting.** The Bureau of Ocean Energy Management plays an essential role in offshore wind siting. Developing national guidelines for siting and a streamlined permitting process could expedite the siting process and address the need to protect ocean wildlife and minimize conflict with other human uses.
- **Support investments in supply chain and infrastructure** through regional planning goals and funding for transmission and port upgrades to service the offshore wind sector.
- **Reduce uncertainty by supporting targeted research** that proves and optimizes large-scale floating offshore wind installations; assesses the capacity value of offshore wind and its cost effectiveness as part of electricity portfolio planning; and assesses and mitigates potential environmental or human-use impacts from turbine installations.
- **Direct funding to advance technology development.** Improvements to turbines, design standards, and integrating technology will help improve the value proposition of offshore wind as a decarbonization strategy.

Marine renewables

- **Continue research and development** to advance MRE technologies from small-scale prototype testing to large prototype testing, demonstration, and finally early commercial stage. Augmenting funding to existing programs such as the Pacific Marine Energy Center and the Water Power Technologies Office at the Department of Energy (DOE) could support this goal.
- **Direct the DOE to identify the most promising markets for MRE** in order to right-size deployments to market needs, such as ocean observation and navigation, marine vehicle charging, aquaculture, algae farming, desalination, power for island communities, and disaster recovery efforts.
- **Apply the recommendations listed above for OSW once MRE technologies and markets** are more mature. Once MRE technology is more mature and an MRE industry is poised to launch, many of the policies we have recommended for offshore wind related to siting and permitting could be adapted to support scaling-up of MRE.

Context

Reducing the greenhouse gas (GHG) emissions from electric power generation is one of the most significant strategies for mitigating climate change. Technologies in commercial use today could enable the U.S. to achieve a 90 percent carbon-free electricity system by 2035, and doing so would reduce economy-wide GHG emissions by 27 percent (Aggarwal and O'Boyle 2020). Renewable energy sited on land—primarily solar and wind—has been the backbone of electric system decarbonization and the transition to an economy powered by clean energy. Renewable energy sited in the ocean—including OSW and other MRE technologies[26]—account for just 0.003 percent of the nearly 1,050 GW of electric generating capacity in the U.S. today. In spite of this small current share, continued renewable energy technology improvements and cost declines as well as increasing state commitments to clean energy and potential federal action on climate change are likely to encourage further consideration of the role of the ocean in providing energy, capacity, and space for clean electricity generation.

Offshore wind is a technology that utilizes fixed-bottom or floating platforms to site large wind turbines in the ocean. Fixed-bottom turbines emerged first—with the first project installed in Denmark in 1991—and have predominated in the market thus far. But floating foundation technologies, which emerged in the last three years, will allow for OSW in deeper water and farther out to sea. There are 28 GW of OSW turbines installed globally, including 65 MW of floating turbines (IRENA 2020; Lee 2020). In contrast, the U.S. has only two OSW projects online—the 30 MW Block Island Wind Farm, and the 12 MW Coastal Virginia Pilot that just completed construction in June 2020. U.S. states have selected nearly 6,300 MW of OSW projects in procurement solicitations, however, and industry estimates that the total pipeline of U.S. OSW projects totals over 9,000 MW (AWEA 2020).

Marine renewable energy technologies include a range of technologies that harness energy from waves, tidal streams, currents, salinity gradients, and ocean thermal gradients. In comparison to OSW, MRE technologies are early stage, with only 0.53 GW installed globally (IRENA 2020). Wave and tidal technologies have advanced slightly beyond more novel technologies, like ocean thermal and salinity gradient technologies (IEA 2019a). Floating solar photovoltaic is another potential form of ocean renewable energy, but projects to date have been built on inland lakes and reservoirs; we did not include this technology in our assessment.

[26] In this report we use "marine renewable energy technologies" to mean technologies that harness energy from waves, tidal streams, currents, salinity gradients, and ocean thermal gradients. Marine renewables are distinct from offshore wind.

Mitigation potential

Electric power generation accounts for 27 percent of U.S. GHG emissions (U.S. EPA 2015). The mitigation potential of ocean renewables in the U.S. will depend both on how much OSW and MRE are built by 2030 and 2050 as well as the mix of clean and carbon emitting resources in the overall electric system portfolio. Achieving major carbon emissions reductions in the electric sector will require development of hundreds of GW of new renewables by 2050. Wind and solar make up ~9 percent of U.S. generating capacity today and are projected to compose a dominant portion of cleaner electric system portfolios in 2050 (EIA 2020). Projections vary about the future role of less prominent technologies like OSW and marine renewables, as detailed in the Methodology Appendix.[27]

Our analysis of OSW mitigation potential is based on the data from the IEA ETP 2017, U.S. Department of Energy (DOE) Wind Vision, and IRENA Future of Wind scenarios. For MRE, we relied on IEA scenarios. The IEA ETP scenarios are designed to achieve major carbon reductions to limit global warming to 2 degrees Celsius. The 2DS scenario reduces emissions to limit warming to 2 degrees Celsius, and the B2DS scenario limits warming to 1.75 degrees Celsius. The DOE Wind Vision study was designed to assess the feasibility of achieving specific wind energy deployment levels. The IRENA Future of Wind study builds on IRENA's REMap analysis, which assesses a portfolio to limit rise in global temperatures to 1.5 degrees Celsius, including increasing land and OSW energy to one-third of the energy supply by 2050.

Mitigation potentials for OSW and MRE range from 27.4 to 95.8 million tonnes in 2030, and 118.7 to 520.3 million tonnes CO_2 in 2050. At the high end, this represents roughly 30 percent of CO_2 emissions from electric generation in the U.S. today. The calculated emissions reduction potential from OSW in the U.S. are based on IEA's 2DS and B2DS scenarios, the DOE Wind Vision "Central" scenario, and the IRENA Future of Wind scenario are provided below. A summary of the sources and methodology used in this analysis is provided in the Methodology Appendix.

Mitigation option		2030 Mitigation potential (Mt CO_2e/year)	2050 Mitigation potential (Mt CO_2e/year)
Offshore wind deployment	IEA ETP	27 – 38	75 – 106
	DOE Wind Vision	45 – 48	145 – 171
	IRENA Future of Wind	46 – 96	314 – 462
Marine renewable energy deployment	IEA ETP	0	47 – 58
Total		**27 - 96**	**119 - 520**

Costs and benefits

OSW is currently significantly more expensive than land-based renewable energy, although cost parity is expected in the next two decades. OSW currently costs up to four times more than land-based wind and solar, which have fallen below $40/megawatt hour (MWh) today on a levelized, long-term basis (EIA 2020). In some European countries that began developing OSW over a decade before the U.S., however, OSW prices are competitive with fossil fuels today without subsidies (IRENA 2019). In the U.S., OSW costs are expected to decline rapidly, approaching today's solar and land-based wind prices by 2050 (NREL 2019) or much earlier (IEA 2019b) and becoming competitive in some regional markets by 2030 or 2040 (Musial 2020). Evidence shows this is already happening for fixed-bottom OSW: in 2019 and 2020, Vineyard Wind and Mayflower Wind on the U.S. East Coast were awarded contracts at $65/MWh and $58/MWh (45-60 percent higher than the levelized cost of energy for solar) (Foxwell 2020). While prices for floating OSW will lag behind fixed bottom given that this technology emerged roughly 25 years later, floating OSW will benefit from commercial experience of fixed-bottom developments, leading to sharper cost declines in the next two decades (Musial 2020).

[27] For example, scenarios for OSW deployment in the U.S. by 2050 range from 47 GW (the International Energy Agency's Energy Technology Perspectives 2DS scenario) to 164 GW (International Renewable Energy Agency). The DOE Wind Vision analysis estimates offshore wind could reach 87 GW in 2050. By way of comparison, the IEA's 2DS scenario includes nearly 500 GW of solar photovoltaic and 450 GW of land-based wind in the U.S. in 2050.

Beyond price, OSW also provides significant capacity value in an electric power system. OSW has a high average annual production (capacity factor) and produces energy relatively consistently in the evening and throughout the night, serving as a complementary resource for solar to balance demand (Dundas et al. 2020; DOE and Department of the Interior 2016; Hull 2019). Its seasonal profile, with high productivity in the winter, also complements solar (IEA 2019b). Given its attractive generating profile and proximity to coastal population centers, OSW provides an opportunity to help replace fossil fuel power plants in coastal states that disproportionately pollute disadvantaged communities ("Ocean Climate Action Webinar: Recommendations of the Select Committee on the Climate Crisis" 2020). Furthermore, as states approach their 100 percent carbon-free electric system goals and seek to eliminate the last fossil-fuel facilities on the electric system, a diversity of technologies probably will be necessary to maintain reliability, making some resources that are less cost effective today much more cost effective in the future (IEA 2019a).

OSW offers significant opportunities for economic development, job creation, and improvements to public health. Developing 30 GW of OSW installations by 2030 could create 83,000 jobs in construction, operations, supply chain, manufacturing, and supporting industries and $25 billion in annual economic output (Hensley and Wanner 2020). OSW can also help transition workers employed in oil and gas industries with experience in offshore construction and operations and allow workers to leverage their experience (IRENA 2018b). State and national governments also stand to benefit from the industry's success: at a scale of 86 GW, OSW could provide $440 million in annual lease payments to the federal government and $680 million in annual property taxes (DOE and Department of the Interior 2016). By comparing the monetary value of avoided climate impacts, health benefits, and water consumption savings from OSW to the projected levelized cost (ranging from $140/MWh to $45/MWh) and integration costs for OSW, the High Level Panel for a Sustainable Ocean Economy found the benefit-cost ratio for OSW averages 12:1, meaning there may be economic benefits from OSW investment even if prices remain relatively high and without including economic development benefits such as job creation (Konar and Ding 2020). A study of public health impacts on the U.S. East Coast suggests that OSW could yield $75 million to $690 million in public health benefits due to reduced air pollution from the displacement of fossil fuel electric power generation (Buonocore et al. 2016).

A potential indirect cost of OSW is its impact to the ocean environment, but these impacts should be considered relative to impacts from fossil fuel generation and land-based renewables. Each gigawatt of OSW will require roughly 100 - 150 square miles of sea space (DOE 2015). Through construction, operation, and occupation of ocean space, OSW has the potential to negatively affect species and habitats, including seabirds and marine mammals. OSW turbines may also interfere with commercial fishing, national defense activities, and navigation and may affect viewsheds and cultural and tribal resources. The lack of data on OSW in the U.S. results in significant uncertainty about the significance or severity of these potential impacts, although evidence from Europe indicates that impacts are relatively minimal or can be appropriately mitigated (Konar and Ding 2020). Impacts will also depend on decisions about OSW siting, the unique environment and human-use characteristics of a particular ocean region, and the ability to mitigate or avoid those impacts. Decisionmakers and stakeholders should seek to minimize negative effects of OSW while also considering the acceptable level of risk or impact in the context of alternative sources of electric power generation. While OSW provides a zero-carbon source of electric generation, building or extending the life of fossil fuel power plants would further contribute to climate change. Siting hundreds of gigawatts of new renewables, energy storage, and associated transmission infrastructure on land will have different, albeit significant, environmental and human-use impacts.

Most MRE technology is in too early a stage of development to permit understanding of system-wide costs and benefits at a large scale. MRE technologies have yet to advance beyond small prototype testing phases (IEA 2020). Therefore, MRE technologies remain expensive, with projected costs at least four times the levelized cost of utility-scale solar photovoltaic for years to come; it is unclear when MRE technologies will reach maturity and when costs will become competitive (Musial et al. 2020; LiVecchi et al. 2019). Thus, the energy system benefits of MRE, the potential economic benefits of this technology, and the potential environmental impacts of widespread deployment are largely unknown.

Geographic opportunities

The technical potential of OSW off the coasts of the contiguous U.S. plus Hawaii and in the Great Lakes is 7,200 terawatt hours (TWh) per year, according to the DOE (DOE and Department of the Interior 2016). This is 1.8 times the total electric generation in the U.S. today (EIA 2019b). As of June 2020, there are two OSW projects online in the U.S.—the 30 MW Block Island Wind Farm and the newly completed Coastal Virginia 12 MW pilot. The Block Island project generates roughly 100 GWh/year (EIA 2019b)), or 0.003 percent of total U.S. electric generation. The Bureau of Ocean Energy Management has issued 15 leases off the U.S. East Coast, establishing a pipeline for an estimated 28 GW of development, which would represent an almost 700-fold increase in OSW in the U.S. over the next decade (AWEA 2020).

While the U.S. OSW industry shows promise, it is certainly young, and challenges vary by region.

East Coast

East Coast states have led in OSW planning and development, driven by strong state policies (mandating or targeting large-scale OSW deployment), relatively high electric market prices in the region, and a dearth of other "in-state" renewable options to achieve clean energy goals (McClellan 2020). In 2020, New York State issued a procurement solicitation for 2.5 GW of OSW, the largest solicitation in the nation to date. The East Coast could see at least 30 GW of OSW in the next two decades, with even greater deployment possible if projects expand into deeper waters and utilize floating platforms (Musial 2020).

West Coast

On the West Coast, there are far more regional land-based renewable resources to compete with OSW. The steep continental shelf off the West Coast necessitates floating OSW turbines. While this is a newer technology, it will benefit from industry's experience with fixed-bottom foundations and could reach commercial maturity in half the time (Musial 2020). California has been conducting planning and research for OSW, catalyzed by the Bureau of Ocean Energy Management's (BOEM) call for nominations in 2018 for three potential OSW development areas off the central and northern coasts. But objections from the Department of Defense (DOD) have delayed BOEM's progress toward conducting lease auctions.

Great Lakes

In the Great Lakes, the 20.7 MW "Icebreaker" project would have been the first OSW demonstration project in the region, but project permits would have imposed severe operational restrictions. This and future projects will need to manage both ice floes and likely operational limitations to protect bats and birds in Great Lakes migratory zones (Tomich 2019; Musial 2020).

Gulf Coast

In the Gulf Coast, early research shows promising technical potential, but soft soil, lower wind speed, and hurricane risks combined with low political will and unfavorable markets may limit development interest (Musial, Tegen, et al. 2019; Musial 2020).

Alaska, Hawaii, and U.S. Territories

BOEM issued a call for nominations in Hawaii in 2016, following an unsolicited proposal from one company in 2015, and received one additional indication of commercial interest in response to the call. But BOEM hasn't yet hosted lease auctions in Hawaii (Bureau of Ocean Energy Management 2020). Congress has also shown some interest in creating a process for OSW development in U.S. territories, with the introduction of a bill in 2019 calling for OSW lease auctions in economic development zones and revenue sharing of auction proceeds (Froese 2019). In Hawaii and the U.S. territories, isolation from larger grids and supply chains has created substantial dependence on fossil fuels—particularly petroleum-based electric generation (EIA 2014; 2019a). OSW could support GHG reductions, electricity rate reductions, and energy independence for these islands. In Alaska, there is vast technical potential for OSW (nearly twice the technical potential of the entire rest of the U.S.), but the remote location of potential OSW developments, distance from load centers, and availability of plentiful land-based wind resources may all limit demand for OSW in this state (Doubrawa Moreira et al. 2017).

The technical potential for MRE in the U.S. is estimated to be 2,300 TWh/year, which is roughly half of U.S. total generation today (LiVecchi et al. 2019). The technical potential of wave and ocean-thermal energy conversion technologies are greatest among MRE technologies, at 1,229 TWh/yr and 576 TWh/yr, respectively (Musial, Beiter, et al. 2019). The first MRE installation (a 250 kW wave project) in the U.S. will be tested in Hawaii, and wave energy testing continues in Oregon through university partnerships (Kopf and Ling 2019; Pacific Marine Energy Center 2020). Projects will need to scale up to closer to 10 MW to reach commercial maturity. Although wave and tidal technologies have dominated the global market, no single design or technology, nor any region in the U.S., has emerged as a leader in MRE.

Policy, research, and technology needs

Offshore wind

Policy

To achieve its mitigation potential, federal policymakers will need to 1) help grow the market for OSW through a combination of market signals and direct financial support; 2) identify sufficient sea space for the development of OSW through ocean planning and efficient permitting; and 3) support investments in supply chain and infrastructure through planning and funding for transmission and port upgrades.

Establish offshore wind deployment targets. Broad federal clean energy policy—such as using the Clean Air Act to require states to develop plans for electric system decarbonization or the adoption of a federal clean electricity standard (Aggarwal and O'Boyle 2020)—as well as state renewable or clean portfolio standards will drive development of a range of renewable resources. As a young industry, however, specific target- and goal-setting for OSW deployment will help coordinate and direct public planning and infrastructure development, send market signals to stimulate private investment, and achieve scale to optimize economic benefits (Hensley and Wanner 2020). East Coast states have collectively set targets for 29 GW of OSW as of September 2020 (AWEA 2020). This has resulted in billions of dollars in private investment as well as substantial infrastructure planning to jumpstart the industry. Target setting should continue at the state level, given states' important roles in energy portfolio planning and utility regulation, but the federal government should also adopt an OSW goal to guide national and regional planning and policy. This will be particularly important for improving the siting process for OSW and for directing transmission planning and investment at the right scale. The House of Representatives' House Select Committee on Climate Crisis ("Select Committee") recommends assessing transmission needs to support 50 GW of OSW (Ocean Conservancy 2020b). A National Ocean Industries Association report suggests that a 28 GW by 2030 target is achievable in the U.S. (IRENA 2018b). The Biden campaign has called for a clean energy revolution that includes "thousands of wind turbines off our coasts," which equates to a goal of over 10 GW ("The Biden Plan to Build a Modern, Sustainable Infrastructure and an Equitable Clean Energy Future" 2020). The purpose of goal setting is to help develop a market and drive planning at sufficient scale to address barriers to OSW development. Thus, more aggressive targets—even beyond what may be projected as a likely level of deployment to 2050—may be beneficial. A combination of medium-term (2030) and long-term (2050) targets will also balance near-term action and long-term planning. The market, technology improvements, and siting constraints, along with policy, will ultimately determine how much OSW is built in the U.S.

Provide direct financial support. The federal government should provide financial support to the OSW industry in the same way it has supported solar and land-based wind and, to a larger extent, fossil-fuel industries (EIA 2018). Between 2009 and 2015, American Recovery and Reinvestment Act investments in clean energy totaled $90 billion and leveraged $150 billion in private investment. On the East Coast, financial incentives from states, either through resource carve-outs or price subsidies, have created a large pipeline of projects that will come online this decade and drive efficiencies and improvements to make OSW independently competitive in future decades (McClellan 2020). Financial support should include a long-term investment tax credit for OSW with a direct pay option (Aggarwal and O'Boyle 2020; Ocean Conservancy 2020b) and extension of the production tax credit for OSW (Beaudreau et al. 2020). The federal government should also support infrastructure for OSW by providing matching funds to states for interstate transmission, funding upgrades to coastal transmission infrastructure, and providing loan guarantees for private and public-private port and transmission upgrade projects (Aggarwal and O'Boyle 2020; Ocean Conservancy 2020b; Middlebury Institute of International Studies at Monterey Center for the Blue Economy and Blue Frontier 2020).

Conduct ocean-spatial planning and develop guidelines at the regional level oriented toward offshore wind deployment goals. The federal government, through BOEM, has an essential role in OSW siting. Development of national guidelines for identification of OSW energy areas could help expedite the siting process while addressing the need to protect ocean wildlife and minimize conflict with other human uses (Middlebury Institute of International Studies at Monterey Center for the Blue Economy and Blue Frontier 2020). Guidelines should be regionally differentiated and responsive to the unique environmental, commercial, and human-use interests of each region, through engagement with state and tribal governments and stakeholders in the Northeast, Southeast, Gulf Coast, West Coast, and Great Lakes (Ocean Conservancy 2020b).

Regional ocean-spatial planning could also help identify the best potential locations for OSW through a more comprehensive understanding of how species and human uses interact across a region and the cumulative impact of multiple OSW developments within that region. For example, conducting widespread marine spatial planning with the DOD early on could help avoid a scenario in which DOD presents BOEM with a "red map" of areas where it opposes development after BOEM has taken the first steps to prepare for lease auctions, as occurred in California. Similarly, the Vineyard Wind environmental assessment was delayed due to a lack of understanding of the cumulative impacts to the commercial fishing industry from multiple projects in the region (McClellan 2020). Ocean-spatial planning could also reduce permitting risk (Dundas et al. 2020). However, both guideline development and ocean-spatial planning should be oriented around an OSW deployment goal, as suggested by the Select Committee, and with the goal of identifying all usable OSW hotspots and making leases available quickly, as recommended by OCAP (Middlebury Institute of International Studies at Monterey Center for the Blue Economy and Blue Frontier 2020; Ocean Conservancy 2020b). The guideline-development and mapping process should be directed by a regional entity or a national authority that understands how to engage scientists and stakeholders as well as the commercial development requirements for offshore development. DOE's National Offshore Wind Consortium, as administered by the New York State Energy Research and Development Authority (NYSERDA), may be a suitable national lead, or this effort could be delegated to BOEM's Northeast, Mid-Atlantic, and West Coast Regional partnership frameworks. Importantly, orienting the ocean-spatial planning and guideline-development processes around specific OSW deployment goals will ensure that guidelines and planning maps are not overly restrictive and will limit delays in identifying wind energy areas.

Make permitting more efficient and predictable. Improved siting should result in more predictable and efficient permitting, especially if done in combination with advancements in research on OSW impacts. BOEM has developed a phased approach for permitting OSW, beginning with pre-lease environmental assessment, and ending with approval of a final environmental impact statement on a developer's construction and operation plan, and including multiple rounds of public comment (Rowe et al. 2017; AWEA and University of Delaware College of Earth, Ocean, and Environment 2020). Delays in permitting the Vineyard Wind project indicate that improvements in the process and capacity of BOEM staff will be necessary to facilitate efficient permitting of multiple large-scale projects simultaneously in the coming decades. The Bipartisan Policy Center recommends increasing capacity by supplementing the budget of the BOEM office responsible for renewable siting (Beaudreau et al. 2020). The BOEM process must also integrate with individual state permitting requirements given that OSW projects in federal waters that also require infrastructure and transmission through state waters and coastal lands will be multi-jurisdictional. In California, the Marine Renewable Energy Work Group identified five state agencies that will be involved in permitting OSW projects (California Ocean Protection Council 2011). Improved utilization of the DOD Siting Clearing House process and better coordination between BOEM and DOD will also be important. In all regions, OSW developers will need a clear process and sequence that aligns state and federal permitting processes, provides proper opportunity for stakeholder input, identifies problems early on, and offers regulatory certainty (IEA 2018; Dundas et al. 2020). The Renewable Energy Action Team model of state-federal coordination in California between 2009 and 2015 was a good example of successful and efficient clean energy permitting that enabled California to efficiently deploy renewable energy facilities to take advantage of the American Recovery and Reinvestment Act funds (DOE Office of Energy Efficiency & Renewable Energy 2008).

Improve transmission planning. OSW, just like land-based renewables, will require new transmission infrastructure, both to connect turbines to an interconnection point on land and, unless there is unutilized capacity given other resource retirements, to deliver OSW energy from this point of interconnection to centers of demand. Federal policy to improve transmission siting, planning, and investment will be needed to bring massive quantities of new land-based and ocean-based renewables online in the next two to three decades. The federal government should require improvements to regional transmission planning, cost allocation, and interconnection pricing to support all renewables, including OSW (Aggarwal and O'Boyle 2020; McClellan 2020). The Federal Energy Regulatory Commission (FERC) should require regional transmission planning that will reduce the cost burden for new transmission and interconnection on individual renewable projects and instead share costs across a broader set of beneficiaries (Aggarwal and O'Boyle 2020). For example, on the East Coast, a proposed OSW subsea transmission "grid" could help connect multiple projects, provide efficiencies, and allow for cost sharing (Anbaric 2020). Similarly, regional transmission operators should be required to prioritize planning to achieve state and federal clean energy and climate policies. Specific to OSW, the Select Committee recommends that a) DOE assess transmission needs to support 50 GW of OSW; b) FERC develop a national OSW transmission plan; and c) FERC open a rulemaking to address cost allocation for OSW transmission (Ocean Conservancy 2020b).

Contribute to and coordinate supply chain and infrastructure investments. Construction and maintenance of OSW will also require new or upgraded port infrastructure for staging, assembly, and transportation of turbine and foundation components. Providing a new revenue stream and business opportunity will also help revitalize struggling port cities (Polefka and Cornish 2018). The federal government should direct regional port infrastructure planning guided by a specific OSW deployment goal to stimulate private investment and coordination among OSW developers, port authorities, the construction industry, and port operators. More directly, Congress could provide funding for improvements to ports through authorization of maritime programs in the National Defense Authorization Act and through funding to Department of Transportation grant programs (Beaudreau et al. 2020; Ocean Conservancy 2020b).

