AN ACTION PLAN FOR MARITIME ENERGY AND EMISSIONS INNOVATION

Department of Energy United States of America

Department of Transportation United States of America

United States Environmental Protection Agency

U.S. Department of Housing and Urban Development

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1. EXECUTIVE SUMMARY

1.1 Intent and Purpose

The Action Plan for Maritime Energy and Emissions Innovation (the action plan) lays out a strategy to reduce and eliminate nearly all greenhouse gas (GHG) emissions in the U.S. maritime sector by 2050, in line with the U.S. economy-wide goal of net-zero GHG emissions by 2050. To reach this goal, the action plan outlines actions, objectives, targets, and activities to scale low- and net-zero emissions fuels, energies, and technologies; strengthen the maritime workforce; bolster shipbuilding capacity; and expand complementary landside infrastructure. The action plan supports industry, mariners, communities, civil society, sub-national governments, and other interested parties that will decarbonize the maritime sector alongside the U.S. government.

The transportation sector is the largest source of GHG emissions in the United States, contributing to the climate crisis that is worsening the quality of life in American cities, towns, and rural communities. Emissions from the transportation sector also contribute to poor air quality, which disproportionately impacts underserved and low-income communities. To address the climate crisis, we aim to eliminate nearly all GHG emissions from each part of the transportation sector by 2050[1] and implement a holistic strategy to achieve a future mobility system that provides clean, safe, resilient, accessible, and equitable transportation options for people and goods.

In 2023, the U.S. Department of Energy (DOE), U.S. Department of Transportation (DOT), U.S. Environmental Protection Agency (EPA), and U.S. Department of Housing and Urban Development (HUD) released the U.S. National Blueprint for Transportation Decarbonization (Blueprint).[2] The Blueprint provides a roadmap for how we can provide better transportation options, expand affordable and accessible options to improve efficiency, and transition to zero-emissions vehicles and fuels. The Blueprint is built on five principles:

- Initiate bold action
- Embrace creative solutions across the entire transportation system
- Ensure safety, equity, and access
- Increase collaboration
- Establish U.S. global leadership.

This action plan is one of several that covers each part of the transportation sector and builds on the foundation presented in the Blueprint. In addition to maritime, individual sector action plans are being developed to address rail, medium- and heavy-duty vehicles, light-duty vehicles, and off-road vehicles. The 2021 United States Aviation Climate Action Plan[3] was previously released, and action plans have also been developed to address the Blueprint's convenience and efficiency strategies.

1.2 Key Actions

Achieving U.S. and international maritime decarbonization will require bold action. Strong U.S. leadership will set an example and help rally the international maritime community. A multifaceted, strategic approach must be deployed to achieve the U.S. and international emissions targets.

Given the scope of the challenge to decarbonize the maritime sector, this plan proposes the creation of a new initiative, the "**Sustainable Maritime Fuel Grand Challenge**," that would work with industry and government to quickly deploy competitive, scalable fuels and technologies needed in the near term while building long-term capacity and infrastructure requirements. The

Sustainable Maritime Fuel Grand Challenge would be modeled after the Sustainable Aviation Fuel Grand Challenge.[4]

Core to this action plan is the transition to a new set of low-GHG fuels, including green ammonia and methanol for ocean-going vessels (OGVs), the use of sustainable[5] drop-in[a] fuels where necessary, and the adoption of electrification and fuel cell technology[6] for smaller vessels where feasible. **To help support these efforts, this plan calls for the federal government to formally define sustainable maritime fuel (SMF) in 2025.**

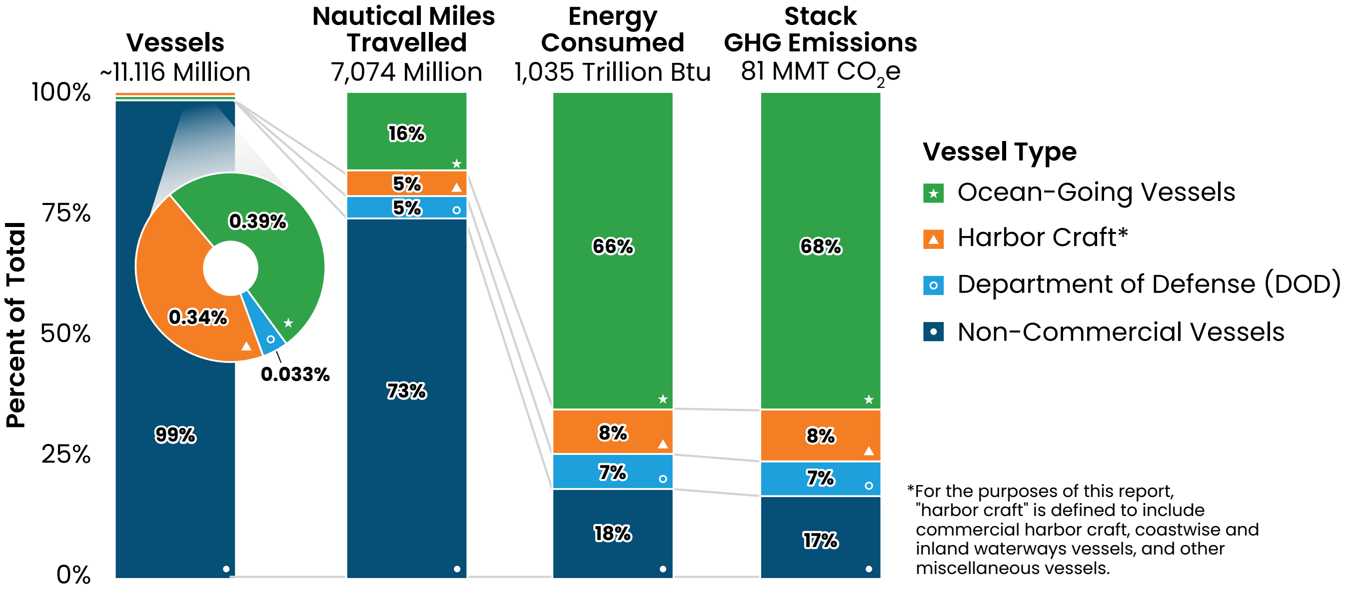
This plan also calls for international collaboration through continued U.S. leadership in the **Mission Innovation: Zero-Emission Shipping Mission (ZESM)**,[7] work within the **International Maritime Organization (IMO)**,[8] and our commitments under the **Green Shipping Challenge**[9] such as advancing green shipping corridors.

1.3 The Maritime Sector Today

Multiple decarbonization solutions are needed to match the variety of vessels and their applications in the U.S. maritime sector. Figure ES-1, which represents the first common energy and emissions inventory of all U.S. bunkering (maritime fuel sold in the United States), shows that large OGVs represent approximately 68% of all GHG emissions from fuel bunkered in the United States. The complementary landside infrastructure must also be developed to enable the use of onboard sustainable fuels, energies, and technologies.

Because the U.S.-flagged OGV fleet is relatively small, the action plan considers both U.S.-flagged vessels and international vessels that bunker within the United States. Specifically, the action plan considers the emissions associated

U.S.-flagged and foreign-flagged vessels per maritime market segment



*For the purposes of this report, "harbor craft" is defined to include commercial harbor craft, coastwise and inland waterways vessels, and other miscellaneous vessels.

Figure ES-1 shows the scope of the U.S. maritime market, including U.S.-flagged and foreign-flagged vessels that bunker in the United States. Each of these vessel types has unique decarbonization solutions ranging from more efficient operations to the use of electrification and the use of sustainable maritime fuels (SMF).

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[a] Drop-in fuels are alternative fuels that can be directly substituted for conventional fuels without major modifications to fueling distribution, fueling infrastructure, or existing engines for parallel structure and flow.

with the U.S. bunkered fuel and the labor and safety standards of those vessels within U.S. waters.

Bunker fuel (e.g., heavy fuel oil [HFO], marine diesel oil) and distillates (e.g., diesel) are the predominant fuels for maritime vessels. When combusted, these fuels emit GHGs and criteria air pollutants, which contribute to negative health impacts, especially for communities near ports and freight hubs. Decarbonizing the maritime sector and reducing criteria air pollutants are twin priorities to promote environmental justice.

Globally, 92.6% of vessels burn conventional fuels, but about half of vessels on order or under construction can accept low-GHG fuels (Figure ES-2). As the world's largest importer and second-largest exporter, the United States must ramp up vessel production and keep pace with the infrastructure needs of these vessels.

Alternative fuel uptake in the world fleet by gross tonnage

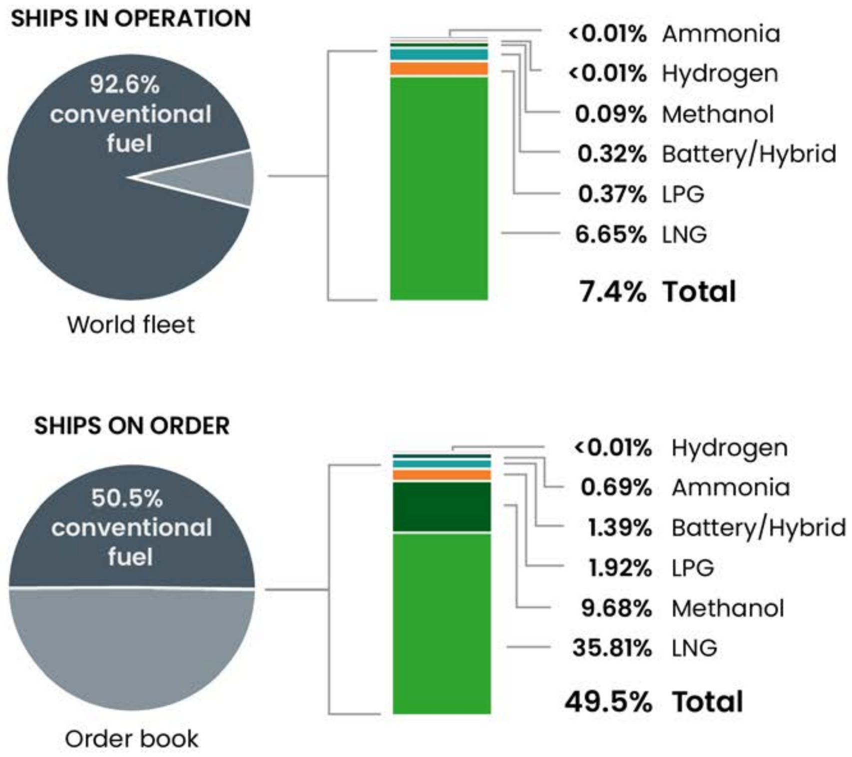

Figure ES-2 compares the fuel types required by the 2024 global fleet (left) to the fuel types required by ships on order at the time (right). Most ships on order that are capable of utilizing renewable fuels are designed to burn liquified natural gas (methane). Alternative fuel-capable vessels in the world fleet in gross tonnage, as of October 2024, reported by IHS Markit (ihsmarkit.com) and DNV's Alternative Fuels Insights for the shipping industry—AFI platform (afi.dnv.com). Note that these figures indicate vessels "capable" of operating on alternative fuels but are not necessarily doing so nor could necessarily do so without further major refits (tankage, fuel management systems, etc.). However, these numbers are indicative of the potential use for alternative fuels in the future fleet that is either already or will soon be operational.

1.4 Strategy to Decarbonize the Maritime Sector

1.4.1 SUSTAINABLE MARITIME FUEL GRAND CHALLENGE

A shift to net-zero emissions necessitates developing and deploying new zero- and near zero-emission fuels on a life cycle basis, building new or retrofitting existing ships to efficiently run on the new fuels, and upgrading port infrastructure to supply these novel fuels. Currently, fuels with zero- and near zero-emission over their full life cycle are more expensive and less available than traditional fossil fuels. Scaling these zero- and near zero-emission life cycle fuels depends on sourcing clean energy and feedstocks, building new or repurposing existing manufacturing sites, and transporting the fuels to ports and bunkering facilities. To reduce costs, expedite technology maturation, and ensure a robust workforce and supply chains, **this plan calls for the formation of a public-private partnership that spans multiple government agencies and industry under a new Sustainable Maritime Fuel Grand Challenge**. Building on the existing Clean Fuels and Products Shot,[b] the goal of this Grand Challenge will be to set common targets across government and industry in each portion of the maritime sector; to cooperate on research, development, and demonstration; to share data and learnings from early deployments; and to plan infrastructure across the different vessel operators, ports, fuel providers, and government agencies at all levels. The Grand Challenge will also serve to share information about U.S. maritime decarbonization activities on an international level.

Key to this action plan is the use of zero- and near zero-emission life cycle fuels, also referred to as SMFs. As the use of alternative fuels increases, and the policy and regulatory framework to incentivize them develops, it is important to define SMFs. For the purposes of this action plan and taking into account work underway at the IMO, a maritime fuel is considered sustainable if it meets 1) requirements for environmental and socio-economic sustainability, and 2) requirements for significantly reduced GHG intensity relative to traditional maritime fuel. Fuels that may be considered SMFs include sustainable low-carbon biofuels (such as certain biodiesel, renewable diesel [RD], renewable gasoline, and bio-intermediates [BI]), clean (i.e., derived from clean electricity) methanol, clean ammonia, and clean hydrogen. **This action plan calls for the federal government to develop a formal definition of SMF in 2025.**

1.4.2 INTERNATIONAL COOPERATION

The United States is leading decarbonization momentum internationally. In 2023, the IMO[c] adopted a revised strategy to reach net-zero GHG emissions from international shipping by or close to 2050. The IMO also set a new global target to increase the uptake of zero- or near zero-emission technologies, fuels, and/or energy sources such that they represent at least 5% while striving for 10% of the energy used by international shipping by 2030.[1] The action plan aligns with IMO levels of ambition by setting even more ambitious interim targets to reduce total annual GHG emissions from international shipping by 37% by 2030 and 96% by 2040, compared to a 2008 baseline, and achieve net-zero GHG emissions from international shipping by 2050 to help meet the goal of limiting global temperature rise to 1.5°C.

The United States is also a founding member and co-lead of the Zero-Emission Shipping Mission (ZESM),[7] which aims to demonstrate the commercial viability of net-zero emissions shipping by enabling 600 large international ships running on zero- and near zero-emission life cycle fuels, also referred to as well-to-wake (WTW)[d] zero-emissions fuels, enabling the global production of 16 million metric tons (4.7 billion gallons) of

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[b] The Clean Fuels and Products Shot aims to meet projected 2050 net-zero emissions, demands for 100% of aviation fuel; 50% of maritime, rail, and off-road fuel; and 50% of carbon-based chemicals by using sustainable carbon resources.

[c] The United States has been a member of the IMO since 1950.

[d] Well-to-wake emissions include all upstream emissions from producing, transporting, and storing fuels in addition to stack emissions.

HFO-equivalent[e] WTW zero-emission fuels, and enabling 20 key global ports to offer these fuels, all by 2030. **Aligning with these goals and using scenario modeling, the action plan sets an annual U.S. production goal of approximately 700 million HFO-equivalent gallons by 2030, which equates to just over 10% of the projected U.S. maritime fuel sales and exceeds the U.S. IMO and ZESM goals and commitments.**

The United States co-launched with Norway the **Green Shipping Challenge**[9] to encourage international shipping stakeholders to make concrete maritime decarbonization announcements to help put the shipping sector on a pathway this decade that is aligned with the goal of limiting global temperature rise to 1.5°C. As an international leader, the United States committed to developing a national strategy for maritime decarbonization, which is fulfilled by this action plan.

1.4.3 NEW FUEL PATHWAYS

This action plan proposes a four-point fuel strategy:

- Increase vessel, engine, and operational efficiency to the extent possible (e.g., hull design, exhaust treatment).
- Electrify and hybridize where feasible.
- Implement the use of SMFs (e.g., clean hydrogen, clean methanol, clean ammonia, and renewable natural gas/e-methane) where electrification is not feasible.
- Reserve drop-in fuels (e.g., RD, renewable gasoline) for legacy vessels that are not easily replaced or for vessels that are most sensitive to low fuel energy density.

To identify potential fuel and energy solutions, this action plan segments U.S. maritime sector vessels into three broad categories (Figure ES-3): ocean-going vessels, or OGVs; harbor craft,[11] including coastwise and inland waterways vessels; and non-commercial vessels.

Ocean-Going Vessels (OGVs)

DESCRIPTION:

Ocean-going vessels sail long distances (up to several weeks at a time).

EXAMPLES:

Container ships, bulk carriers, tankers, car carriers, commercial fishing vessels, lake freighters (lakers), general cargo vessels, and cruise liners

Harbor Craft

Commercial Harbor Craft, Coastwise, and Inland Waterways Vessels

DESCRIPTION:

Harbor craft operate over shorter distances than OGVs and typically return to port more frequently, allowing more opportunities to refuel or recharge.

EXAMPLES:

Towboats, commercial fishing vessels, offshore supply vessels, and ferries

Non-Commercial Vessels

DESCRIPTION:

Non-commercial vessels are designed for personal use with low utilization throughout the year, returning to marinas regularly or being stored on land.

EXAMPLES:

Personal watercraft, outboard motorboats, pontoons, fishing vessels, and speedboats

Figure ES-3 offers a breakdown of the three maritime categories with a description of each.

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[e] HFO-equivalence is the amount (volume or weight) of a zero- and near zero-emission life cycle fuel that has the same amount of energy as 1 gallon or ton of HFO.

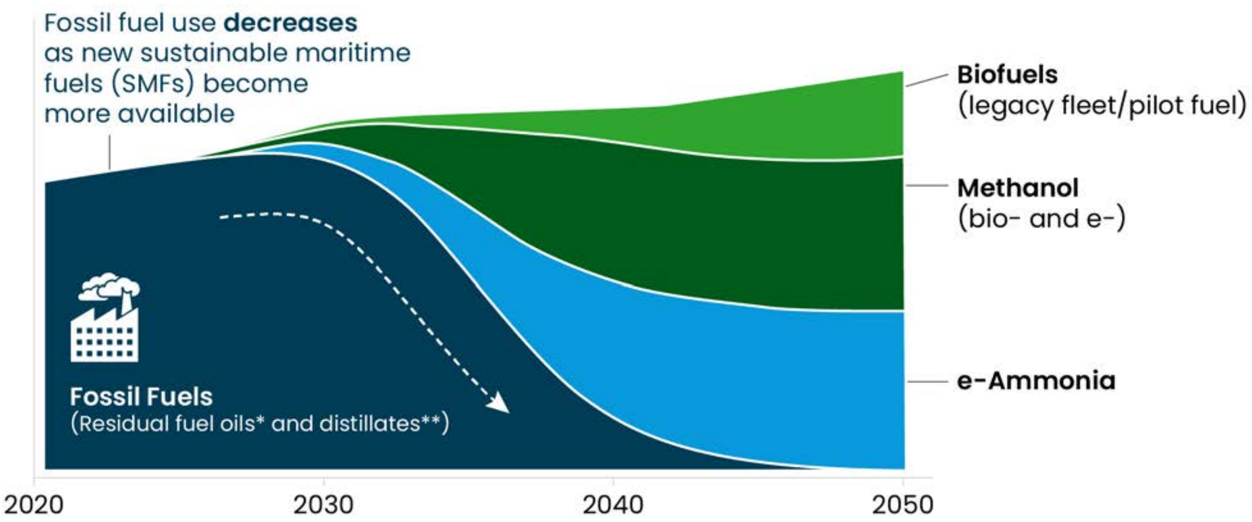
The action plan generally focuses on the following fuel strategies for each vessel category (see section 4.4.2 Sustainable Vessel Developments for definitions):

1. **Ocean-Going Vessels:** Prioritize implementation of clean methanol and ammonia fuels by 2050 while integrating sustainable biofuels as direct drop-in and pilot fuel[f] as appropriate in the near term.
2. **Harbor Craft:** Prioritize low- to zero-emission vessel technology—hybrid electric, battery electric, and hydrogen fuel cell by 2050 while integrating biofuels where route and vessel characteristics allow in the near term.
3. **Non-Commercial Vessels:** Prioritize sustainable drop-in fuels while focusing on advancing efficiency improvements such as hull designs, hybrid electric, battery electric, and hydrogen propulsion systems by 2050.

We expect a transition in fuels, energies, and technologies from now through 2050, as represented in Figures ES4–ES6. The Sustainable Maritime Fuel Grand Challenge can support and accelerate this transition.

Ocean-Going Vessels

2050: Methanol and ammonia, supported by biofuels



*e.g., heavy fuel oils (HFOs) and very low sulfur fuel oils (VLSFOs)
**e.g., diesel fuels and fuel oils

Figure ES-4 illustratively depicts OGV fuel usage over time showing the reduction of fossil fuels as the production and use of various SMFs increases from our current fuel make-up to 2050. It is important to note that sustainable production pathways including biogenic (bio-) and electro (e-) for methanol and ammonia will be required to lower the life cycle GHG emissions of these fuel types.