Research

Research to advance OSW in the U.S. should focus on addressing three areas of uncertainty: 1) proving and optimizing large-scale floating OSW installations; 2) assessing the capacity value of OSW and its cost-effectiveness as part of overall portfolio planning; and 3) observing and mitigating potential environmental and human-use impacts from turbine installations. Continued funding to the DOE,[28] national laboratories, regional work groups, state agencies, and independent scientists will be essential (Ocean Conservancy 2020b).

Prove and optimize floating offshore wind technology. Fixed-bottom OSW turbines connect directly to the seabed with a fixed foundation. Floating OSW is installed by a floating foundation that attaches to the seabed by a mooring line. Nearly 200 MW of floating turbines are installed in Europe today. In the U.S., an estimated 60 percent of suitable OSW sites will require floating technology due to water depths, including all projects on the West Coast (Hockenos 2020). But policymakers and stakeholders are hesitant to embrace floating OSW, given that it is relatively new and unproven in U.S. waters. Furthermore, the scale of early projects in Europe is much smaller than will be needed to achieve commercial viability in the U.S. Additional research and assessment of existing floating OSW projects could help developers and policymakers understand whether there are any real technology risks for floating technology, apply lessons learned from Europe and from fixed bottom operations, and address any expected challenges for larger floating OSW installations. For example, the California Energy Commission recently awarded funding to a company that will create a “digital twin” of an OSW turbine in order to optimize performance and lower maintenance costs for a planned installation in Humboldt (Dundas et al. 2020). Other researchers have identified the need to study wake effects to support proper plant design (DOE and Department of the Interior 2016; Sathe et al. 2020) in larger installations, as well as the need to conduct research and develop turbine design standards that are suited to the specific environment of the outer continental shelf (DOE and Department of the Interior 2016; Musial 2020).

Conduct long-term portfolio planning to assess the value of offshore wind. To understand the value of OSW and its cost effectiveness compared to other technologies or decarbonization strategies, utilities and policymakers must understand the total value proposition for OSW. Existing studies have shown that OSW has a generation profile that is highly complementary to solar and that it exhibits less seasonal variability than other intermittent renewables (Dundas et al. 2020; DOE and Department of the Interior 2016; Hull 2019; Sathe et al. 2020). But portfolio planners need a more holistic method for assessing the value of OSW that includes potential ancillary services and other grid benefits. OSW has the potential to provide late afternoon and evening capacity that could reduce reliance on fossil fuel resources while also avoiding the need to over-invest in solar and batteries for multi-hour load shifting (Energy and Environmental Economics, Inc. 2019). Better understanding and quantification of these ancillary benefits will be essential to properly valuing OSW (Sathe et al. 2020). Longer-term resource planning—with 20-year rather than 10-year planning horizons—will also capture the relative cost-effectiveness of diverse resources like OSW as carbon reduction goals increase. Similarly, portfolio planners will need modeling tools that are sophisticated enough to select resources based on more holistic valuation of energy, capacity, and grid benefits (Aggarwal and O’Boyle 2020).

Perform smart data collection, observation, and mitigation research on environmental and human-use impacts. Balancing the environmental and socio-economic tradeoffs of OSW, given its need and value as part of the clean energy transition, will be critical. There is broad consensus among environmental groups that additional research is needed to understand the impacts from OSW construction and operation on wildlife, habitats, and other human uses (IEA 2018; DOE and Department of the Interior 2016; Sathe et al. 2020; Ocean Conservancy 2020b; NRDC and Ocean Conservancy 2020). To ensure that research on potential impacts moves the OSW industry forward, funders and policymakers should prioritize research and develop research frameworks that are coordinated and systematic and that address the greatest unknowns and areas of concern in the most likely areas for wind development. It will also be important to consider the right timing and spatial scope for research. For example, performing early baseline data collection in the areas of greatest commercial interest could support an efficient and comprehensive permitting process. On the other hand, it may not be necessary to conduct data collection or research across an entire coast before concluding a siting process when commercial, legal, or other use conflict constraints will likely already limit developable space. Policymakers should encourage collaboration between environmental NGOs and industry to help identify research gaps and priorities, through forums such as the American Wind Wildlife Institute (AWWI).

[28] Examples include ARPA-E’s ATLANTIS program, Offshore Wind Advanced Technology Demonstration Projects, National Offshore Wind R&D Consortium, and DOE Loan Programs.

The potential human-use impacts from OSW include interactions with the commercial and recreational fishing industry, the U.S. Navy, and shipping, as well as aesthetic changes and effects on tribal heritage and cultural practices. Impacts to the fishing industry warrant further research and may be difficult to assess given fishers' hesitancy to disclose the details and location of fishing activities. The National Renewable Energy Laboratory awarded funds to the state of New York and a fishing industry stakeholder group to identify opportunities to reduce risk to commercial fishers from OSW farms (NREL 2020). At the Block Island wind farm, surveys indicate that recreational fishing has increased due to the creation of artificial reefs at turbine foundations (ten Brink, Dalton, and Livermore 2018). Commercial fishers may also seek direct compensation from OSW developers to offset potential impacts (Kearns & West 2018). Additional research and stakeholder engagement, combined with early, high-level ocean-spatial planning, as described above, could help identify the greatest areas of concern for human-use conflicts and aid future siting and permitting processes (Konar and Ding 2020). Ongoing monitoring and mitigation after OSW facilities are constructed will be equally, if not more, important.

Technology

Governments can accelerate OSW technology improvements by funding research and enacting policies that grow equipment pipelines and drive private investment.

Advance technology through research funding and market development. Improvements to turbines, design standards, and integrating technology will help improve the value proposition of OSW as a decarbonization strategy. Turbine technology advancements could allow turbines to be sited in deeper water, expanding the total resource potential. Larger turbines could be more efficient and cost effective (IRENA 2019; DOE and Department of the Interior 2016). GE Renewable's 12 MW Haliade X turbine is the largest turbine available today and is double the size of turbines in the U.S. Block Island Project (Sathe et al. 2020). In addition to size, improvements in design and materials could reduce capital costs by making turbines cheaper to build, and could reduce operations and maintenance costs by improving turbine performance and durability. Technology improvements can also increase turbine resilience to ocean and meteorological conditions (IEA 2019a). Modeling in each OSW coastal and Great Lakes region will enable development of design standards to ensure turbines are suitable for different ocean conditions (Musial 2020). Finally, advancements in clean-energy-integrating technologies could increase the value of OSW to the grid. Of particular note is the use of grid-forming inverters with wind resources (Aggarwal and O'Boyle 2020; DOE Office of Energy Efficiency & Renewable Energy 2010) and the concept of pairing OSW with offshore hydrogen production through electrolysis, which would take advantage of the strong and consistent generation profile of OSW, while at the same time avoiding the challenge of building new transmission infrastructure (Musial, Tegen, et al. 2019; IEA 2015).

Marine renewables

Continue to fund research and development. Given the early stage of MRE, significant government support will be needed to enable MRE to reach its carbon mitigation potential by 2050. Continued research and development will be needed to advance MRE technologies from small-scale prototype testing to large prototype testing, demonstration, and finally early commercial stage (IEA 2020). For the earliest-stage technologies, such as salinity gradient, policy support should focus on research and design to prove the concept. For the moderately more advanced technologies, such as wave energy, research should focus on standardization to address a variety of ocean conditions, simplification of installation process, and improvement in sensing control and power take-off systems, all of which will help bring down technology costs (IEA 2019a). Additional research and testing should determine which MRE technologies are best suited to different ocean environments and conditions. Researchers should also evaluate which technologies have the greatest potential for standardization and, ultimately, large-scale production to achieve economies of scale. The federal government should continue to fund MRE research and development through programs like the Pacific Marine Energy Center and DOE's Water Power Technologies Office.

Identify the best market opportunities for marine renewable energy technologies. Government programs could also help identify the most promising markets for MRE. For example, DOE has been investigating the potential for MRE to serve off-grid remote and maritime electricity needs to support activities such as ocean observation and navigation, marine vehicle charging, aquaculture, algae farming, and desalination, and also to provide power during coastal disaster recovery and for isolated island and coastal communities (LiVecchi et al. 2019). Understanding the most likely markets for MRE will help determine the right scale and role for the technology, which in turn will determine the right policy support.

Apply lessons and policy models from offshore wind. During early-stage technology development, regulators should provide for a more flexible permitting process that allows for iterative design and testing (LiVecchi et al. 2019; National Hydropower Association 2020). The Select Committee also recommends financial support, through extension of the Production Tax Credit for MRE and the addition of a direct pay option (Ocean Conservancy 2020b). Once MRE technology is more mature and an MRE industry is poised to launch, many of the policies we have recommended for OSW could be adapted to support scaling-up of MRE.

Key assumptions, data limitations, and caveats

The mitigation potential from OSW and marine renewables in this analysis is based on CO_2 emissions associated with energy generation alone rather than a lifecycle analysis of the GHG emissions associated with manufacturing, construction, operation, and decommissioning of all components of the facilities. This is a standard approach for assessing the GHG emissions benefits of clean energy technologies as compared to fossil fuel generating facilities, but likely underestimates the emissions benefits of clean energy given the relative lifecycle GHG intensity of fossil fuel industries (NREL 2013).

We also note that the mitigation potential from OSW and MRE in 2030 and 2050 will ultimately depend on wider electric power system markets, policies, politics, and technology advancement that are indirectly related to this mitigation strategy itself. Electric system markets and portfolios are dynamic, meaning the decision to reduce generation from any one resource (e.g., a natural gas power plant in one location) can result in changes to how other resources will be dispatched (e.g., turning on another natural gas plant to run for greater hours to make up for this loss). To most accurately assess carbon reduction potential from the addition of OSW or marine renewables, we would need to run electric system dispatch models for various coastal and Great Lakes electric systems to understand how the addition of a quantity of OSW would affect the dispatch of different resources and associated emissions over the course of the year. In addition, there are multiple future scenarios for how OSW and marine renewables could reduce electric system emissions in the U.S. over the next three decades. These technologies are two components of potential clean energy strategies, but they cannot solve for a clean electric system on their own any better than rooftop solar could alone: clean energy technologies and complementary strategies, like energy storage, energy efficiency and demand response, must work together. Yet ocean renewables, and OSW in particular, offer significant mitigation potential and are likely to be an important component of future low- and zero-carbon electric systems in the U.S.

2. Coastal "blue carbon" ecosystem protection, restoration, and cultivation

This section estimates the climate mitigation potential of coastal blue carbon ecosystems via the actions of conserving and restoring mangroves, salt marshes, and seagrasses, as well as cultivating seaweed for purposes of carbon sequestration.

Highlights

Mitigation potential

- Total mitigation potential of coastal blue carbon (BC) ecosystems is 15.01 Mt CO_2e per year by 2030.
- Conservation of existing ecosystems represents 98 percent of the total BC mitigation potential by 2030, by preventing the release of immense amounts of carbon stored in these habitats. Restoration of previously lost habitat accounts for less than 2 percent of the total BC mitigation potential by 2030, in large part because less area is available for restoration in the U.S. in comparison to other coastal countries.
- Seaweed cultivation could have a greater mitigation impact than BC restoration alone, but advances in technology and policy are needed to develop large-scale offshore cultivation solely for the purpose of carbon sequestration. Seaweed produced for human or animal consumption, which does not sequester carbon but which could offset higher-emissions alternatives, was not modeled.

Costs and benefits

- Continued coastal ecosystem degradation due to human impacts puts coastal communities at risk of further physical and economic damage from erosion, flooding, sea-level rise, and extreme weather events, which are expected to worsen.
- Protection of coastal ecosystems is more cost effective than restoration, but both achieve benefit/cost ratios of greater than 4:1.
- Restoration can create 17 - 30 jobs for every $1 million invested, a more cost-effective approach to job creation than infrastructure or fossil fuel-based industries.
- Seaweed cultivation has potential for significant job creation, given its labor intensity.

Policy recommendations

Conservation and restoration

- **Strengthen policies to bring BC habitat loss rates to zero**, such as a "no net blue carbon loss" policy and implementing recommendations to strengthen the compensatory mitigation rule for unavoidable habitat loss under the Clean Water Act.
- **Integrate BC habitat protection and restoration into shoreline protection plans and policies** for coastal flooding and emissions benefits.
- **Identify and integrate climate change impacts in conservation and restoration management plans** to ensure BC ecosystems are able to protect carbon storage and sequestration in the face of sea-level rise, coastal erosion, and wetland migration.
- **Provide long-term funding for BC ecosystem conservation and restoration**, especially for continued monitoring of greenhouse gas (GHG) emissions.
- **Establish national governance of BC to maintain a standardized inventory**, such as the proposed Interagency Working Group on Blue Carbon that will develop and maintain a national map and inventory of BC ecosystems, identify roadblocks to restoration, assess impacts of climate change on BC ecosystems, and ensure continuity of BC data.

Seaweed cultivation

- **Fund research and development** to evaluate the use of seaweed aquaculture for climate mitigation.

Context

Coastal and marine ecosystems that naturally remove CO_2 from the atmosphere are commonly referred to as coastal BC ecosystems. Similar to trees on land, BC ecosystems sequester CO_2 in plant tissue and roots and trap organic matter in marine soils. BC ecosystems include mangrove forests, tidal salt marshes, subtidal seagrass meadows and, to a lesser extent, seaweed.[29] With the exception of seaweed, BC sequesters upwards of 10 times more carbon per area than terrestrial ecosystems, including tropical rain forests (Mcleod et al. 2011).

When coastal ecosystems are degraded or destroyed, the carbon stored in the plants and soils—which may have accumulated over hundreds or thousands of years—is "oxidized" and emitted back to the atmosphere. Just as avoiding deforestation and planting more trees are critical land-based strategies to mitigate GHG emissions, both protecting and restoring BC habitat are integral ocean-based mitigation strategies.

The U.S. coastline contains all major BC ecosystems. Salt marshes are found along all U.S. coastlines, as are seagrass meadows (Mcowen et al. 2017). Yet most seagrass meadows and all mangrove forests are located in the U.S. Gulf of Mexico and southern Florida (Thorhaug et al. 2019; McKenzie et al. 2020). Seaweeds grow along all coastlines but kelp, the fastest growing seaweed, grows along the Alaskan, West, and Northeast coasts. While nascent, the seaweed cultivation sector is growing in the U.S. through a mix of government support, research, and early-stage commercial operations (Mayer and Fantom 2020).

BC ecosystems in the U.S. contain approximately 760 Mt of carbon.[30] For reference, this represents at least 2,740 Mt CO_2e—a value that nears half a year's worth of net CO_2e emissions in the U.S.[31]

BC ecosystems draw down an estimated 15 Mt CO2e annually.[32] For comparison, U.S. grasslands sequestered 12.8 Mt CO_2e in 2018 (EPA 2020). Existing carbon storage in BC ecosystems and annual carbon sequestration rates differ among the four BC habitats (Table 1).

[29] Seaweeds differ from mangroves, salt marshes, and seagrass in that seaweeds encrust bare rock and so do not sequester organic carbon in soils. Seaweeds lack roots and woody structures and so do not permanently store carbon in their living tissues. When seaweed dies off, most of the carbon stored in seaweed tissues is released back into the water as CO_2. Nonetheless, a small portion of carbon does get sequestered in the deep ocean and so seaweeds may be categorized under the rubric of BC (Krause-Jensen and Duarte 2016).
[30] Based on data from Table 4; see Methodology Appendix for details on data sources. This number is similar, but slightly lower, than the EPA's 870 Mt C estimate due to the more detailed modeling performed by the EPA (EPA 2020).
[31] U.S. net emissions were 5,903.2 Mt CO_2e in 2018 (EPA 2020).
[32] Based on data from Table 4; excludes methane (CH4) emissions from wetlands, estimated at 3.6 Mt CO_2e annually (EPA 2020).

The U.S. has lost much of its historic BC habitat.

- **Mangroves:** Estimates of historic mangrove loss are uncertain, ranging from 3 to 23 percent in Florida (Fish and Wildlife Service 1999). Losses are primarily driven by direct human impacts such as impoundment, shoreline development, and real estate. Recent annual losses for mangroves are lowest out of all BC ecosystems (Table 5).
- **Salt marshes:** An estimated 50 percent of historic salt marsh cover has been lost (Kennish 2001). Most often, salt marsh is converted to open water due to erosion and subsidence as a result of human impacts including modified hydrology via the construction of dams, levees, and canals, and oil, gas, and groundwater removal (Kennish 2001; Gittman et al. 2019). Such hydrological changes weaken salt marshes' resilience to climate stressors, such as sea-level rise and storms, thereby exacerbating erosion. Cutting off tidal flow to salt marshes (e.g., for transportation infrastructure or mosquito management) is also a significant cause of salt marsh decline (Kroeger et al. 2017).
- **Seagrasses:** An estimated 33 percent of U.S. seagrass meadows have been lost (Waycott et al. 2009). Losses are largely due to poor water quality resulting from sediment and nutrient run-off but are attributable in part to extreme climatic events (Orth et al. 2006).
- **Seaweed (kelp):** Kelp cover has declined on average but trends fluctuate greatly by region (Krumhansl et al. 2016). Recent losses in California have been linked to a multi-year warming event and the proliferation of sea urchins, which graze on kelp and prevent revegetation (Rogers-Bennett and Catton 2019).

Policies and regulations have been critical in conserving BC (Crooks et al. 2018), but BC habitat continues to decline each year in the U.S. (Table 5). This is largely due to direct human impacts and is exacerbated by sea-level rise (Kennish 2001; Gittman et al. 2019). Conservation and restoration of BC ecosystems can both help address long-standing human impacts and offer climate mitigation opportunities.

Table 5. Summary of U.S. blue carbon ecosystem characteristics. See Methodology Appendix for methods and data sources.

Habitat	Current extent (km^2)	Recent annual loss rate	Carbon stock* (Mg C/ha)	Annual sequestration rate (g C/m^2)
Mangroves	2,551	0.27%	645	92
Salt marshes	18,200	0.54%	206	121
Seagrass	14,422	1.24%	152	119
Kelp	1,352	1.16%	12	1

*Carbon stored in soil and/or in living plant tissues

Mitigation potential

The mitigation potential of BC ecosystems in the U.S. is estimated based on the following possible actions:

1. C**onservation and protection** to prevent habitat loss.[33] Habitat degradation leads to both a release of carbon stock back into the atmosphere and loss of carbon sequestration. Estimating the mitigation potential of avoided BC habitat conversion is based on the assumptions that present-day loss rates will continue until 2050, a portion of stored carbon in soil and live biomass will be emitted back into the atmosphere following habitat conversion, and habitat conversion will result in a loss of active carbon sequestration by that area.
2. **Restoration** of previously lost or degraded habitat. Restoration of BC ecosystems contributes to climate mitigation via renewed capacity for carbon burial (increased sequestration). The carbon sequestration potential from restoration is estimated based on current restorable area (for mangroves) and known habitat loss since the 1980s (for salt marshes and seagrasses), and it is scaled by previous success rates of BC restoration projects in the U.S.
3. **Expansion of seaweed cultivation** for the purpose of carbon capture and sequestration (CCS). Large-scale seaweed cultivation would provide an entirely new pathway for climate mitigation and requires evaluation. The impact of seaweed cultivation is based on the potential of kelp cultivation specifically, as this seaweed provides the highest mitigation potential due to fast growth rates. Carbon sequestration estimates are based on assumptions that large-scale farming (3,000 ha) will be achievable by 2026, the industry will expand, and the majority of carbon sequestered in harvested biomass will be permanently sequestered.[34]

Mitigation potential of coastal BC ecosystems and kelp cultivation is estimated to be 15.01 Mt CO_2e annually by 2030 (Table 6).[35] This would reduce annual CO_2e emissions by 0.25 percent in 2030.[36]

Table 6. Annual mitigation potential of BC ecosystems through conservation, restoration, and expansion of seaweed cultivation by the years 2030 and 2050

Mitigation option	Habitat	2030 (Mt CO_2e yr^{-1})	2050 (Mt CO_2e yr^{-1})
Conservation and protection	Mangroves	1.04	1.03
	Salt marshes	7.38	7.44
	Seagrass	6.18	6.18
	Kelp	0.05	0.04
	Conservation subtotal	14.66	14.69
Restoration*	Mangroves	0.01	0.04
	Salt marshes	0.05	0.15
	Seagrass	0.17	0.51
	Kelp	0.00	0.00
	Restoration subtotal	0.24	0.71
Seaweed cultivation**	Kelp	0.12	0.66
	Total	**15.01**	**16.06**

*Mitigation potential of cumulative area restored since 2021, with full area restored by 2050

**Assumes 100 percent of harvest is sequestered

[33] Rising sea levels are already causing wetland loss. Protecting the current extent of wetlands requires conserving space for wetlands to migrate landwards with sea-level rise in order to maintain the same area.

[34] Potential carbon sequestration pathways using kelp include sinking to the deep ocean or storage in long-lived bioproducts, but these methods have not been tested or developed yet.

[35] This is lower than the NASEM's total BC mitigation potential estimate of 37 Mt CO_2 yr-1 by 2030, which includes the use of BC ecosystems for storing carbon-rich materials (e.g., wood, biochar) (National Academies of Sciences, Engineering, and Medicine 2019a).

[36] Based on current policies, annual U.S. CO_2e emissions are expected to reach near 6 Gt by 2030 (Climate Action Tracker 2020).

1. Conservation

Avoided habitat conversion represents 98 percent and 92 percent of the total BC mitigation potential by 2030 and 2050, respectively. Avoided habitat conversion has by far the largest impact on CO_2 mitigation potential due to the large quantity of organic carbon in soils that would be remineralized back into CO_2 each year following deforestation or habitat conversion (Table 5).

As the percent of avoided habitat conversion is assumed stable, the areal opportunity of mitigation shrinks in size each year and the annual mitigation potential of avoided habitat conversion decreases from 2030 to 2050. The annual sequestration benefit gained from avoided habitat conversion increases from 2030 to 2050 and is largest for seagrass, followed by salt marshes.

Overall, salt marsh conservation contributes most to mitigation via conservation based on the assumption that 100 percent of the carbon stored in soils is returned to CO_2 upon habitat conversion, most often via soil erosion and conversion to open water (Pendleton et al. 2012). In contrast, seagrass habitat conversion is assumed to be less than 100 percent, as soils may not deteriorate entirely. Kelp conservation contributes to less than 0.4 percent of total mitigation potential of BC conservation by 2030, due to low carbon sequestration rates by this ecosystem.

2. Restoration

The impact of restoring lost habitat is relatively small compared to that of avoiding habitat conversion, but impacts of restoration grow over time as cumulative restored area increases (Table 5). Restoration of mangroves, salt marshes, and seagrass accounts for less than 2 percent of the total sequestration potential of BC ecosystems by 2030, and less than 5 percent by 2050. As more organic carbon is stored in the ground than is sequestered annually, avoided emissions achieved by conservation have a much greater impact on climate mitigation than the annual gains in sequestration achieved by restoration.[37] The scenarios modeled here assume ambitious investments in restoration (see Methodology Appendix for details) and so represent an aggressive mitigation action. Seagrass restoration is estimated to have the biggest mitigative potential as it has suffered the most extensive losses, followed by salt marshes and mangroves.[38] Kelp restoration represents 0.2 percent of total mitigation potential of BC restoration.

3. Expansion of seaweed cultivation

Kelp cultivation for the sole purpose of carbon sequestration nears the mitigation potential of the combined actions of restoring mangroves, salt marshes, and seagrasses. Unlike restoration, however, mitigation potential of seaweed cultivation can increase due to the additional scope for the areal and species expansion of cultivation.

Kelp cultivation represents 1 percent and 4 percent of the total sequestration potential of BC ecosystems by 2030 and 2050, respectively.[39] Rapid initiation and aggressive expansion of large-scale kelp cultivation could significantly increase the mitigation potential of this strategy beyond what is estimated here.

[37] The relatively low contribution of restoration to overall BC ecosystem mitigation potential is largely due to two factors. First is less spatial area available for restoration vs. protection in the U.S., as compared to other countries. For example, we estimate ~282 ha available for salt marsh protection vs. 64 ha available for restoration—a ratio of protection area to restoration area of 4.4:1. By contrast, at the global scale, the HLP analysis estimated a protection area to restoration area ratio of ~1:1.5, meaning the analysis found 1.5 times more area available for salt marsh restoration than protection globally. The second reason is that global studies of the mitigation potential of natural climate solutions—the protection, improved management, and restoration of ecosystems—generally estimate the highest contributions from protection and management interventions as compared to restoration (Griscom et al. 2017; 2020). See the Methodology Appendix for more details on these assumptions.
[38] The restoration effect is predominately influenced by the estimated area available for restoration, which has been properly assessed for mangroves but not for salt marshes or seagrasses. The area available for restoration is least certain for seagrasses. These estimates are based on historic area lost, as restorable area has not yet been assessed.
[39] This scenario assumes that 36 percent of suitable space for kelp cultivation is occupied by kelp farms in 2050, based on a starting area of 3,000 ha by 2025 and 9 percent industry growth rate (see Methdologpy Appendix for details).