OGVs travel long distances and carry high volumes of cargo, which makes them energy efficient for freight transportation compared to other transportation modes. This action plan focuses on the uptake of low carbon intensity methanol and ammonia fuels, which will be supported by biofuels initially but will eventually be used as direct drop-ins for the legacy fleet of vessels where required.

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[f] A pilot fuel is used to improve the combustion characteristics of low flash point fuels such as methane, methanol, and ammonia in internal combustion engines.

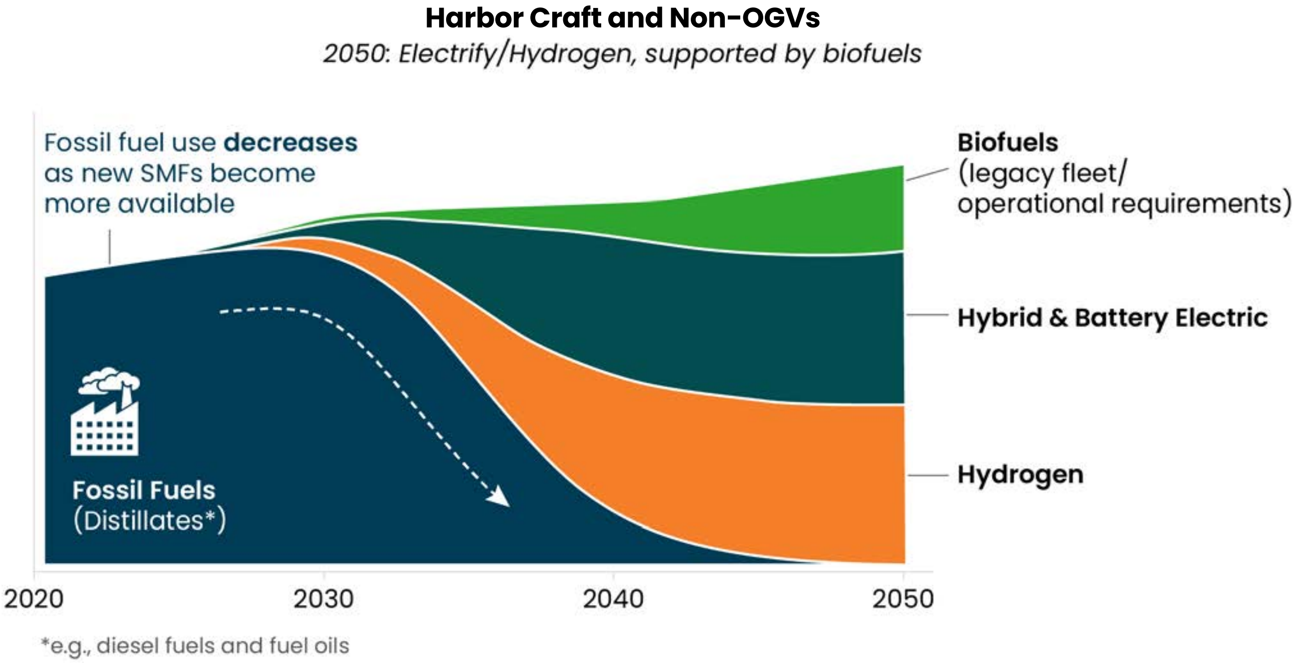

Figure ES-5 illustratively depicts harbor craft fuel usage over time, showing the reduction of fossil fuels as the production and use of battery electric and hydrogen-fueled vessels increase from our current fuel make-up to 2050.

Harbor craft,[12] including coastwise and inland waterways vessels, are the most diverse sector of vessels. See Figure ES-3 for descriptions and examples of harbor craft. Harbor craft operate over shorter distances than OGVs and typically return to port more frequently, allowing more opportunities to refuel or recharge. For the variety of use cases, the harbor craft strategy focuses on electrifying and utilizing clean hydrogen over time while being supported by biofuels where needed on routes.

Tugboat operating in New York Harbor is an example of a harbor craft.

Non-Commercial Vessels

2050: Electrify and hybridize, where feasible increase drop-in availability

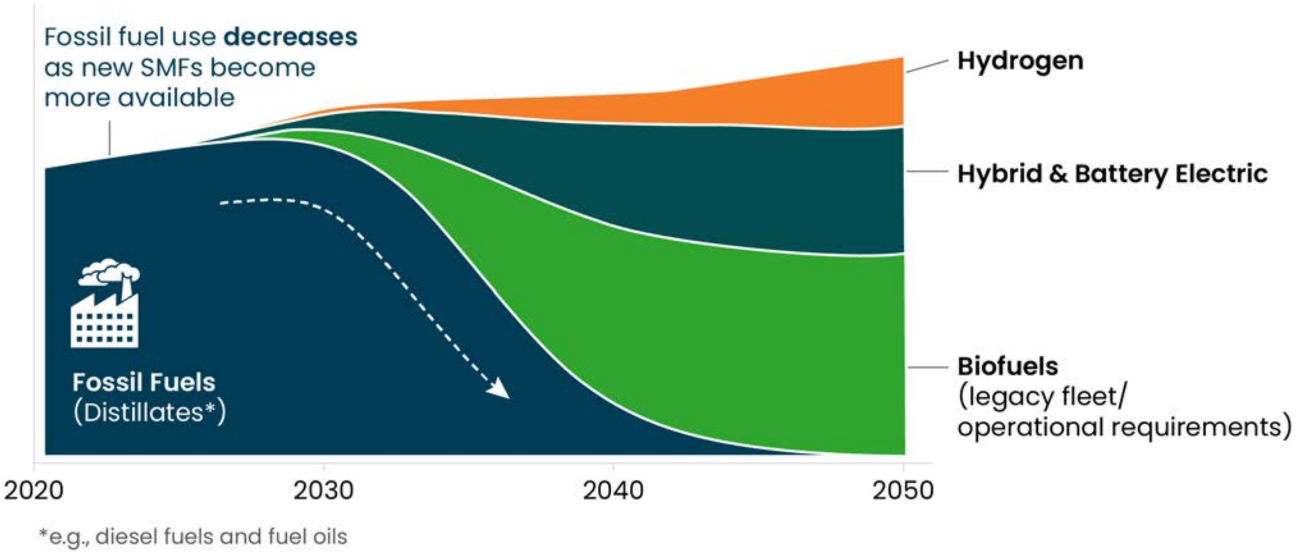

Figure ES-6 illustratively depicts non-commercial vessel fuel usage over time, showing the reduction of fossil fuels as the production and use of biofuels, battery electric, and hydrogen-fueled vessels increase from our current fuel make-up to 2050.

For the purposes of this plan, non-commercial vessels are defined as any vessel or boat that is designed primarily for personal use, or leased, rented, or chartered to a person for personal use, including boats engaged in non-commercial fishing. Therefore, non-commercial vessels consist of a variety of privately owned watercraft such as personal watercraft and boats with outboard motors. Non-commercial vessels are by far the largest market segment within the United States on a per-vessel basis, consisting of 11 to 12 million boats in the United States alone. The overall strategy for non-commercial vessels is to increase the availability of sustainable drop-in fuels such as renewable gasoline and RD, while simultaneously accelerating options for advanced efficiency improvements such as hull designs, hybrid electric, battery electric, and hydrogen propulsion systems by 2050.

A variety of non-commercial vessels docked at a small marina in Georgia.

1.5 A Maritime Sector Transition that Strives for Justice and Equal Access to Benefits

Achieving net-zero emissions economy-wide by 2050 will have many benefits for the U.S. economy and communities—including promoting innovation, maintaining economic competitiveness on the global stage, and reducing the negative impacts of climate change and poor air quality. This transformation will require strategic transitions—including changes to vessels, vessel fueling, component manufacturing processes, fuel production processes, vessel and infrastructure maintenance, and vehicle operations. A thoughtful, strategic approach to transitioning the U.S. workforce and communities will be essential to contribute to a transition that strives for justice and equal access to benefits for all Americans.

Workforce: Maritime decarbonization will not be possible without the maritime workforce, which is the foundation of the maritime economy. Mariners are depended on every day for their specialized skills, expansive knowledge, and resiliency. Today, the U.S. maritime industry directly employs nearly 650,000 workers, including merchant mariners, port operators, longshoremen, stevedores, and other essential personnel that work on the waterfront. Decarbonization will require new technologies and fuels, as well as expanded manufacturing, and this will require a workforce that is trained in their safe handling and operation.

Adoption of new fuels and technologies must prioritize workforce safety, including providing training and skills development. This is an opportunity to strengthen maritime academies and other institutions that are educating the next generation of the maritime workforce, contributing to a stronger and cleaner maritime economy. Transitioning to a decarbonized maritime sector will substantially affect these industries, involving the production of and jobs in vessels, component technologies, and fuels and infrastructure, as well as the reduced production of fossil fuels and internal combustion engines.

Environmental Justice: In addition to supporting American workers, careful and thoughtful attention needs to be given to communities with environmental justice concerns, especially port-adjacent communities and neighborhoods. Port communities, often located in low-income neighborhoods, bear the brunt of air pollution from maritime activities. Emissions from ships, trucks, and port equipment contribute to poor air quality, leading to adverse health effects for nearby residents. In addition to air quality impacts, these communities are impacted by noise and vibrations generated by port operations. Port-related actions, such as implementation of shore power (which enables vessels to connect to the electric grid and turn off onboard engines), noise dampening, and dust and particulate mitigation, need to be prioritized to ensure that port-adjacent communities and neighborhoods can reap benefits to their health and safety.

Continued federal leadership is needed to contribute to a just transition that benefits all communities, including those that are low-income —through actions such as policies and incentives to support high-quality job creation and retention, prioritization of emissions and noise reductions, and ongoing domestic investments in industries, supply chains, and programs to facilitate worker training (including reskilling and upskilling), especially in communities that have faced barriers to entering the workforce. A focus on the human element is a crucial way to achieve a net-zero future.

1.6 Action Plan Moving Forward

The following are high-level actions to decarbonize the maritime sector, with key proposed non-binding targets that characterize the path to a net-zero maritime sector. These targets were developed through stakeholder outreach and technology scenario modeling, as well as with interagency expertise. As the maritime sector intersects with other elements of the U.S. transportation system, it is necessary to consider this strategy holistically with other Action Plans that, taken together, encompass a cleaner, more efficient, and more convenient approach. Conversely, efforts to decarbonize other transportation modes, and the U.S. supply chain more broadly, should reference this Plan as appropriate.

ACTION

1

Decarbonize maritime vessel operations through efficiency improvements, clean fuel and energy sources, and technology integration

KEY TARGETS

- By 2030, increase operational efficiencies to reduce intensity of GHG emissions by 40%, consistent with the IMO goal for cargo- and passenger-carrying vessels.
- By 2030, at least 15% of all OGV port calls at U.S. ports have net-zero GHG emissions while at berth through application of SMF, shore power, or other available technologies, reaching 50% by 2040 and 100% by 2050.
- By 2030, at least 10% of harbor craft (by number) are running entirely on SMFs, reaching 70% by 2040 and 100% by 2050.
- By 2030, at least 25% of all new-build harbor craft are battery electric, hybrid electric, or fuel cell electric, reaching 50% by 2040 and 75% by 2050.
- By 2030, standardize and increase access to charging and refueling infrastructure at ports for harbor craft consistent to support all new-build electrified vessels and existing harbor craft.
- By 2030, at least 15% of new non-commercial vessels sold annually are hybrid, battery electric, hydrogen, or designed exclusively for operation on SMFs, reaching 35% by 2040 and 50% by 2050. Boats with higher use are prioritized for electrification and hydrogen.
- By 2030, at least 10% of marine gasoline consumption is from SMFs (e.g., green gasoline or e-gasoline), reaching 88% by 2040 and 100% by 2050.

ACTION

2

Adopt sustainable, emerging maritime fuels and energies by increasing their development, production, and use

KEY TARGETS

- In 2025, launch a Sustainable Maritime Fuel Grand Challenge that works with industry to quickly deploy SMFs in the near term while building long-term capacity.
- By 2030, support the annual domestic production of SMF to at least 700 million HFO gallon equivalent (HFOGE), the amount of an SMF it takes to produce the same energy content of 1 gallon of HFO. This equates to roughly 10% of fuels bunkered in the United States.
- By 2030, support the annual domestic production of renewable gasoline to at least 80 million gasoline gallon equivalents (GGEs), while simultaneously distributing a majority to U.S. marinas for non-commercial vessels. This equates to roughly 10% of the gasoline these non-commercial vessels use in the United States.
- By 2030, at least 15% of all energy requirements for vessels at port are met by zero-emissions solutions, reaching 50% by 2040 and 100% by 2050.

ACTION 3

Support U.S. maritime ports by advancing infrastructure development and shipbuilding to enable systemwide maritime decarbonization

KEY TARGETS

- By 2030, accelerate the transition to low- and zero-emissions technologies through the deployment of fuels and technologies along green shipping corridors by bunkering SMFs at a minimum of three U.S. ports.
- By 2030, increase infrastructure capacity and availability to enable 10% of harbor craft to run on SMFs and to enable 25% of all vessels repowered/retrofit in the United States to run on battery electric, hybrid electric, and fuel cell electric vessels.
- By 2030, have proper infrastructure in place to support Action 1's key target of achieving at least 15% of all OGV port calls at U.S. ports having net-zero GHG emissions while at berth through application of SMFs, shore power, or other available technologies. Reaching 50% by 2040 and 100% by 2050.

These efforts should be integrated with land-side port planning improvements, such as long-term planning efforts to reduce supply chain distances and investments to provide low-carbon commute options for port workers.

ACTION 4

Strengthen and expand the maritime workforce by prioritizing safety, security, and training

KEY TARGETS

- By 2026, identify existing university and apprenticeship programs addressing decarbonization, including maritime academies and Maritime Administration (MARAD)-designated centers of excellence,[g] and work to expand current and develop new programs and curricula, to enhance maritime decarbonization education and training opportunities.
- By 2030, develop remote diagnostic pathways for decarbonization systems so that technicians may work on the systems without traveling to specific vessels.
- By 2030, establish and build relationships with labor unions and small businesses to provide technical assistance around safely working on and with new high-tier engines, clean fuels, or zero-emissions systems through dedicated engagement workshops and opportunities.

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[g] https://www.maritime.dot.gov/maritime-workforce/maritime-centers-excellence

ACTION
5

Build partnerships and collaborations through strategic planning

KEY TARGETS

- By 2025, complete the Ship Alternative Fuel and Emissions Toolkit (SAFE-T) initiated by MARAD and work to integrate into industry and stakeholder best practice approaches to reducing GHG emissions.
- By 2025, complete the Global Routing Energy and Emissions Network for Transportation (GREEN–T) initiated by MARAD and make publicly available.
- By 2026, engage with networks of regional portside community advocacy working groups to facilitate equitable energy transitions. Focus on safety, air pollution, displacement of local communities, disproportionate impact on jobs and health, and noise incursions.
- By 2027, establish the ability to calculate baseline emissions from vessels operating in U.S. waters and understand emissions implications of measures such as fuel switching, electrification, and operational changes (routing) on total maritime GHG emissions in U.S. waters.
- By 2027, conduct emissions and energy usage inventories on 25% of U.S. ports and associated terminal operations. By 2030, encourage all U.S ports and associated terminal operations to complete annual emissions and energy usage inventories.
- By 2027, identify cross-modal initiatives or high-impact projects that could benefit and possibly leverage funding across modes and agencies grant/financing programs for more rapid decarbonization.

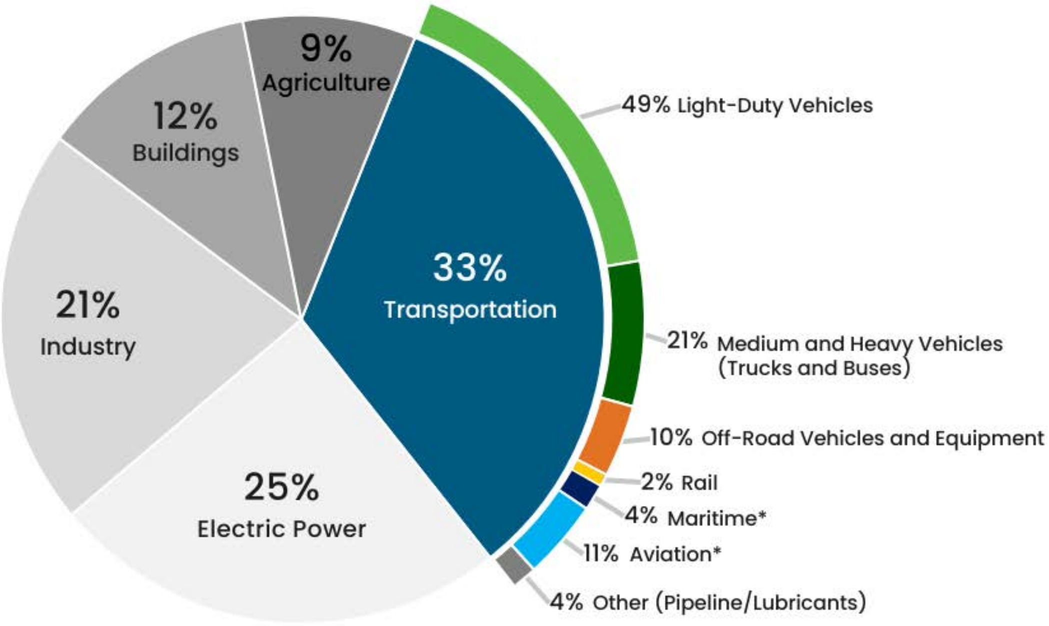
Following Through With Action

The Action Plan for Maritime Energy and Emissions Innovation is envisioned as a living document, with progress on maritime sector decarbonization evaluated at regular intervals. Future updates to this document are anticipated as technology and markets continue to evolve. Ongoing and regular engagement, outreach, and partnership with industry, state and local government, utilities, environmental justice organizations, and communities will be needed to support the transition and must be a priority for the implementation of all programs and strategies. Information sharing, exchange of lessons learned and best practices, support of technical assistance, and project development through partnership formation will be critical to the success of strategies outlined in this action plan.

2. BACKGROUND AND CONTEXT

The transportation sector is now the largest source of greenhouse gas (GHG) emissions in the United States, contributing to the climate crisis that is worsening quality of life in American cities, towns, and rural communities. The maritime sector accounts for approximately 4% of U.S. transportation emissions (Figure 1).

2022 U.S. GHG Emissions



*Aviation and maritime include emissions from international aviation and maritime transport. Military excluded except for domestic aviation.

Figure 1 shows the total GHG emissions from the United States where the transportation sector accounts for 33% of U.S. GHG emissions, and the U.S. maritime sector accounts for 4% of the U.S. transportation GHG emissions.[11]

The U.S. maritime sector connects virtually every aspect of American life—from the clothes we wear, to the cars and trucks we drive, to the food we eat, to the oil and natural gas used to heat and cool our homes.[13] A modern maritime sector is also critical to national and economic security. About 99% of U.S. overseas trade, by weight, enters or leaves the United States by ship. This waterborne cargo and associated activity contribute more than $500 billion to the U.S. gross domestic product (GDP) and sustain over 10 million U.S. jobs.[12] Maritime vessels account for 40% of U.S. international trade value, with trade of goods accounting for 18% of 2020 GDP. In 2020, U.S. waterborne shipping carried nearly 1.5 billion short tons in cargo, valued at over $1.5 trillion—more than any other mode of transportation (Figure 2). This activity generated nearly 500,000 vessel calls (equivalent to more than 10% of global calls).[14] In addition, the non-commercial vessel industry generates more than $230 billion in economic impact across the United States.[15]

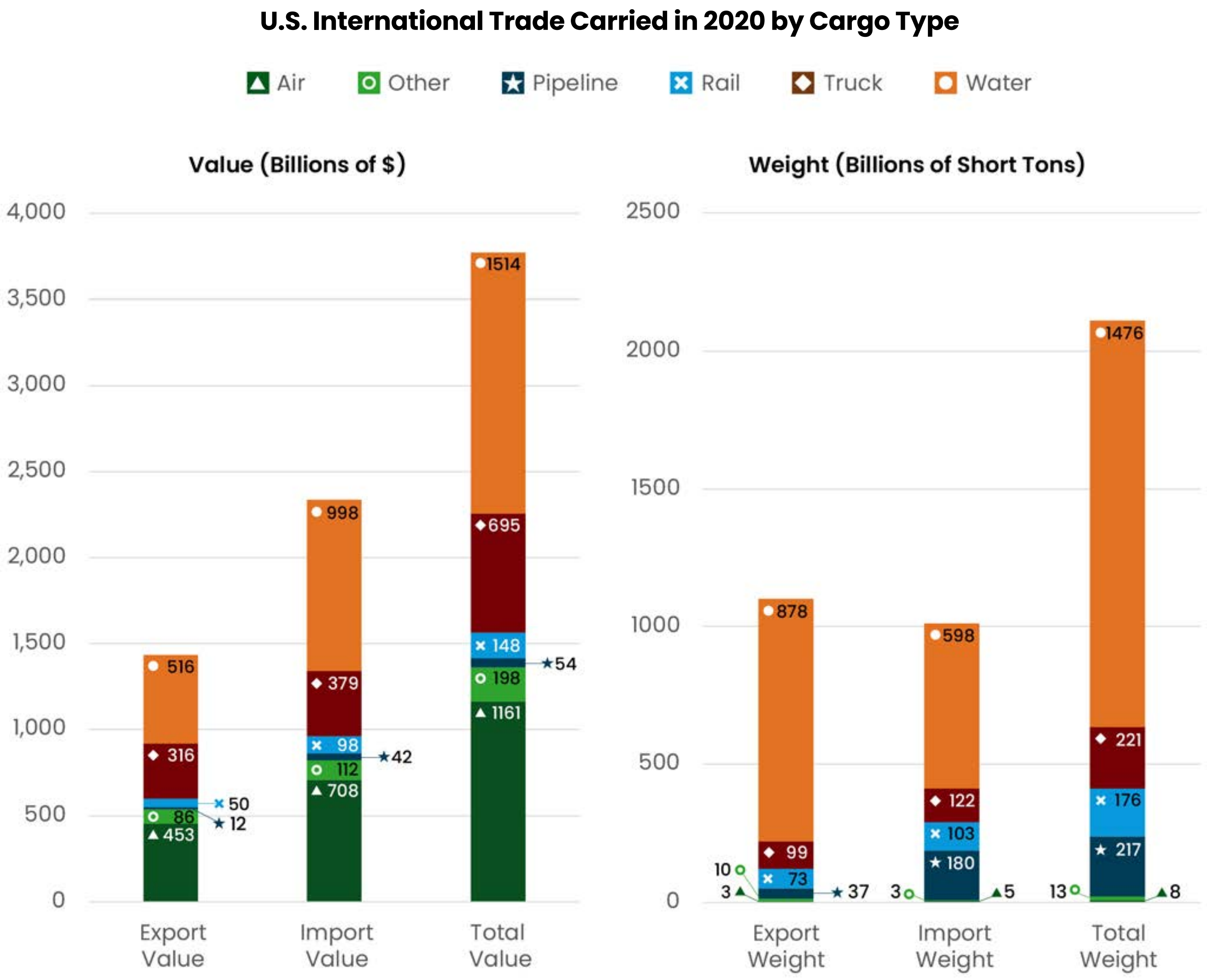


Figure 2 shows the total value and weight of goods transported to and from the United States using all modes of transportation. Freight movement by water, i.e., the maritime sector, accounts for a significant portion of goods movement within the United States.

This action plan describes opportunities for the U.S. government to deepen and accelerate maritime decarbonization, highlighting potential benefits for the U.S. economy, workforce development, and low-income communities.

There are several decarbonization strategies available to the industry, including energy efficiency, operations optimization, low- and zero-GHG emission fuels, electrification, and exhaust treatment. Each of these decarbonization strategies can be effective through the reduction of energy consumption and/or the reduction of life cycle GHG emissions. The maturity of various technologies within each decarbonization strategy varies, as some are conceptual while others are proven in commercial settings and widely used. This plan provides a comprehensive overview of the most important decarbonization pathways and actions to decarbonize the maritime industry.

2.1 Background

The maritime industry is the collection of vessels and ports involved in the transportation of materials, products, and people on the sea or connected waterways and all supporting coastal infrastructure. Domestic waterborne transportation is a safe, reliable, efficient mode of transportation and an established mainstay of America's national transportation system. Vessels registered to the United States are an integral part of this system. As of 2022, there are 178 ocean-going vessels, or OGVs (over 1,000 gross tonnage) in the U.S. flag privately-owned fleet. Of those, 93 vessels are Jones Act vessels.[16, 17] Based on U.S. Army Corps of Engineers data from 2021, there are more than 10,000 U.S.-flagged, self-propelled vessels operating domestically[18] that operate among more than 300 coastal and inland ports and across 3,700 marine terminals.[19] Additionally, there are roughly 11 to 12 million privately owned non-commercial vessels.[20] The U.S. military owns and operates approximately 6,500 boats and ships of varying sizes from small riverboats to ocean-going destroyers. The U.S. non-military fleet (National Oceanic and Atmospheric Administration [NOAA], Maritime Administration [MARAD], and National Science Foundation fleets) consists of about 2,000 vessels. The domestic fleet's vessels are not the only vessels that operate in American waters, as an estimated 8,000 foreign vessels complete approximately 50,000 port calls each year.[21] These ships vary tremendously in shape, size, and power requirements.

According to the IMO's Fourth Greenhouse Gas Study 2020, OGVs contribute about 3% of GHG emissions globally based on 2018 vessel activity data.[22] The study also showed that while the carbon intensity of shipping (e.g., carbon dioxide [CO_2] per ton-km) has decreased, overall emissions are still increasing. This indicates that the measures undertaken to date, such as efficiency improvements, are insufficient to curb, let alone counteract, the growth in GHG emissions from the sector. With the volume of global seaborne trade expected to continually increase through 2050,[23] CO_2 emissions from shipping could account for as much as 17% of the worldwide total by 2050 under a business-as-usual scenario. Vessels registered in the United States are likely to follow a similar growth trajectory and are likely to represent an increasingly significant portion of domestic emissions as other sectors scale up low- and zero-emission technologies.

If the maritime industry maintains a business-as-usual trajectory, GHG emissions are projected to increase from about 90% of 2008 emissions in 2018 to 90%–130% of 2008 emissions by 2050 for a range of plausible long-term economic and energy scenarios.[22]

Commercial maritime transportation faces unique challenges on its voyage to decarbonization:

- The industry is international in scope, and emissions reduction solutions need to be considered within the broader system of global ports, freight network, and fuel/energy infrastructure.
- Vessel owners and operators, port authorities, cargo owners, classification societies, fuel providers, and numerous others create a complex web of relationships. They all represent different parts of the maritime value chain, and each has unique incentives and profit drivers.
- The maritime industry's ability to adopt new technology is affected by decadal contracts, long periods between shipyard or maintenance visits, and high capital costs for new machinery and equipment, resulting in slow turnover rates.
- Heavy fuel oil (HFO) has been the primary fuel for maritime shipping. It is inexpensive, which presents economic barriers to adopting the more costly, low-GHG alternative fuels.
- Many maritime vessel decarbonization technologies (batteries, hydrogen, methanol, ammonia, etc.) have lower energy storage density on board the vessel relative to conventional fuels and propulsion systems, which affects vessel operations.

The challenge is particularly difficult for long-lived maritime assets like commercial vessels. With an average operating life of 30 years or more, the vessels being built today are likely to still be in operation by 2050 or beyond. As a result, these vessels should contribute to actively reducing GHG emissions and achieving the 2050 maritime emissions goals, and increasing the capability of vessels to use newer fuels will be increasingly needed.

The rest of this document will provide an overview of the domestic maritime industry (including vessels and ports), present decarbonization pathways available to the industry, then link those pathways to specific vessel segments, and finally identify specific actions of the agencies to realize the pathways in each segment, including discussion of research, development, and demonstration (RD&D) needs to support sector decarbonization.

2.2 The U.S. Maritime Sector

The U.S. maritime sector comprises a variety of components, including navigable waterways and channels; ports and marine terminals (liquid, dry, and break-bulk as well as container); intermodal connection pathways between waterborne and land transportation systems (highways and rail lines); vessels (commercial, non-commercial, and military); infrastructure (locks and dams); and offshore continental shelf structures (oil exploration and wind energy facilities).

It includes:[13]

- Over 300 ports
- 25,000 miles of navigable channels
- 236 locks at 191 locations
- More than 3,700 marine terminals
- 444 shipyards
- Almost 16.9 million U.S. cruise passengers[24]
- 47,000 federal aids to navigation
- 34,000 commercial fishing vessels
- 1,400 designated intermodal connections
- 233 ferry operators with 640 active vessels providing service through 515 terminals.

A key requirement for a number of these components is reliable fuel and energy sources to support a variety of purposes, including moving cargo around the port, vessel propulsion, and electrical power. Ports meet their energy needs using locally generated power sources or the regional electric grid. Vessels carry their energy in the form of fuels such as residual HFO, marine gas oil (MGO), marine diesel oil (MDO), or gasoline.

Cargo-handling equipment, such as rubber tire gantry cranes, drayage trucks, and short line locomotives, is certainly an important aspect of maritime commerce but is not considered in this document; those are included as part of the U.S. Off-Road, U.S. Rail, and U.S. Medium- and Heavy-Duty Action Plans. The remainder of this section characterizes the details of the U.S. fleet, including vessel numbers, energy, emissions, and fuel details.

2.2.1. FLEET COMPOSITION

Data from 2019 shows a domestic maritime fleet largely comprising of 34,000 commercial vessels,[25] approximately 11 to 12 million privately owned motorized non-commercial vessels,[20] and approximately 6,500 boats and ships owned and operated by the U.S. government for defense and research purposes (Figure 3).

U.S. Commercial Vessel Population in 2019 by Vessel Segment

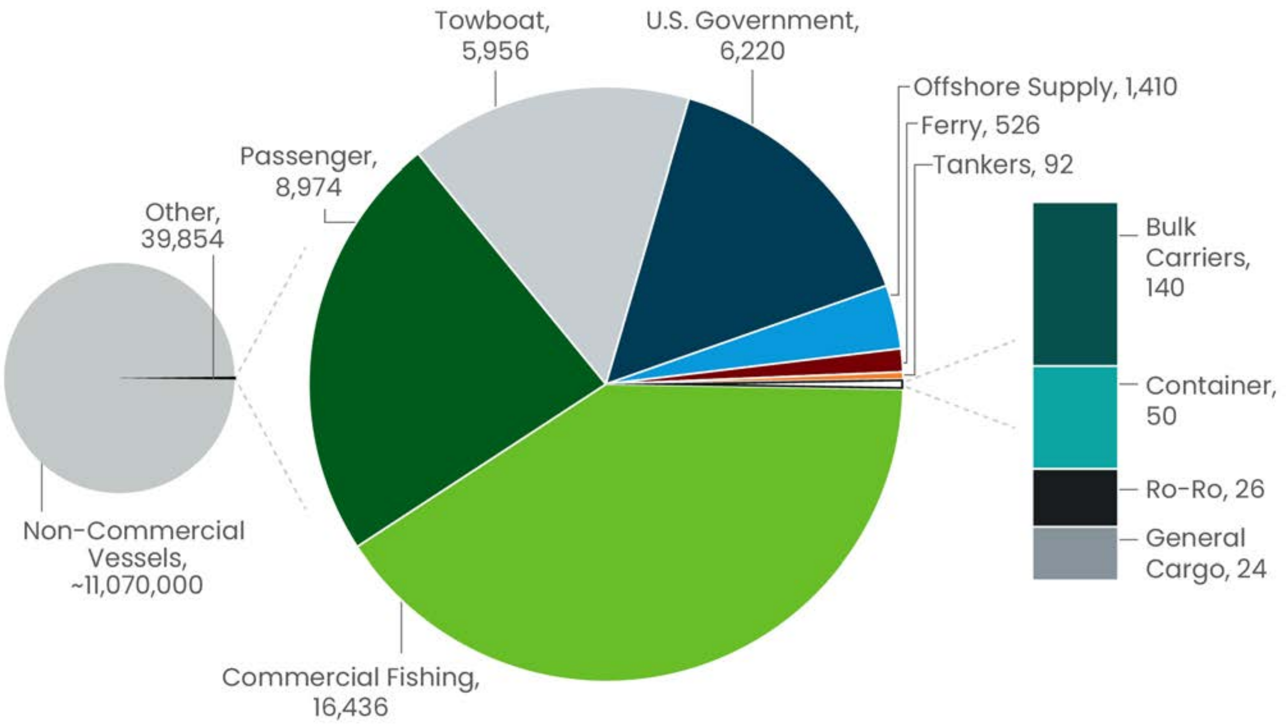


Figure 3 shows the U.S. commercial vessel population in 2019 by vessel segment and the distribution of the remaining number of vessels in the U.S. fleet for 2019 other than non-commercial vessels, which accounts for the vessel type groupings defined in Table 1. Harbor craft, such as commercial fishing vessels, passenger vessels, towboats, offshore supply boats, and ferries, had higher numbers of vessels than the number of U.S.-flagged OGVs, which did not have more than approximately 150 of any OGV type.

Understanding the differences among vessel types in terms of population, energy consumption, emissions, and replacement rates is key to focusing attention on those segments and approaches that could be most impactful for reducing GHG emissions in the coming years. It is important to note that every vessel is unique. Even though vessel types are grouped together within these segments, there will be enormous differences in hull shapes, size, energy demands, duty cycle, hours of operation, and other characteristics on a vessel-by-vessel basis.

Each federal and state government agency characterizes the U.S. fleet of vessels in different ways, which makes baselining the energy consumption, emissions, and number of vessels challenging. This strategy uses the grouping presented in Table 1, which blends ship classification methodologies used by the U.S. Coast Guard (USCG), U.S. Army Corps of Engineers, MARAD, and the U.S. Environmental Protection Agency (EPA).

Table 1: Vessel categories in the maritime industry considered in the action plan

Category	Grouping	Included Vessels
Ocean-Going Vessels	Bulk Carriers	Bulk Carriers
	Container Ships	Containers
	Roll-On/Roll-Off (Ro-Ro)	Ro-Ro Vehicle Carriers
	Tanker	Liquid Bulk Carrier Petroleum/Chemical Carrier Other Tankers
	Cruise Ships	Cruise Ships
	General Cargo	General Cargo
	Ocean-Going Commercial Fishing	Fishing Vessels
Harbor Craft	Commercial Fishing	Fishing Vessels
	Offshore Supply	Offshore Supply
	Ferries	Ferries
	Passenger	Passenger Combination Cargo/Passenger Excursion/Sightseeing
	Tows/Barges	River Towboats/River Barges
	Harbor Tugs	Push Boats Tugboats
Government	Government-Owned	Department of Defense Non-Defense
Non-Commercial Vessels	Low Power (<50 hp)	Personal Watercraft Personal Fishing Pontoon Runabout
	High Power (>50 hp)	Personal Watercraft Pontoon Personal Fishing Runabout
	High Use	Rental fleet* Privately owned, highly used

**Rental fleets can include any non-commercial vessels listed above, under <50 and >50 hp categories.*

The average annual hours of operation by vessel type are shown in Figure 4. While non-commercial vessels compose greater than 99% of the U.S. fleet, they are used on average only 35 to 48[26] hours per year, a fraction of the time commercial vessels (harbor craft or OGVs) are used. Some non-commercial vessels have higher average annual use, such as personal watercraft used in rental fleets (about 156 hours/year). OGVs, which account for the fewest number of ships in the U.S. fleet, are used on average of 6,000 to 7,200 hours annually, operating for approximately three-quarters of the year for days or weeks at a time. Harbor craft on average operate between 1,000 and 3,500 hours per year for shorter periods of time, for daily operations (e.g., daily ferry operations) seasonally, or for continuous operation for several days or weeks. The vast difference in annual hours of operation between vessel types will be a significant factor in their respective decarbonization strategies.

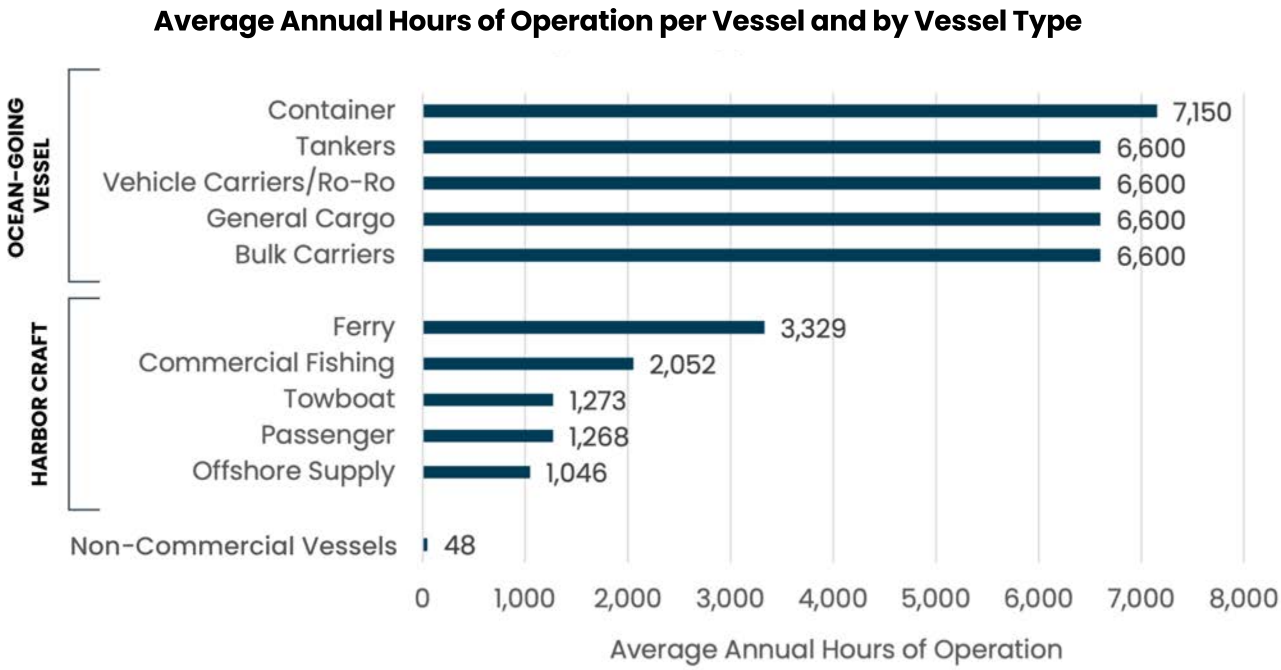


Figure 4: Average annual hours of operation per vessel and by vessel type

2.2.3. FLEET ENERGY CONSUMPTION AND EMISSIONS

To put vessel energy needs in more context, a container ship that carries 10,000 twenty-foot containers is likely outfitted with a large, slow-speed diesel propulsion engine. A Panamax container ship can consume 63,000 gallons of maritime fuel per day[27]—for comparison, a typical 21-foot outboard powered boat[28] can have an 80–100 gallon fuel tank, and the average gas tank of a passenger vehicle in the United States holds 12–20 gallons of fuel. This example does not represent the entire fleet, but it does highlight the immense energy needs for some vessels. Differences in engine duty cycle, maintenance, hull fouling, bad weather, navigation inefficiencies,[29] and numerous other factors can lead to substantial differences in total energy consumption between vessels when measured over time, even for seemingly identical vessels.

In the United States, there are three main maritime fuels: residual fuel oil, distillate, and gasoline. Residual fuel oil is typically used to power the main propulsion engines on large OGVs. Distillate fuel (including "diesel" fuel) is used by auxiliary engines on large OGVs and for the main propulsion engines on harbor craft and some larger non-commercial vessels. In the United States, gasoline is the main fuel for non-commercial vessels. Alternatives to these fuels such as renewable natural gas (RNG), biofuels, methanol, ammonia, clean hydrogen, and battery electric do not yet have widespread adoption, and there is no data available for tracking their uptake across the U.S. fleet. Therefore, they are not considered in these baseline fuel use estimates but are considered in later sections. Figure 5 shows the annual energy consumption by vessel type in 2019. While non-commercial vessels have the lowest use rate and smallest deadweight tonnage[g] of the vessel classifications, the fleet consumes almost the same amount of energy overall as all the other vessel types combined. Despite the low numbers of large OGVs that bunker (take on fuel) in the United States, they can consume significant quantities of fuel per ship, as was portrayed by the example of a large container ship. Among harbor craft, there is a wide degree of variation in the quantities of energy consumed by each vessel type.