Costs and benefits

Conservation and restoration

Continued BC habitat loss carries great economic risk. In Louisiana alone, loss of Mississippi delta wetlands risks $3.6 billion in terms of local buildings and infrastructure assets, $7.6 billion in national economic activity, and $191 billion in structural and economic damages resulting from storms as the loss of wetlands makes inland areas more vulnerable to storm damage (Barnes and Virgets 2017).

BC conservation and restoration are cost effective due to many co-benefits. In addition to carbon sequestration, protecting and restoring BC ecosystems has benefits for coastal protection (from erosion, flooding, and storms), improved water quality, fisheries productivity, biodiversity, tourism, and health and wellbeing of local communities (Konar and Ding 2020; Bindoff et al. 2019). In general, conservation has a higher return on investment compared to restoration, due to the high cost and low success rate of restoration efforts (Konar and Ding 2020). The benefit-to-cost ratio of restoration is estimated to be 4:1, based on the Florida Everglades restoration project (Restore America's Estuaries 2011).

BC restoration creates around 17 - 30 jobs per $1 million spent in the U.S.—an order of magnitude greater than road infrastructure projects and the oil and gas industry (Restore America's Estuaries 2011; P. E. T. Edwards, Sutton-Grier, and Coyle 2013). For example, the Florida Everglades restoration project is projected to create 440,000 jobs over a period of 50 years, resulting in a job-to-cost ratio of 30 jobs per $1 million spent (Restore America's Estuaries 2011). In Louisiana, the coastal restoration and protection economy supports 7,800 to 10,500 jobs each year (Barnes and Virgets 2017).

Seaweed cultivation

Seaweed farming at a large scale creates both permanent and seasonal job opportunities. For example, a 10 hectare (ha) farm employs five people, with the additional need for ~15 employees during harvest season (pers. comm. M. Hajibeigy). At a large scale, a 3,000 ha farm alone could create thousands of jobs depending on farm technology, with additional job creation for various seaweed processing pathways.

Seaweed farming at a large scale is costly, and benefits must be weighed in terms of climate mitigation rather than direct financial returns. As an example, large-scale seaweed cultivation in the North Sea requires a 300 percent increase in seaweed price in high-volume markets to make production profitable (van den Burg et al. 2016).[40] These markets do not target seaweed use for the purpose of CO_2 mitigation, and a 100 percent sequestration of carbon in harvested seaweed (Table 2) means the seaweed cannot be used for other products. Yet various environmental and economic benefits may be gained from seaweed cultivation. These include improved water quality due to the removal of excess nutrients in coastal areas, production of oxygen, increased aquaculture yields of species cultured alongside seaweed (Froehlich et al. 2019), and job creation. Climate benefits must also be weighed against potential unwanted environmental impacts.

[40] This study considered the value of seaweed in the current markets for high-volume seaweed products: hydrocolloids and animal feed.

Geographic opportunities

BC projects and opportunities exist in all coastal states, but projects specific to carbon storage need to be identified and prioritized.[41] Restoration efforts have not always aligned with areas where loss is greatest (Gittman et al. 2019), and restored ecosystem function is often not considered as a measurement of restoration success. Both state and tribal programs are critical for conservation and restoration of BC, and they may be more effective than federal programs as they better address management of the whole watershed and incorporate local goals and policies beyond the Clean Water Act (EPA 2015b). U.S. exclusive economic zone waters are suitable for large-scale seaweed cultivation. Suitable cultivation areas, based on nutrients, temperature, and presence of native seaweeds, include Alaska, the West Coast, and the Northeastern coastal states (Froehlich et al. 2019). Few seaweed farms exist currently, but the industry is growing (Grebe et al. 2019). Seaweed cultivation for the purpose of carbon sequestration will require an increase in seaweed production (i.e., moving from coastal operation in sheltered areas to exposed offshore areas), biomass harvest and transport technologies, and new processing methods and supply chains, all of which still need to be developed. If GHG mitigation via seaweed cultivation becomes economically and environmentally viable, this industry could rapidly grow.

Gulf Coast

The Gulf Coast is the region at greatest risk for large-scale BC habitat loss in the U.S. To date, most estuarine wetland (mangrove and salt marsh) losses have occurred in Louisiana and Florida (Gittman et al. 2019). Louisiana's Mississippi Delta remains at risk and is projected to lose an additional 1,329 km^2 of land during the 2000-2050 period (Barras et al. 2003). Several large-scale restoration efforts have been implemented, including a joint federal and state effort starting in 1990 that authorized 218 wetland restoration/protection projects in Louisiana, and the RESTORE Act of 2012, which aims to boost restoration efforts following the *Deepwater Horizon* oil spill in 2010.

Hydrology restoration and nutrient management are key for BC conservation. Because BC ecosystems depend on the greater upstream watershed, conservation and restoration often require land management far beyond the local habitat. This is critical both in Louisiana and Florida. For example, the Comprehensive Everglades Restoration Plan[42] in Florida aims to restore hydrology upstream, which will benefit downstream BC ecosystems.

Florida seagrass restoration has been successful for BC, but full recovery requires improved methods. Improvements in water quality management have led to successful seagrass restoration in Tampa Bay (Tomasko et al. 2005). Tampa Bay has undergone a BC assessment, and BC restoration projects are estimated to have removed 0.2 Mt CO_2e between 2006 and 2016 (ESA 2016). Across 33 restoration projects in Florida, however, seagrass cover in restored areas is 37 percent lower than in undisturbed areas, and standardized and long-term monitoring would improve the development of restoration methods (Rezek et al. 2019).

[41] The Great Lakes were not included in the BC mitigation model; however, freshwater ecosystems also store significant amounts of carbon. Including freshwater wetlands would expand the mitigation potential of this climate action area.
[42] The Comprehensive Everglades Restoration Plan was approved by Congress in 2000, and is estimated to cost $10.5 billion and take over 30 years to complete (NPS 2019).

East Coast

Salt marsh emissions may be curtailed with tidal restoration by reconnecting impounded or drained lands with ocean tides. An estimated 27 percent of salt marsh area has been impounded along the U.S. Atlantic coast, meaning the salt marshes have been cut off from the ocean due to reduced flows, dams, seawalls, and other barriers. (Kroeger et al. 2017). Such habitat conversion increases the amount of freshwater in the soils, which leads to methane (CH_4) emissions by soil microbes. Restoring tidal flows—through dam removal, restoring upstream flows, and removing barriers—brings saltwater back into the habitat and keeps the carbon sequestered in the soil. Tidal restoration can be a one-time action and has a greater impact on GHG mitigation than either conservation or restoration actions that target carbon sequestration through revegetation (Kroeger et al. 2017).

The Chesapeake Bay has lost half of its seagrass and is a focal area and model for seagrass restoration. Since the 1980s, state and local regulatory bodies have integrated numerous policies aimed at seagrass conservation by tackling multiple drivers of habitat degradation and initiating restoration goals and projects (Orth et al. 2010). Management and restoration remain a challenge due to the continued human pressures on the watershed and climate change impacts (Orth et al. 2019). Yet seagrass restoration has been extremely successful in some areas of the bay (Orth et al. 2019). As the biggest success, a 7 km^2 meadow has been restored in the outer South Bay in Virginia (Oreska et al. 2020). The success of the project has allowed managers to take the first steps toward using this project in the voluntary carbon market (e.g., the purchase of carbon offsets), and selling carbon credits could cover approximately 10 percent of the restoration costs (Oreska et al. 2020).

Seaweed cultivation is gaining momentum in the Northeast. Small coastal, land-based, or pilot scale farms are currently operating or in planning stages in Maine, New Hampshire, Massachusetts, Connecticut, and Rhode Island (author research; Grebe et al. 2019).

West Coast

New mapping efforts show that 85 percent of tidal wetlands have been lost on the West Coast and identify new opportunities for restoration (Brophy et al. 2019). Areas with greatest historical loss include the San Francisco Bay (Brophy et al. 2019), a designated estuary of national significance.[43] As part of restoration efforts in this region, the South Bay Salt Pond Restoration Project is one of the largest restoration projects in the U.S. Started in 2003, the project aims to restore 15,100 acres of industrial salt ponds to tidal wetlands and other habitats over 50 years. The project has restored 3,040 acres to salt marsh to date and is already seeing the return of species of native fish and endangered species like the salt marsh harvest mouse.

Seaweed cultivation on the West Coast could offset emissions from state industries. As an example, cultivating seaweed in 3.8 percent of the West Coast exclusive economic zone would completely offset California's agricultural emissions (Froehlich et al. 2019). Small coastal, land-based, or pilot scale farms are currently operating or in planning stages in Washington, Oregon, and California (author research; Grebe et al. 2019).

Alaska, Hawaii, and U.S. Territories

U.S. territories have both mangroves and seagrasses, with opportunities for improved BC management. For example, the 2017-2022 management plan for Jobos Bay National Estuarine Research Reserve in Puerto Rico includes BC research and monitoring (NOAA 2017).

Seaweed cultivation has successfully been promoted by the State of Alaska, as part of a large mariculture initiative (Box 3). While the focus of seaweed farms has not been on CO_2 sequestration per se, this industry is increasingly focused on the mitigation impact of seaweed production and products.

Tribal Nations

Tribal nations are active in BC habitat restoration and conservation. In 2009, the Lummi Nation in Washington established the first tribal wetland mitigation bank (EPA 2016).[44] So far, the Lummi have enhanced 200 acres (0.8 km2) of wetlands and sold $1.7 million in mitigation credits.

[43] The EPA designates 28 estuaries along the Atlantic, Gulf, and Pacific coasts and Puerto Rico as estuaries of national significance, as part of its National Estuary Program.
[44] Wetland mitigation banks create credits (e.g., via restoration) that can be sold to offset or compensate for wetland losses elsewhere.

Box 3. Alaska Mariculture Initiative

The Alaska Mariculture Initiative was launched by the Alaska Fisheries Development Foundation (AFDF) in 2014, with the aim of building a $1 billion aquaculture industry in 30 years. The initiative is an example of how to rapidly invest in and expand coastal mariculture. The initiative has three prongs: expand the stakeholder base for successful development and implementation, develop a three-phase economic analysis of successful mariculture elsewhere, and build a strategic plan with input from diverse stakeholders (AFDF 2016).

The initiative gained governmental support and led to the creation in 2016 of a state-level Alaska Mariculture Task Force, which manages several advisory committees on research, investments, environmental impacts, workforce development, marketing, and public education (Mattson 2017b). By 2018, the task force had published the Alaska Mariculture Development Plan, which supports AFDF's goals by aiming to build a mariculture industry worth $100 million in the next 20 years (Baird and Wilber 2018). The task force holds frequent meetings that are open to the public and is currently developing a five-year action plan to develop the industry, infrastructure, capital, business models, training programs, marketing, public outreach, legislation, and research.

The mariculture industry in Alaska has been growing rapidly as a result of the initiative. By 2017, the state had received permit applications for over 1,000 acres of new oyster and kelp farms, and several state bills were passed to support responsible growth of the industry with support from diverse stakeholders (Mattson 2017a). By 2019, 51 applications had been submitted for farms of oyster, seaweed, or both, encompassing 2,000 acres (Welch 2019).

Policy, research, and technology needs

Conservation and restoration

Policy to support conservation and restoration

Strengthen policies to bring habitat loss rates to zero. This may include creating a federal "no net blue carbon loss" policy, preventing private wetland habitat conversion, and making restored carbon sequestration a required measurement of wetland management and restoration success (Ocean Conservancy 2020b). Unpreventable habitat loss requires compensatory mitigation under the Clean Water Act.[45] Yet this mandate has not been successful in mitigating wetland loss, nor has it been able to restore ecosystem function in mitigated areas (Turner, Redmond, and Zedler 2001; National Academies of Sciences, Engineering, and Medicine 2019a, 2). Recommendations to strengthen the compensatory mitigation rule have been outlined but have not yet been implemented (Turner, Redmond, and Zedler 2001). Given that significant BC habitat has already been lost, the rule could require a greater area of compensatory mitigation than the area permitted for conversion. This change would likely help to expand BC ecosystems and their mitigation potential.

Integrate BC ecosystems in the development of coastal protection. The Living Shorelines Act (H.R. 3115) introduced in June 2019 calls for funding to support projects that use natural materials for the purposes of coastline protection, which includes restoration and expansion of BC ecosystems (Pallone 2019). Establishing BC habitat for coastal protection purposes will also have CO_2 mitigation benefits. Demonstration projects are necessary to quantify benefits and develop robust monitoring methods for future use.

[45] Compensatory mitigation means restoration, establishment, enhancement, or preservation of wetlands to compensate for unavoidable adverse impacts on wetlands elsewhere (EPA 2015a). The amount of compensatory mitigation required is usually referred to as an areal ratio in acres ranging from 1:1 (1 acre of restoration per acre of altered wetland) to 3:1, depending on the type of wetland.

Provide long-term funding for BC projects. Long-term funding is necessary to support maintenance of restoration and conservation projects, especially for the continued monitoring of GHG. Developing new funding schemes that account for BC ecosystem services other than GHG mitigation (such as their co-benefits for habitat creation or coastal protection) could help support funding these projects over longer timeframes (Hoegh-Guldberg et al. 2019; Emmett-Mattox and Crooks 2018). These funding mechanisms could include payments for ecosystem services, for example.

Fund research on BC ecosystems, and the ocean carbon cycle in general, to better understand climate change impacts on BC ecosystems and the climate co-benefits BC ecosystems provide (Ocean Conservancy 2020a; 2020b). This knowledge is necessary for developing management plans and may be accomplished through existing grant programs at NOAA and the EPA (Ocean Conservancy 2020b).

Establish national governance of BC to maintain a standardized inventory on BC and GHG. Proposed legislation addresses existing data gaps. In January 2020, Rep. Suzanne Bonamici introduced the bipartisan Blue Carbon for Our Planet Act, H.R. 5589 (Bonamici 2020). The legislation would establish an Interagency Working Group on Blue Carbon that would develop and maintain a national map and inventory of BC ecosystems, identify roadblocks to restoration, assess impacts of climate change and other human stressors on BC ecosystem function, and preserve continuity of BC data. Standardized practices are needed across different federal agencies (Ocean Conservancy 2020a).

Develop an inventory of "Coastal Carbon Areas of Significance" (Ocean Conservancy 2020b). This recommendation also includes funding riverine restoration, which is needed to restore water quality necessary for restoration and conservation of BC ecosystems.

Include seagrass in the Inventory of U.S. GHG Emissions and Sinks. The current inventory includes wetlands, both mangroves and salt marshes, but not seagrasses due to the sparsity of data and challenge of hindcasting.

Research and technology to support conservation and restoration

Identify and integrate climate change impacts in BC management plans. Gains in BC conservation and restoration will still be threatened by climate change. Predicting how BC ecosystems and their carbon stores will respond to climate change impacts (e.g., sea-level rise, coastal erosion, wetland migration) is necessary to develop BC management plans that can protect the carbon storage and sequestration of that habitat in the future (Emmett-Mattox and Crooks 2018).

Improve mapping of current, degraded, and lost BC habitats to identify restoration and conservation opportunities. Mapping of BC habitat, especially seagrass, which is lacking a national monitoring program,[46] is necessary for tracking change and mitigation potential. BC habitats that are healthy, at-risk, degraded, or lost need to be mapped and categorized. Such data will also help identify and target "Coastal Carbon Areas of Significance" for special protection (Ocean Conservancy 2020b).

Improve and standardize reporting of GHG gas accounting in BC ecosystems. In addition to areal cover, estimating BC mitigation potential requires detailed knowledge about annual habitat conversion rates, soil carbon content, carbon sequestration rates, and other GHG emissions. Many such data gaps exist for U.S. seagrass meadows and, to even a greater extent, for seaweed. For salt marsh and seagrass, we need improved estimates of the percentage of soil carbon that is emitted back into the atmosphere or water as CO_2 after habitat conversion. In addition, not all organic carbon produced by BC ecosystems is sequestered locally. Some organic carbon leaves the habitat and ends up sequestered in the surrounding coastal areas or the ocean (Duarte and Krause-Jensen 2017). This carbon is currently unaccounted for. Standardized protocols for assessing ecosystem function of restored areas and standard reporting practices are also needed (Gittman et al. 2019; Ocean Conservancy 2020a).

[46] The NASA-USGS National Blue Carbon Monitoring System only tracks coastal wetlands (mangroves and salt marshes), and seagrasses are not yet included in the EPA's U.S. National Greenhouse Gas Inventory.

Seaweed cultivation

Policy to support seaweed cultivation

Support legislation to fund research and development to assess carbon drawdown benefits, co-benefits, and environmental impacts; reduce production costs; and advance cultivation technologies and pilot scale projects (Energy Futures Initiative 2019). As seaweed cultivation for the purposes of carbon sequestration has not been tested and would require significant technological innovation and governance, more research is needed to properly evaluate this climate mitigation strategy.

If seaweed cultivation for carbon sequestration proves to be an effective mitigation method, policy recommendations include:

Develop an efficient governance and permitting process for offshore aquaculture, including seaweed. For example, current aquaculture lots are 40 ha or less (Grebe et al. 2019), and economically efficient cultivation for climate mitigation is estimated to require 3,000 ha or more per individual farm (ARPA-E 2017). Over the past 30 years, numerous bills have been introduced in Congress to establish a permitting system for offshore aquaculture in federal waters, and currently the industry is regulated by several federal agencies and laws.

Provide incentives for starting a seaweed farm. This could include federal insurance programs (e.g., integrate seaweed cultivation into the Federal Crop Insurance Act), tax breaks for demonstrable carbon capture, training programs for fishers to transition to seaweed crops, efficient processing of business loans, federal and state-level programs to create new seaweed markets specific to climate mitigation, and creating a carbon accounting protocol for farm integration into the voluntary carbon market (B. Smith, Bowman, and Johnson 2019; Middlebury Institute of International Studies at Monterey Center for the Blue Economy and Blue Frontier 2020).

Research and technology to support seaweed cultivation

Develop methods for storing the carbon sequestered in harvested seaweed. Carbon stored in seaweed can be actively sequestered in two ways: the seaweed can be sunk to the deep sea where it is effectively sequestered from the atmosphere, or the seaweed can be used on land (e.g., integration into building materials).[47] Both options require technological innovation to ensure permanent carbon sequestration and life-cycle assessments for proper GHG accounting. Passive sequestration occurs when seaweed naturally sloughs off prior to harvest, and several research groups are quantifying this sequestration with the aim of developing a methodology for the voluntary carbon market.

Assess co-benefits of seaweed cultivation. Seaweed cultivation can be used in polyculture with farmed fish and shellfish (e.g., regenerative ocean farming) and boost production as a result of nutrient recycling and water oxygenation. Farms create new three-dimensional habitat that could also improve local marine biodiversity and fisheries. In addition, farms could be integrated with other offshore infrastructure, such as windfarms.

Assess environmental impacts of seaweed cultivation. Environmental impacts have not been fully assessed, and both positive and negative impacts can be expected (van den Burg, Dagevos, and Helmes 2018). Major risks of large-scale cultivation relate to loss of materials from farms with consequences for safety at sea, entanglement of marine life, and general contribution to marine debris. Biosecurity risks include the potential for genetic mixing with local species, spread of diseases and parasites, and creation of stepping stones for invasive marine species. Large-scale cultivation would likely result in nutrient competition with the local ecosystem, with currently unknown impacts.

Develop and pilot new technologies for seaweed cultivation in the U.S. exclusive economic zone. Large-scale cultivation of seaweed for carbon sequestration requires cultivation to move offshore where there is more space, but farms have greater exposure to storms, ocean currents, and waves. Accordingly, new farm infrastructure and harvest and transport methods must be developed. Some advances in this area were made via the ARPA-E MARINER program, which funded 21 research projects from 2017 to 2020 on large-scale seaweed production technologies, modeling and monitoring tools, and optimizing seaweed growth (ARPA-E 2017).

[47] Seaweed used for biofuels, animal feed, human consumption, or other products does not lead to carbon sequestration, but rather to CO2 offsetting, by replacing materials with greater CO2 footprints.

Key assumptions, data limitations, and caveats

Aggressive investments in conservation, restoration, and kelp cultivation would be required to achieve the climate mitigation potential of coastal BC ecosystems modeled in this chapter. As an illustration, kelp cultivation for the sole purpose of CCS is not currently piloted anywhere in the U.S. As such, the model represents a best case scenario of the climate mitigation potential of BC ecosystems in the U.S. Full details on the methodology used for this analysis are available in the Methodology Appendix.

Conservation and restoration

The BC mitigation model assumes no change in future habitat conversion rates and does not account for increasing climate change or sea-level rise impacts on carbon sequestration rates and storage of soil carbon. Protecting the current extent of wetlands requires protection of space for wetlands to migrate landwards with sea-level rise.

Restoration assumes an immediate return to the carbon sequestration rate of a healthy ecosystem. This assumption contributes to an overestimate of the mitigation potential of restoration, as it can take years for restored ecosystems to return to historic sequestration rates (Greiner et al. 2013; Gittman et al. 2019).

The restoration model assumes full restoration of lost habitat by 2050. This is an ambitious scenario and would require implementation of thousands of projects over the next 30 years. For seagrass specifically, there is no national database or monitoring program for seagrass habitat, and restorable area was assumed to equal historic area lost, likely leading to an overestimate of the true area available to restoration.

Expansion of seaweed cultivation

The model assumes that 100 percent of the carbon in the harvested kelp biomass is sequestered (methods for which still need to be developed), but the mitigation potential is reduced by 16 percent due to GHG emissions associated with cultivation practices (Froehlich et al. 2019). This overestimates mitigation potential by seaweed cultivation, as it does not include the GHG production associated with the processing method that will be required for permanent storage of the organic carbon. In addition, kelp biomass may also be used in bioproducts not intended for the sole purpose of carbon sequestration, further decreasing the mitigation potential of the assumed biomass production.

The model assumes that a 3,000 ha farm is operational in 2025, which is ambitious but not impossible. Current cultivation methods can expand an individual farm by 10 ha per month (S. Crooks personal communication). To achieve a 36 percent use of potential area for kelp cultivation by 2050, a 9 percent expansion rate would be required. This translates to three new projects with a 10 ha per month expansion rate in 2030 and 18 new projects per month in 2050.

Exclusion of non-CO_2 GHG emissions

Production of non-CO_2 GHGs associated with BC ecosystems and kelp cultivation inherently reduces the mitigation effect of carbon sequestration when considering net GHG flux. Non-CO_2 emissions were not included in the model because detailed site data are needed to accurately estimate these effects. Non-CO_2 GHG emissions from U.S. wetlands alone are estimated to be 3.6 Mt CO_2e annually (EPA 2020).

For salt marsh and mangrove restoration, rewetting of previously drained soils can lead to methane production (193.7 kg CH_4 ha^{-1} y^{-1}) if salinity is less than 18 ppt (Hiraishi et al. 2014). Methane production from rewetting may only occur in the first few years and is highly dependent on many local factors such as previous land use, vegetation, and water table depth (Hiraishi et al. 2014). If one assumes production of 193.7 kg CH_4 ha^{-1} for only one year following restoration, CH_4 production in units of CO_2e is approximately equal to the amount of one year's worth of CO_2 sequestered by that restored area. For reference, U.S. estimates point to a total of 0.01 Mt CO_2e in CH_4 emissions annually due to the conversion of land to vegetated coastal wetlands (EPA 2020).

Kelp produce short-lived halocarbons, predominantly $CHBr_3$ (Keng et al. 2020), that in large-scale cultivation could partially offset the CO_2 sequestration benefit of kelp CCS. This effect was not modeled, as myriad environmental factors affect halocarbon production, and field studies are needed to more accurately assess their contribution to and impact on climate change (Keng et al. 2020).

3. Decarbonizing U.S. shipping

This section estimates the climate mitigation potential of efforts to reduce emissions from U.S. domestic and international shipping through development and deployment of zero-emission vessels (ZEVs) and operational measures to reduce emissions.

Highlights

Mitigation potential

- Shipping has the potential for a full decarbonization of its operational emissions. Eliminating GHG emissions from shipping would reduce annual GHG emissions by 61 Mt CO_2 in 2050.
- U.S. emissions from shipping—both international and domestic—totaled 75.3 Mt CO_2 in 2019. Under business as usual (BAU) projections, annual shipping emissions probably will decrease modestly, by 7 Mt CO_2 annually in 2030, and by 14 Mt CO_2 in 2050.
- Reductions in emissions from international shipping accounts for the majority of mitigation potential in U.S. shipping. Approximately 8 - 21 Mt CO_2 in 2030 and 23 - 58 Mt CO_2 in 2050 can be reduced through operational measures and transitioning to ZEVs.