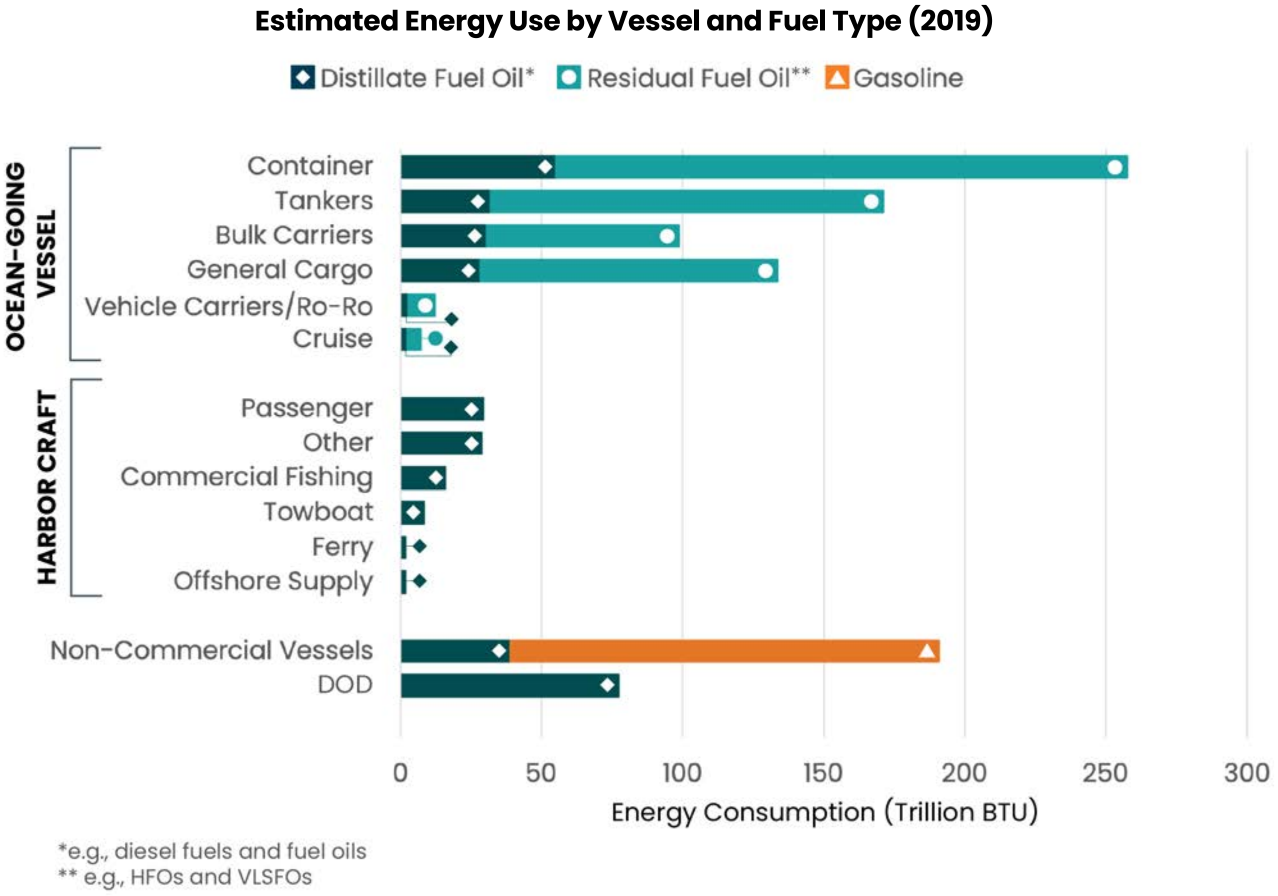


Figure 5: Estimated energy use by vessel and fuel type (2019). Figure Source: National Renewable Energy Laboratory.

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[g] Deadweight tonnage is the total weight a ship can carry, not including the weight of the ship.

Combustion of fuel in internal combustion engines (ICEs) leads to emissions of GHGs and air pollutants. The Action Plan for Maritime Energy and Emissions Innovation considers GHG emissions resulting from all maritime fuel supplied in the United States, including fuel combusted abroad and used in government vessels. The GHGs considered are CO_2, methane (CH_4), nitrous oxide (N_2O), and hydrofluorocarbons (HFCs) which are reported in CO_2 equivalent (CO_2e) using AR5 100-year global warming potential (GWP).[12] Stack, or tank-to-wake (TTW), GHG emissions associated with all maritime fuel supplied in the United States are estimated to total 81.1 million metric tons (MMT) CO_2e in 2019. The total amount of maritime GHG emissions from the United States (U.S.-flagged, bunkered in the United States, and U.S. Department of Defense [DOD] vessels) is estimated at approximately 101.2 MMT on a well-to-wake (WTW) basis. Emissions attributed to each vessel segment are shown in Figure 6. Non-commercial vessels were responsible for almost half of CO_2 emissions from the U.S. fleet, similar to their percentage for energy consumption.

Figure 6 provides perspective on the relative composition and contribution of each vessel type in the U.S.-flagged fleet to the total number of vessels, nautical miles traveled, annual energy consumption, and annual GHG emissions based on 2019 data. Non-commercial vessels dominate the fleet by numbers but represent just under half of total fleet energy consumption and contribute just under half of total fleet stack GHG emissions. The other half of GHG emissions is from a mixture of harbor craft and OGVs with important shares from bulk carriers, containers, towboats, commercial fishing vessels, and government vessels. The top image shows only U.S.-flagged vessel stack emission while the bottom image accounts for emissions related to fuel sold in the United States regardless of flag due to the limited number of U.S.-flagged vessels. This is very important because many emissions come from foreign-flagged vessels that bunker in the United States. These emissions still need to be accounted for in the U.S. maritime decarbonization strategy. Emissions from foreign-flagged vessels that do not bunker in the United States are unaccounted for in either image because there is currently no accurate way to estimate this data.

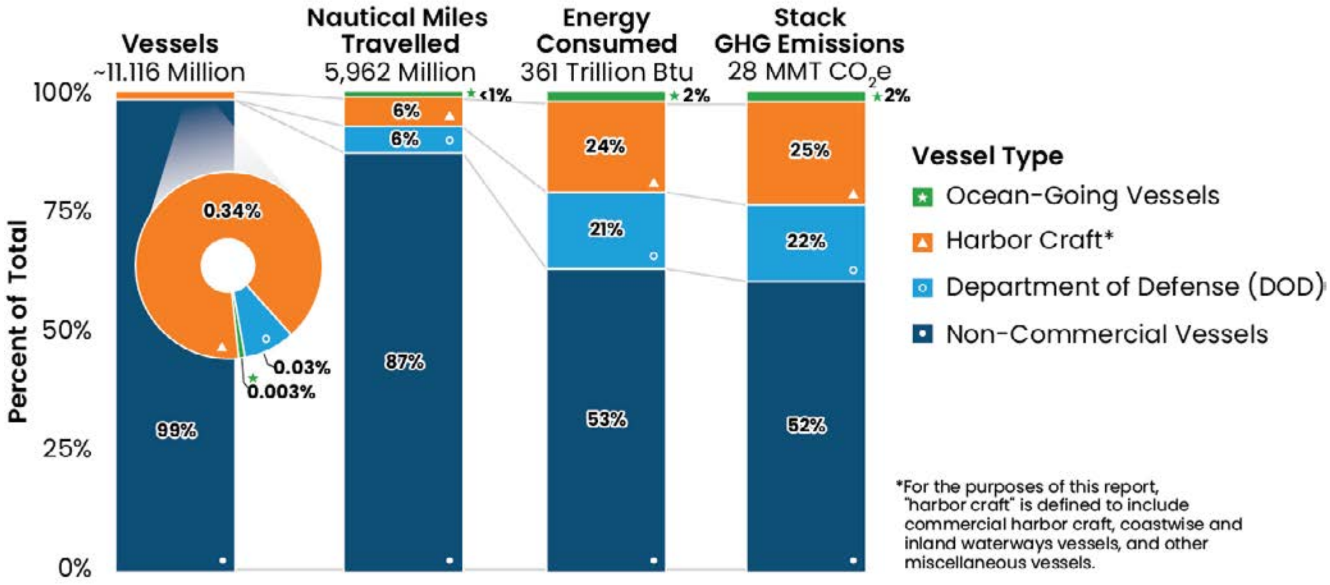
While determining strategies for decarbonizing the U.S. maritime industry, it is important to note that the U.S. fleet is not responsible for all maritime energy consumed or GHG emissions in the United States as most OGVs visiting U.S. ports are registered internationally (foreign-flagged vessels). To account for these emissions, the action plan also incorporated fuel that is bunkered to these foreign-flagged vessels. As seen in Figure 6, OGVs become a much larger portion of the energy consumed and GHG emissions by fuel sold within the United States, while non-commercial vessels, harbor craft, and government vessels become a smaller portion.

2.3 Contributing to a Just Transition

Environmental justice and equity issues in the maritime sector are significant concerns that highlight disparities in the distribution of environmental benefits and burdens, as well as the impact of maritime activities on underserved, overburdened, and low-income communities. Actions taken to decarbonize the maritime sector and ports should make every effort to mitigate and improve on these impacts. In addition, ensuring the creation, retention, and improved access to high-quality jobs and career pathways in marginalized communities and throughout the maritime sector should be a key outcome, and will be a key enabler, of decarbonization. Several key aspects contribute to understanding these issues in the context of the maritime sector:

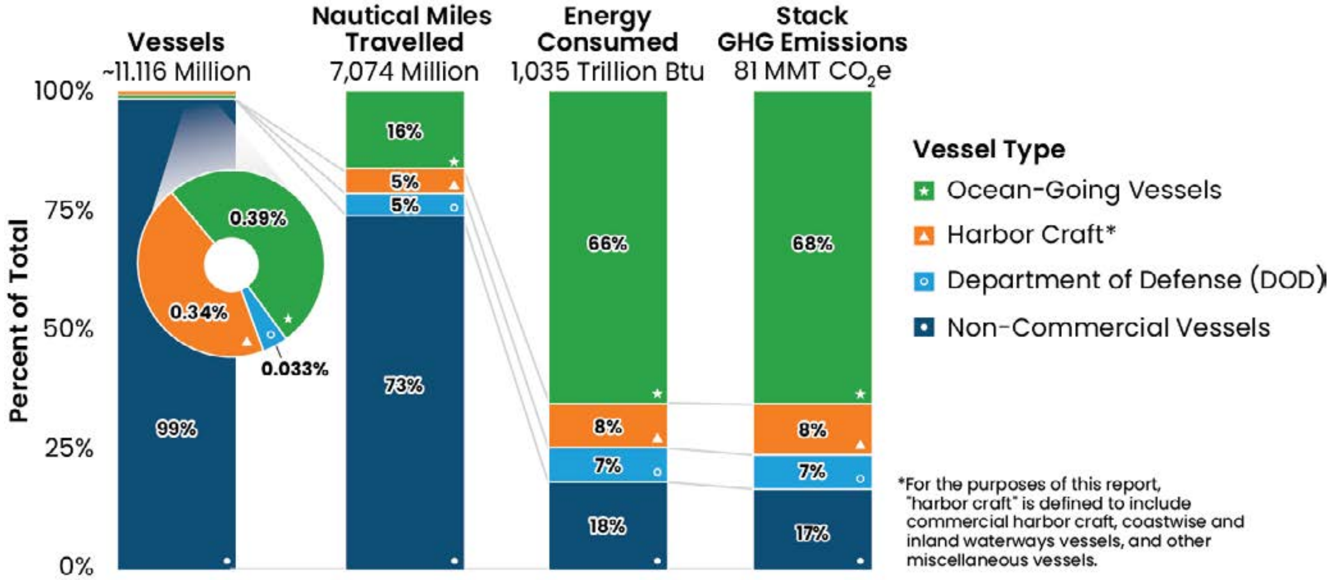
Air Pollution: Port communities, often located in low-income neighborhoods, bear the brunt of air pollution from maritime activities. Emissions from ships, trucks, and port equipment contribute to poor air quality, leading to adverse health effects for nearby residents. The emissions from shipping traffic, including sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM) contribute to air pollution in coastal areas. Communities residing near major shipping routes and ports are

Portion of TTW (stack) GHG emissions by U.S.-flagged vessels per maritime market segment as compared to the portion of TTW (stack) GHG emissions by fuel sold in the United States to both U.S.-flagged and foreign-flagged vessels per maritime market segment



*For the purposes of this report, "harbor craft" is defined to include commercial harbor craft, coastwise and inland waterways vessels, and other miscellaneous vessels.

U.S.-flagged and foreign-flagged vessels per maritime market segment



*For the purposes of this report, "harbor craft" is defined to include commercial harbor craft, coastwise and inland waterways vessels, and other miscellaneous vessels.

Figure 6: Percentage of vessels, their miles traveled, energy consumption, and stack GHG emissions for U.S.-flagged vessels operating from U.S. ports (top) and emissions related to fuel sold in the United States regardless of flag (bottom) state.

disproportionately exposed to these pollutants. Low-income communities and communities of color are more likely to live near ports.

Community and Safety Disruptions: The noise and vibrations generated by port operations disproportionately affect nearby communities. The construction of new fuel and energy infrastructure, including shore power and fast-charging infrastructure, represent additional disruptions to communities near ports, which may affect property values. Construction, road closures, and new pipelines or electric lines contribute to noise, dust, and other community and safety concerns. Low-income neighborhoods and communities of color near ports may experience higher levels of stress and health issues due to constant disruptions.

Displacement of Local Communities: Large-scale coastal development projects, including ports and shipping terminals, can lead to the displacement or bisection of local communities. Indigenous communities may lose access to traditional lands, impacting cultural practices and social cohesion. Additionally, climate change-induced sea-level rise poses a threat to coastal communities, particularly those with limited resources.

Economic and Social-Environmental Disadvantages: Employment opportunities in the maritime industry are inequitably distributed. Low-income communities face barriers to accessing well-paying jobs in the sector, contributing to socio-economic disparities. Indigenous and coastal communities face challenges in retaining access to traditional maritime resources, such as fisheries and seaweed farming, due to a failure to consider their rights in carrying out commercial activities and developing regulatory frameworks. Disparities in regulatory compliance and enforcement can exacerbate environmental justice issues. Communities with less political influence and fewer economic resources struggle to ensure that environmental regulations are enforced.

It is important to understand the above issues, including the historic context, so that they can be addressed or avoided in the future as the industry undergoes changes to move to a low-GHG and lower-emissions sector. Additional discussion of workforce issues is included in section 5.1.

U.S. port operating near local communities.

3. EMISSIONS AND ACCOUNTING

3.1 Sector Emissions and Accounting

This action plan's baseline emissions data represents direct GHG emissions from the use phase of vessels, often referred to as stack emissions or TTW emissions. This data accounts for approximately 80%–90% of full life cycle or WTW GHG emissions when operating on combustion of fossil fuels. However, the maritime sector also includes GHG emissions that, on a life cycle basis, come from direct and indirect sources associated with the production and distribution of fuels and electric power—including fuels/power used at ports and on board vessels; from vessel manufacturing and end-of-life disposition of vessels; and from construction, maintenance, and disposal of supporting infrastructure. Future versions of the action plan should account for these full life cycle emissions, as practicable, which are particularly important to consider when evaluating potential alternative fuels. One example model for evaluating emissions on a life cycle basis is the Greenhouse gas, Regulated Emissions and Energy use in Technologies (GREET®) model, which has been developed to address direct and indirect emissions across transportation sectors, and adapted and customized for specific uses.

Many transportation decarbonization solutions rely on electricity directly or indirectly through the production of hydrogen or other sustainable electrofuels (e-fuels). Therefore, decarbonizing the electric grid by 2035, largely through new solar and wind energy development, will be a critical co-strategy to support transportation decarbonization.

The carbon emissions from the full life cycle of a product or service—often referred to as "embodied carbon"—are significant and must be addressed in all strategies to decarbonize transportation and when considering alternative pathways. This is a core tenet of the overall Blueprint. Figure 1 (above) identifies transportation as 33% of economy-wide emissions. To avoid double counting across sectors and modes within sectors, this figure only addresses direct emissions. Similarly, the baseline estimates of maritime emissions in Figure 6 represent the direct stack GHG emissions. While decarbonizing upstream emissions from other economic sectors (e.g., electric power generation, industry, commercial and residential, and agriculture) is the focus of other government-wide initiatives that complement this action plan, consideration of the overall life cycle emissions of fuel, energy, and vessel construction and decommissioning is essential to avoid adopting policy solutions that inadvertently increase the sector's overall emissions rather than drive them down.

3.1.1 ESTIMATED EMISSIONS

Combustion of fuel in ICEs leads to emissions of GHGs and air pollutants. The action plan considers GHG emissions resulting from all maritime fuel supplied in the United States, including fuel combusted abroad and used in government vessels. The GHGs considered are CO_2, CH_4, N_2O, and HFCs and are reported in CO_2e using AR5 100-year GWP.[30] Stack, or TTW, GHG emissions associated with all maritime fuel supplied in the United States are estimated to have totaled 81.1 MMT CO_2e in 2019 (Figure 8).

The action plan recognizes the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories, also known as the good practice guidance on the reporting of emissions from ships in international transport. The action plan is not intended to supersede or comment on accounting for the purposes of Nationally Determined Contributions under the Paris Agreement. Rather, the action plan recognizes that reductions of GHG emissions from maritime fuels sold in the United States would result in decreased emissions regardless of the flag of the vessel.

Based on U.S. fuel sales (U.S. and foreign-flagged), EPA estimates that in 2019, 40 MMT CO_2e of GHGs were emitted domestically from the maritime sector, excluding government vessels.[30, 31] Total stack GHG emissions from domestic operation of commercial vessels were 26.3 MMT CO_2e (32%), and non-commercial vessels emitted 13.8 MMT CO_2e (17%) (Figure 7). Additionally, international bunkering fuel, residual fuel oil, and distillate fuel oil sold in the United States, but combusted abroad, accounted for 35.3 MMT CO_2e (44%) of GHG emissions in 2019. It is important to note that emissions from foreign-flagged vessels that do not bunker in the United States are excluded from these numbers. Current methods to estimate these emissions are being developed. Combined, stack GHG emissions from domestic commercial vessels, domestic non-commercial vessels, and international bunkering fuel totaled 75.3 MMT CO_2e in 2019, accounting for approximately 3% of U.S. transportation GHG emissions.[2] More recent analysis suggests this estimate to be approximately 4% (See Figure 1). Additionally, DOD ships accounted for approximately 5.75 MMT CO_2e in 2019, or approximately 7% of maritime TTW GHG emissions.[32]

Stack TTW GHG Emissions Based on U.S. Fuel Sales

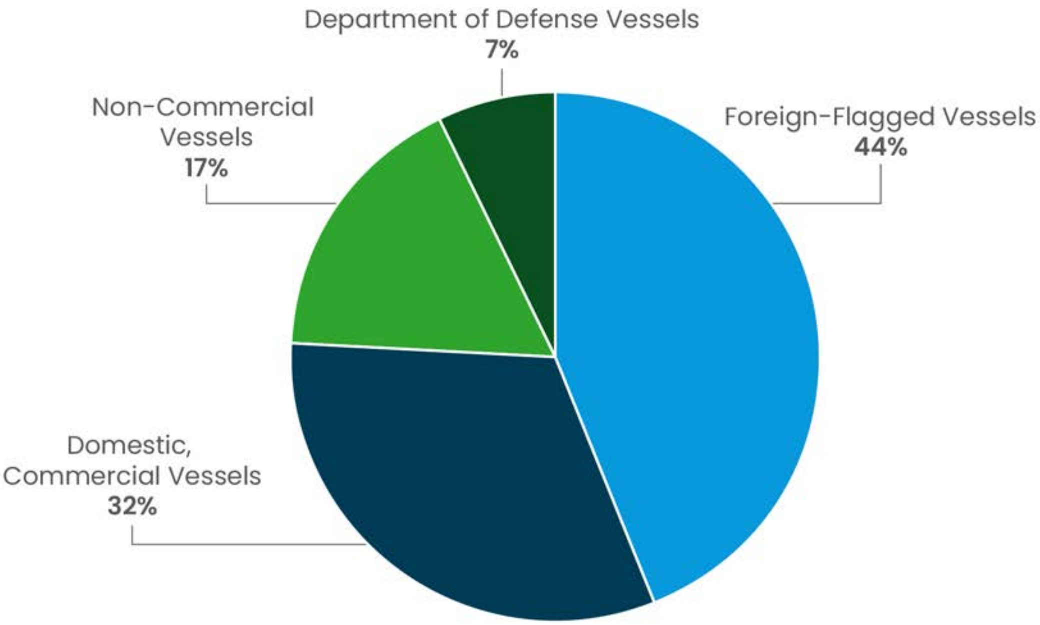


Figure 7: Relative amounts of stack produced (TTW) GHGs as measured in CO_2e of U.S. maritime fuel sales

GHG emissions estimates, consisting of emissions associated with the combustion of residual fuel oil, distillate fuel oil, and gasoline, are presented in Figure 8 for non-commercial vessels, harbor craft, OGVs, and DOD vessels. Residual fuel oil accounts for over half (53%) of all maritime GHG emissions, distillate fuel oil—including diesel—accounts for over a quarter (28%), gasoline accounts for approximately 15%, and HFCs account for the remaining 5%.