Costs and benefits

- In the U.S., partially decarbonizing the shipping sector would require an estimated $3.5 - 4.9 billion of annual investment through 2050.
- Investments in decarbonizing shipping can create jobs and contribute to economic recovery, potentially bringing $84 - 637 billion to the U.S. economy in the 2020-2050 period with a benefit-to-cost ratio of between 2:1 and 5:1 in 2050.
- Reducing ship emissions, especially near populated coastal areas, can reduce negative health outcomes associated with air pollution, especially for low-income and Black, Indigenous, and people of color communities.

Policy, research, and technology needs

- Leverage EPA authority to set federal emissions reduction targets in line with or exceeding International Maritime Organization (IMO) targets for rapid decarbonization of the U.S. shipping sector.
- Implement national mandatory vessel speed reduction programs within 200 nautical miles from shore.
- Reduce localized emissions and promote environmental justice by mandating zero at-berth emissions for ships in port.
- Establish a centralized monitoring, reporting, and verification data collection system for U.S. shipping.
- Provide funding to the Maritime Environmental and Technical Assistance program for research on ZEV ships and port technologies.

Context

The international shipping industry is responsible for about 90 percent of global trade by volume (T. Smith 2014). In the U.S., the maritime transportation industry is a major contributor to the economy, responsible for carrying 38 percent of exports by value and accounting for close to 300,000 jobs (Chambers and Liu 2012). In 2019, the water transportation sector, which includes shipping and recreational boating, added $15.7 billion to the U.S. economy (Bureau of Economic Analysis 2019).

On a per tonne-kilometre (tkm) basis, shipping is the most efficient mode of transport—by a large margin. Large container vessels can transport goods at rates as low as 3 grams CO_2 per tkm, compared to 80 g CO_2 per tkm and 435 g CO_2 per tkm for trucks and air cargo, respectively (T. Smith 2014).

Due to the enormous volume of goods moved, shipping is still a major contributor to global greenhouse gas (GHG) emissions. According to the Fourth GHG Study of the IMO—the United Nations agency responsible for regulating global shipping—global shipping emissions in 2018 were 1,076 Mt CO_2e/yr (2.89 percent of total GHG emissions and 90% of 2008 emissions) and are expected to increase to 90 - 130 percent of 2008 levels by 2050 (Faber et al. 2020). The U.S. is a major contributor to global shipping emissions due to its coastal orientation along both the Pacific and Atlantic Oceans and its reliance on international trade, especially with Asia. Due to shipping's reputation as the most energy-efficient mode of transportation, the sector is sometimes excluded from mainstream international conversations about mitigating climate change (Gilbert and Bows 2012). Furthermore, the complex and global nature of the shipping industry can hinder unilateral action to incentivize low-carbon technologies and operational practices (Gilbert, Bows, and Starkey 2010).

U.S. shipping-related emissions can include those from international and domestic trade, recreational boating, and commuter transportation on ferries.[48] Ports in the U.S. produce a significant amount of the nation's localized air pollution and GHG emissions—both from ships idling nearby and from the trucks and trains that transport cargo to and from the ports. In coastal areas around the country, the communities located adjacent to ports are often low-income and/or communities of color, and they often bear the brunt of elevated levels of air pollution (Bailey et al. 2004). Therefore, continued innovation in the port and maritime sector is crucial not only for mitigating GHG emissions, but also for promoting environmental justice.

Mitigation potential

Table 7. U.S. shipping mitigation scenarios (2030 and 2050)

Ocean-based climate action area	Mitigation option	Description	2030 Mitigation potential (Mt CO_2/year)	2050 Mitigation potential (Mt CO_2/year)
Shipping	Reducing emissions from domestic shipping	Shipping between two or more U.S. ports, including inland waterways and port emissions. Recreational boating is excluded.	0*	0 - 3.0
	Reducing emissions from international shipping	Shipping between a U.S. port and foreign ports on ships that fly an American flag, including emissions in port.	8 - 21	23 - 58
Total			**8 - 21**	**23 - 61**

*Low-end mitigation potential from domestic shipping is greater than 0, but according to EIA, Domestic shipping emissions have already fallen significantly, from 17.5 Mt CO_2 in 2008 to 6.2 Mt CO_2 in 2019. This is likely the result of a change in accounting methodology rather than major emission reductions in the last 11 years.

Shipping has the potential for a full decarbonization of its operational emissions. Eliminating GHG emissions from shipping would reduce annual GHG emissions by 61 Mt CO_2 in 2050. The timescale of decarbonization depends on the how quickly zero-carbon technologies can replace or retrofit current shipping vessels and infrastructure. Operational measures such as slow steaming—realized through aggressive, goal-based operational carbon intensity measures—can reduce emissions in the short term, providing 8 - 21 Mt CO_2 of mitigation potential in 2030. Full decarbonization will require widespread adoption of ZEVs compatible with zero-emission ports for recharging or refueling. ZEVs can take the form of battery-powered electric ships that recharge with renewable energy or zero-carbon fuels such as green hydrogen, ammonia, or biofuel, generated with electricity from renewable energy.[49]

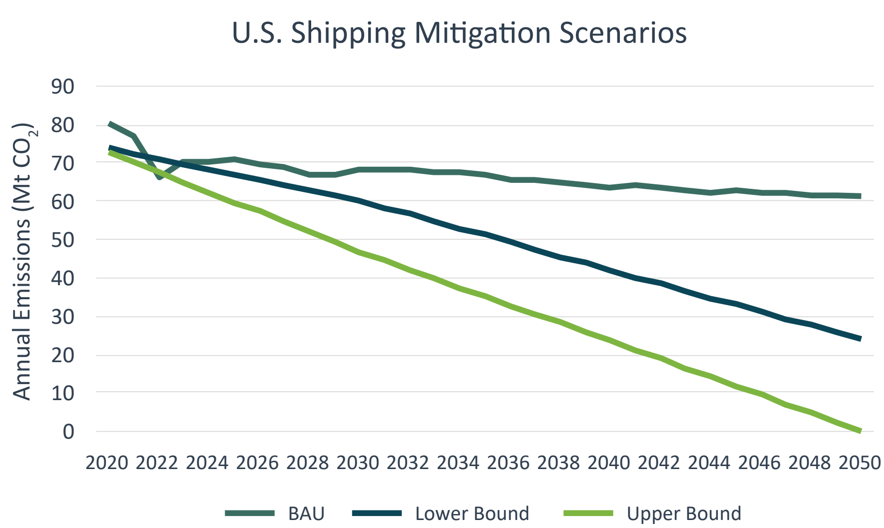
[48] In this report, "domestic shipping" refers to shipping between two or more U.S. ports, while "international shipping" refers to shipping between a U.S. port and a foreign port.
[49] The adjective "green" describes the process of producing hydrogen, ammonia, and biofuel with environmentally sensitive production methods and renewable energy so that the fuel is fully zero carbon, instead of shifting emissions upstream.

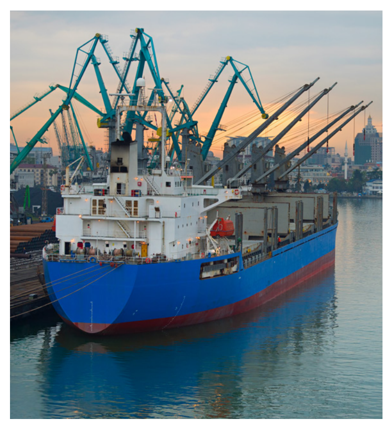
Under BAU projections, annual shipping emissions probably will decrease modestly, by 7 Mt CO_2 annually in 2030, and by 14 Mt CO_2 in 2050. CEA modeled total U.S. emissions from shipping—both international and domestic—to be 75 Mt CO_2 in 2019.[50] In a BAU scenario, emissions from shipping could decrease by 9 percent to 68 Mt CO_2 in 2030 and by 19 percent to 61 Mt CO_2 in 2050. This reduction only considers current U.S. and international policies and is mostly driven by a small decrease in the demand for shipping, coupled with a 0.6 percent increase in the fuel efficiency of ships and a transition of some fuel consumption from distillate fuel oil and residual fuel oil to liquefied natural gas (LNG), which has a lower emissions factor (emissions released per unit of energy produced). But the use of LNG in shipping can move emissions upstream, including via methane slip (leakage of unburned methane in fuel combustion), which has greater global warming potential than does carbon dioxide alone. These methane emissions are not inventoried as part of shipping emissions (Pavlenko et al. 2020).

U.S. shipping emissions have the potential to decrease far beyond BAU projections, by 20 - 39 percent in 2030 and 50 - 100 percent in 2050, through operational measures and infrastructure decarbonization. These measures would require significant policy, technology, and research developments. We modeled two different mitigation scenarios based on abatement potential from 2008-level emissions. For the lower bound mitigation scenario, we modeled a 20 percent reduction of 2008 emissions by 2030 and a 50 percent reduction by 2050. For the upper bound scenario, we modeled a 39 percent reduction of 2008 emissions by 2030 and 100 percent by 2050 (see Hoegh-Guldberg et al. 2019). The lower bound scenario is based on the IMO's target to reduce the GHG emissions of international shipping by at least 50 percent from 2008 levels by 2050, while the upper bound scenario is based on the technical potential.[51]

The lion's share of mitigation potential comes from international shipping. Domestic shipping in 2019 accounted for only 7.5 percent of the total U.S. shipping emissions. Domestic shipping emissions have already fallen significantly, from 18 Mt CO_2 in 2008 to 6 Mt CO_2 in 2019. However, this drop may be due to a change in EIA's accounting mechanism for domestic shipping. In a BAU scenario, domestic shipping emissions are projected to fall to 4 Mt CO_2 in 2030 and 3 Mt CO_2 in 2050, outpacing our lower bound mitigation targets. In the upper bound full decarbonization scenario, emissions from domestic shipping can fall to zero by 2050, allowing for 3 Mt CO_2 of mitigation potential. For international shipping, which has stayed constant since 2008 and is projected to decrease only slightly to 2050, 37 - 58 Mt CO_2 of mitigation potential is possible in 2050.

Figure 8. U.S. shipping mitigation scenarios (2020-2050)





[50] To calculate U.S. shipping emissions projections and mitigation potential to 2050 for this study, we used emissions data from the U.S. Energy Information Administration (EIA). The EIA parameters for U.S. shipping include all ships used for international or domestic shipping that fly a U.S. flag. An unknown amount of U.S. international shipping emissions to or from U.S. ports is not accounted for in EIA's estimates because it occurs on foreign-registered ships. For more information on our methods, see the Methodology Appendix.

[51] In 2018, the IMO set an initial strategy to reduce GHG emissions from ships. The strategy aims to reduce the GHG emissions of international shipping by at least 50 percent by 2050. Domestic shipping is excluded from the IMO targets but was included in the CEA analysis because identical policies, technology, and research are needed for the decarbonization of domestic and international shipping.

[52] The dramatic change of emissions for domestic shipping between 2008 and 2019 is likely due to a shift in the way the EIA accounts for domestic shipping emissions. The number of U.S. flagged ships fell from 225 in 2018 to 182 in 2019 (Bureau of Transportation Statistics 2019) and there has been some increase in the efficiency of ships and a shift toward LNG fuels. But these changes do not fully account for the 65 percent drop in domestic shipping emissions from 2008 to 2019. This accounting change increases the uncertainty of our analysis—however, domestic shipping makes up <10 percent of total U.S. shipping emissions so this uncertainty does not have an outsize influence on the total mitigation potential of the U.S. shipping sector for 2030 and 2050.

Costs and benefits

Reducing global shipping emissions in line with the IMO GHG targets will require significant investment in both proven and novel technologies—an estimated $1 - 1.4 trillion between 2030 and 2050 (~$50 - 70 billion/year) (Krantz, Søgaard, and Smith 2020). Specifically, a range of existing and emerging technologies (such as improved battery storage and zero-carbon fuels) are required to decarbonize the sector through electrifying port and bunkering infrastructure and building out a fleet of ZEVs to phase out fossil fuel-based ships. To achieve a 100 percent reduction in CO_2 emissions (in line with the upper bound mitigation scenario from this report), an additional $400 billion would be required (Krantz, Søgaard, and Smith 2020). For context, the total global investment in energy from 2015 to 2050 needed to reach a 65 percent share of renewable energy in the electricity grid mix is about $120 trillion (IRENA 2018a). The investment needed to decarbonize shipping is therefore only a small fraction of the massive global investment needed in energy transformation and low-carbon technologies.

The largest proportion of investment is needed in land-based infrastructure and production facilities for zero-carbon fuels (e.g., investments in hydrogen production, ammonia synthesis, and land-based fuel storage and bunkering infrastructure) (Krantz, Søgaard, and Smith 2020). Only 13 percent of the estimated investment would be directed toward energy-efficiency technologies, the construction of zero-carbon engines, and energy storage technology (Krantz, Søgaard, and Smith 2020).

In the U.S., $3.5 - 4.9 billion could be required annually to partially decarbonize the shipping sector, but more rigorous estimates are needed. Although there are currently no robust estimates of the investment required to decarbonize the shipping sector specifically in the U.S., CEA's calculations show that U.S. shipping constitutes about 7 percent of global shipping (calculated as a share of global emissions). A proportional transfer of investment would imply a $70 - 98 billion investment through 2050 ($3.5 - 4.9 billion annually) in the U.S., in line with the lower bound mitigation scenario from this chapter. For context, the U.S. investment in solar in 2019 was $25 billion, which helps support 250,000 jobs in the industry (Feldman, O'Shaughnessy, and Margolis 2020). The vast majority of this investment would be directed toward on-land infrastructure to support shipping decarbonization and would have cross-sectoral stimulating effects across other renewable energy and low-carbon fields. Though the long-term investment to fully decarbonize shipping in line with our upper bound scenario is ambitious, significant mitigation potential can initially be achieved with little effort through operational measures. Operational mandates such as slow steaming, discussed in more detail in the Policy, Research, and Technology needs section, can slash emissions without the need to construct new infrastructure.

Investments in decarbonizing shipping can create jobs and contribute to economic recovery. Looking at the 2020-2050 period, Konar and Ding (2020) estimate that decarbonizing international shipping by 2050 could yield a net benefit of $1.2 - 9.1 trillion to the global economy, with an estimated benefit-to-cost ratio of between 2:1 and 5:1 in 2050 (Konar and Ding 2020). Assuming a proportional 7 percent share of global shipping in the U.S., this benefit translates to roughly $84 - 637 billion added to the U.S. economy over the 2020-2050 timeframe relative to a BAU scenario (~$2.7 - 20.5 billion annually). For context, the water transportation sector added about $15.7 billion to the U.S. economy in 2019, meaning that decarbonizing shipping could potentially double the benefits of the industry on an annual basis (Bureau of Economic Analysis 2019).

Reducing ship emissions, especially near populated coastal areas, has significant human health implications, especially for low-income and Black, Indigenous, and people of color communities. Combustion of shipping fuel releases fine particulate matter (PM2.5), nitrogen oxides (NOx), and sulfur oxides (SOx), which can react in the atmosphere to form sulfate (SO4) aerosols that contribute to acid rain. These pollutant chemicals are estimated to cause ~400,000 premature deaths from lung cancer and cardiovascular disease and ~14 million childhood asthma cases annually across the world (Sofiev et al. 2018). In the U.S., where low-income communities are often concentrated close to shipping ports and exposed to other sources of pollution, these health hazards can be an additional burden on the most marginalized citizens (Bailey et al. 2004). In California alone, the California Air Resources Board (CARB) estimates that 3,700 premature deaths per year are directly attributable to ports and goods movement activities statewide, at an economic cost associated with deaths, medical care, and missed school and work days of $30 billion annually (Marquez and Vallianatos 2012).

In addition to the emission of CO_2—a prominent GHG—and $PM_{2.5}$, NOx, and SOx—which are harmful to human health—burning heavy fuel oil for ships releases black carbon, which can act as a powerful radiative forcing agent by reducing the surface albedo of ice and snow. Ship activity near Anchorage, Alaska, contributes a significant amount of black carbon emissions to the Arctic, which is a particular threat to already vulnerable ecosystems. Increased shipping in the Arctic region, including U.S. shipping through Alaska, can also carry an increased chance of fuel spills, which harm local fauna and can be difficult to clean up (Comer et al. 2017).

At the federal level, the U.S. has taken a step to regulate particulate emissions through the IMO's establishment of an emission control area (ECA), but it has not proposed any legislation to limit the GHG emissions from shipping. The North American ECA became enforceable in August 2012 and mandates that ships within 200 nautical miles of the U.S. coastline reduce their NOx, SOx, and $PM_{2.5}$ emissions. The North American ECA's annual benefits in 2020, mostly in monetized health benefits, are expected to be worth $110 billion and to cost about $3.2 billion per year to implement and enforce (EPA Office of Transportation and Air Quality 2010). Additionally, the benefits are expected to reduce premature deaths from air pollution by about 14,000 people per year and reduce respiratory symptoms for nearly 5 million people in the U.S. annually (EPA Office of Transportation and Air Quality 2010).

Geographic opportunities

Shipping is a sector that touches every coastal area of the U.S., including the Great Lakes region. Though 40 of the 50 U.S. states have either river, lake, or ocean-based ports, five states—Louisiana, Texas, California, New Jersey, and Washington—control 69 percent of the water-traded goods by weight in the U.S. (Army Corps of Engineers 2018). Targeting states or regions with the most vessel traffic would be the most effective way to reduce emissions in the shipping sector.

East Coast

The largest port on the U.S. East Coast, in terms of weight of traded goods, is the Port of New York and New Jersey. The East Coast region is less of a shipping center than the Gulf Coast and West Coast, and individual states generally have smaller coastlines (with the exception of Maine and Florida). As a result, the East Coast is an area where regional or federal legislation is preferred to regulate shipping, because a patchwork of state regulations for the 14 coastal East Coast states could be difficult to enforce. Some promising examples of shipping coordination on the East Coast already exist, however, such as the North Atlantic Ports Association, a trade association of commercial seaports spanning from Virginia to Canada.

The most notable East Coast shipping regulation to date is the Right Whale Slow Zones, a program of the National Marine Fisheries Service (NMFS) that mandates vessel speed reduction to no more than 10 knots for all vessels longer than 65 feet to minimize collisions with North Atlantic right whales. NMFS has created seasonal management areas from Massachusetts to Florida that enforce vessel speed reduction in established whale migratory areas and also promote voluntary dynamic management areas, which mariners can voluntarily avoid or reduce speed in if recent whale sightings have occurred (NMFS 2008). The federally regulated approach of vessel speed regulation by NMFS helps ensure that whales are protected throughout their migratory range along the Eastern seaboard.

West Coast

The West Coast shipping industry is dominated by California, which handles more than 40 percent of all inbound cargo containers to the U.S. (Haveman and Hummels 2004). California, home to many of the largest ports in the U.S., has taken the most aggressive stance on reducing shipping emissions, making it a model for further action on the West Coast and providing lessons for other states and, for the country as a whole.

In 2007 CARB adopted the At-Berth Regulation for six of its largest ports, forcing vessels to either connect to shore power while in port (a practice known as "cold ironing") or use alternative technologies to reduce emissions to the same levels. The regulation began with a target of 50 percent emissions reduction in ports by 2014, ramping up to 80 percent emissions reduction by 2020 (California Air Resources Board 2007). In August 2020, CARB expanded this rule to include tankers and auto carriers, leading to a 90 percent decrease in harmful air pollution (California Air Resources Board 2020). CARB estimates that this policy reduces CO_2 emissions in California by 0.5 Mt CO_2 annually and has reduced NOx emissions by 4.3 tons per day and $PM_{2.5}$ emissions by 0.066 tons per day (California Air Resources Board 2018a).

Finally, several ports in California have been effective at implementing a voluntary vessel speed reduction program (VSRP) to reduce speeds offshore. Between 2005 and 2016, the VSRP helped the Port of Los Angeles cut NOx emissions by 40 percent, diesel $PM_{2.5}$ emissions by 90 percent, SOx emissions by 98 percent, and GHG emissions from oceangoing vessels by 28 percent (Starcrest Consulting Group, LLC 2015). In 2018, 91 percent of the more than 3,000 ocean-going vessels entering and leaving the harbor were voluntarily slowing within a distance of 20 nautical miles (Port of Los Angeles 2018). The mayors of Los Angeles and Long Beach in 2017 signed an agreement directing their port to spearhead a zero-emission goods movement system by 2035, including zero-emissions cargo-handling equipment and trucks to transport goods from docked ships (Barboza 2017).

Outside of California, Washington has showed leadership on the electrification front. The greater Seattle and Puget Sound area depends on ferries for transportation. The passenger water transportation sector, which includes cruise ships and ferries, supports 3.3 percent of total maritime jobs in Washington and paid $138 million in wages in 2015 (Washington State Department of Commerce and DNV GL 2019). Of the current fleet, all but 13 vessels are more than 30 years old. As a result, in January 2019, the Washington State Department of Transportation announced the 2040 Long Range Plan, which includes converting all vessels to electric-hybrid models and electrifying all but three ports (Washington State Department of Transportation 2019). These on-the-water pilots will be important to showcase the efficacy of zero- and low-carbon vessels as the rest of the country and world look to convert their fleets.

The West Coast as a region is also important for establishing a transpacific zero-emission corridor for trade between the U.S. and Asia. Reports have already assessed the feasibility of this route, which can be scaled for maximum effectiveness by creating a network of zero-emission bunkering ports throughout the West Coast region (Mao et al. 2020).

Gulf Coast

The Gulf Coast region is a vital component of the U.S. shipping industry, particularly considering the Mississippi Delta, which provides maritime access to the interior. The port of South Louisiana is the largest port in the U.S. by weight of goods shipped, due largely to its handling and processing of grain exports from areas in the Mississippi watershed. Louisiana, with its direct access to the Mississippi River, has five of the top 50 largest ports in the U.S., controlling over 23 percent of U.S. water-traded goods (Army Corps of Engineers 2018). Texas has six of the top 50 largest ports in the U.S. and controls another 22 percent of U.S. water-traded goods (Army Corps of Engineers 2018). Though this region has not historically acted to regulate emissions from shipping, the significant mitigation opportunities concentrated in several large ports could bring jobs to local communities. For example, the region has some of the largest fossil fuel-exporting ports in the country, and federal policy could lay the groundwork for transitioning local economies to exporting green fuels that power ships and trucks both domestically and abroad.

Great Lakes

Inland ports, such as the ports of Cincinnati-Northern Kentucky, St. Louis, Duluth-Superior, and Chicago, play an important role in transporting goods to and from the interior of the country. Illinois, home to the Port of Chicago and the Port of St. Louis (which it shares with Missouri), processes the seventh-largest amount of waterborne tonnage by weight out of all 50 states—more than coastal states like Virginia and Alabama (Army Corps of Engineers 2018). While there is overall less shipping traffic in America's interior than along its coasts, shipping emissions and pollutants can be concentrated along a narrower waterway. More than 800 ocean-going vessels travel to or through the Great Lakes each year, and the five interior ports along the Lower Mississippi have some of the highest levels of marine pollution in the country (Scott and Sinnamon 2008). Furthermore, the Great Lakes vessel fleet is older and less carbon efficient than many of the U.S. coastal fleets. In 2019, the first new freighter to serve the Great Lakes region since 1983 was built (Gmiter 2019). Policies in the Great Lakes region and along the waterways that feed it should focus on reducing air pollution for adjacent communities.

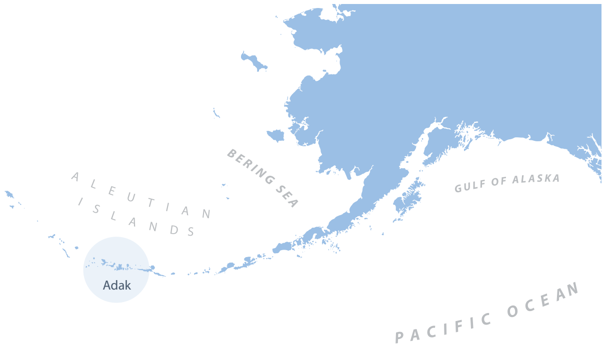
Alaska, Hawaii, and U.S. Territories

While the ports of the States of Alaska and Hawaii, as well as the ports of other U.S. territories are not currently major players in international trade, these states are entirely dependent on domestic shipping for transporting goods to and from the mainland U.S. In Alaska, the delicate ecosystems are particularly vulnerable to black carbon emissions and oil spills. The IMO has introduced a draft ban on the use of heavy fuel oil in the Arctic, which would regulate some areas of northern Alaska, but the regulation has exemptions and waivers for many ships until July 1, 2029 (Comer 2020a). These loopholes, depending on how much they are used, could result in little to no protection of the vulnerable Arctic region from shipping-related air pollution. Western Alaska and the Arctic region are also excluded from the North American ECA, so communities there remain vulnerable to emissions from shipping fuels that are not subject to reductions in $PM_{2.5}$, NOx, and SOx concentrations.