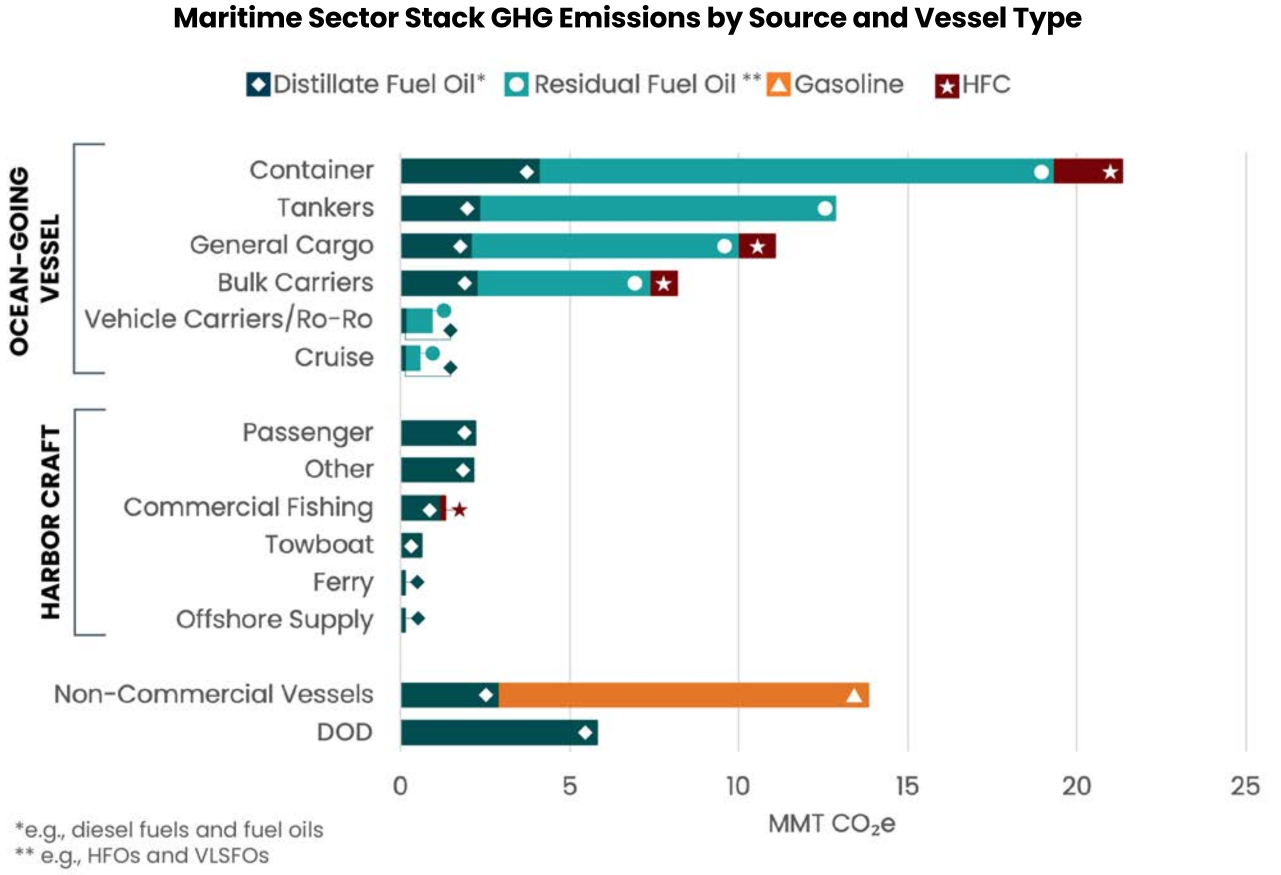


Figure 8. Maritime sector stack GHG emissions by source and vessel type

Over 99% of vessels registered in the United States are non-commercial vessels and account for approximately half of energy consumed by U.S.-registered vessels and GHG emissions from U.S.-registered vessels (Figure 6). That proportion diminishes significantly (17%; 14 MMT CO_2e) when considering all maritime fuel supplied in the United States in 2019. Harbor craft stack GHG emissions contribute 7% (5.7 MMT CO_2e) while OGVs account for 65% of all stack emissions (53 MMT CO_2e). Of this 65%, most OGV emissions are attributable to vessels that do not fly a U.S. flag but rather bunker within the United States. Of these OGVs, only 0.7% (0.57 MMT CO_2e) are estimated to originate from U.S.-flagged OGVs.

Full fuel life cycle emissions, or WTW emissions, capture all upstream emissions from producing, transporting, and storing fuels in addition to stack emissions, but don't consider vehicle manufacturing and emissions associated with infrastructure to support maritime. When considering full fuel life cycle emissions associated with the use of residual fuel oil, distillate fuel oil, and gasoline, 2019 maritime energy consumption is estimated to result in life cycle GHG emissions of 101.2 MMT CO_2e. Figure 9 shows estimated total WTW GHG emissions and stack GHG emissions for each vessel type.

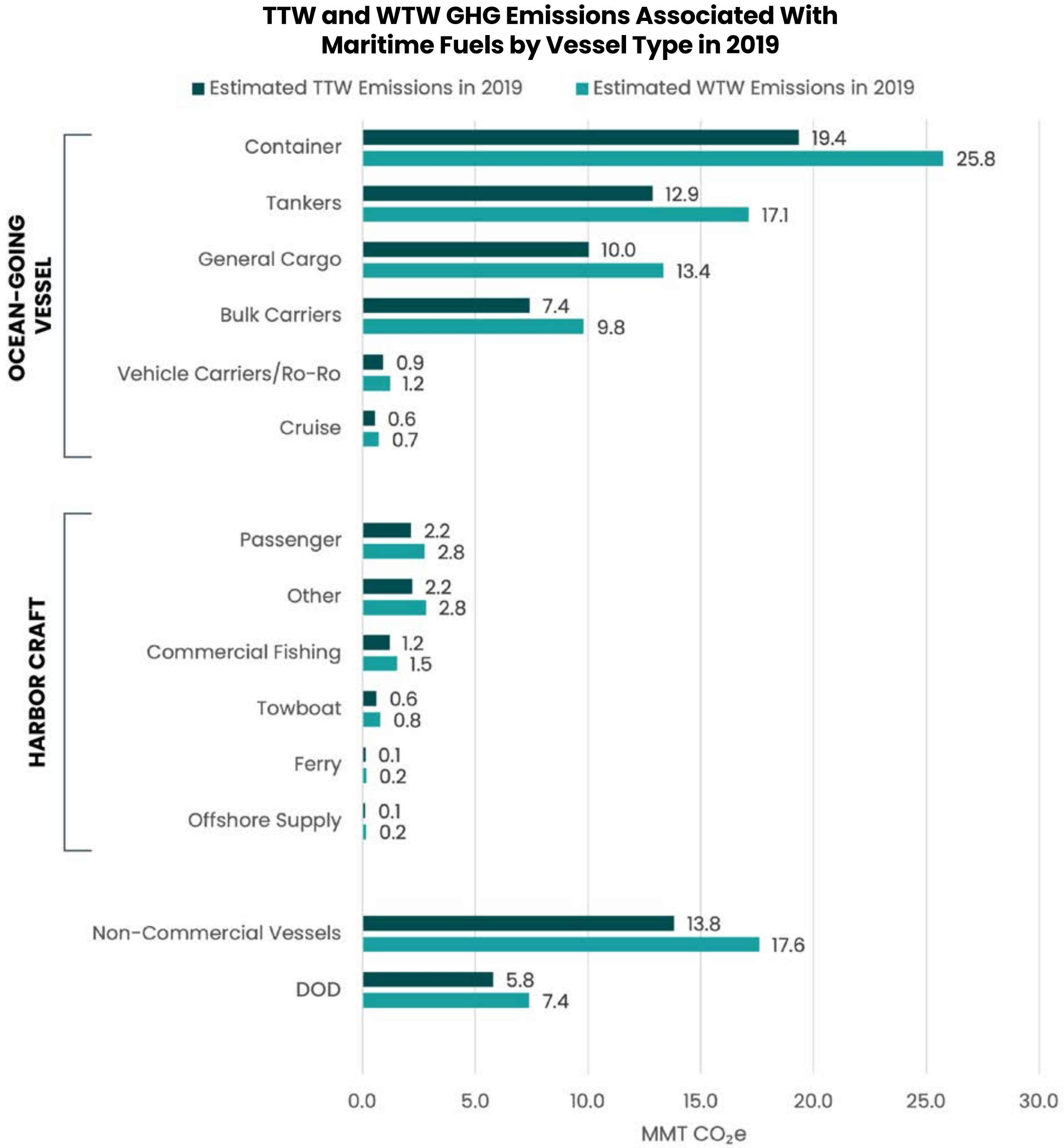


Figure 9. TTW and WTW GHG emissions associated with maritime fuels by vessel type in 2019. Note: HFCs are excluded for TTW emissions. Data Sources: GHGI,[29] GREET2023,[30] USCG,[24] Volpe.[33]

3.1.2 ACCOUNTING FOR EMISSIONS (METHODS AND LIMITATIONS)

This action plan starts reporting 2022 stack (TTW) emissions for the initial GHG estimates for the maritime sector as they relate to the other U.S. transportation sectors, reported at 4% of total emissions. These emissions correspond to the classification used by EPA in their GHG Emissions Inventory. Upstream emissions, such as electricity production or vessel construction, are accounted for in different sectors in the EPA GHG Emissions Inventory. To be consistent with the EPA methodology, we do not include life cycle emissions for our initial estimates for the maritime sector GHG emissions in this report. For the 2022 emissions, life cycle emissions track very closely with stack emissions (accounting for approximately 80% to 90% of total life cycle emissions),[30] as nearly all vessels rely on fossil fuels. However, the total emissions reduction potential of different technology pathways depends in part on the upstream emissions. For example, ammonia produced through the traditional Haber-Bosch (HB) process with natural gas as a feed has significantly more production-related GHG emissions than ammonia produced using waste CO_2 from an ethanol production facility and renewable electricity.[h] Currently, use-phase emissions make up the bulk of GHG emissions for a vessel. However, there are many examples where the upstream emissions far outweigh the reduction in stack emissions during the use phase, even for zero-emission technologies. For example, GHG emissions from battery manufacturing for non-commercial vessels with very low annual hours of use are significant. Similarly, although ammonia-burning technologies have very limited CO_2e emissions, current ammonia production pathways produce so much GHG that the overall life cycle emissions of utilizing ammonia are worse than simply using HFO.[30]

Building out a data pipeline to estimate life cycle emissions for the maritime sector is a near-term priority. We assume that by 2050, clean electricity and clean hydrogen will be abundant, based on the current trajectory of these sectors. The clean electricity grid will be powered by various sources including solar, wind, hydropower, biomass, geothermal, and nuclear facilities in the interim, understanding the upstream emissions implications for different fuel types and operating profiles and locations is important for prioritizing deployment of different equipment types. For example, replacing a highly used diesel ferry that operates on a highly specified route in a location with access to clean electricity with an electric ferry will lead to greater GHG emission reductions than replacing an infrequently used ferry that operates on an as-needed basis where the grid is still heavily reliant on coal.

Life Cycle Analysis

The data reported in this action plan is direct emissions from the use phase of vessels and transportation systems (i.e., stack emissions). However, the strategies and recommendations in this action plan consider full life cycle GHG emissions, including the production and end-of-life phases of vehicles and fuels/energy sources. These life cycle emissions cover GHG emissions from fuel production and processing; vessel manufacturing and disposal; and construction, maintenance, and disposal of transportation infrastructure. Inclusion of these life cycle emissions is important as the U.S. transportation sector evolves towards new powertrain systems with new fuels/energy sources. The Department of Energy (DOE) has a long history of using life cycle analysis (LCA) to assess energy technologies and inform how we can advance these systems and reduce their environmental footprint. For the transportation sector, the GREET model is a suite of publicly available, best-in-class models used by the federal government and other stakeholders to assess the energy and environmental impacts of vehicles, fuels, chemicals, and materials across their life cycles. While the GREET model originated with a focus on transportation technologies, GREET currently covers the full life cycle, including manufacturing, industrial, and power sector impacts.

Reducing and ultimately eliminating life cycle emissions from these sectors is critical to achieving a fully sustainable transportation future and economy-wide decarbonization. While these modal plans are targeted to a given mode, related strategies and plans are subject to other government-wide initiatives that complement the Blueprint. For example, decarbonizing the electric power sector is identified as a key long-term strategy of the United States. Although outside the scope of this action plan, this co-strategy would greatly reduce the emissions associated with energy production that is used to power EVs and transportation systems. In summary, these action plans focus on the transportation use phase, but acknowledging a whole-of-government approach across multiple sectors and agencies is truly necessary to eliminate all GHG emissions along every phase of the life cycle of the transportation system.

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[h] Appendix B.1.3: Ammonia, Figure B, GHG intensity of ammonia

4. MARITIME DECARBONIZATION TECHNICAL CONSIDERATIONS

A commercial vessel lifespan ranges 15–70 years or more depending on vessel type and operation. As shown in Figure 10, the average age is about 30 to 35 years, with some outliers over 100 years old. This means the ships being built in 2024 will likely be in operation beyond 2050. This highlights the need for immediate action to increase the ability of these vessels to accommodate new sustainable maritime fuels (SMFs) or technologies to meet future GHG emissions reduction targets. Understanding and planning for certain constraints will be key to developing a comprehensive strategy to transition the fleet and decarbonize the U.S. maritime industry. Many constraints were considered when developing the overall maritime decarbonization strategy presented in section 6 of this report. The first type of constraints that were considered revolve around the maritime sector itself and its ability to transition to new technologies. The main sector constraints considered were 1) vessel replacement rates, 2) uptake of advanced technologies (including repowering and retrofitting), and 3) availability of SMFs. The action plan also considered constraints around route characteristics for the specific vessel type, mode of operations, fuel and energy sources, and fueling infrastructure. This report does not include analysis related to U.S. investment in low- or zero-emission ship building, but given the strategic importance and economic implications of domestic ship building, we recommend that such a strategy be published in a future Blueprint Action Plan.

U.S. Commercial Vessel Age by Vessel Segment, 2022

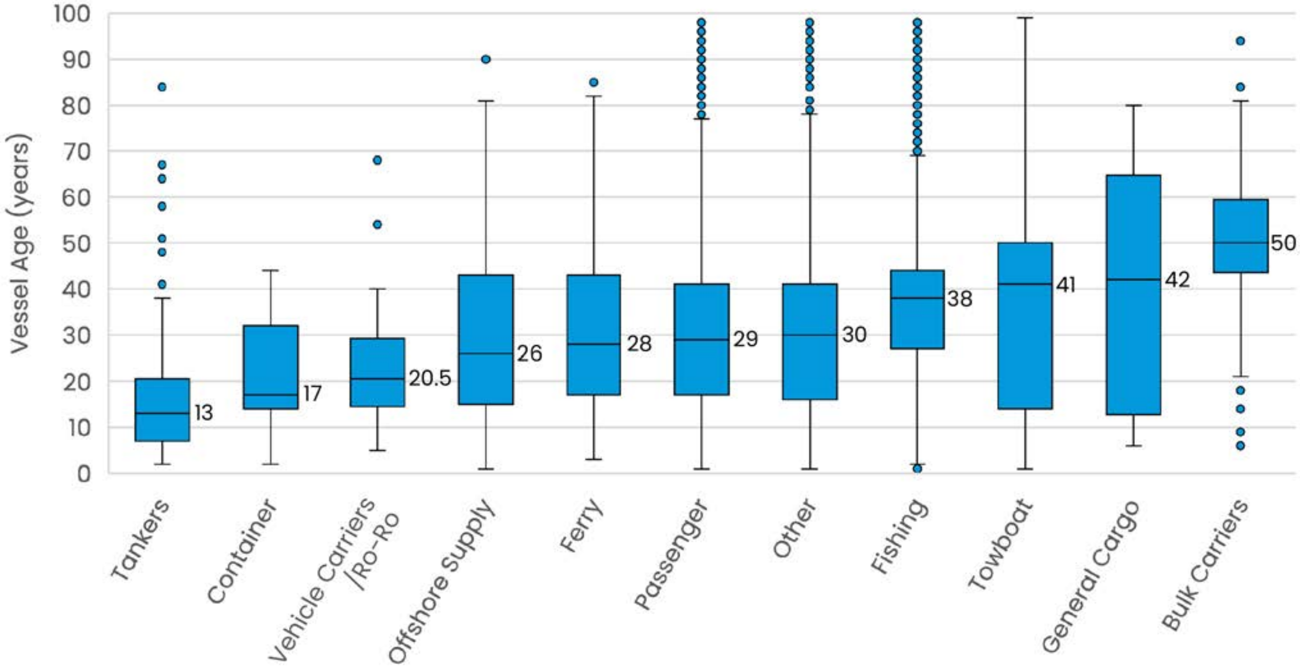

Figure 10: Vessel age for U.S. fleet segments for operating commercial vessels with valid or pending USCG certificates of documentation[5, 34–37]

4.1 Maritime Sector Constraints

Constraint #1: Vessel Replacement Rates

The associated annual replacement rates of vessels in the United States are very low, resulting in a need for a blend of fuels and technologies to ensure the fleet in 2050 can meet decarbonization targets. This low replacement rate is caused by many factors, including the large cost for new OGVs and harbor craft, the time to construct the new vessels, the limited availability of U.S. shipyards and dry docks, and individuals purchasing non-commercial vessels for pleasure and not necessity.

Where a vessel operates often impacts how long the vessel remains in service. Vessels that operate mostly in freshwater experience longer lives compared to vessels that operate mostly in saltwater, largely due to freshwater being less corrosive than saltwater. There are several commercial waterways in the United States that are freshwater, specifically the Great Lakes region and major river systems like the Mississippi River.

In comparison to other vessel types, large ocean-going cargo vessels such as containers, Ro-Ros, and tankers have low production volumes in the United States: typically, one or two ships built per year. The production rate of each commercial vessel segment in the United States from 1990 through 2021 is shown in Figure 11. This data does not capture all vessels that enter the fleet, as some may be “reflagged” to change the country of registration. Over 92% of commercial vessels operating in the United States are built domestically, which aligns with the requirements of the Jones Act.[17]

The rate of new commercial vessel construction across all segments in the United States has been gradually declining since a peak in the early 1980s. In 1981, several support systems that allowed U.S. ship building to grow were withdrawn. For example, Title V of the Jones Act (Merchant Marine Act of 1936) allowed subsidies for the construction of foreign-trade ships, whereas Title VI provided subsidies for their operation.

Examples

Non-Commercial Vessel Turnover Rates

The average annual scrappage rate for non-commercial vessels from 2015 to 2019 was only about 1.7%. This means if all new non-commercial vessels were to switch to alternative low carbon intensity fuels, such as clean methanol or clean hydrogen, or go fully electric, starting in 2024, 44% of non-commercial vessels in 2050 will still be dependent on drop-in biofuels or e-fuels. Differences in engine technology availability and fuel applicability will contribute to these adoption rates as well—drop-in fuels could extend the life of younger in-service vessels while allowing new engine technologies that are compatible with alternative fuels to enter the market as older vessels age out and are replaced.[26]

The Jones Act

The “Jones Act” refers to a section of the 1920 Merchant Marine Act that, strictly speaking, only applies to cargo being transported by water between two points in the United States. The law requires that this cargo is to be shipped solely aboard vessels that are U.S. built, U.S. citizen owned, registered in the United States, and crewed by Americans. The goal of this regulation is to encourage a strong U.S. Merchant Marine, including a robust U.S. commercial shipbuilding industry, for both economic security and national defense by fostering a U.S.-flag fleet that can contribute to U.S financial well-being, and act as a sealift resource for the transportation of supplies in time of contingency.

While this poses significant challenges to upgrading and replacing U.S. vessels on a timeline aggressive enough to reach U.S. goals for decarbonization, there remain distinct opportunities to grow and modernize the U.S maritime sector while expanding the workforce and generating domestic economic benefits.

Title XI of the same act provided guaranteed financing from the U.S. government to build U.S.-flag ships in U.S. shipyards. The subsidy under Title V and the guaranteed financing under Title XI were eliminated in August 1981 under the Omnibus Budget Reconciliation Act.[38, 39] As a result, U.S. ship production gradually fell. Another sharp decrease occurred in the year 2000. In 1999, the United States handed over the Panama Canal to Panama, and several U.S. ships strategically switched flags to Panama. The current total production volume of commercial vessels is almost half of its value from two decades prior. More recently, from 2012 to 2018 the rate of commercial vessel production hovered around 200 vessels per year but began to decline in 2019 and reached 177 vessels in 2023 (Figure 11). By way of comparison, there are well over 50,000 vessels globally.[40] These estimates do not include non-commercial vessels, which have significantly higher domestic production.

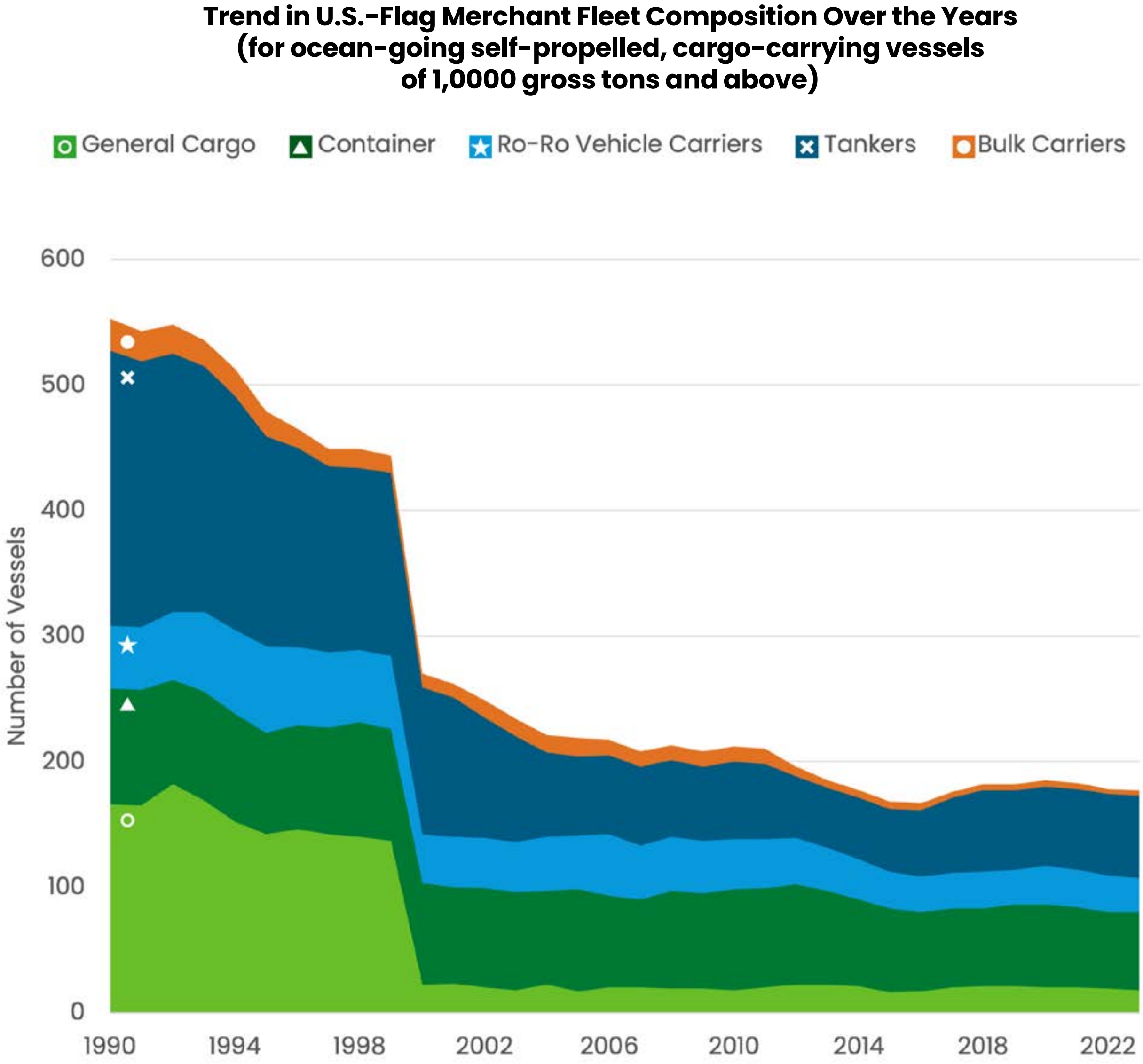

Figure 11: Annual production rate of U.S. commercial vessels (1990–2023).

Constraint #2: Uptake of Advanced Technologies

Adoption rate of advanced technologies is an indicator of how quickly newer technologies will enter the mainstream market and be incorporated into vessel designs and normal operations. Ongoing investment in research and development are crucial for the continuous improvement and adoption of newer technologies. Funding and support for innovative projects contribute to the evolution of the maritime industry. Emissions standards and incentive programs may drive faster adoption rates. Total cost of ownership also impacts adoption rates. The federal government can play an active role in supporting each of these factors. Vessel owners and operators are interested in vessel propulsion system options that can operate on new low carbon intensity fuels like clean methanol, ammonia, and hydrogen to reduce their carbon footprint. At the same time, vessel owners desire propulsion systems that are still backwards compatible with conventional fuel oils (HFO, MDO, etc.) and biofuels (e.g., biodiesel [BD], renewable diesel [RD]) if alternative fuel availability is delayed or it takes longer for alternative fuels to become cost competitive with conventional fuels. As a result, advanced technology propulsion systems that can offer backwards compatibility may see higher adoption rates in the near term to midterm.[41]

Constraint #3: Availability of Sustainable Maritime Fuels

Alternative fuel availability and accessibility will help determine how much conventional diesel and gasoline can be replaced in traditional maritime vessels and non-commercial vessels, respectively. Availability will depend directly on feedstock supply, fuel production technologies, and their scalability.[42] Advancements in the design and construction of storage and bunkering infrastructure for alternative fuels, such as new clean hydrogen refueling stations, ammonia bunkering facilities, and fast-charging infrastructure, contribute to fuel and energy availability. Initial infrastructure support for fuel production, storage, distribution, and bunkering will help increase alternative fuel availability and accelerate the energy transition. Predictable and continued policy support will encourage long-term planning among the fuel developers. Expanded RD&D support from government, including for pilot projects, will be crucial to understand and mitigate risks regarding fuel production technologies and ensure that more fuel is available.

4.2 Route Characteristics

Route predictability and efficiency are two of the key concerns for adoption of fuels, energies, and technologies with low power density, particularly battery electric and hydrogen.[43] More predictable and efficient routes allow for minimizing the battery and hydrogen storage system capacity needed for the route so that fewer operational sacrifices are required. More informed decisions can also be made in installing charging infrastructure with more route predictability.

Long-distance routes, such as cross-ocean voyages, are less likely to be supported by electrification or clean hydrogen due to the mismatch among high energy demand, low energy density, and limited onboard energy storage capacity. Fuels with decreased energy density compared to residual fuel or diesel, such as methanol and ammonia, can cover large distances but will require larger fuel tanks or more frequent bunkering to do so.

4.3 Vessel Operation

Vessel size is one of the major features to determine whether electrification is a viable decarbonization solution. Large OGVs and large harbor craft are difficult to electrify, especially along longer routes. The increased battery size for large vessels is a major deterrent for electrification. Power-to-tonnage ratio is another factor to be considered in decarbonization. For example, tugboats are very powerful with high torque factors, and have more transient power demand than other vessels, but do not generally carry any cargo (tonnage). Examples of battery, clean hydrogen, and clean methanol powered tugboats are showing promise.

4.4 Clean Fuels, Emerging Technologies, and Infrastructure

As the maritime industry moves to more sustainable technologies, many factors will need to be considered—factors such as energy content of a fuel, as some fuels have a higher energy density, for example, HFO (about 140,000 British thermal units [Btu]/gallon) versus other alternative fuels like methanol (about 58,000 Btu/gallon) that contain less energy per unit when combusted. These differences impact the distance a vessel can travel on an equivalent volume of fuel or energy and impact considerations for fuel storage capacity, refueling frequency, and charging requirements and frequency. Additionally, factors like energy content will impact design decisions such as fuel and battery type, quantity of fuel bunkered and ship route.[27, 44, 45]

4.4.1 SUSTAINABLE MARITIME FUEL AND ENERGY DEVELOPMENTS

Traditionally, HFO and lighter distillates such as MDO and liquified natural gas (LNG) have been the primary fuels used for international shipping, but they also create substantial air emissions. HFO, MDO, and LNG combustion emits GHGs. HFO and MDO also emit criteria air pollutants (PM, NO_x, SO_x, etc.). In 2019, total HFO and MDO consumption in the United States by domestic and internationally flagged ships that bunkered at U.S. ports was approximately 0.5 quads and 0.25 quads of energy, respectively. Besides that, the domestic non-commercial vessels industry primarily uses fossil-based gasoline, followed by diesel fuel. In 2019, the total gasoline consumption by non-commercial vessels in the United States was just under 0.2 quads of energy (Figure 12). If comparing energy consumed only by the U.S. flagged vessels, non-commercial vessels consumed approximately three times more energy than U.S. flagged commercial vessels. However, the approximately 0.2 quads of domestic non-commercial boating energy consumption is not even one-third of the energy consumed by all (domestic and international) commercial vessels (approximately 0.75 quads).

Discussion – Maritime Energy Requirements

Fossil-based residual fuel oil (e.g., HFO) and distillates (e.g., diesel and gasoline) used to power ships are very energy dense, which has made them attractive to use as fuels. In fact, a single gallon of HFO contains enough energy to boil over 123 gallons of room temperature water. On the other hand, many of the new fuels have less energy per unit volume. For instance, a single gallon of methanol will boil about 50 gallons of room temperature water. A modestly sized container ship (Panamax) can use upwards of 63,000 gallons of HFO per day,[27] which is the same amount of energy it would take to operate almost 1,100 EVs for a full year[44] of typical operation. In 2019, the entire U.S. maritime industry used 0.75 quads (a quad is 1 quadrillion Btu) of energy or 750 trillion Btu, which equates to roughly 5.3 billion gallons of HFO, enough energy to power Los Angeles,[45] CA for almost 10 years.

Panamax sized container ship leaving the Port of Los Angeles.

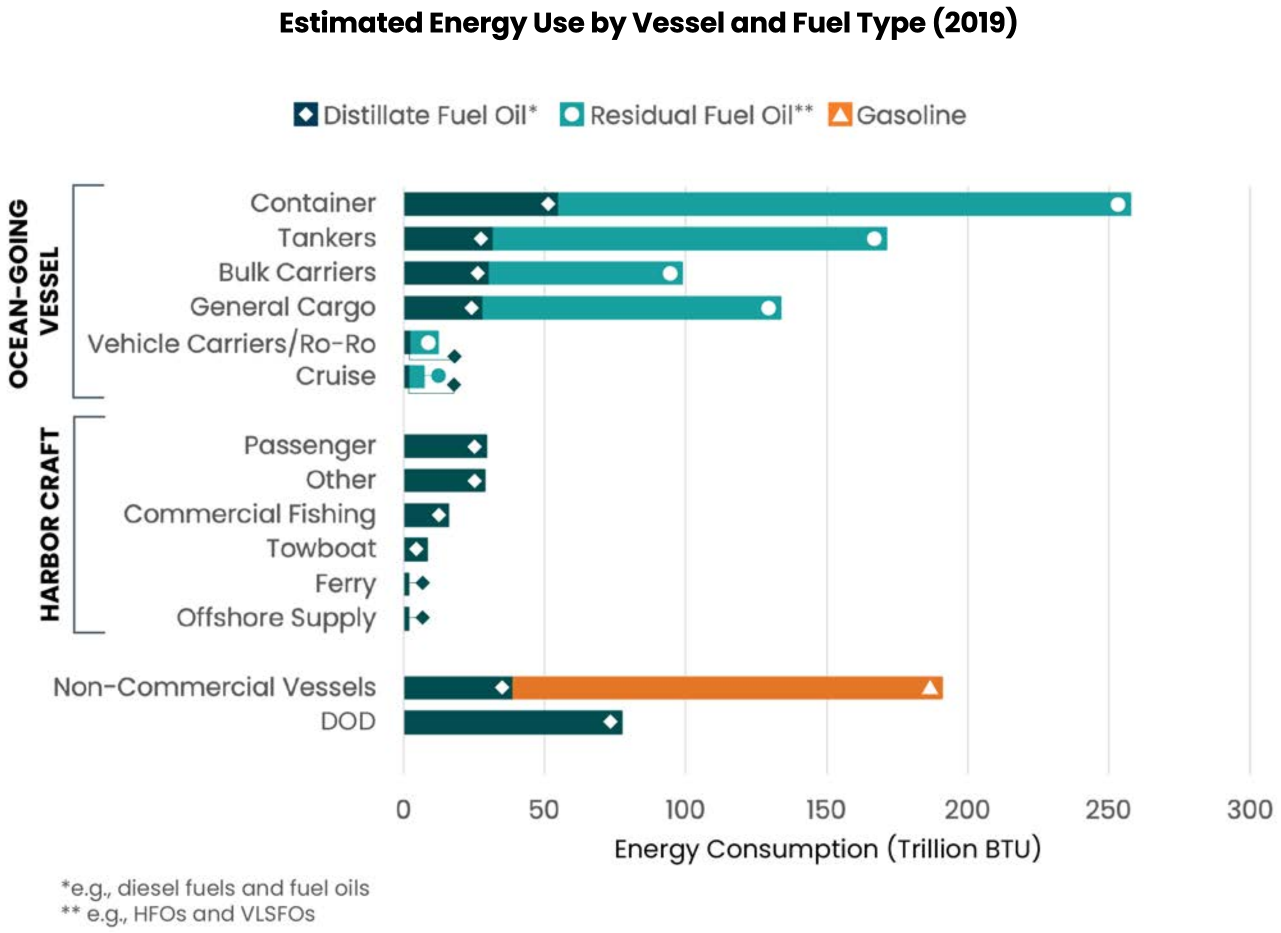

Figure 12: Estimated energy use by vessel and fuel type (2019)

To navigate towards a sustainable future, the maritime industry must increase the availability and uptake of SMFs and ensure that vessels have the technology to use them. These fuels, derived from renewable or recycled sources like biomass, waste oils, clean electricity, and captured CO_2, offer a transformative opportunity. As a major part of its strategy,[46] the IMO includes widespread adoption of SMFs to reduce GHG emissions by 100% by or close to 2050, a critical step towards meeting global climate goals. However, the mass or volume of SMFs this will require will depend on the fuel characteristics, such as density and lower heating value (LHV) (Figure 13). If the density and heating value is low, it will require more fuel by volume to achieve the same quantity of energy value as a conventional fuel.

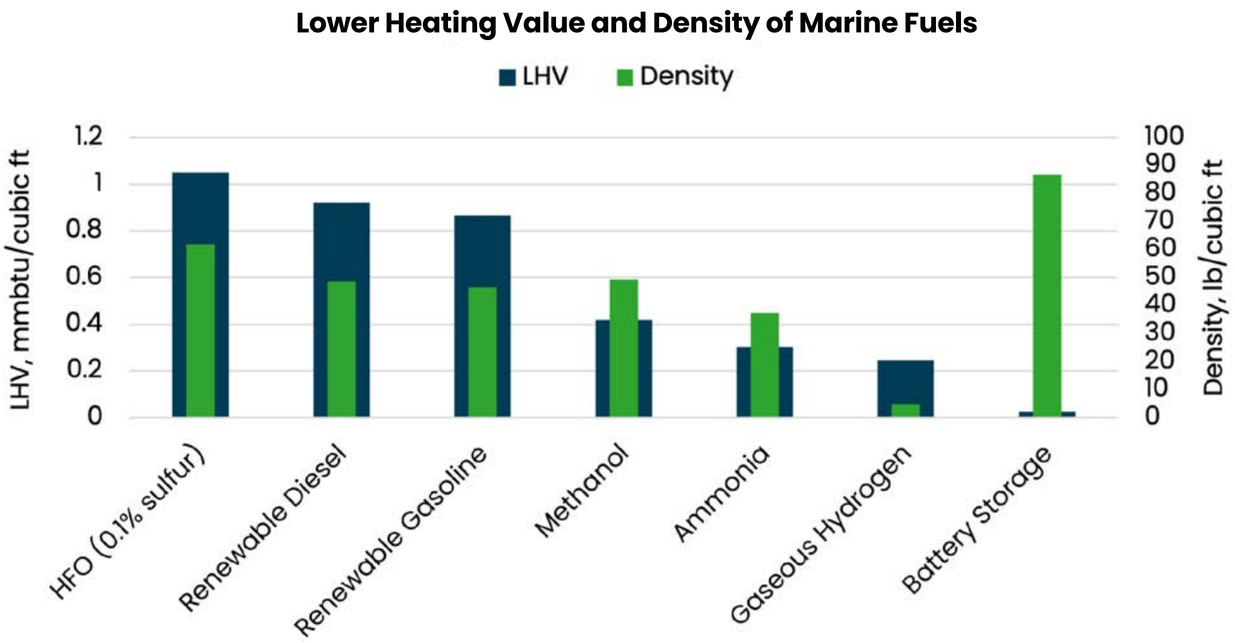

Figure 13: Lower heating value (LHV) and density of maritime fuels[20]
Note: For electricity, volumetric energy density or mass refers to energy content per battery volume.

The total life cycle GHG emissions from each fuel production pathway determines its WTW GHG emissions. As seen in Figure 14 (below), e-methanol produced via electrolysis using waste CO_2 has an almost neutral GHG footprint for a full WTW life cycle, whereas more traditional methanol synthesis pathways that use natural gas will result in almost as much GHG emissions per unit as HFO. It is important that sustainable, low carbon intensity versions of these fuels be domestically available as the industry moves to vessels that can run on new fuel types.

Oil tanker, a type of OGV, offloading its cargo.

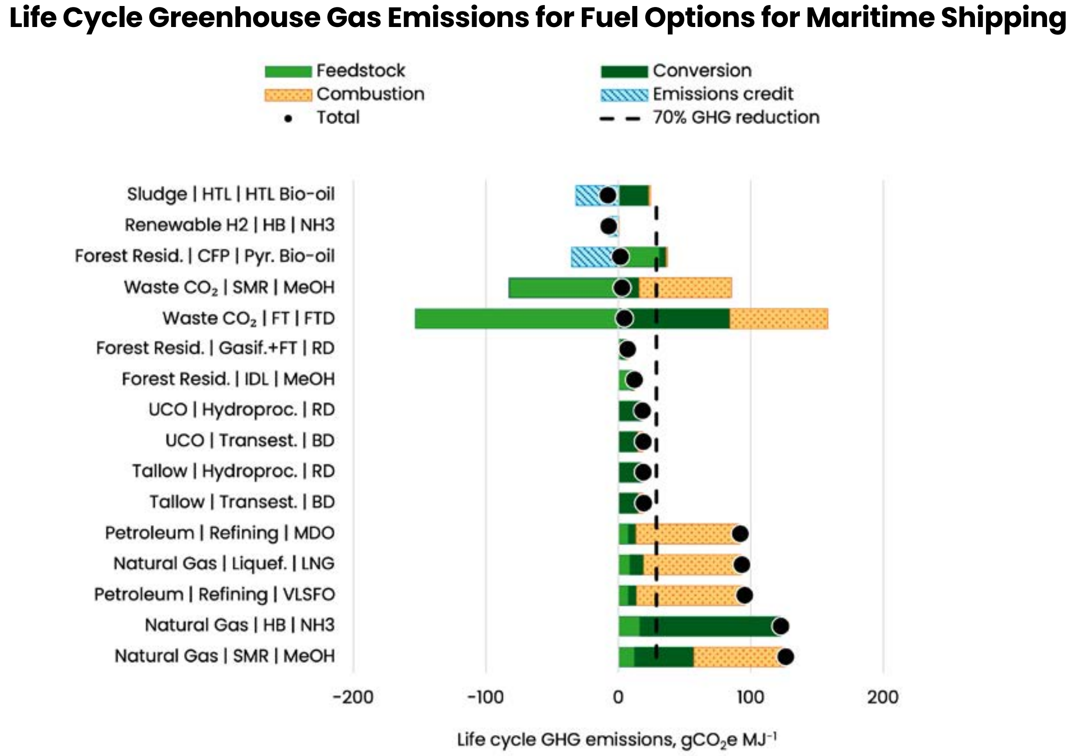

Figure 14. Life cycle GHG emissions for fuel options for maritime shipping.[j, k, 30] *The 70% GHG reduction line is relative to conventional VLSFO with 0.5% sulfur content by weight and reflects consistent system boundaries, calculation approaches, and background data. LCA results will vary depending on case-specific details and differences in calculation approaches specific to the intended use. These results are representative and do not reflect determinations for fuel credits or other regulatory purposes.*

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[j] Abbreviations: SMR = steam methane reforming; HB = Haber-Bosch process; VLSFO = very low sulfur fuel oil (0.5% S by mass); LNG = liquefied natural gas; MDO = marine diesel oil (0.5% S by mass); UCO = used cooking oil; IDL = indirect liquefaction; FT = Fischer-Tropsch; CFP = catalytic fast pyrolysis; Pyr. = pyrolysis; Hydroproc. = hydroprocessing; Gasif. = gasification; Transest. = transesterification; Liquef. = liquefaction; MeOH = methanol; NH_3 = ammonia; FTD = FT diesel; BD = biodiesel; RD = renewable diesel; Resid = residue. Estimates are based on IPCC AR6 100-year GWPs.