Hawaii and the islands of the U.S. territories are small compared to Alaska, meaning all areas of the islands are in close enough proximity to the ports to suffer the effects of air pollution. The potential for oil spills can also pose a particular risk to coral reefs near island communities (Knap et al. 1983). Policies to reduce the health effects of air pollution from shipping and the ecological risks of oil spills in these communities are therefore important to consider.

Alaska and Hawaii could become more influential players in global trade if transpacific zero-carbon vessels reroute to refuel midway through their journeys. A pit stop in either location, which is only a minor detour for most routes, could help bridge the gap for ZEV technology that currently may not be feasible for the longest transpacific journeys (Mao et al. 2020). If vessels stop midway in Alaska or Hawaii to refuel or recharge, these states could become major hubs for green fuels and renewable energy.

Tribal Nations



Some areas of the U.S. coastline and interior waters belong to tribes, but few major ports in the U.S. exist on Native American reservations. Consequently, tribal lands are not a high-priority area for emissions reductions in shipping.

A possible future scenario exists for those coastal tribal lands that have a high potential for renewable energy production and lie on well-trafficked vessel routes. For example, the port of Adak in Alaska's Aleutian Island chain is wholly owned by the for-profit Aleut Corporation. Adak lies in an area of the Aleutian Islands with rich potential for wind, tidal/wave, and geothermal energy production and is also squarely along the North Pacific Great Circle Route, where transpacific vessels travel between North American and Asian port destinations. With the proper investment in green energy production and storage infrastructure, Alaska's Aleut people could play an important role in providing the green energy needed to decarbonize the shipping industry and serve as a refueling stop along this popular trade route.

Policy, research, and technology needs

Policy action aimed at decarbonizing shipping is challenging for the same reason that documenting emissions is—the international geography of most shipping emissions presents an obstacle to regulating the industry. Shipping regulations typically come top-down from the IMO, which has historically been slow to set ambitious emissions reduction targets. Many of the IMO regulations, such as the January 2020 adoption of a 0.5 percent sulfur content requirement in fuel and a draft ban in the Arctic slated to partially take effect in 2024, are full of loopholes that will result in limited adoption and minimal climate impact (Comer 2020b; 2020a).[53] The U.S., given its disproportionate contribution to both global emissions and shipping traffic, has an important role to play in exceeding international targets set by the IMO. Several other countries have already introduced incentives or measures to reduce shipping emissions, including the UK Clean Maritime Plan, domestic commitments to reduce shipping emissions in several Scandinavian countries, and a China National Action Plan (Hoegh-Guldberg et al. 2019). If the U.S. does not act quickly on shipping, it risks becoming a fringe player in future international conversations regarding regulation of the sector. Federal policy and stimulus are necessary to kickstart the decarbonization process, and urgent action can allow the U.S. to become a leading player in developing the technology that other countries will use to decarbonize their shipping industries.

Policy

Near-term

Leverage EPA authority to set federal emissions reduction targets in line with or exceeding IMO targets for rapid decarbonization of the U.S. shipping sector

The first and most important step to decarbonizing U.S. shipping is to set ambitious federal emissions reduction targets. The Clean Air Act authorizes the EPA to set GHG emissions standards for marine engines when emissions “may reasonably be anticipated to endanger public health or welfare” (“42 U.S. Code § 7547 - Nonroad Engines and Vehicles” n.d.). The EPA also has a legal and financial obligation to clean up areas that are designated as “nonattainment” based on health standard levels for certain air pollutants, and many ports are located in counties that are failing to attain standards for NOx, SOx, and/or PM2.5. It is within the power of the president to direct the EPA, as part of the executive branch, to exercise this authority to regulate shipping. The EPA recently acted to propose the first-ever national aircraft emissions standards, though many environmental organizations criticized the proposal for being too weak (Bowden and Beitsch 2020). The president should direct the EPA to follow the aircraft emissions standards with a set of shipping emissions standards that are, at a minimum, in line with IMO medium- and long-term targets.

Emissions action in the U.S. has thus far only occurred at the federal/international level with the establishment of the North American ECA. This regulation has been important for reducing toxic emissions from shipping in vulnerable areas. Yet limiting sulfur emissions can have an inverse effect on atmospheric warming by reducing the radiative cooling of aerosols, which cause a decrease in radiative forcing when suspended in the atmosphere (Sofiev et al. 2018). Sulfur reduction policies, while important for human health, need to be coupled with overall GHG emissions reduction targets to provide environmental benefits in tandem.

The IMO target to reduce the GHG emissions of international shipping by at least 50 percent by 2050 should be the floor of any U.S. intervention (in line with the lower bound mitigation scenario in this chapter). If all sectors were to decarbonize proportional to their share of global emissions, the global shipping industry would have only until 2034 to fully decarbonize in line with a 1.5°C scenario (Pacific Environment and CDC 2020). While full decarbonization by 2034 is probably unrealistic, a 2050 target for decarbonization would still require ZEVs to be market-ready and on the water by 2030 to steadily replace fuel-based ships in the following two decades (in line with the upper bound mitigation scenario in this chapter) (Lloyd’s Register and UMAS 2017). Immediate action is needed to lock in emissions reductions for the long term and to avoid the possibility of shipping emissions starting to rise if fuel prices are further reduced and the currently popular practice of slow steaming is scaled back. Importantly, federal targets must cover emissions from both international and domestic shipping. The IMO targets only address international shipping emissions, ignoring the 8 percent of emissions in the U.S. which come from domestic shipping. U.S. emissions targets should therefore cover all shipping emissions and use the IMO targets as a baseline from which targets can be ratcheted up.

[53] The IMO sulfur content requirement allows for the use of scrubbers as an alternative to purchasing low-sulfur fuel. Over 4,000 ships have installed scrubbers, which generate contaminated wash water that is often dumped into the ocean. The IMO Arctic heavy fuel oil ban allows for exemptions and waivers for many ships until July 1, 2029, so the ban is not ambitious enough to tackle the environmental problems posed by burning heavy fuel oil in vulnerable ecosystems.

Implement national mandatory vessel speed reduction programs for 200 nautical miles from shore

An easy first step to immediately achieve certain emissions reductions targets through operational measures would be to enact a federal vessel speed reduction program (VSRP). A 10 percent across-the-board speed reduction for all ships has been shown to reduce overall GHG emissions by as much as 13 percent, which would be key to meeting near-term 2030 emissions targets (Faber et al. 2012). Several California ports have been successful in implementing a voluntary VSRP that financially incentivizes slow steaming within 20 or 40 nautical miles of port. The success of these programs shows that voluntary VSRPs with financial incentives can reduce emissions in the absence of mandatory enforcement and with limited funding. The VSRP for the Santa Barbara Channel Region and San Francisco Bay Area reduced approximately 17,026 tons of regional GHGs in 2019 at an operating cost of about $200,000/year (The Protecting Blue Whales and Blue Skies Partners 2020; 2019). The Port Authority of New York and New Jersey's Clean Vessel Incentive program, which awards points for vessel speed reduction and a vessel's Environmental Ship Index score, enrolled 272 qualifying vessels and offered $515,000 in incentivized payouts during the first quarter of 2017 (AJOT 2017). The nation's top 10 largest ports probably could each implement a robust, aggressive VSRP for $1 - 5 million per year.

The 20 and 40 nautical miles reduction zones have been implemented primarily to protect near-shore whale populations. While they have been effective at reducing harmful emissions near ports as a co-benefit, expanding these vessel speed restrictions to the extent of the U.S. exclusive economic zone at 200 nautical miles from coastlines will lead to further emissions reductions that can limit shipping's contribution to climate change.

According to a report by CE Delft (2017), speed regulations should be mandatory and coupled with an enforcement mechanism to most effectively reduce emissions (Faber, Huigen, and Nelissen 2017). Two possible enforcement mechanisms in the U.S. by which NMFS could mandate a federal VSRP are the Marine Mammal Protection Act and the Endangered Species Act. NMFS has regulatory responsibility for implementing laws to protect endangered species such as certain species of whales, and VSRPs, such as the Channel Islands Region Incentive-Based Vessel Speed Reduction Program, have been designed to protect local whale populations from vessel strikes (as opposed to minimizing emissions). Future VSRPs should take into account local megafauna, be mandatory, and be designed to maximize environmental impact, but without economic disruption.
Mandatory VSRPs are unlikely to have a significant economic impact, although more research is needed. The CE Delft (2017) report modeled the effect of vessel speed reduction for exports from South America to the EU and found that a 30 percent reduction in vessel speed for all South American exports could cause a corresponding 0.03 - 0.09 percent drop in GDP (Faber, Huigen, and Nelissen 2017).

Medium-term

Reduce localized emissions and promote environmental justice by mandating zero at-berth emissions for ships in port. Emissions from ships idling in ports are both a large source of shipping pollution and a major health hazard that disproportionately affects low-income communities of color in urban areas (Bailey et al. 2004). The EPA estimates that connecting ships at berth to shore power could reduce overall pollutant emissions by up to 98 percent, depending on the mix of energy sources (EPA 2017). By mandating zero at-berth emissions, federal regulators can protect local communities while allowing the flexibility for vessel owners to choose the technology that best suits their needs. The major barrier to reducing port emissions through cold ironing is the up-front capital investment needed to install low-carbon infrastructure. U.S. investment in ports, such as through increased funding for the Department of Transportation (DOT) or EPA grant programs, should upgrade port equipment and be paired with financial or regulatory drivers to incentivize participation from all vessels. Policies to reduce local emissions and promote environmental justice should also include matching federal grants for the electrification of U.S. port infrastructure; making shore power available at all major ports; and securing robust involvement in the planning process by members of adjacent impacted communities to ensure public participation and reduce litigation (Middlebury Institute of International Studies at Monterey Center for the Blue Economy and Blue Frontier 2020).

In California, CARB has successfully reduced ship emissions through its At-Berth Regulation, which mandates reduced emissions for vessels while docked at port. Seattle and Juneau have independently introduced cold ironing infrastructure for cruise ships (Zis 2019). State-level and/or federal action is needed to further limit at-berth emissions, especially in states with multiple large ports. States should look to California and to the EU's current draft regulations for guidance on regulating localized ship emissions in ports, and the federal government should consider a national mandate drawing guidance from California's approach (Ship & Bunker News Team 2020).

Reducing emissions in ports has bipartisan support in Congress because of the opportunity to reduce emissions, create jobs, and clean up impacted communities. The U.S. government could further seize the opportunity of decarbonizing ports to promote safe and well-paying jobs, as well as funding job retraining programs for workers displaced by automation. The Climate Smart Ports Act, H.R. 7024, introduced by Rep. Nanette Diaz-Barragan (D-CA-44), directs the EPA to establish a grant program for eligible entities that purchase and install zero-emissions port equipment. The bill also contains strong labor provisions to protect dockworkers from automation by barring entities from using grants to purchase or install automated cargo handling equipment. Four other bills (S. 4025, S. 2302, H.R. 6084, and H.R. 7304) introduced in the 116th Congress by senators and representatives on both sides of the aisle focus on greening ports through research and funding projects while also creating local climate action plans that incorporate elements of environmental justice.

Support green fuel and renewable energy infrastructure near ports

Beyond operational measures such as slow steaming and at-berth emissions reduction, further decarbonization efforts in the shipping industry are connected to and contingent on the adoption rate for renewable energy and low-carbon fuels. While more technology development is needed to create cost-efficient ZEVs that can fully substitute for fuel-based ships in international shipping, ZEV development should be paired with the scaling of renewable energy and green fuel infrastructure on land. Approximately 87 percent of the investment needed to decarbonize shipping is in hydrogen production and ammonia synthesis, storage, and distribution (Krantz, Søgaard, and Smith 2020). Renewable energy is needed to power the production of hydrogen and ammonia to avoid shifting shipping emissions upstream, and investing in the renewable energy necessary to power a fleet of ZEV ships is an important opportunity for the U.S. to further decarbonize the national electric grid. Port infrastructure upgrades could be paired with infrastructure to support and service offshore wind, which would provide additional zero-carbon renewable energy to the port and nearby coastal and marine areas.

The need for a long-term economic recovery package to address the economic devastation caused by the COVID-19 pandemic creates an opportunity to scale up investments in a clean energy transition for the shipping sector. The American Recovery and Reinvestment Act, signed by President Barack Obama during the 2009 Great Recession, was the single largest investment in clean energy in U.S. history. The law was effective in stimulating job creation in the energy efficiency and renewable energy sectors and established roughly 900,000 job-years in clean energy fields from 2009 to 2015,(White House Council of Economic Advisors 2016). A similar effort during the pandemic could help push the U.S. in the direction of developing zero-carbon fuels and infrastructure for shipping in line with the technical potential scenario of our mitigation analysis. Creating a 100 percent renewable energy grid in the U.S. by 2045, which would be essential to making shipping emissions net zero (in line with the upper bound scenario from this chapter), could support about 530,000 jobs each year (Phadke et al. 2020).

Long-term

Ratchet up the efficiency of ships built in the U.S. through federal subsidies

As a result of Section 27 of the Merchant Marine Act of 2017, also known as the Jones Act, all U.S. ships that transport goods between U.S. ports (i.e., domestic shipping) must bear a U.S. flag and consequently be built in the U.S. Though many ships used in U.S. international shipping are built abroad, ships built in the U.S. for purposes of domestic shipping have the opportunity to showcase American ingenuity in efficient design.

At the global level, the IMO has developed the Energy Efficiency Design Index (EEDI), which mandates constructing new ships with increasing levels of efficiency. The EEDI sets an initial 10 percent emissions reduction requirement for new ships, which will be ratcheted up every five years. Beginning in 2025, new ships must be at least 30 percent more efficient than the average ship built between 2000 and 2010. Although important progress has been made, this rate of increase in shipping efficiency will not meet the IMO emissions reduction targets—the lower bound mitigation scenario of this study—nor will it sufficiently incentivize the construction of ZEVs to ensure market-ready ZEVs will be on the water by 2030. The U.S. can go beyond the EEDI in piloting ultra-efficient ships or ZEVs built on American soil. A Lloyd's Register and UMAS report (2018) on how to make ZEVs cost competitive by 2030 found that currently no zero-emission options satisfy shipowner requirements, and regulatory intervention is needed in the near future to close the gap on voyage costs (Lloyd's Register and UMAS 2017).

Federal subsidies could help close the cost gap to make ZEVs on the water by 2030 a feasible goal. Federal subsidies are already required to make U.S.-produced ships cost competitive with China, Korea, and Japan, where 90 percent of ships today are built (Payne and Chokshi 2020). Further subsidies could encourage integrating state-of-the-art technology into efficient ship design.

Research

Short-term

Establish a centralized monitoring, reporting, and verification data collection system for U.S. shipping

An important component of controlling emissions from U.S. shipping is to quantify emissions consistently. The U.S. Energy Information Administration (EIA) estimates from its Annual Energy Outlook (AEO) that are used in this report quantify fuel usage and CO_2 emissions in the shipping sector for U.S. flagged ships only; the estimates do not count emissions from ships with foreign flags as U.S. emissions, even if those ships are transporting U.S. goods to or from a U.S. port. To avoid strict safety standards or higher taxes, ship owners often elect to fly a "flag of convenience" registered in a foreign country. As a result, global inventories have attributed the majority of CO_2 emissions to six flag states: Panama (15 percent), China (11 percent), Liberia (9 percent), Marshall Islands (7 percent), Singapore (6 percent), and Malta (5 percent) (Olmer et al. 2017). While the Jones Act mandates that all domestic shipping occur on vessels registered in the U.S., an unknown amount of U.S. international shipping emissions to or from U.S. ports is not accounted for in EIA's estimates because it occurs on foreign-registered ships. While several ports independently choose to inventory their emissions, some large ports such as the Port of Savannah have refused to develop a dedicated GHG inventory (Jones 2020). Furthermore, international shipping was omitted from national inventories under the Kyoto Protocol, creating a data gap with policy and technical implications for decarbonizing the sector. The Paris Agreement also does not provide a playbook to inventory international shipping emissions, leaving confusion about where these emissions fall (Transport & Environment 2018).

A centralized monitoring, reporting, and verification data collection system for U.S. shipping would ensure a consistent approach that details the geographical sources of shipping emissions and provides data on the most common shipping routes. The EU has a similar system that requires large ships over 5,000 gross tonnes to monitor and report their related CO_2 emissions. The IMO recently established the IMO Data Collection System, which requires owners of large ships engaged in international shipping to report fuel consumption data to the flag states of those ships, who then report aggregated data to the IMO. But the IMO data remains confidential, omits domestic shipping, and is only published in an anonymous public database that excludes important information such as specific route data.

The U.S. should establish a centralized monitoring, reporting, and verification scheme within the EPA or the United States Coast Guard to capture shipping emissions data on a more granular level. The existing EPA Greenhouse Gas Reporting Program tracks emissions at the facility level and lacks the granularity necessary for data to be useful in regulating the sector. A shipping monitoring, reporting, and verification data collection system should include all vessels entering U.S. waters, not just vessels with U.S. flags, to best protect the health and safety of U.S. citizens. For example, shipping emissions near ports and coastlines pose dangerous health threats to Americans regardless of whether the ship is bearing a U.S. or foreign flag. Tracking specific route data is also important for the establishment of pilot routes for ZEVs or creating future areas for vessel speed reduction or emissions controls. A centralized data system will be essential to monitor and enforce any new shipping regulations and will help fill a key data gap to inform future U.S. policy in the shipping sector.

Medium-term

Produce more research on the economic impacts of reducing emissions in the shipping sector

The majority of research into reducing emissions in the shipping sector has focused on benefits to the environment and to health. More research is needed on the economic benefits of decarbonizing shipping, such as potential job creation in the sector. Future research should also quantify any cost adjustments to transporting goods through operational measures like slow steaming, in line with the Faber et al. (2017) study for South America-EU trade but in the U.S. context (Faber, Huigen, and Nelissen 2017). More cost-benefit analysis of different zero- or low-carbon shipping technologies is also needed to understand the path forward for decarbonizing the industry in the manner that will most benefit America's environment, health, and economy.

Technology

Short-term

Provide funding to the Maritime Environmental and Technical Assistance program for research on ZEV ships and port technologies

ZEVs need to be market ready and on the water by 2030 to begin decarbonizing the U.S. shipping fleet (Lloyd's Register and UMAS 2017). The U.S., as a dominant force in shipping and a leading nation in technological innovation, should be urgently spearheading this movement for ships built domestically.

In addition to infrastructure development, technological advancements are needed to make ZEVs safe, reliable, and economical. The International Energy Agency's (IEA) Energy Technology Perspectives (ETP) guide ranks the readiness level of different low-carbon technologies on a scale from 1 to 10. The rankings for deployable ammonia-fueled engines and hydrogen fuel cell electric vessels are 4-5 and 7, respectively, and bunkering technology for hydrogen fuel receives a score of 3 (IEA 2020).[54] More technological development is needed before ZEVs can fully replace fuel-based vessels.

The U.S. has the opportunity to be at the forefront of ZEV technology if immediate and extensive action is taken. Research and development of ZEVs at the federal level falls under the purview of DOT's Maritime Environmental and Technical Assistance program. Senate bill S. 4025, Expanding the Maritime Environmental and Technical Assistance Program, would authorize $3 million to the program to research ZEVs and zero-emission port technologies. Congress should pass this bill to authorize baseline funding for ZEV research in the U.S., though additional funding is needed in the next few years to ensure ZEVs will be on the water by 2030.

Create financial incentives for zero-emission technology for domestic ferries

Ferries, an important component of the U.S. public transportation system, are also an easy place to begin decarbonization efforts through federal funding because of their relatively small size and short transit lengths. In the U.S., 143 active public transport ferry vessels provide employment for almost 4,600 employees and deliver over 360 million passenger-miles annually (Chambers and Liu 2012). Washington State has already begun construction on a fleet of electric ferries, which are expected to roll out between 2022 and 2028. The higher up-front capital costs of construction for electric passenger ferries is offset through reduced operational costs over the lifetime of the vessels ("Testimony of Peter Bryn, ABB Marine and Ports, Before the Subcommittee on Coast Guard and Maritime Transportation of the Committee on Transportation and Infrastructure" 2020). H.R. 2, the House Democrats' comprehensive infrastructure bill, increases funding authorizations for ferry boats and related infrastructure by 50 percent to $120 million and authorizes DOT to make grants for zero- or reduced-emission passenger ferries (House Select Committee on the Climate Crisis 2020). The ferry components of this bill should be enacted, either through H.R. 2 or as a separate bill, to facilitate this necessary infrastructure development.

Encourage U.S. support for the International Maritime Research and Development Board at the IMO

A group of international shipowner associations representing over 90 percent of the world merchant fleet has proposed creating an International Maritime Research and Development Board to accelerate ZEV technology. The proposal would levy a mandatory contribution of ~$2/tonne of fuel oil purchased for a research and development fund, raising $5 billion over a 10-year period (BIMCO et al. 2019). The U.S. could play an important role in encouraging the adoption of the Board through representation at the IMO. Yet while the Board is an important first step to raising funds for R&D, it is insufficient as a full market mechanism to steer the existing fleet toward rabid decarbonization. The U.S. representation at the IMO should push for the creation of the Board while also considering instituting a more aggressive tax and redistribution effort domestically that would provide additional funds and steer the market toward zero-carbon technologies.

Medium-term

Incorporate shipping fuels into the Renewable Fuel Standard (RFS) and Low Carbon Fuel Standard (LCFS) markets
An important component of scaling up ZEVs in the American maritime fleet is making low-carbon shipping fuels like green hydrogen and ammonia eligible for credits under the EPA's RFS or a future LCFS, such as the one that exists in California under CARB. The current structure of the RFS requires minimum volumes of renewable fuel production for biomass-based diesel, cellulosic biofuel, advanced biofuel, and total renewable fuel. The environmental impact of these fuels is subject to debate, so an expansion of the RFS should include green hydrogen and ammonia fuels while also taking into account the lifecycle GHG emissions of any biofuels used in shipping vessels. Congress should amend the Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007 to include zero-carbon shipping fuels that are essential to the success of a future ZEV fleet in the U.S.

[54] Ammonia is generally considered the preferred candidate for zero-carbon fuel because it is 50 percent denser than liquid hydrogen, but technical hurdles exist in the hard-to-ignite combustion process and low flame speed.

Key assumptions, data limitations, and caveats

ZAt a national level, shipping emissions and mitigation potential are difficult to quantify because the vast majority of emissions in shipping comes from international trade. International shipping was also omitted from national inventories under the Kyoto Protocol, creating a data gap with policy and technical implications for decarbonizing the sector.

The EIA Annual Energy Outlook (AEO), the source of data for our models, counts as U.S. shipping emissions only those emissions from ships flying a U.S. flag, while not counting emissions from ships that use U.S. ports but fly foreign flags. We used the EIA dataset for our mitigation analysis, meaning that the BAU emissions projections to 2050 for international shipping could actually be significantly higher, with a proportionally greater mitigation potential, depending on what is considered under "U.S. shipping." The AEO also shows a significant drop in domestic shipping emissions from 2008, the baseline year from which our 2030 and 2050 targets are pegged. This drop is likely exaggerated due to a change in accounting mechanisms, introducing some uncertainty into the mitigation projections for domestic shipping. Furthermore, the AEO only captures CO_2 emissions (not all GHG emissions), so the total emissions and corresponding mitigation potential in this analysis is likely a conservative underestimate.

A number of assumptions are also folded into our mitigation model, including using the IMO GHG targets as the lower bound for the U.S. abatement of shipping emissions, even though the U.S. has not yet taken any steps toward reducing GHG emissions in shipping. The full set of assumptions, data limitations, and caveats are laid out in the Methodology Appendix.

4. Fisheries and aquaculture efficiency improvements and dietary shifts

This section estimates the climate mitigation potential of seafood through addressing key emissions sources in fishing and seafood farming and transitioning U.S. consumption toward lower-carbon proteins.