[k] Notes: The avoided emissions estimates shown in this figure assume specific counterfactual scenarios described in the corresponding peer-reviewed publications where GHG pollutants would otherwise be emitted to the atmosphere. In a decarbonized economy (i.e., a 2050 scenario), where these emissions may not have occurred in the first place, the avoided GHG emissions estimates may not be applicable. Similarly, the e-fuel pathways assume the use of zero-GHG electricity that meets requirements for additionality. This is not reflective of the current U.S. grid mix. It should also be noted that each feedstock has a distinct technical potential for scale-up. Wastes such as UCO, tallow, sludge, and other wet wastes do not have scale-up potential comparable to those for agricultural and forestry residuals and energy crops. Refer to the 2023 Billion-Ton Report for estimates of the technical scale-up potential for biomass and waste feedstocks.[47] The use of ammonia as a fuel for maritime shipping is subject to emissions of N_2O, which have not yet been characterized in practice. While emissions controls such as selective catalytic reduction are available to reduce such emissions, N_2O is a potent GHG (100-year GWP of 273 gCO_2-eq./g N_2O based on IPCC AR6, i.e., 1 kilogram of N_2O released causes the same amount of radiative forcing as 273 kilograms of CO_2). Results for LNG reflect fugitive CH_4 emissions and CH_4 slip from ship engines, which vary widely in practice. CH_4 is another potent GHG involving potentially significant use-phase CH_4 slip and fugitive emissions. CH_4 is a potent GHG (100-year GWP of 29.8 gCO_2-eq./g CH_4 based on IPCC AR6). Pathways involving hydrogen may also incur GHG impacts associated with releases of hydrogen itself. Hydrogen is not currently included in GREET life cycle GHG calculations, but studies are indicating hydrogen contributes to GHG effects, and so H_2-related GHG effects may be incorporated in GWP once consensus is reached about the characterization factor to be used. The use of methanol and ammonia in ship engines may require the use of pilot fuel to improve combustion characteristics. The results here reflect only the methanol and ammonia share of GHG impacts and would need to be supplemented with pilot fuel considerations to more accurately reflect GHG effects in practice. The ammonia pathway shown here includes a credit for avoided emissions associated with an electricity co-product from the ammonia production process. VLSFO and MDO are both based on fuel with sulfur content of 0.5% sulfur by mass. **Note that LCA results will vary depending on case-specific details and differences in calculation approaches specific to the intended use of results. These results are representative and do not reflect determinations for fuel credits or other regulatory purposes.**

SMFs are already gaining momentum. In 2023, the SMF market was valued at $46 billion, projected to increase to $325 billion by 2036.[48] However, many of these fuels will also be in demand by non-maritime markets, which adds another challenge to decarbonizing the sector. Major fuel producers are investing heavily in research and development, and several ports are now offering bunkering facilities for sustainable fuels. Increasing numbers of new ships on the order book (from IHS Markit) are compatible with alternative fuels (Figure 15), such as LNG, methanol, liquid petroleum gas (LPG), and battery/hybrid propulsion systems. While LNG-fueled vessels are included in new ship orders with non-conventional fuels, LNG provides only modest GHG reductions and is therefore not included in the definition of SMFs used for this plan. However, LNG dual-fuel engines can potentially be retrofitted to operate on methanol or ammonia in the long term and can use RNG (biomethane and e-methane) when they become available, which makes LNG-powered vessels an attractive transitional technology.

The added complexity of synthesizing or refining SMFs makes their production cost higher than HFO, a gap that will persist but narrow as demand and production volumes grow. To help narrow this gap more quickly, government and industry stakeholders must collaborate to incentivize production, invest in infrastructure, and establish clear regulations to ensure the sustainability of these fuels throughout their life cycle.

Alternative fuel uptake in the world fleet by gross tonnage

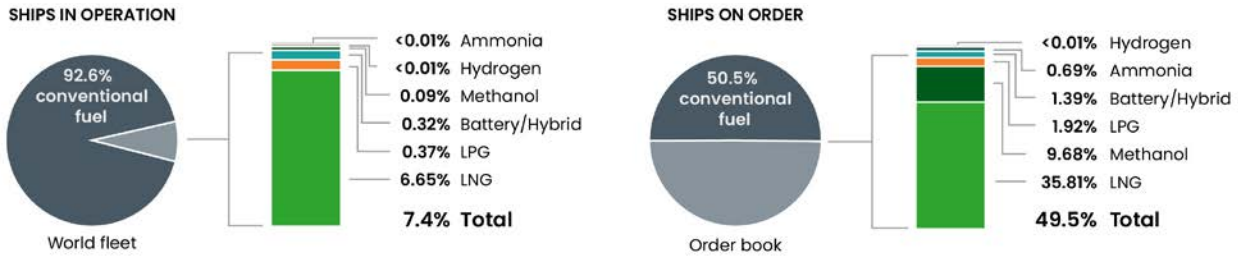

Figure 15: Alternative fuel-capable vessels in the world fleet in gross tonnage, as of October 2024, reported by IHS Markit (ihsmarkit.com) and DNV's Alternative Fuels Insights for the shipping industry—AFI platform (afi.dnv.com). Note that these figures indicate vessels that are "capable" of operating on alternative fuels but are not necessarily doing so. These vessels may also need further major refits (tankage, fuel management systems, etc.). However, these numbers are indicative of the potential use for alternative fuels in the future fleet that is already, or will soon be, operational.

Sustainable Maritime Fuels

As the use of alternative fuels increases, and the policy and regulatory framework are developed, it is important to define "sustainable maritime fuel" (SMF). For the purposes of this action plan and considering work underway at the IMO, a maritime fuel is considered sustainable if it meets 1) requirements for environmental and socio-economic sustainability, and 2) requirements for significantly reduced GHG intensity relative to traditional maritime fuel. Depending on the fuel feedstock and production pathways, SMF will have significantly reduced life cycle GHG emissions compared to traditional maritime fuel. Fuels that may be considered SMF include sustainable low-carbon biofuels (such as certain BD, RD, renewable gasoline, and BI), clean (i.e., derived from clean electricity) methanol, clean ammonia, and clean hydrogen. **This action plan calls for the federal government to develop a formal definition of SMF in 2025**. As important as SMFs will be to the decarbonization of the U.S. maritime industry, the use of electrification and fuel cell technologies where possible will also be very important for certain vessel types. The following highlights the variety of fuels included under the action plan. See Appendix B: Sustainable Maritime Fuels for a detailed description of each fuel type.

Biofuels

Biofuels[42] are "drop-in," liquid fuels produced from converting biomass[49] (e.g., crop waste, municipal solid waste [MSW], purposed grown energy crops). Biofuels include BD, RD, and renewable gasoline, as well as BI (e.g., pyrolysis bio-oils and hydrothermal liquefaction biocrudes). While biofuels are often considered a direct replacement for fossil fuels for non-commercial vessels, harbor craft, and OGVs, their actual chemical composition differs from that of their conventional counterparts. This difference requires that they undergo additional testing, certification, and related diligence to ensure that they are compatible and optimized for the highly refined engines they will be used in. See Appendix D for additional biofuel information.

Methanol

Methanol[50] is a liquid alcohol that can be produced using renewable sources like biomass, RNG, or captured CO_2 using renewable electricity. Methanol is likely to be a key fuel in the decarbonization of both harbor craft and OGVs. Methanol has a large global footprint today, as it is one of the world's largest chemical commodities. Much of this methanol, however, is produced using coal and natural gas, which results in high carbon intensity life cycle GHG emissions. Safety must also be considered as methanol burns with a clear and invisible flame, which adds another layer of complexity in the event of a fire. This requires additional safety precautions during storage, handling, and bunkering.

Ammonia

Ammonia is a colorless gas with a pungent odor, commonly used in fertilizers and refrigeration. Although not a traditional fuel source, ammonia has several favorable attributes. It's increasingly being recognized as a promising alternative fuel for the shipping industry due to its potential to reduce GHG emissions when low-carbon hydrogen is employed during production. Ammonia is toxic and flammable, and poses safety challenges in terms of handling, storage, and transportation. Robust safety measures and regulations will be essential. The toxicity challenges and related safety risks may limit the types of ships and even the types of ports for which it is a suitable sustainable fuel. Studies and demonstrations are underway to develop safety measures for bunkering and utilizing ammonia as a maritime fuel.[61] Additionally, ammonia can be a "hydrogen carrier," meaning it has a high capacity for hydrogen storage, three hydrogen molecules per ammonia molecule. However, to access hydrogen from ammonia, a significant energy input is required. As such, ammonia is primarily envisioned for use by OGVs because the need for scale and control favors a more complicated use environment. This does not preclude use by smaller vessels in the long term but may make the application of other fuel more favorable.

Hydrogen

Hydrogen is the simplest and most abundant element, and low-carbon clean hydrogen can be produced using diverse domestic resources. Pure hydrogen can be combusted to produce thermal energy in a modified combustion engine, or it can produce electrical energy in a fuel cell by combining pure hydrogen with pure oxygen.[52] Fuel cells can create power from hydrogen without criteria air pollutants, while at the same time, hydrogen ICEs are not as sensitive to impurities and will likely be part of the decarbonization solution. Hydrogen's maritime use will likely be focused on harbor craft; however, there may be some niche and supporting applications in non-commercial vessels and OGVs.

Electricity

Electrifying vessels can take the form of battery electric (all vessel loads are run by battery power) or hybridization where batteries support or supplement vessel power needs. For hybrid vessels, batteries and hybridized ICEs work together to optimize the efficiency over a traditional ICE propulsion system. Electric power can be used for various onboard functions beyond propulsion, like powering auxiliary equipment and hotel loads, as well as reducing overall reliance on the main engine fuels. Electrification of as many non-commercial vessel harbor craft as possible is emphasized in this action plan.

Methane

Methane is currently being used by a small portion of OGVs in the form of LNG. Although LNG can sometimes reduce TTW GHG emissions compared to HFO, CH_4 slip from marine engines, as well as CH_4 leaks from the supply chain, usually results in greater WTW GHG emissions than petroleum-derived fuels.[48] For this reason, this action plan looks at RNG as a direct replacement for LNG as well as a blendstock for LNG in the near term. RNG, also known as biomethane or biogas, is CH_4 produced from organic sources such as agricultural waste, landfills, wastewater treatment plants, and organic residues. RNG's primary uses will likely be in the OGVs, particularly within the cruise industry as well as in RNG tankers shipping RNG internationally. It will be important to eliminate, as far as practicable, CH_4 slip and fugitive CH_4 emissions from marine engines and ships to align with WTW decarbonization goals.

Fuels	Pros	Cons
Biofuels	• Can be a near drop-in petroleum fuel replacement, blendable, and can use much of today's infrastructure • High energy density (Figure 13 – above) • Pathways for low to negative carbon intensity on full life cycle basis (Figure 15- above)	• Wide variation in life cycle GHG emissions; some biofuels are more GHG-intensive than traditional fuels on a WTW basis • Criteria air pollutants remain • Feedstock resource limitations exist and will need significant increase in feedstock production to the full U.S. potential[47] • End-use competition (aviation, off-road, rail, etc.)
Methanol	• Multiple sustainable production pathways (bio and electro) for low life cycle GHG production • Large criteria air pollutant reduction • Methanol-using vessels are starting to come online	• Lower energy density • Limited feedstock resource • Large clean electricity requirement for production • Safety considerations • Potential for traditional methanol enabler • End-use competition (chemical industry)

Fuels	Pros	Cons
Ammonia	• Large potential GHG reductions • Limited criteria air pollutants other than nitrogen species • Abundant nitrogen feedstock (air)	• Lower energy density • Large clean electricity requirement for production • Potential NO_x and N_2O emission issues • Safety concerns • Potential for traditional ammonia enabler • End-use competition (agricultural industry)
Hydrogen	• Large potential GHG reductions • No criteria air pollutant emissions (with fuel cells) • Large ongoing U.S. investment (Regional Clean Hydrogen Hubs Program)[53]	• Large market competition for clean hydrogen (sustainable fuel production for all modes of transportation, chemical production, agriculture, traditional petroleum refining) • Difficult to store both on and off board vessels • Low energy density of gaseous hydrogen
Electrification	• Large potential GHG reductions • No local criteria air pollutant emissions • Large U.S. commitment to 100% clean electricity by 2035[54]	• Charging infrastructure requirements • Energy density and battery efficiencies need to be increased • Route predictability and length requirements
Methane	• Reduced criteria air pollutants • Current supply-side infrastructure in place	• Fugitive CH_4 emissions during combustion (CH_4 slip) and across supply chain • Potential reliance on fossil CH_4 • RNG feedstock resource limitations exist

4.4.2 SUSTAINABLE VESSEL DEVELOPMENTS

4.4.2.1 Vessel Types

For the purposes of this report, the U.S. maritime fleet has been divided into three categories: OGVs, harbor craft—including coastwise and inland waterways vessels (generally referred to as “harbor craft” in this document)—and non-commercial vessels. OGVs are large ships designed to carry cargo and people across large bodies of water, including oceans, seas, and the Great Lakes. Popular vessel types include tankers, container ships, bulk carriers, Ro-Ros, and cruise ships, and they include the commercial

A car carrier, an OGV often referred to as a Ro-Ro (roll-on/roll-off) offloading its cargo in Benicia, CA.

deep-sea fishing fleet. Harbor craft are commercial vessels (workboats) that are used to provide a service.[11] In this report, the classifications of harbor craft considered are ferries, commercial fishing vessels, offshore supply vessels (OSVs), passenger vessels, and towboats/tugboats/push boats. For the purposes of this plan, non-commercial vessels are defined as any vessel or boat designed primarily for personal use, or leased, rented, or chartered to a person for personal use, including boats engaged in non-commercial fishing.

4.4.2.2 Ocean-Going Vessels

OGVs are characterized as vessels traveling long distances (up to several weeks at a time). They are the largest vessel types and carry the highest amount of cargo (making them a very efficient means of goods transport), but also consume the highest amount of energy per unit of distance travelled. This makes them sensitive to reductions in energy storage density and is why battery and hydrogen are not included in the OGV solutions within the maritime projections to 2050.[55-57] However, as battery and hydrogen energy storage density improve, this may change. As mentioned in the previous section on SMFs, OGVs are assumed to be reliant on liquid low-carbon fuels (mainly methanol and ammonia, with support from drop-in biofuels and e-fuels) for main propulsion energy, with the potential of electric power assistance at maneuvering speeds, at berth (cold ironing), or with auxiliary loads.

On average, OGV lifespans range from 10–25 years (for tankers, containers, and Ro-Ros) to 40–50 years (bulk carriers) or longer. Currently, almost half of the new U.S. ship orders are designed to be powered by conventional fossil fuels. This means that for the near future, drop-in, low carbon intensity liquid fuels will be required to help decarbonize OGVs until enough methanol- and ammonia-capable vessels are produced and the fueling infrastructure is sufficient to support a complete transition. Some vessels like tankers are designed to operate on the fuel they are transporting, giving them greater flexibility in fuel type. As SMF options increase, the diversity of tanker propulsion will as well. Cruise ships are another unique vessel type, many of which are planning to use a combination of LNG and shore power to decrease GHG and criteria emissions. Methanol is a potential future fuel for the cruise industry as it transitions away from fossil-based fuels. During the near term, other aspects such as vessel efficiency improvements, enhancement in shipping logistics, engine retrofits, and onboard carbon capture are options to help reduce emissions.

4.4.2.3 Harbor Craft

Commercial harbor craft operate on shorter distances than OGVs and are typically returning to port more frequently, allowing more frequent opportunities to refuel or recharge. For this reason, harbor craft are more likely to electrify or operate on clean hydrogen, although some offshore operations requiring longer time away from port may see other fueling systems. On the other hand, inland river operators will primarily depend on alternative liquid fuels such as RD, methanol, or ammonia because they transport cargo over longer transportation distances with less regular access to charging stations. Requiring more frequent charging and refueling to support electrification and hydrogen could significantly disrupt freight movement.

Electrification of ferries and other harbor craft primarily depends on the size of the vessel, trip distance, and charging time allowed at the port during loading and unloading. Depending on these factors, electrification can be full or partial (hybrid). Ferry routes, as discussed in section 4.2. Route Characteristics, are predefined and predictable, which helps in electrification of that vessel type. Ferries with shorter trips can be fully electrified, while others using low-carbon liquid fuels or hydrogen can enjoy the benefit of increased efficiency from hybrid battery propulsion systems.

For coastwise general cargo vessels, package freight vessels that operate on consistent routes with shorter distances, less than 20 km, have greater potential for full electrification.[43, 57] Like ferries, hybrid electric propulsion systems are also a prime candidate for such vessel types. Coastwise general cargo that transports to/from large ocean ports will likely have access to clean methanol and clean hydrogen and will likely use these options.

Because clean methanol and clean hydrogen are assumed to be available at larger international ports, fishing vessels operating out of large ports could be operated on these fuels. Hydrogen fuel cells and hydrogen ICEs are also possible for trips ranging more than 20 km. For trips shorter than 20 km from shore/port, full electrification of fishing vessels is possible.[57] For routes where full electrification is not possible, various configurations of hybridization could be primary solutions.

Washington State Ferry, considered a type of harbor craft, traversing the Puget Sound.

Non-commercial vessel traveling in through canals in Fort Lauderdale, FL.

4.4.2.4 Non-Commercial Vessels

Non-commercial boating constitutes approximately 65% of GHG emissions from all U.S.-flagged vessels while constituting roughly 20% of GHG emissions from all vessels fueled within the United States. While non-commercial vessels are privately owned and operated and could be considered the "light-duty" portion of the U.S. maritime fleet, they do not operate like light-duty automotive vehicles and decarbonization solutions from on-road vehicles cannot be broadcasted onto non-commercial vessels. Part of the reason is that they are used on average only 35–48 hours per year. Given the low use rate, it is incredibly important for advancements in GHG reductions in battery production and efficiency improvements to continue as we begin to electrify the floating fleet. While battery-powered boating has these embodied GHG emission challenges, it is attractive because of low noise, no criteria pollutant emission, and less winterization maintenance in colder climates. Hydrogen-powered boating is another low-emissions technology, and several companies are exploring this space, both with fuel cells and hydrogen ICEs.

However, even with an aggressive assumption that 100% of new non-commercial vessels sold in the United States starting in 2024 would have net-zero GHG emissions technologies (assuming consumer acceptance and the same annual sales as previously), under a business-as-usual scenario, about 55% of the non-commercial vessel fleet in 2050 would still comprise 2023 model year and older vessels with conventional propulsion systems. This means that without a low or net-zero emission drop-in fuel option for legacy non-commercial vessels (like renewable gasoline), more than 20% of the current U.S. maritime GHG emissions would still be emitted in 2050. It is also important to note that ethanol-free gasoline is used for marine applications, and although renewable gasoline is a biofuel, it can be used as a direct drop-in fuel as it is more compatible with the use cycle. The current renewable gasoline production quantity is negligible because it is considered a low-value product and requires economic and policy support to boost production. For example, Renewable Fuel Standard (RFS) data indicates that in 2023 there was about 3 billion gallons of RD / sustainable transportation fuel (e.g., SAF) production along with imports, but only about 75 million gallons (or about 2.5%) of naphtha (a potential marine gasoline additive or replacement) and renewable gasoline were produced or imported.[58] Transitioning a significant portion of the non-commercial boating industry to renewable gasoline will increase the fuel's value and production. Renewable naphtha consists of hydrocarbon chains consisting of 5 to 11 carbon (C5-C11) each. Naphtha has a relatively low octane number, with a research octane number value ranging from 50 to 70, and could be used directly in future engines.[59–61] However, for current and legacy engines, renewable naphtha can be mixed with biofuel, electro-fuel, or fossil fuel higher-octane components such as alkylate and iso-paraffins, to enhance its performance and produce environmentally friendly gasoline with a lower carbon footprint for the industry than is currently available today.[62, 63]

4.4.2.5 Vessel Energy Efficiency

Reducing emissions from the maritime industry depends on both reducing energy use and ensuring that the energy is provided by zero or near-zero emission fuels. Energy efficiency is concerned with getting the most work out of energy inputs (i.e., fuel) by reducing losses. The conversion of chemical energy in a fuel to mechanical work for propulsion involves numerous energy losses along the way, which present opportunities for improvement (Figure 16). This section reviews some of the major energy-efficiency improvements that can be made to vessel machinery through waste heat recovery, energy efficient designs of vessel equipment and auxiliary machinery, and shipboard power management systems. These methods will be of particular importance for vessel operators seeking compliance with IMO regulations such as the Energy Efficiency Existing Ship Index (EEXI), which was first enforced in January 2023.