Highlights

Mitigation potential

- Total mitigation potential from improving the efficiency of seafood and aquaculture production is 7.17 Mt CO_2e per year by 2050.
  - Effectively managing fisheries informed by sound science, which the U.S. does under the Magnuson-Stevens Act, is a proven way to ensure carbon-efficient production. Maintaining this seminal legislation, and ensuring fisheries can be managed adaptively as the climate changes, is essential.
  - Supporting energy-efficiency measures for fishing vessels and providing incentives for the adoption of hybrid and zero-emission vessels can drive additional emissions reductions in the fishing sector.
  - Converting on-vessel refrigeration equipment to low- or no-global-warming potential (GWP) technologies can further reduce greenhouse gas (GHG) emissions from wild-capture fishing.
  - Aquaculture in the U.S. has low levels of emissions and mitigation potential, but reducing the carbon intensity of fish feeds could lower the emissions intensity of the production of carnivorous species.
- Total mitigation potential through shifting consumption patterns toward a more seafood-heavy diet is 10 - 39 Mt CO_2e per year by 2050.
  - Shifting diets represents the greatest opportunity for emissions reductions for seafood but has historically been the most difficult to achieve due to the challenges of influencing consumption patterns. Tax, policy, or behavioral incentives at a large scale would be required to achieve these reductions.

Costs and benefits

- Sound fisheries management can improve stock health, improve economic value, and reduce emissions.
- Energy-efficiency improvements can reduce fuel costs for vessels, but payback periods can be long, which would necessitate financial incentives to spur uptake.
- Expanding the U.S. bivalve and seaweed aquaculture industries could create jobs, reduce pollution, create fisheries habitat, and reduce emissions—but the industry faces headwinds from a competitive global aquaculture industry. Any offshore production system should minimize resource use to the extent possible, to ensure emissions and other impacts remain low.
- Shifting diets away from red meat toward seafood and other lower-carbon foods would reduce cardiovascular disease risk and bolster producers of low-carbon foods, including fish producers, but would reduce the market share of red meat.

Policy, research, and technology needs

- Maintain and strengthen fisheries management by defending and strengthening the Magnuson-Stevens Act, incorporating climate adaptation into fisheries management, and managing fisheries to maximum economic yield.
- Provide grants and loan guarantees for efficiency upgrades and for low- or zero-emission fishing vessel technology.
- Ratify the Kigali Amendment to the Montreal Protocol and develop an implementation plan that includes refrigeration equipment for the fishing sector.
- Streamline the regulatory process for offshore aquaculture while providing protections for the environment and other ocean stakeholders.
- Increase the recommended amount of seafood consumption in the U.S. dietary guidelines.
- Promote American-produced seafood.

Context

In 2017, the U.S. landed more than 5 million metric tons of seafood from its oceanic wild-capture fisheries, making it the world's third-largest producer (FAO 2020). The U.S. is the world's 17th largest aquaculture producer, farming approximately 440,000 metric tons of seafood in 2017 (FAO 2020).[55] Almost 60 percent of U.S. farmed production occurs in freshwater systems (e.g., catfish, crawfish), while oyster and clam production accounts for more than 85 percent of farming in the ocean. The U.S. is also the world's fourth-largest seafood consumer (FAO 2019). Seafood production and consumption can both play a role in reducing GHG emissions. Interventions such as improving fisheries management, enhancing the energy efficiency of fishing fleets, zero-emission fishing vessels (ZEVs), and reducing the carbon footprint of aquaculture feeds can reduce emissions from seafood production. On the consumption side, shifting people's diets away from GHG-intensive foods to lower-carbon seafood could significantly reduce emissions.

Reducing emissions from wild-capture fishing

Annual GHG emissions from fuel use in U.S. wild-capture fisheries are approximately 8 to 12 Mt CO_2e, or 0.2 percent of total annual U.S. GHG emissions.[56] CEA estimates that annual GHG emissions from fuel combustion by the U.S. fishing fleet are approximately 10 to 12 Mt CO_2e, or 0.2 percent of total U.S. emissions in 2018. In 2018, Parker et al. estimated that U.S. fisheries generate 8 Mt CO_2e annually.[57] In addition to fuel combustion, leaking refrigerants from refrigeration equipment on fishing vessels is a source of GHG emissions. Hydrofluorocarbons (HFCs), which are the most-used refrigerants, are GHGs that are hundreds to thousands of times more potent than carbon dioxide (Box 1). We are unaware of any estimate of refrigerant usage in U.S. fisheries, but studies have estimated that refrigerant emissions represent 13 - 37 percent of total GHG emissions for wild-capture fisheries depending on the target species (Ziegler et al. 2013; Farmery et al. 2015). Assuming that refrigerant emissions account for 13 - 25 percent of fisheries emissions, refrigerant leakage could account for an additional 1 - 4 Mt CO_2e of GHG emissions from U.S. fisheries.

Box 4. The Montreal Protocol and refrigerant emissions in fisheries

Emissions of refrigerants do not garner the same level of attention as emissions from fossil fuel combustion, but they are an important and addressable part of the climate challenge. In the 1970s, the first synthetic refrigerants, chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), were found to be damaging the earth's ozone layer.

In response to this challenge, the global community came together and approved the Montreal Protocol, a global agreement to phase out ozone-depleting substances (ODS), primarily CFCs and HCFCs. The agreement has been successful in phasing out ODSs, but HFCs, which replaced ODSs in the market, are powerful GHGs. Recognizing the growing climate threat posed by HFCs, the world came together again in 2016 and created the Kigali Amendment to the Montreal Protocol. The amendment sets a schedule for the phasedown of the production and consumption of HFCs (U.S. Department of State n.d.). Over 100 countries have ratified the amendment (UN Environment Programme 2020), but the U.S. has yet to do so.

Although refrigerants are not always front of mind when considering the impacts of the fishing sector, they can be a significant source of GHG emissions. In 2019, Trident Seafoods settled with the EPA on alleged violations of the Clean Air Act from emissions of ODS refrigerants from equipment on the company's fishing vessels. Under the settlement, the company agreed to upgrade or retire refrigeration equipment on 14 vessels and improve its leak monitoring and repair practices. The impact of this settlement with just one seafood company was estimated to be equivalent to taking 143,000 cars off the road for a year (EPA 2019).

[55] Includes seaweeds and freshwater production.
[56] CEA calculations.
[57] Personal communication with Dr. Robert Parker. Parker et al. (2018) estimated that the U.S. landed 5.2 million tonnes of wild-capture seafood and applied a 1.6 kg CO_2-eq per kg GHG intensity factor to arrive at 8.2 Mt CO_2e.

There are several strategies for reducing emissions from the wild-capture fishing sector, including:

1. **Improving fisheries management.** When fish stocks are overfished or there are too many boats on the water, vessels must fish harder or longer, or go farther to maintain catch levels. Allowing fish stocks to recover and managing overall fishing effort can increase overall catch levels, increase catch per unit of fishing effort, and reduce emissions. A global study found that wild-capture landings could increase by 13 percent by 2030 with fishing effort roughly halved (World Bank 2017). The opportunity for fisheries management improvements to reduce emissions is smaller in the U.S. than in much of the world as federal fisheries are relatively well managed.[58] In 2019, 19 percent of U.S. federally managed fish stocks were overfished and 7 percent were subject to overfishing[59] (NOAA Fisheries 2020). Managing U.S. fisheries to maximize economic yield would increase profitability for the sector and reduce fuel emissions.
2. **Improving the efficiency of fishing.** There are several approaches for increasing the efficiency of fishing vessels, such as upgrading engines or propellers, improving maintenance, regularly maintaining the hull to reduce drag, and reducing vessel speed. Changing gear type, upgrading to modern gear, prioritizing fuel-efficient gears, and minimizing ocean-floor carbon disruption can reduce emissions. Each of these measures can deliver incremental improvements in efficiency and, when multiple measures are combined, can deliver significant reductions in fuel use (Johnson 2011).
3. **Adopting hybrid or zero-emission fishing vessels.** Hybrids and ZEVs are an emerging technology, with the first electric fishing boat deployed in Norway in 2015 (The Maritime Executive 2015). Hybrid technologies can dramatically reduce emissions, while ZEVs can completely eliminate on-vessel combustion emissions.
4. **Adopting climate-friendly refrigeration.** Upgrading refrigeration technologies on fishing vessels to ones that use low- or zero-GWP refrigerants can slash HFC emissions. Climate-friendly refrigerants, such as ammonia or carbon dioxide refrigerant systems, are becoming more widely available and used on fishing vessels.

Reducing emissions from aquaculture

Emissions from freshwater aquaculture and ocean mariculture in the U.S. are approximately 0.8 Mt CO_2e per year, or 0.01 percent of total U.S. emissions (M. MacLeod et al. 2019; FAO 2020). Emissions come primarily from freshwater production of catfish and crawfish, as well as marine shellfish production. Emissions from farmed seafood can come from on-farm energy use, the production of fish feed, application of pond fertilizer, and N_2O and CH_4 emissions from ponds. In particular, the carbon footprint of feeds for finfish and crustacean farming has been identified as a large source of emissions (Robb et al. 2017). Although it is the world's third-largest producer of wild-capture seafood, the U.S. farms relatively little seafood and is the world's 17th largest producer of farmed seafood (FAO 2020). Most of U.S. production by volume is non-fed (e.g., shellfish) or omnivorous (e.g., catfish) species, which have relatively low emissions intensity (M. J. MacLeod et al. 2020; FAO 2020).

Total aquaculture production in the U.S. is approximately the same as it was in the mid-1990s. Recent efforts to streamline permitting could encourage a growth in domestic production (NOAA 2016; Trump 2020), but these efforts are being challenged in federal court (Hill 2020), and even with aggressive efforts to expand fish farming, it is unlikely that the U.S. will become a major producer of fed-aquaculture in the near future.

As fishmeal and fish oil become relatively less available and more expensive, the carbon footprint of alternative ingredients will greatly influence the carbon intensity of fed-species production (Hoegh-Guldberg et al. 2019). For example, bovine (e.g., blood and bone meal) and chicken (e.g., feather meal) byproducts are regularly used to supplement carnivorous fish feed. It is yet unclear how best to assign the carbon footprint for byproducts that will exist irrespective of their final use; still, their inclusion can be the key emissions drivers in carnivorous aquaculture systems (Parker 2018). Soy byproducts (e.g., protein concentrate) are also used in composite feeds for fish and carry relatively high emissions factors as well. Preliminary studies suggest that novel feedstocks may be associated with considerably decreased environmental impacts, with one study suggesting that both certain bacteria and yeast-based feeds are better than standard soy-based feeds across multiple environmental indicators (e.g., climate change, water, acidification); in general, yeast concentrate was much more environmentally friendly than bacteria feed, especially with regard to climate-related impacts (Couture et al. 2019). While these and other (e.g., algae) alternative feedstocks offer a promising future for commercial aquaculture feeds, it is crucial that policymakers and markets factor in carbon emissions when considering future feed formulations.

[58] State-managed fisheries may have more opportunity for improvement, but the overall mitigation potential from these fisheries is probably small due to their overall landings and proximity to shore.
[59] NOAA Fisheries' Office of Sustainable Fisheries includes three definitions for fish stock status: (1) overfishing – the annual rate of catch is too high; (2) overfished – the population size is too small; (3) rebuilt – a previously overfished stock that has increased in abundance to the target population size that supports its maximum sustainable yield.

Reducing emissions by shifting diets

Emissions from the production and transport of food consumed in the U.S. account for 10 percent of total U.S. GHG emissions. GHG emissions associated with the production and transport of food consumed in the U.S. in 2016 are estimated to be 587 Mt CO_2e (Heller, Keoleian, and Rose 2020), approximately 10 percent of total U.S. GHG emissions (EPA 2020).

Seafood is a lower-carbon and healthier alternative to red meat, but driving dietary shifts at scale is challenging. On a per kilogram basis, meat from ruminant animals—primarily cows and sheep—can have a GHG intensity that is more than seven times that of many seafood products and more than 100 times that of many plant products (Heller, Keoleian, and Rose 2020). High levels of red meat consumption have also been linked to greater risk for cardiovascular disease, cancer, diabetes, and premature death (Department of Health and Human Services and Department of Agriculture 2015).

While shifting diets toward vegetarianism offers the greatest potential carbon savings, shifting diets to include more seafood and less red meat also has significant GHG mitigation potential (Hoegh-Guldberg et al. 2019). However, incentivizing dietary changes at a scale sufficient to achieve large climate benefits would require policy, tax, and behavior change solutions on a large scale (Hoegh-Guldberg et al. 2019). There are a few main approaches to encourage additional seafood consumption and encourage a shift away from GHG-intensive red meat products.

1. **Increase seafood production.** Providing incentives for seafood production (e.g., tax incentives) or streamlining regulatory requirements for ocean fish farming could reduce production costs, increase production, lower the price of seafood in the market, and subsequently drive increased consumption of seafood. This increase in seafood consumption would come from substitution away from other food products, partly beef and lamb. Wild-capture landings, both globally and in the U.S., have been stable since the 1980s and are being fully exploited. Therefore, any increase in seafood production will have to come primarily from fish farming, 90 percent of which occurs in Southeast Asia. Globally, aquaculture accounted for approximately 12 percent of seafood production in 1990 (Shamshak et al. 2019), but it is expected to overtake wild-capture production in 2020 (Rabobank 2019). U.S. consumption preferences have shifted along with the rise of aquaculture. Predominantly farmed species such as shrimp, salmon, tilapia, and catfish/pangasius now account for 4 of the top 5 consumed products in the U.S. (Shamshak et al. 2019). Although some farmed species, such as shrimp, can have high carbon footprints, on average farmed seafood has significantly lower GHG emissions than red meat (Nijdam, Rood, and Westhoek 2012). With limited farmed production in the U.S., domestic policies that encourage increased production of seafood are unlikely to drive dietary shifts that would substantially lower GHG emissions, although supporting domestic seafood production could have other important benefits such as job creation and improved economic competitiveness.

2. **Carbon taxes.** Carbon taxes on the agricultural sector have been proposed as a market-based tool to encourage emissions reductions from food production. Such a tax would increase the price of GHG-intensive products (e.g., beef, lamb), which would drive a shift in consumption to less carbon-intensive products, including seafood.

   There are many complexities in designing and implementing a carbon tax on food products, but several studies have concluded that such a tax would significantly reduce GHG emissions (Havlík et al. 2014; Key and Tallard 2012; Wirsenius, Hedenus, and Mohlin 2011). One study found that a global tax on methane of $15 to $100 per tCO_2e would drive emissions reductions of 2.8 and 9.9 percent, respectively (Key and Tallard 2012). This study did not include seafood as an alternative food product, but subsequent research in France shows that fish and shellfish would experience some of the largest market share gains among animal products under a carbon tax on meat and marine products, although the overall market share gains were still modest (Bonnet, Bouamra-Mechemache, and Corre 2018). The impact of a carbon tax on seafood consumption would likely be marginal in the U.S., as consumers would shift from high-carbon products to a variety of other food products, only some of which would be seafood.

3. **Behavior change.** A final mechanism for shifting diets is to encourage behavior change through education and communication. Seafood-focused efforts could include highlighting the health benefits of a seafood-rich diet, encouraging greater seafood consumption through nutritional guidelines, or promoting the consumption of domestically produced seafood (which may have lower emissions than imported seafood). Analysis of public campaigns addressing major public health issues—such as seatbelts, alcohol consumption, and smoking—has shown that they can significantly influence behaviors, but their effects are typically modest in size (Abroms and Maibach 2008; Snyder et al. 2004; Elder et al. 2004). Likewise, adherence to U.S. dietary guidelines is limited (Banfield et al. 2016).

Mitigation potential

Table 8. Fisheries and aquaculture mitigation scenarios (2030 and 2050)

Mitigation	2030 Mitigation potential ($Mt\ CO_2e$)	2050 Mitigation potential ($Mt\ CO_2e$)
Wild-capture fisheries	3.9 - 6.3	4.1 - 6.9
Fuel use	*3.1 - 3.5*	*3.1 - 3.5*
Low/no GWP refrigerants	*0.8 - 2.8*	*1.0 - 3.4*
Aquaculture	0.06	0.17
Dietary choice	8 - 33	10 - 39
Total	**12 - 39**	**14 - 46**

Overall mitigation potential from wild-capture fisheries, aquaculture, and shifting diets is estimated to be 12 - 39 Mt CO_2e in 2030 and 14 - 46 Mt CO_2e in 2050.

Wild-capture fisheries

The estimated mitigation potential from reduced fuel use in U.S. wild-capture fisheries is 3.1 - 3.5 Mt CO_2e in 2030 and 2050. This estimate is based on the potential to reduce emissions in U.S. fisheries by improving fisheries management, which could reduce fishing effort while maintaining catch levels. *The Sunken Billions Revisited* report suggests that North American fishing effort is 26 percent greater than it would be under an optimal management regime targeting maximum economic yield (World Bank 2017). Effort reductions are closely correlated with fuel-use reductions, and thus we assume that emissions from the wild-capture fleet could be reduced by 26 percent. We also evaluate a scenario in which the fuel use intensity reaches 1.1 t CO_2e per tonne of catch under optimal fisheries management (Hoegh-Guldberg et al. 2019; World Bank 2017).

Emissions reductions could also be achieved through the adoption of hybrid or zero-emission fishing vessels. ZEVs could eliminate on-vessel combustion emissions for the sector, but this nascent technology will require significant support to gain traction in the market. Energy-efficiency improvements could also reduce emissions, but a fleet-level estimate has not been modeled.

Phasing out high-GWP refrigerants could further reduce wild-capture fishing emissions by 0.8 to 3.4 Mt CO_2e. The Kigali Amendment to the Montreal Protocol requires ratifying countries to phase down their consumption of HFCs, which are used as refrigerants in cooling and refrigeration equipment. We estimate that reductions in the use of HFCs on fishing vessel refrigeration equipment could mitigate 0.8 to 2.7 and 0.9 to 3.3 Mt CO_2e in 2030 and 2050, respectively. This mitigation potential assumes a 70 percent reduction in HFC consumption by 2030 and an 85 percent reduction by 2050 for the fishery sector, which is in line with the reductions required under the Kigali Amendment (U.N. Environment n.d.). This reduction would be realized using no- or low-GWP refrigeration equipment. These technologies are available and are already being adopted on fishing vessels (Hafner, Gabrielii, and Widell 2019).

Aquaculture

With low levels of farmed seafood production in the U.S., the mitigation potential from aquaculture of 0.06 Mt CO_2e in 2030 and 0.167 Mt CO_2e in 2050 is significantly lower than that of wild-capture fisheries. Aquaculture appears to offer relatively little opportunity for GHG reductions given low production levels in the U.S. and the overall mitigation potential of the sector globally. A recent assessment of the mitigation potential of aquaculture globally estimated an emissions reduction potential from lower carbon feeds of 16 to 43 Mt CO_2e per year. With the U.S. producing less than 0.39 percent of global farmed production, the mitigation potential in the U.S. is estimated at 0.062 Mt CO_2e in 2030 and 0.167 Mt CO_2e in 2050 (Hoegh-Guldberg et al. 2019; FAO 2020).

Shifting diets

Shifting diets toward low-carbon food sources, including seafood, has significant mitigation potential of 8 - 39 Mt CO_2e per year, but driving dietary shifts at the scale necessary to achieve that level of mitigation would require major tax, policy, and behavior change incentives. If policies and education campaigns were able to shift 11 percent of the U.S. population from a standard diet to a pescatarian diet, emissions could be reduced by 33 Mt CO_2e in 2030 and 39 Mt CO_2e in 2050. Under a policy scenario, a carbon tax on methane of $15 per ton CO_2e could reduce emissions from animal production by 2.8 percent, which would reduce emissions by 8 and 9.6 Mt CO_2e in 2030 and 2050, respectively. It is important to note that these emissions benefits would come primarily from reductions in the consumption of red meat, so the most efficient way to achieve this technical potential is to target reductions in red-meat consumption directly. Efforts that encourage the consumption of seafood apart from other dietary changes will have more modest GHG impacts, as increasing seafood consumption will decrease consumption of multiple food products, not just high-carbon meat.

Costs and benefits

Wild-capture fisheries

Strong management can improve stock health, improve economic value, and reduce emissions. Measures such as catch limits, limited entry, and catch shares are proven management tools for maintaining stock health and reducing overcapacity, which should drive emissions reductions. The tradeoff with well-managed fisheries is that they tend to employ fewer people, consolidating the economic benefits among a smaller group of people. For example, catch shares have resulted in more efficient fisheries and an increase in economic value, but have led to a decline in the number of participating vessels (University of Washington 2016). Mechanisms have been developed to mitigate this impact on fishers and small fishing communities. For example, catch shares can provide a financial benefit for fishers that choose to exit the fishery as they can sell their shares in the fishery. Community quota banks have also been used to help support ongoing community participation in fisheries. Additionally, well-managed fisheries are better positioned to adapt to a changing climate and will support the resilience of U.S. fisheries in future decades (Gaines et al. 2018).

Energy-efficiency improvements can reduce the fuel costs for vessels, but many of these approaches have long payback periods and do not make sense without financial incentives. Some energy-efficiency improvements, such as hull maintenance and propeller upgrades, can have short payback periods, but these opportunities may not be front of mind for vessel owners. Hybrids and ZEVs are emerging technologies and will need significant financial support during this early stage of development.

Aquaculture

Developing a more robust domestic aquaculture industry could create jobs, improve ocean health, and improve climate resilience, particularly if states and regions thoughtfully plan new farms. As fish stocks become less reliable in the face of a changing ocean climate, ocean farming offers a supplementary source of seafood and jobs. NOAA estimates that expanding U.S. aquaculture production to 2.5 times its current level in 10 years could create 109,500 - 133,400 jobs and add $10.7 - 12.8 billion to the U.S. economy (Lipton, Parker, and Duberg 2019). Certain aquaculture production, including shellfish and seaweeds, can actually make marine food systems more climate resilient if done properly. But generally speaking, development of the domestic marine aquaculture industry has been limited by the relative lack of competitiveness of U.S. production in the global marketplace, including a challenging regulatory structure (Engle and Stone 2013).

The best mariculture for ocean health is properly sited bivalve and seaweed aquaculture. These species offer several environmental co-benefits beyond the low-carbon food they produce. They utilize and store excess nutrient pollution, they can augment habitats, and certain species can even sequester carbon directly. Research into siting optimization, community resilience benefits, and promoting market demand for bivalve and seaweed consumption could all encourage increased domestic production of the most beneficial aquaculture species.

Shifting diets

Beyond emissions benefits, the greatest benefits of shifting diets away from red meat are the human health benefits. The global annual healthcare costs associated with the consumption of processed and red meats have been estimated at $285 billion (Springmann et al. 2018). Interventions that lead to significant dietary shifts will also have distributional impacts in the food production system, as producers of lower-carbon and more healthful foods stand to benefit, while producers of higher-carbon foods are likely to lose market share.

Policy, research, and technology needs

Policy

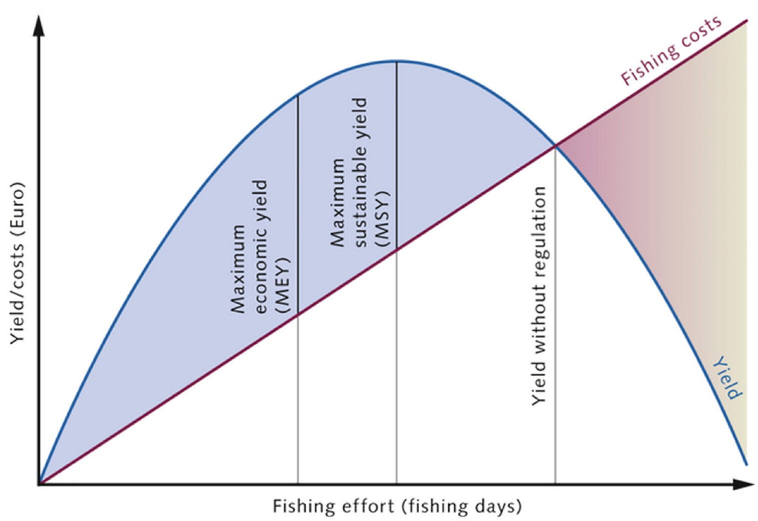
Policies to ensure the continued productivity of U.S. fisheries

The most effective policies for reducing emissions from wild-capture fisheries are ensuring fishery stock health and sound fisheries management. Good fisheries management prevents too many boats from chasing too few fish, which is a primary cause of overfishing and GHG emissions from the sector. The following recommendations can ensure the U.S. continues to have healthy and economically productive fisheries.

Defend the Magnuson-Stevens Act. Fisheries management in the U.S. has improved considerably since the passage of the Magnuson-Stevens Act and its reauthorizations over the last quarter century (Hilborn et al. 2020). In 2019, 19 percent of U.S. fisheries stocks were overfished and 7 percent were subject to overfishing (NOAA Fisheries 2020). The Act and its requirements to set annual catch limits, prevent overfishing, and implement mandatory rebuilding plans have been instrumental in making U.S. fisheries some of the best-managed fisheries in the world. Previous proposals have sought to strip some of the key provisions of the Magnuson-Stevens Act. Continuing to defend the Act is essential for maintaining stock health and productive fisheries.

Manage fisheries to maximum economic yield. As previously discussed, U.S. fisheries are well managed overall. Current federal management under the Magnuson-Stevens Act targets the maximum sustainable yield of a fishery, seeking to produce the highest output that can be consistently sustained year after year (Department of Commerce 2007). If instead the U.S. managed its fisheries to maximum economic yield, fisheries could become more profitable, use less fishing effort, emit less pollution, and increase the stock abundance and resilience (see Error! Reference source not found.). For example, a 10 percent uniform reduction in effort would eliminate 1 - 1.2 Mt CO_2e of emissions annually based on current emissions. Such a reduction, however, would also likely generate slightly less catch and benefit fewer fishers than the existing management approach.

Figure 9. Maxiumum sustainable yield and maximum economic yield explained



(Sustainable Fisheries n.d.)

Incorporate climate adaptation into fisheries management. Climate change is profoundly affecting fish stocks and ocean ecosystems. Fish stocks are migrating, population dynamics are changing, and ecosystems are shifting. In this changing environment, fisheries management must be more adaptive and responsive to ensure fisheries regulations and catch limits are keeping pace to protect stock health, jobs, coastal communities, and ecosystem health. Support is needed to identify and promote climate-adaptive fisheries management approaches and provide resources and opportunities for collaboration between regions and within NOAA. Funding should also be provided to advance scientific understanding of how climate change affects fisheries and potential management solutions.

Protect essential fisheries habitat. Protecting fish habitat enhances fisheries productivity and improves resilience to climate change and other stressors. Additional critical habitat should be identified and protected through essential fish habitat designations or marine protected areas.

Policies to promote energy efficiency of fishing vessels and reduce HFC emissions

Provide grants and loan guarantees for efficiency upgrades and low- or zero-emission technologies. Vessel improvements such as optimized hull design, propeller improvements, switching to LED lights (particularly for squid-jiggers), and upgrading to more fuel-efficient engines can reduce fuel use (Gulbrandsen 2012; An et al. 2017; Curtis, Graham, and Rossiter 2006). Modifying fishing gear can also improve fuel efficiency. Lighter gear, shorter trawl times, and shifting away from dredge and trawl gears altogether in favor of less fuel-intensive methods would help, too. Likewise, adoption of refrigeration technologies with no- or low-GWP refrigerants can slash GHG emissions from refrigerant leakage. Finally, ZEVs can eliminate onboard fuel combustion emissions from fishing vessels. Yet without additional incentives (e.g., government mandates, vessel improvement subsidies), fishers will be unlikely to make these investments due to long or insufficient payback on investment. Providing financial support for these emerging technologies can increase uptake and help bring down their cost.[60]

Ratify and implement the Kigali Amendment to the Montreal Protocol. The Kigali Amendment to the Montreal Protocol sets a timetable for countries to reduce their consumption of HFCs—potent GHGs that are used primarily as refrigerants. The U.S. should ratify the Kigali Amendment and institute implementation plans to phase down the use of climate-warming refrigerants, including their use in refrigeration and freezing equipment on fishing vessels. More than 100 countries have already ratified the amendment (UN Environment Programme 2020), which is one of the most important international climate agreements ever reached.

Policies to promote aquaculture production

Streamline the regulatory process for offshore aquaculture. The U.S. is not a major mariculture producer for a variety of reasons, but a complex regulatory structure has contributed to the challenges for the industry. Offshore aquaculture developments require approval from several different federal agencies, but there is no clear authority for permitting. Several aquaculture bills have been introduced in Congress over the last decade, including ones that seek to constrain offshore aquaculture production as well as ones that seek to streamline the regulatory process (Upton, n.d.). Moving forward, legislation that simplifies the regulatory process while also addressing the concerns of other ocean stakeholders and protecting the environment would address one of the barriers to the growth of offshore fish farming.

Support restorative aquaculture production. Although the U.S. has not been a major aquaculture producer, shellfish production has been increasing, especially for species such as clams and oysters. Bivalve farming is low impact, emits low levels of GHGs, and can even improve ecosystem health by improving water quality and providing habitat.[61] A recent assessment of areas where restorative aquaculture could deliver benefits identified North America as a high-opportunity area for shellfish cultivation (Theuerkauf et al. 2019). Policies are needed to support the development of restorative aquaculture and to streamline permitting. This could include financial mechanisms that improve the economics of shellfish aquaculture, such as nitrogen removal credits (Theuerkauf et al. 2019).

[60] Note that the fishing sector has accessed funds from the Diesel Emissions Reduction Act to upgrade engines on vessels.
[61] Aquaculture production that helps restore ecosystem function and contributes to positive social outcomes is called “restorative aquaculture.”

Policies to promote the consumption of lower-carbon seafood

Increase the recommended amount of seafood consumption in U.S. dietary guidelines. The 2015-2020 dietary guidelines recommend 8 ounces of seafood consumption per week and 26 ounces of meat, poultry, and dairy (Department of Health and Human Services and Department of Agriculture 2015). Given the health benefits of seafood consumption and the negative health impacts of higher meat consumption, the next set of dietary guidelines should increase the recommended proportion of seafood consumption and decrease the recommended consumption of red and processed meats.

Incorporate measures to eliminate fishing subsidies in trade agreements. Globally, fisheries receive an estimated $35.4 billion in subsidies (Sumaila et al. 2019). An estimated $22.2 billion of these subsidies are directed to areas like fuel or vessel construction that drive increased fishing effort, overfishing, and GHG emissions. The U.S. should seek to eliminate subsidies in trade agreements that contribute to illegal fishing, overcapacity, or overfishing. These measures will ensure that U.S. fisheries face a more level playing field and help drive more efficient fisheries management around the world.

Promote American-produced seafood. Transportation emissions typically account for less than 25 percent of total emissions from seafood (Ziegler et al. 2013), but in some cases, when products are shipped by air freight, product transport can be the largest source of emissions. According to NOAA, the U.S. imports 80 percent of the seafood consumed domestically, but a significant portion of these imports were actually originally caught in the U.S. and shipped abroad for processing (NOAA n.d.). Much of this exporting and reimporting occurs via at-sea shipping, which is the most fuel-efficient means of moving goods. While economic factors have driven the shift of fish processing overseas, there may be a modest opportunity to reduce transport-related emissions by promoting fish produced in the U.S. and expanding U.S. processing capacity to discourage the export of U.S.-caught seafood for foreign processing. Consumption of U.S.-produced seafood can be encouraged through government procurement guidelines and product marketing support for American seafood producers.

Technology

Fisheries

Develop and demonstrate ZEVs and supporting infrastructure. Hybrid and zero-emission fishing vessels are still emerging technologies and will need significant support to gain traction in the market. The government should provide support for on-the-water technology demonstrations, as well as necessary shore-side infrastructure such as electrical hookups or hydrogen fuel. Fishing vessels could also benefit from increased effort to develop green hydrogen and ammonia infrastructure, which will be needed to power a zero-emissions shipping sector.

Develop new monitoring technologies and applications. Lack of visibility of activity at sea is an ongoing fisheries management challenge. Developing new tools that can increase the visibility of fishing activity on the open ocean and confidence in fisheries data will support improved oceans and fisheries management. This could include development of new or improved monitoring applications for bioacoustics, electronic monitoring technologies, and eDNA.

Aquaculture

Promote the development of novel, low-carbon aquafeed. Among the largest drivers of carbon emissions for offshore mariculture is the composition of the composite feed utilized to grow a seafood crop (e.g., salmon) (Parker 2018). One of the best ways to mitigate future carbon emissions associated with these systems is to develop new plant-based or other low-carbon aquafeeds to meet the demand for ingredients. There is considerable effort underway to develop novel alternatives to fishmeal and fish oil, but new research suggests that different alternatives (i.e., yeast, bacteria, algae) have very different resource utilization profiles (Couture et al. 2019). These new feedstocks should be thoughtfully developed with their climate impact in mind to avoid creating a new environmental challenge for the seafood industry.

Support the development of large-scale and more automated aquaculture production methods. Farming of high-value seafood is becoming more technologically advanced and automated. Massive-scale and highly automated offshore production is likely to be part of the industry’s future. Support should be directed to the development of proof-of-concept projects and early-scale pilots that can demonstrate reliable, low-impact, and highly automated offshore fish farming at scale.

Research

Wild-capture fisheries

Research on climate impacts on fisheries. Climate change is already affecting fisheries and will continue to do so in more significant ways in the coming years. Research is needed to better understand and predict how climate change and ocean acidification will affect U.S. fisheries and how management can better adapt to this new reality.

Aquaculture

Research on climate-friendly aquafeeds. As the global aquaculture industry grows, there will be more demand for alternative fish feed ingredients given the limited supply of fishmeal and fish oil. Assessing the GHG footprint of these alternative feed ingredients can help steer the industry toward more climate-friendly inputs.

Improve understanding of the environmental impacts of expanded aquaculture production. Increases in seafood consumption will come largely from scaling farmed production. More research is needed to understand the environmental implications of increased fish cultivation.

Shifting diets

Explore the efficacy of approaches for shifting diets. Addressing dietary choice at a meaningful scale will require a combination of policy approaches (e.g., carbon tax), incentives, and behavioral nudges. Further research is needed to better understand which approaches are most effective, how to best design interventions, and the implications for the food system.

Key assumptions, data limitations, and caveats

The analysis and findings have been developed by CEA Consulting and have been reviewed by two external reviewers. We offer a synthetic assessment of the opportunity to reduce GHG emissions by altering fishing and farming practices and shifting diets in the U.S., which necessarily limits the scope of this brief. There may be additional studies and research, particularly into novel technologies and areas for additional research, which were not covered by this analysis.

Emissions calculations and mitigation scenarios are based on multiple peer-reviewed studies and novel methods. The data used to inform these calculations were drawn from multiple sources and different years. While we expect that there is little year-to-year variation in terms of landings and vessel effort, the use of data from different years is a limitation.

We assume that the total volume of U.S. fisheries and aquaculture will remain the same in the future, as production as remained roughly flat for the last 30 years.

In many cases there are no existing datasets for sector-level emissions. For example, we are not aware of any data on HFC emissions from fishing vessels. In these cases, we have used best estimates based on information in the literature. Finally, estimates of how emissions will shift under behavior-change campaigns and/or carbon tax regimes are highly uncertain. There is huge uncertainty about how effective such efforts would be and the dietary shifts they would induce.

5. Carbon dioxide storage below the seabed

This section estimates the emissions reduction potential of a suite of technologies and related supply chains required to capture carbon dioxide from point sources, to compress and transport the carbon dioxide into geological formations, and to permanently store it in porous rock several thousand meters below the seabed.

Highlights

Carbon capture and storage (CCS) is a proven technology. Its deployment is vital for meeting international climate goals.

- CCS encompasses a suite of proven technologies to capture, liquefy, and transport carbon dioxide (CO2) for permanent storage in underground geologic formations such as saline aquifers and depleted oil and gas fields.
- Most future climate scenarios that limit warming to below 1.5 degrees include negative emissions approaches such as CCS. The amount of CO_2 captured via CCS each year might have to multiply by more than 125 times by 2050 from 2016 levels to meet climate goals.
- CCS has primarily been designed to mitigate emissions from large stationary sources (e.g., power plants, heavy industry, and refineries). But components of CCS are also a prerequisite for the two negative emission technologies that the IPCC deems essential for meeting international climate goals: bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS).
- Twenty years of sub-seabed storage experience in Norway suggests that offshore CCS is technically feasible, with relatively low risks.

Offshore storage potential in the U.S. is vast, and rapid scale-up is possible given federal ownership of seabed space.

- Potential storage sites are vast, both onshore and offshore. In the U.S., sub-seabed formations probably could store trillions of tons of CO_2, equivalent to thousands of years of current emissions.
- A major advantage of offshore storage is that most of the pore space is owned by the federal government and managed by the Bureau of Ocean Energy Management (BOEM). This avoids questions of title, ownership, and local acceptance and provides a single point of access for leasing acreage.

A lack of financial incentives is the primary barrier limiting both onshore and offshore CCS in the U.S.

- Large stationary emissions in the U.S. add up to 2.6 Gt CO_2 per year (almost half of U.S. emissions), currently representing the upper limit for carbon capture. However, CCS is currently limited to demonstration efforts of 1.1 Mt CO_2 per year, equivalent to 0.04 percent of stationary emissions.
- Under current policies, CCS operations are only viable if costs remain below $50 per ton of CO_2 stored. Yet current CCS costs exceed $100 per ton of CO_2 for 85 percent of stationary emissions. This is significantly more expensive per ton than other land- and ocean-based mitigation measures (e.g., reforestation or agricultural practices to enhance soil carbon storage).
- Costs decrease with higher purity of CO_2 in the flue gas (e.g., ammonia, hydrogen, and ethanol production, as well as natural gas plants), emission clusters, and proximity to storage sites.

Amendments to federal and state policies could boost CCS deployment, both onshore and offshore

- An ambitious enhancement and extension of the 2018 45Q tax credit, as well as state amendments of the Clean Energy Standard and the Low Carbon Fuel Standard, could realistically trigger onshore CCS deployment of approximately 300 million tons of CO_2 per year by 2050.
- Low-cost CCS opportunities that are co-located with suitable offshore storage sites can mainly be found in Texas and Louisiana (approximately 15 million tons of annual CO_2 emissions), and onshore storage sites are ample, making it difficult to estimate offshore deployment in the near future.
- Based on expert interviews, we estimate that sub-seabed storage in the U.S. will go online in 2025 and grow to approximately 60 million tons of CO_2 per year by 2050.

Context

CCS is a suite of technically viable technologies to mitigate CO2 emissions from large point sources. Almost half of all U.S. emissions (or 2.6 Gt CO_2 per year) come from large point sources, so-called stationary emissions (see Error! Reference source not found.). Of these, 70 percent are based on fossil fuel combustion in power plants, and the remainder are industry emissions. To keep CO_2 out of the atmosphere, it can be captured from the flue gas of a power plant (e.g., coal plant) or from industrial sources (e.g., cement plant) before it is transported, and it can then be securely stored underground. Industrial CCS probably will play a bigger role in the near future given its lower costs (higher purity of CO_2) and lack of alternatives for decarbonization.

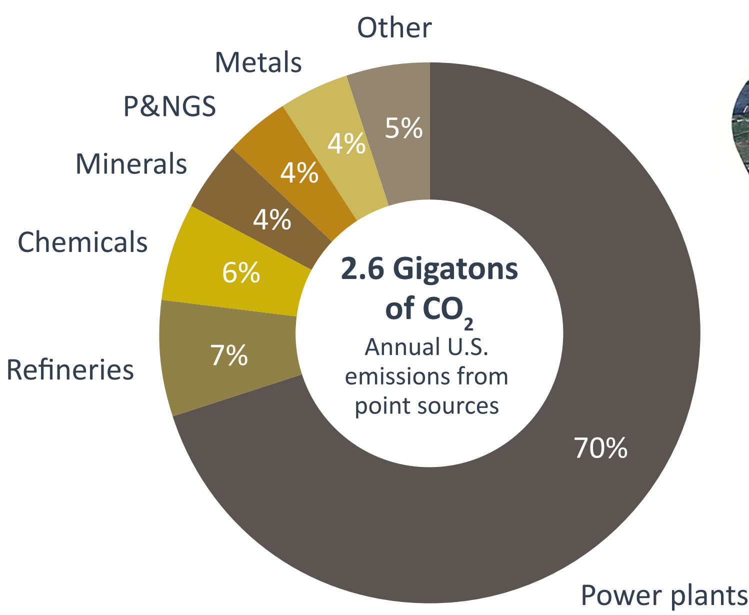
Box 5. CCS supply chain

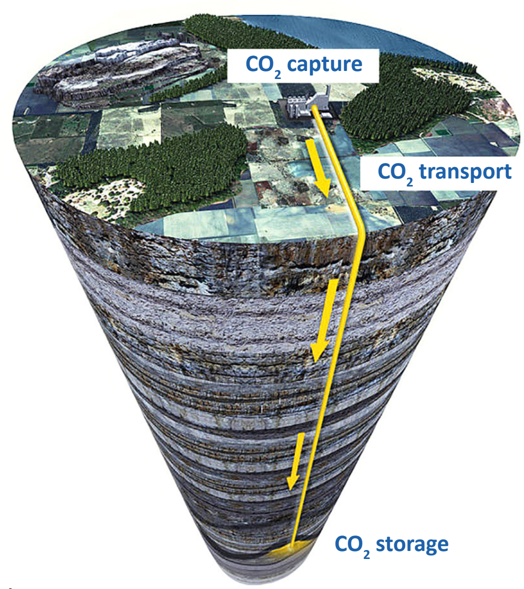
Capture: Point sources of CO_2 are stationary power plants and other industries that emit CO_2. In the large majority of cases, CO_2 is produced and emitted along with other gases. From a technoeconomic standpoint, the most important aspect of capture is separating CO_2 from other gases, most commonly accomplished through amine absorption, although many technologies exist. CO_2 capture is the most expensive part of CCS and cost tends to be lower for industrial CCS than for power sector CCS due to the purity of CO_2 in industrial emissions.

Transport: Compressed CO_2 can be transported by rail, truck, ship, and barge. Pipeline transmission of CO_2 over longer distances is considered most efficient when the CO_2 is in a "supercritical" phase (high pressure and high temperature), since in this phase the fluid has the density of a liquid and the viscosity and compressibility of a gas. While operational expenditures (OPEX) of pipeline transport is by far the lowest of all transportation modes, infrastructure is often lacking, making transport by ship and rail more economical.

Storage: When CO_2 is compressed, it starts behaving like a fluid and can be stored in geological formations. The most abundant and most practical formations for storage are saline formations, depleted oil and natural gas reservoirs, and un-mineable coal seams. In the ocean, sub-seabed saline aquifers and depleted oil and gas fields are the most likely candidates in the near future. However, mineralization of CO_2 in basalt formations is being explored as a potential storage option.

Figure 10. U.S. CO_2 point source emissions





2018 P&NGS refers to petroleum and natural gas systems (data from https://www.epa.gov/ghgreporting, image from Global CCS Institute).

CCS is considered an important piece of the puzzle to avoid dramatic consequences of global warming. Several major assessments since 2014 have highlighted how important CCS is to ensuring that emissions stay within the 1.5-degree-pathway budget. The IPPC (2014) Synthesis Report suggests that mitigation costs are doubled in pathways that do not include CCS. In three of four pathways of the IPCC (2018) Special Report, CCS is a necessary mitigation component; the IEA (2019) World Energy Outlook projects that 9 percent of the cumulative mitigation effort must come from CCS between 2020 and 2050; and a McKinsey (2020) report finds that "the math simply does not work" to chart a 1.5-degree pathway that does not remove CO_2, citing CCS as a critical component. The amount of CO_2 captured via CCS each year would have to multiply by more than 125 times by 2050 from 2016 levels. In addition to CCS from power plants and industrial emissions, the IPCC deems negative emission technologies an indispensable strategy to reaching international climate goals, most notably BECCS and DACCS. Both benefit from and rely on components of power CCS and industry CCS ("Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change" 2014; Masson-Delmotte et al. 2018; IEA 2019c; Henderson et al. 2020).

If CCS scales in the U.S., sub-seabed geological formations might become attractive alternatives to onshore storage sites. Geological formations suitable for CO_2 storage include saline aquifers, depleted oil and gas fields, and basaltic rock. All of these are found both onshore and offshore, deep under the earth's crust. Offshore storage might gain in popularity for several reasons. A major advantage of offshore storage is that most of the pore space is owned by the federal government and managed by the BOEM. This avoids questions of title, ownership, and local acceptance and provides a single point of access for leasing acreage. Furthermore, if DACCS is deployed offshore, powered by offshore wind, sub-seabed geologic formations would be logical storage sites.

Mitigation potential

Sub-seabed geologic storage of CO_2 in the U.S. is nonexistent today but could increase to approximately 60 million tons per year by 2050 if ambitious policy were instituted. Table 9 provides an estimate for theoretical and economic potential of CCS today (both offshore and onshore), in 2030 and in 2050. While there is no question that sub-seabed geologic formations could hold thousands of years worth of current U.S. emissions, ***there is currently no CCS project in the U.S. with offshore storage in place***. In fact, although CCS technologies have existed for decades, only 1.1 million tons of CO2 per year is stored in geologic formations in the U.S.[63] However, recent amendments to U.S. tax code and near-term opportunities to amend and enhance federal and state legislation probaby will increase the economic potential for ***onshore*** CCS to 120 and 320 million tons of CO_2 per year by 2030 and 2050, respectively. It is more difficult to estimate the economic potential of ***offshore*** CCS, but based on a dozen interviews with experts around the world, we believe that the U.S. might see one offshore CCS project (5 million tons per year each) go online every two years starting in 2030, with 60 million tons of CO_2 stored offshore by 2050. Estimates for 2050 might easily be off by an order of magnitude if the U.S. fully committed to net-zero emissions by 2050. In that case, we would expect financial incentives to further increase the economic potential of both onshore and offshore CCS.

Table 9. Theoretical, technical, and economic potential of CCS (onshore and offshore) between 2020 and 2050.

Supply chain segment	Current	2030 Capacity	2050 Capacity
Theoretical offshore storage potential		36 trillion tons of CO_2	
Technical potential of CCS from stationary emissions		2,600	
Economic potential of terrestrial CCS, assuming increasingly favorable economics and policy incentives	1.1	120	320
Economic potential for offshore storage of CO_2 captured in the U.S.	**0**	**10**	**60**

Unless otherwise specified, all units are in million tons of CO_2 per year

[63] Another 25 million tons of CO_2 are annually captured and used for enhanced oil recovery, all of it onshore.

Box 6. Enhanced oil recovery

Enhanced oil recovery (EOR) involves injecting CO_2 into the reservoir rock of an existing oil field. The CO_2 displaces oil, which is released from the pores of the reservoir rock, allowing "recovery" of more oil and natural gas than would otherwise have been produced. EOR has been the main driver of CCS in the U.S. to date. Due to the high capital costs of EOR and the low prices for oil, CO_2 demand is not expected to rise much further in the U.S. under current incentive systems. Offshore EOR is expected to have significantly higher operational expenditures and capital expenditures. Given the mature and well-regulated nature of terrestrial EOR in the U.S., it is unlikely that offshore EOR projects will be seriously considered in the near future.

CCS is technically feasible for 2.6 billion tons of CO_2 emissions per year, but current CCS volume remains at 1.1 million tons per year (approximately 0.04 percent of technical feasibility). A 2019 analysis by the National Petroleum Council ("The Dual Challenge") finds that the U.S. has more than 6,500 large stationary sources emitting approximately 2.6 billion tons of CO_2 per year (44 percent of 2018 U.S. emissions); almost 70 percent of these emissions are associated with energy generation, while most of the rest relate to refining, pulp and paper production, chemical manufacturing, cement/concrete, and iron/steel (National Petroleum Council 2019). The analysis shows that today, a total of 25 million tons of emissions from ten plants in the U.S. are captured and stored. However, nine out of ten projects (96 percent of CCS emissions) are for enhanced oil recovery (EOR), not storage (National Petroleum Council 2019). The only CCS project that actually stores its CO_2 in saline formations is a 1.1Mt/year bioethanol operation: The "Illinois Industrial CCS" is a demonstration project that has been de-risked with a U.S. Department of Energy grant of $141 million, with a five-year timeline and a total capacity of 5 million tons of storage (ADM 2017). Even though the U.S. is a world leader in CCS, only 0.04 percent of stationary emissions are captured and stored. The Global CCS Institute CoRE database and 2019 Status Report identify roughly a dozen CCS projects in planning. Currently, the biggest such project is the Wabash Valley Resources Ammonia plant, aiming to store 1.5Mt of CO_2 per year starting in 2020 (OGCI 2019).

New pipeline infrastructure is costly and it takes years to move a project from inception to deployment. Today, there are nearly 50 CO_2 transportation pipelines in the U.S., with a combined length of over 4,500 miles, transporting approximately 68 million tons of CO_2 per year (Wallace et al. 2015). But the vast majority of the CO_2 pipeline system is dedicated to EOR, and only a fraction is located close to the ocean, notably the 314-mile-long Green Pipeline operated by Denbury Resources in Louisiana and Texas. The Green Pipeline currently transports approximately 1.1 million tons of CO_2 per year from industrial sources, sold for use in EOR (Denbury 2017). The Alberta Carbon Trunk Line, currently the biggest CO_2 pipeline in construction, was first planned in 2004 and was completed in July 2020. In its initial phase it will transport less than 2 million tons of CO_2 per year, and its maximum flow capacity is estimated at just over 14 million tons per year (Bakx 2020). Future projects can learn from past efforts, and project timelines may shorten from 16 years (the timeline for the Alberta line) to five to ten years. Still, pipeline construction probably will remain a significant bottleneck for CCS if it entirely relies on building new pipelines.

Retrofitting existing decommissioned gas pipelines and reversing the direction of the gas flow to store captured CO_2 in depleted gas fields could significantly accelerate onshore and offshore deployment. The biggest concern with reusing existing natural gas pipelines is the pipelines' integrity of long-term exposure to CO_2 fluxes (Leung, Caramanna, and Maroto-Valer 2014). For offshore storage, the Convention for the Protection of the Marine Environment of the North East Atlantic (OSPAR Convention) and the London Protocol might, in some cases, limit or delay the reuse of existing gas pipelines. These treaties do not allow waste dumping in marine environments and they also limit the cross-border transport of pollutants. However, some of the biggest European CCS projects, including the Porthos project in the Port of Rotterdam, are doing just that: they are giving natural gas pipelines a second life by reversing the flow and storing CO_2 in depleted gas fields, not far from the shore.

Offshore geological formations offer vast storage potential but probably will remain more expensive than onshore alternatives in most cases. Pore volume of offshore geological storage has been estimated at approximately 36 trillion tons (House et al. 2006). While some uncertainty exists about how much of this pore volume could be economically accessible, even a fraction of this volume would allow for the storage of thousands of years worth of current stationary emissions. Saline aquifers are the most abundant formation for CO_2 storage, but other geological formations have been tested for storage capacity and viability, including basalt and depleted oil and gas fields. Offshore storage is expected to be more expensive than onshore storage for early project development, particularly for smaller projects (i.e., <10 million tons of CO_2 per year) (Budinis et al. 2018).

Still, sub-seabed storage sites could, in some cases, become more attractive for project developers if i) permitting and social acceptance issues block onshore storage, ii) CO_2 is taxed differently onshore vs. offshore, or iii) the reuse of existing offshore oil and gas fields makes offshore CCS economically competitive with onshore alternatives. A combination of these ingredients has driven almost all EU CCS projects offshore, including the Northern Lights project in Norway and Porthos project in the Netherlands, the only projects aiming to store > 1 million tons of CO_2 per year (International Association of Oil & Gas Producers 2020). Onshore EOR projects have a long history in the U.S., and social acceptance of onshore CCS might not be as strong as in Europe, but offshore storage in the U.S. has the advantage that most of the pore space is owned by the federal government and managed by BOEM. This avoids questions of title, ownership, and local acceptance, provides a single point of access for leasing acreage, and might eventually make offshore CCS projects competitive with onshore alternatives.

Costs and Benefits

CCS costs in the U.S. would exceed $100 per tonne for 85 percent of emissions but represents the only option for key emitters to reduce emissions. Capture costs account for the vast majority of costs for CCS projects (up to 75 percent), particularly when older plants have to be retrofitted for CO_2 capture and when partial pressure (or "purity") of CO_2 in the treated gas stream is low.[64] The costs of transport and storage (responsible for approximately a quarter of CCS costs) increase with distance to capture sites and are more than twice as expensive for offshore than for onshore storage sites per ton of CO_2 avoided (Irlam 2017). A cost curve provided by NPC (2019) suggests that only about 50 million tons of emissions could currently be captured and stored for less than $50 in the U.S., while another 350 million tons could be captured and stored for less than $100 (National Petroleum Council 2019).

CCS remains more expensive than other prominent mitigation and decarbonization opportunities, but current cost profiles should not detract from its importance in the mitigation/decarbonization portfolio. There are two ways to potentially compare CCS costs with those of other decarbonization or mitigation strategies.

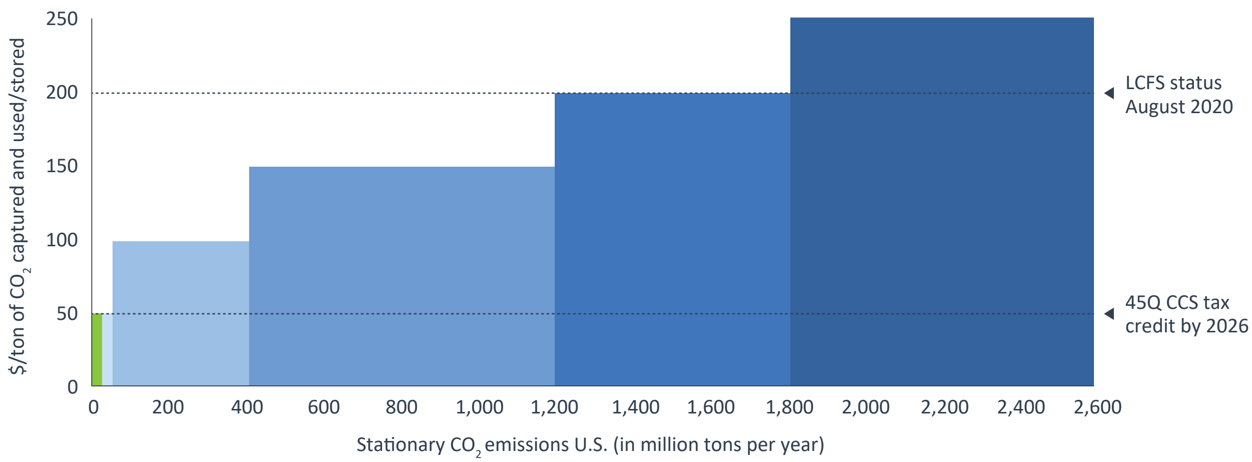
- First, power-sector CCS can be compared to other low- or zero-emission energy sources through an estimate of levelized cost of energy (LCOE).[65] The Lazard (2019) LCOE analysis (one of the most cited analyses in the field) estimates that unsubsidized LCOE for new coal plants with carbon capture (but without costs of transport and storage) is approximately $150 per MWh, while utility-scale solar photovoltaic and wind energy cost $32 - 44 and $28 - 54, respectively.[66]
- Second, the costs of industry-sector CCS can be compared to costs of other mitigation efforts and negative emission technologies, such as estimated by the National Academies of Sciences, Engineering, and Medicine (2019). In this report, afforestation/reforestation is estimated at <$20 per ton of CO_2 removed and costs of agricultural practices to enhance soil carbon storage are estimated at $20 - 100 per ton of CO_2 removed.

While CCS is not cost competitive in comparison to other renewable energy sources and mitigation options, it should not dismissed as too expensive. The main reason is that current climate goals cannot be met without the large-scale use of CCS. More than 80 percent of global electricity generation still relies on fossil fuel combustion, and CCS provides a viable decarbonization option for the sector as renewable energy is ramped up. Further, CCS is the cheapest decarbonization option for many industrial processes that require very large amounts of thermal energy (Friedmann et al. 2019). Investing in capture technologies, transport infrastructure, and storage capacity would reduce costs and support a technology that will also be a required component of the currently most prominent negative emissions technologies, including BECCS and DACCS.

[64] Where emission sources with high partial pressure are generated, for example in ammonia or hydrogen production, these sources require only dehydration and some compression, and therefore they have lower capture costs.
[65] LCOE is the present value of costs per unit of electricity generated over the life of a particular plant. It is a measure frequently used to analyze the commercial viability of particular power generation technologies.
[66] LCOE of gas combined cycle is lower than for coal ($44-68 per MWh), but Lazard does not provide estimates of gas combined cycle with CCS

The 2018 45Q tax credit makes CCS economically more attractive, but additional incentives are needed to stimulate private investment in CCS projects and to scale deployment. In 2018, section 45Q of the U.S. tax code ("26 U.S. Code § 45Q - Credit for Carbon Oxide Sequestration," n.d.) was amended to increase the cash incentive for equipment owners at stationary emission plants who use flue gas CO_2 for either EOR or CCS. By 2026, 45Q will subsidize CCS with $50 per ton sequestered, for 12 consecutive years ("26 U.S. Code § 45Q - Credit for Carbon Oxide Sequestration," n.d.). This means that even considering the 45Q credit, CCS (and EOR) is currently only economically viable for 2 percent of stationary emissions in the U.S. Even increased efficiencies in supply chains (production and transport clusters) will not significantly move the needle. Edwards and Celia (2018) assess the economic viability of a pipeline network that transports CO_2 from Midwest ethanol biorefineries to the Permian Basin in Texas (R. W. J. Edwards and Celia 2018). While the combination of ethanol (cheap capture), pipeline networks (economies of scale), and qualities of the Permian Basin (high demand for EOR) are ideal for the economics of CCS, the authors find that "a network earning commercial rates of return would not be viable" for CCS. This indicates that, ***in the absence of comprehensive climate legislation or government funding of supply chain infrastructure, the 45Q credit as currently structured is insufficient to trigger widespread CCS investments.***

Figure 11. CCS cost curve, based on data presented in NPC (2019).



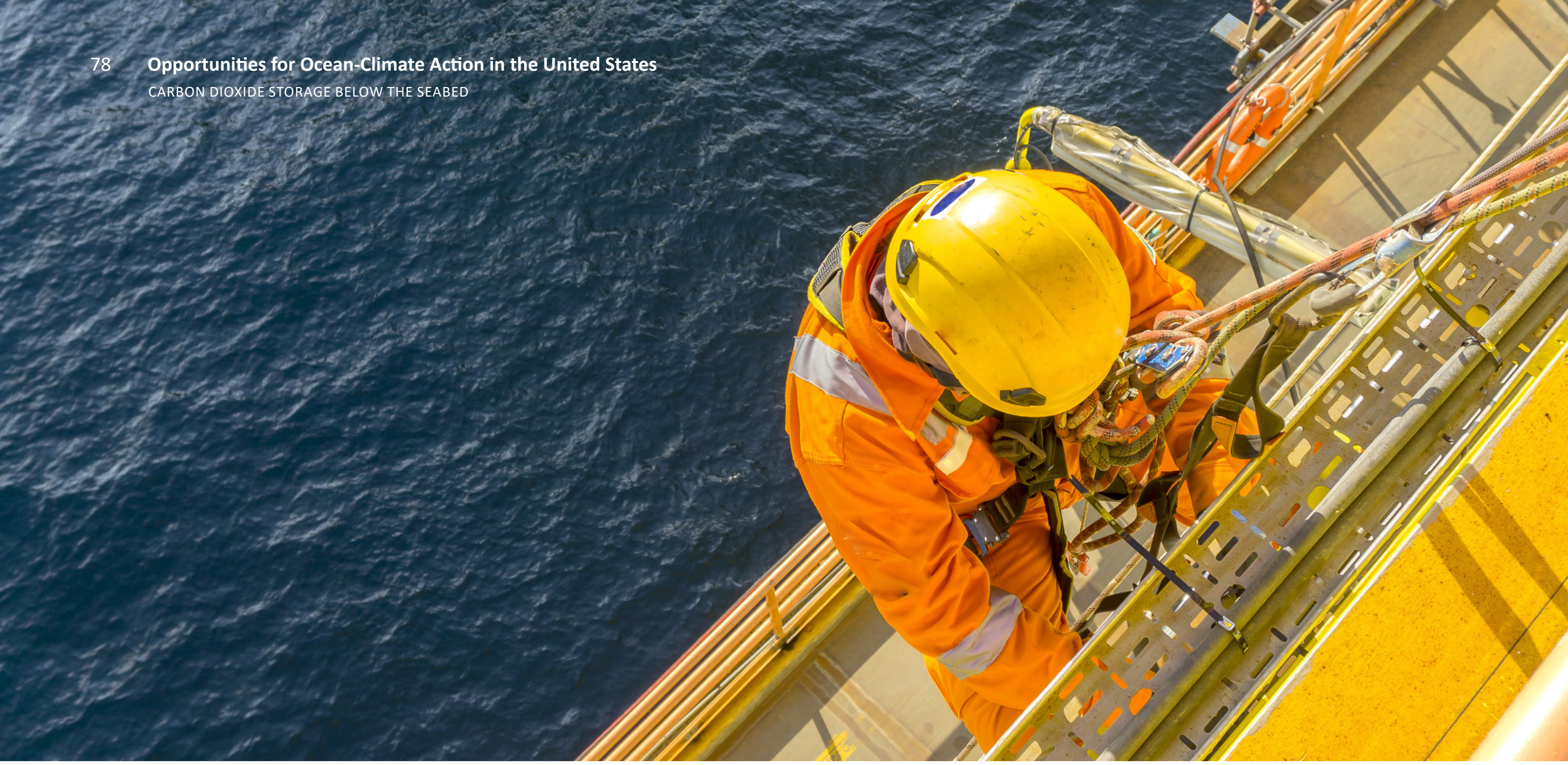
Green shading represents the current level of CCS in the U.S., while blue shadings (increasingly expensive with darker shading) are emissions for which CCS is technically feasible. The analysis encompasses carbon capture, use, and storage, which includes the use of carbon in EOR and other products (e.g., fuels).

Widespread CCS has several important co-benefits that should be considered in any cost-benefit analysis, including:

- **Jobs:** The Rhodium Group (2020) estimates that 100 million tons of annual capture from industrial CCS would create approximately 60,000 "job-years" within a 10-year timeframe (i.e., approximately 60 jobs per million tons per year). Offshore CCS estimates of up to 15 million tons per year by 2030 and 55 million tons per year by 2050 would translate into roughly 38,000 job-years between 2020 and 2050.
- **Health and climate justice**: Adding CCS to existing power systems generally reduces criteria pollutant emissions like SOx, NOx, mercury, and particulates, which currently impact health, especially in disadvantaged communities (Friedmann, Ochu, and Brown 2020).
- **Extending the lifetime of infrastructure and deferring decommissioning costs:** As an example, where oil or gas production fields are at the end of their lives, there may be opportunities to re-use existing oil and gas infrastructure by repurposing it for CO_2 transport and storage (Townsend, Raji, and Zapantis 2020).

Box 7. The 45Q tax benefit

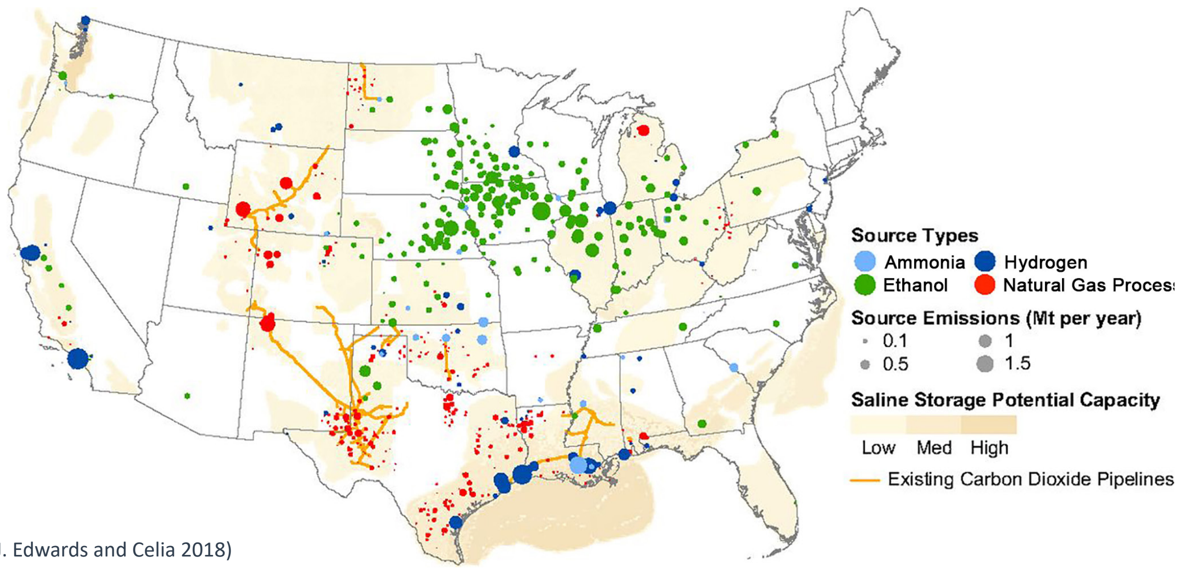
Section 45Q provides a tax credit on a per-ton basis for CO_2 that is sequestered. From 2008 to 2018, an incentive of $20 per metric ton for CO_2 geologic storage and $10 per metric ton for CO_2 used for EOR or enhanced natural gas recovery was available. This tax credit was capped at 75 million tons and in 2014, the IRS reported that 35 million tons had already been claimed. In February 2018, with the passage of the Bipartisan Budget Act of 2018, the tax credit was updated. The tax credit will increase to $35 per metric ton for EOR and $50 per metric ton for geologic storage by 2026. The $35 tax credit is also available for non-EOR CO_2 utilization and direct air capture projects.



Geographic opportunities

Sub-seabed storage would be most attractive in the Gulf of Mexico. The region features saline formations so vast that they could safely hold many decades, if not centuries, worth of current stationary emissions. These formations are co-located with stationary emissions that could be captured at low cost. A key cost driver of CCS technology is the purity of CO_2 in the flue gas, which makes ammonia, hydrogen, ethanol, and natural gas processing the cheapest emissions for carbon capture. Data provided by Edwards and Celia (2018) suggests there is capacity for annual low-cost capture of 8 million tons of CO_2 per year in Texas and 6 million tons in Louisiana. The approximately 1 million tons of CO_2 captured and stored in the region is exclusively used for EOR, however, and there is no indication that other large-scale CCS operations in the region are planned.

Figure 12. Co-location of low-capture-cost emissions, pipeline infrastructure, and saline formations in the U.S.



(R. W. J. Edwards and Celia 2018)

Policy, research, and technology needs

Policy

Enhance and extend the 45Q tax credit. As discussed above, only a fraction of carbon capture is economically viable for subsequent use in EOR (without the 45Q credit) and there is probably not much additional CCS (let alone sub-seabed CCS) that could currently be financed through the 45Q credit alone. Under current policy, 45Q provides a tax credit of $50 per ton of CO_2 that is captured and stored. This tax credit expires at the end of 2023 (construction can take up to 6 years after project launch). Arguably the most practical immediate opportunity to boost CCS investments in the U.S. is to enhance the 45Q credit (increase $ per ton of CO_2 captured and stored) and to extend its lifetime beyond 2023 (see, for example, Friedmann, Ochu, and Brown 2020; King et al. 2020). Note that, at the time of writing, there were active legislative negotiations to modify the 45Q credit substantially. This includes:

- **Extending the timeline** for qualification and possibly making the credit permanent.
- **Increasing the value** for saline formation storage to above $65/ton, thereby likely making saline aquifer storage more lucrative than EOR in almost every jurisdiction.

Amend the Low Carbon Fuel Standard (LCFS) in California to include offshore storage. In January 2019, the California Air Resources Board included a protocol for CCS as well as direct air capture, or carbon removal, in its LCFS, which can be combined with the 45Q credit. The LCFS is currently trading at approximately $200 per ton, which means that most CCS could become economically viable in the U.S. (California Air Resources Board 2020). But the LCFS CCS protocol specifies that it "applies to CCS projects that capture CO_2 and sequester it onshore, in either saline or depleted oil and gas reservoirs" (California Air Resources Board 2018b). This excludes offshore storage, at least until the protocol is amended.

State-based opportunities. States have an important role to play in creating the regulatory certainty and financial incentives that will trigger more widespread CCS investment.

- **The Clean Energy Standard** is Obama-era legislation that requires an electric utility to supply a certain fraction of its electricity sales from qualifed clean energy sources. The standard includes energy generation from fossil fuels in combination with CCS, and utilities can comply with the standard by either owning or contracting for delivery from clean energy generating assets, or by purchasing tradable credits (Center for Climate and Energy Solutions 2019). Nine states have 100 percent clean electricity standards that would qualify CCS for rate recovery (as renewable portfolio standards have in the past for wind and solar). This probably will increase the pool of viable CCS power projects nationwide.
- **Adopt LCFS in other states.** Prior to COVID-19, legislatures in New York, Oregon, and Washington were poised to pass their own LCFS. In addition to the LCFS, the New York legislature considered approving funding to pilot an offshore wind project that also would harness direct air capture to remove CO_2, using wind, and store the CO_2 in shallow basalt formations on the seafloor. The work is guided by research at Columbia University, where experts are optimistic that funding for the pilot will materialize next year. Scholars at Victoria University, in British Columbia, are seeking resources to build and test a similar wind-to-direct-air-capture pilot in the waters off British Columbia. They have applied to the MacArthur Foundation for support.

Streamline the permitting framework for CO_2 storage to accelerate technology scale-up. A seminal report on negative emission technologies by the National Academies of Sciences lists existing regulatory frameworks and best practices promulgated by the EPA and the Department of Energy and concludes that important regulatory frameworks are currently missing for the research and deployment of CCS at scale (National Academies of Sciences, Engineering, and Medicine 2019b). These include:

- **Long-term liability:** It remains unclear who will bear the long-term financial responsibility for storage sites, once a project is closed and abandoned. Lack of clarity on this issue remains one of the biggest barriers to CCS scale-up in geological formations.
- **Pore space ownership:** Both national and sub-national laws (regarding mineral rights, water rights, surface rights, and other beneficial land uses) govern sub-surface pore ownership and usage, and there is no streamlined mechanism in place to identify, on a project-by-project basis, who can grant the right to sequester CO_2 in subsurface pore space. Accelarating CCS upscale would require a much more streamlined permitting process for geologic sequestration.
- **Regulatory impediments:** Regulatory requirements remain challenging and expensive, driving up costs and increasing the delay in technology scale-up.

Research and technology

Conduct a national assessment of the carbon storage potential in deep seafloor environments. A 2019 joint publication by the Bipartisan Policy Center and Energy Futures Initiative identified 23 separate appropriations accounts within nine federal departments and agencies that contain program elements with sufficiently broad research program scope to encompass research, design, and development (RD&D) support for carbon removal (Hezir et al. 2019). Some of these represent opportunities to add or redirect federal funding to support RD&D projects related to CCS, particularly accounts from the Department of Energy. Drawing on the National Academies of Sciences, Engineering, and Medicine (NASEM) report (2019), the authors identify research opportunities worth $2.5 billion to fund basic research, demonstration, and deployment, as shown in Table 10.

Table 10. Breakdown of NASEM research agenda for CCS

Stage of research	Specific research needs	Funding needs (Millions of dollars over 10 years)
Basic research and development	Reduce risks of induced seismicity	$850
	Improve secondary trapping prediction and methods	
	Improve simulation models for performance prediction	
	Improve secondary trapping prediction and methods	
Development/ Demonstration	Improve site characterization and selection	$1,450
	Improve and reduce cost for monitoring and verification	
	Co-optimize CO_2 with EOR and sequestration	
Deployment	Assess and manage risk of CO_2 leakage	$210
	Research on best practices and public engagement	

(Hezir et al. 2019)

Key assumptions, data limitations, and caveats

The mitigation potential of ocean-based carbon dioxide sequestration depends on a long list of factors, including the economic incentives for CCS, the permitting structures for onshore vs. offshore storage, and the pace of deployment of CCS infrastructure. In the Mitigation Potential section we describe these factors and their current trajectories in detail. The table below provides an overview of assumptions that were used to estimate 2030 and 2050 values for ocean-based CCS mitigation potential.

Variable	Value	Source	Comment
Theoretical U.S. offshore storage volume in sub-seabed geological formations	36,000 Gt	House et al. 2006	This refers to total (not annual) capacity and would allow storing thousands of years of current U.S. CO_2 emissions.
Technical potential of CCS from stationary emissions	2.6 Gt/yr	National Petroleum Council 2019	Stationary emission sources from industrial and power generation facilities represent nearly 50% of total U.S. CO_2 emissions. The U.S. has more than 6,500 large stationary sources.
Current economic potential of CCS, assuming increasingly favorable economics and policy incentives	25 Mt/yr in 2020	National Petroleum Council 2019	Only 1 Mt/yr is CCS; the remainder is EOR. The only operational CCS plan in the U.S. is located in Illinois.
Future economic potential of CCS, assuming increasingly favorable economics and policy incentives	120 Mt/ yr in 2030, 5% annual growth thereafter	King et al. 2020; Friedmann, Ochu, and Brown 2020	Assumes that enhanced and permanent 45Q tax credits are implemented and trigger CCS investments.
Current economic potential for offshore storage of CO2 captured in the U.S.	0 Mt/yr		Currently, no offshore CCS projects exist or are planned within the U.S. exclusive economic zone.
Future economic potential for offshore storage of CO_2 captured in the U.S.	In 2030, 1 project is in place After that, another one goes online every 2 years Each project grows to a capacity of 5M tons/yr	Author's estimate	Experience in the EU shows that offshore CCS takes 5-10 years from planning to deployment, even when supply chains run efficiently and projects have full governmental support. Deployment before 2030 is ambitious since, to our knowledge, no offshore projects are currently in planning.

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