Use of Propulsion Energy on Board a Small Cargo Ship, Head Sea, Beaufort 6

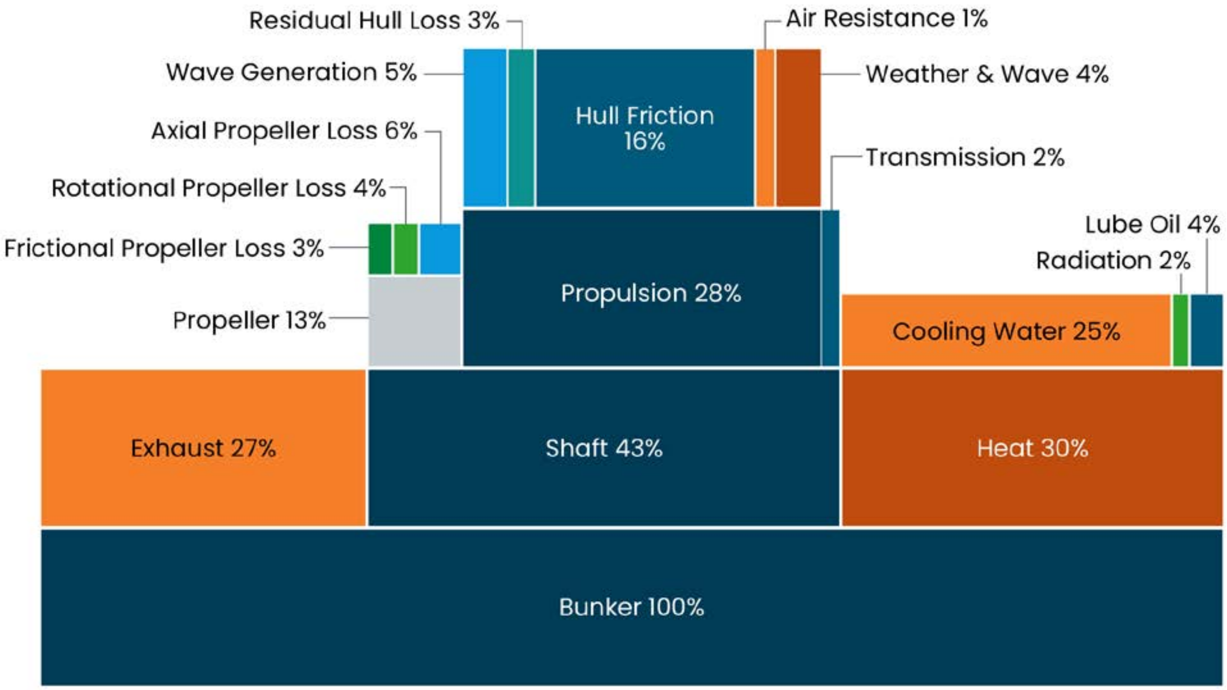

Figure 16: Use of propulsion energy on-board a small, well-maintained cargo ship in a rough sea (courtesy of IMO)[64]. In this example, of the energy contained in the bunkered fuel, only 28% generates propulsion.

4.4.2.5.1 Slow Steaming (Intentional Speed Reduction)

Slow steaming refers to the practice of operating maritime vessels at lower speeds than their maximum capabilities to reduce fuel consumption and improve energy efficiency. This strategy involves deliberately reducing a vessel's speed, typically by a significant percentage below its maximum design speed, during transit between ports. Slow steaming has become increasingly common[65] in the shipping industry to lower operating costs, mitigate environmental impact, and comply with some emissions regulations.

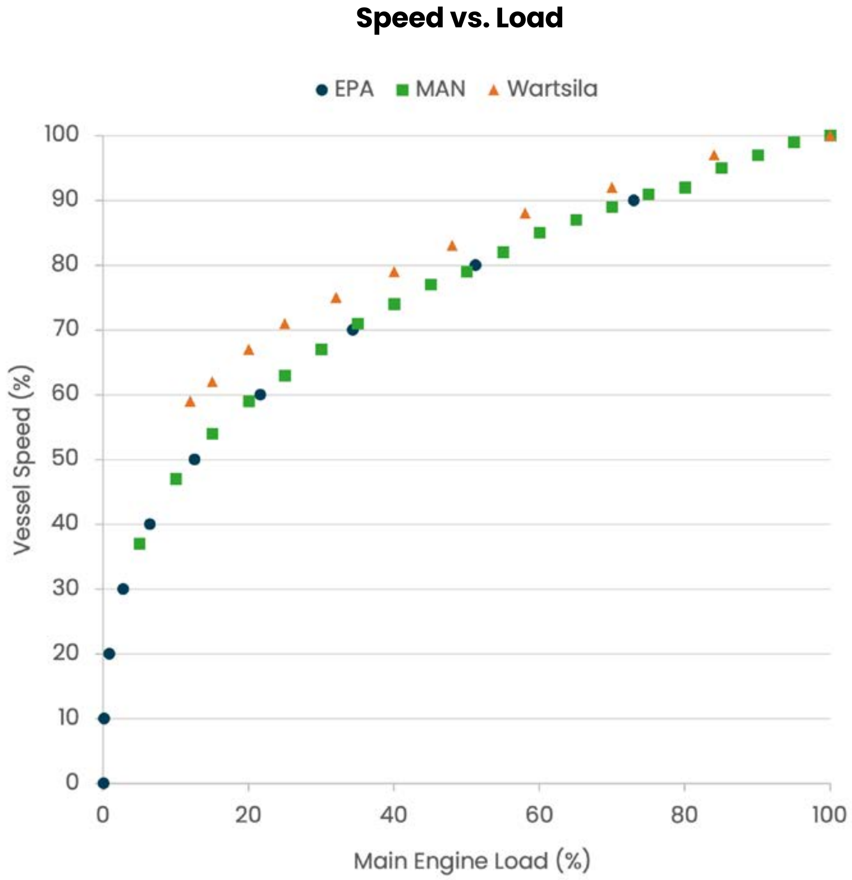

Figure 17: Data from engine manufacturers, MAN and Wartsila, as well as EPA shows the relationship of vessel speed to engine load. As engine load increases, and therefore the fuel use and GHG emissions increase, only incremental increases in vessel speed are seen.

4.4.2.5.2 Hull Design and Cleanliness

Most of the energy consumed to propel a vessel can be attributed to the hydrodynamic forces of the interaction of the vessel with the water, namely hull friction, residual hull loss, and wave generation. Improved hull design can afford up to a 10% reduction in fuel consumption and GHG emissions.[66] Air lubrication systems fitted to some hulls can reduce fuel consumption (and GHG emissions) by up to 10%. On the other hand, biofouling can increase the fuel consumption and GHG emissions, and maintaining a clean hull can have up to a 5% impact.[67] Regular hull cleaning is important to minimizing hull friction, fuel consumption, and GHG emissions.

The Pyxis Ocean is an ocean-going vessel that has implemented the use of wind-assisted ship propulsion technology. Image courtesy of Cargill.

4.4.2.5.3 Wind-Assisted Ship Propulsion (WASP) Systems

While maintaining a clear hull or adding air lubrication could provide meaningful vessel operational GHG reductions up to approximately 10%, wind-assisted ship propulsion (WASP) systems have demonstrated fuel consumption savings and GHG emissions reductions between 4.5% and 9% and have been calculated to provide potential GHG savings up to 30%.[68–73] They can also have a positive impact on a ship's energy efficiency ratings such as EEXI and the Energy Efficiency Design Index. WASP systems, such as sails, rotors, and kites, are currently the most common types in consideration for large OGVs.[69] Like many solutions, naval architectural and cost challenges exist to widespread WASP adoption, but long-term strategies should include WASP systems as a means of energy-efficient vessel operation.

4.4.2.5.4 Hybridization

Hybridization involves the combination of multiple power sources working in concert to propel the vessel or power ship operations in a more energy-efficient manner. Common applications include the use of batteries with an energy converter to allow for the most efficient operation of the energy converter. Hybridization strategies can vary depending on the vessel type and operations. While vessels can't recover energy from their motion (like regenerative braking in on-road vehicles), battery-stored energy could help supplement auxiliary power demands, such as hotel electrical loads, maneuvering thrusters, pumps, air compressors, or other work machinery. Battery hybridization could also assist the main engine(s) in the propulsion system to operate more efficiently. For instance, hybrid electric propulsion systems have improved low load torque and are already employed in tugboats to increase both efficiency (by 22%-38%) and transient response time.[74] In addition, hybridization lessens the portside electrical requirements, which may allow for more system resilience.

The Crowley e-Wolf, an electric tug, operating in the Port of San Diego. Image courtesy of Crowley.

4.4.2.5.5 Full Battery Electrification

Battery electric vessels can operate more efficiently than engine-powered vessels because the electricity is produced upstream of the vessel. Battery propulsion efficiency is around 90%, whereas engine thermodynamic efficiencies can be as high as just over 50%, depending on the engine mode of operation. However, most commercially available large batteries have a much lower energy storage density than fuels that power ICEs and fuel cells. Batteries are also composed of critical materials (lithium, graphite, etc.), and their use in the maritime sector will likely compete for other uses, such as in automobiles and for grid-scale storage. Still, due to the potential efficiency gains from battery propulsion, the technology should be deployed wherever feasible by the vessel energy storage requirement, charging requirements, and use profile.

4.4.2.5.6 Small Nuclear Modular Reactors (Vessel Propulsion)

Small Nuclear Modular Reactors or microreactors can potentially be used on board commercial vessels to eliminate TTW GHG emissions. The technology is already widely used by defense vessels. They have higher energy density than battery energy storage, but their cost can be prohibitive depending on the application. A recent American Bureau of Shipping study[75] shows conceptual designs of two large (14,000 twenty-foot equivalent units [TEUs]) container vessels that could operate for 25 years and refuel only once while emitting zero stack GHG emissions. While the potential GHG savings are immense, there are also risks to vessel operators and the public that must be addressed. As such, the DOE has an Office of Nuclear Safety,[76] and in 2021, the Foundational Infrastructure for Responsible Use of Small Modular Reactor Technology (FIRST)[77] was founded. The FIRST program aims to establish international safety and security standards while taking advantage of technology innovations and many uses for the clean energy produced.

4.4.2.5.7 Emissions Reduction Technologies

Most of the U.S. maritime sector will be powered by ICEs operating on SMFs through at least 2050; it is important that local emissions from these vessels are minimized. Exhaust aftertreatment systems can effectively reduce criteria air pollutant emissions, but typically reduce engine efficiency (and therefore increase fuel consumption) because of increased engine exhaust system back-pressure. However, when comparing technologies to reduce engine criteria pollutant emissions, exhaust aftertreatment systems can have a lower fuel consumption penalty than other technologies. A similar challenge exists with exhaust carbon capture systems to be able to effectively capture CO_2 emissions from the engine exhaust. Not only can the carbon capture system reduce the efficiency of the engine because of exhaust back-pressure, but the system can also require additional energy inputs to function (such as electricity or heat from boilers). Further, the captured carbon will need to be managed. In some cases, the captured carbon may be reconverted into e-fuels, while other captured carbon may be sequestered using existing and planned infrastructure.[78] Although there are many challenges, studies[79, 80] have shown that onboard carbon capture can be a solution if high capture rates, low fuel penalties, reductions in retrofit, and low CO_2 deposit costs can be achieved.

4.4.3 SUSTAINABLE INFRASTRUCTURE AND PORT DEVELOPMENT NEEDS

U.S. ports—the infrastructure they embody, and their role in orchestrating and convening a myriad of transportation and industrial activities—are vital assets underpinning the country's economy. Ports are essential for effective, efficient, and resilient goods movement as well as a range of other strategic, economic, and logistic functions. Actions described in this plan to transition vessels to new energy sources are inextricable from the need to build new port infrastructure that enables this transition.

Enabling ports to provide the new infrastructure and facilities for near-zero to zero-emission shipping will occur in the context of a diverse and complicated nexus of activity—all of which involve other modes and industries also planning for rapid decarbonization. Providing for a new generation of vessels therefore requires consideration on how energy and infrastructure provided to decarbonize vessels may affect how other sectors decarbonize, all while ensuring the continued vitality and resilience of the broader port system. Charging infrastructure, shore power, type of fuels being bunkered, need for microgrids, and increased grid capacity will all need to be considered as ports plan for a decarbonized future.

Other action plans will address requirements of various transportation modes within the port ecosystem such as heavy-duty vehicles and cargo-handling equipment. This section seeks to look specifically at key infrastructure and related considerations at ports that are essential to near- and longer-term decarbonization goals for vessels. The primary enabling infrastructure for vessel energy transition will be supply and storage of alternative fuels. This could also include charging infrastructure and battery-swap facilities for smaller vessels and harbor craft. Technologies such as shore power may also support energy transition in areas where it offers a more cost-effective alternative to using sustainable fuels while at berth.

4.4.3.1 Alternative Fuel Bunkering and Storage at Ports

In all long-term decarbonization scenarios for vessels that align with U.S. and IMO goals, alternative liquid fuels like methanol, ammonia, and biofuels play a dominant role. Currently, almost no ports in the United States are equipped to provide these fuels, nor is there clear and ready supply available even if they were. Supply of these fuels depends fundamentally on creating a strong market demand. Emerging IMO regulations are expected to promote availability of such fuels for international vessels, but the rate of that demand growth and how it may translate to demand in most of the categories of vessels covered by this action plan are unclear. Meeting these uncertain fuel needs requires that ports are prepared to provide the fuel through appropriate methods. This means providing for physical aspects of the fuel supply chain while ensuring that safety, permitting, and security considerations are also developed and deployed in concert.

4.4.3.1.1 Fuel Supply, Storage, and Distribution at Ports

The United States will eventually need hundreds of new fuel production facilities to produce enough fuel to power the maritime transition over the coming decades. Production of these new fuels will occur in many ways from co-processing of biofuels with current infrastructure, to hydrogen-based fuels relying on our network of regional clean hydrogen hubs (RCHHs),[53] to standalone production facilities. In fact, even nontraditional means of production are being investigated by industry, such as offshore production of e-fuels. As these facilities are being planned, constructed, and operated, it will be very important to work with local communities to ensure equity during the transition.

Siting infrastructure to store and deliver alternative fuels will be one of the biggest landside challenges of the energy transition. Many U.S. ports have significant land constraints and are locked into their current footprint. Fuel storage and delivery infrastructure need to be sited in a way that both makes it accessible to the logistics chain that brings furls to the port area and avoids disrupting the other carefully arranged and orchestrated port activities.

In consideration of these physical constraints, fuel supply to vessels is commonly accomplished using barges filled from tanks on nearby terminals. Pipelines, trucks, and other methods are also used depending on the volume and fuel type needed. Many ports have dedicated terminals and facilities for fueling that are as old as the port itself and well-integrated into its operations. Adding new facilities will require additional space in limited areas where cargo-handling and industrial activities are not already active. Solutions include finding areas to site storage and distribution beyond the port boundaries, which competes with a range of other local interests, or to displace revenue activity at the port, which is also unpopular.

For permitting, many of the fuels being considered, such as ammonia, methanol, and hydrogen, require special safety and handling considerations. These substances have standardized storage and handling protocols when they are handled as commodities but usually require a new separate set of standards and permits when used as maritime bunkers or in the port environment. Crafting safety and handling standards specific to maritime use will be needed to address concerns and identify appropriate possible locations for infrastructure that can help reduce uncertainty in any future planning process.

4.4.3.2 Renewable Electricity Supply at Ports

Most large ports already use a significant amount of electricity and are going to require access to more. Because most port authorities are primarily landlords overseeing a diverse range of light-duty and heavy-duty industrial tenants, much of the energy needed for ports is for machinery, process plants, and thermal management. Tenants involved in maritime freight, primarily terminal operators, use a relatively lower amount of electricity. They have even increased their efficiency over the years through measures like LED mast lighting, power factor correction on cranes, and digital controls. Despite these efforts, major new loads from electrifying port equipment, fast-charging systems, shore power systems, and visiting trucks will greatly increase the total amount of power needed for terminal operations.

Providing additional power—which could be equivalent to multiple times the existing amount for all other equipment being considered—has occurred successfully in the past and can be difficult in the port environment. In addition to space constraints for transmission or transformer equipment, the planning and construction needed to install the equipment may disrupt operations or require major redesign or rebuilding of existing specialty infrastructure like high-strength tarmac or rail service lines. This also assumes that additional power can be made available from the local utility to be provided to the area.

4.4.3.2.1 Demand, Regional Capacity, and Integrated Upgrade Planning

The availability of new electricity supply, in particular renewable electricity, can be a challenge for many utilities that provide power for ports. Historically, new supply for increased loads was simply a matter of time and funding: once there was demand, the process for designing, permitting, and financing new projects was reasonably straightforward. Now, with increasing numbers of clients hoping to electrify operations, utility providers are wrestling with how to scale up supplies while decarbonizing generation.

Multifold increases to electricity supply and decarbonizing the grid are both multi-decade processes. Inflation Reduction Act (IRA) tax credits supporting the grid supply chain will help alleviate this constraint. Over the coming decade, major new demands for power are likely to require local utility capacity expansions. If decarbonization is happening at the rate to keep up with national commitments, port areas will be a hub of activity, policy decisions, and implementation. Ports and terminal operators will need to prioritize where power is directed based on their unique needs and operations and coordinate with electric distribution utilities to serve load accordingly. This can look like charging for heavy-duty trucks and cargo-handling equipment or for fast-charging tugboats and harbor craft, or providing shore power for large ships—even if some technologies will be replaced and updated over time. Much of this planning will be dependent on a port-by-port basis by the stakeholders of each individual port and utilities servicing electrical infrastructure. The federal government's role will be to study alternatives, anticipate needs, and help to support states and utilities to ensure sufficient capacity and infrastructure are available so ports can support increased demand. With proper planning, we can tackle this challenge.

Integrating electricity and transportation system plans and investments is critical to build a national network of decarbonized fueling infrastructure

Integrating planning and investment spanning the transportation and electricity systems is essential to accelerating the cost-effective build-out of robust fueling infrastructures across the United States. The increasing demand for electricity, directly for electric vehicles (EVs) and indirectly to produce low-carbon fuels, requires a commensurate response that accelerates the accommodation of these new end uses into electricity policy, utility regulation, and the deployment of needed energy infrastructure.

A refreshed approach to electric grid planning that extends the utility regulatory compact to also include the transportation end uses critical for meeting climate change goals will help ensure the timely provision of reliable, safe, affordable, and resilient electric services. Stakeholders will need to account for new transportation loads, advanced grid management technologies, and new business models in demand forecasts and operating practices. These demand forecasts could extend the time and geography included in their capital infrastructure plans beyond those located in their service territory to reflect and support the achievement of regional or national transportation goals. Importantly, collaboration will facilitate public and private financing to ensure that new decarbonized fuels and electricity are affordable for drivers, fleets, and utility customers alike.

The federal government's longstanding research and development efforts with private industry to advance grid technology have commercialized to enable mass customer adoption of distributed energy resources operating in smarter and increasingly flexible utility systems. Deployment programs in the Infrastructure Investment and Jobs Act (IIJA)[81] and incentives enabled by the IRA are accelerating this modernization. Across the country, while these deployments help lay the foundations for transportation decarbonization, decision-making among the private sector, civic organizations, and the public sector at local, state, and federal levels that guide electric system regulation, planning, and operation must be harmonized to construct fuel networks benefitting all Americans.

In IIJA, Congress established the Joint Office of Energy and Transportation[l] and authorized multi-state freight corridor compacts.[m] Such compacts could facilitate the development and financing of infrastructure while considering the needs of a broad range of stakeholders.

IIJA also established a new planning standard for transportation electrification[n] under the Public Utilities Regulatory Policies Act (PURPA) enabling initial utility actions to expand rates, charging infrastructure, and investment, and to recover associated costs to support EVs. Although these provisions provide initial resources, their distinct frameworks and scopes underscore the need for integrated transportation and energy planning and investment across the United States to respond to customers' growing calls to timely construct a broader, nationwide decarbonized fueling infrastructure network that is economical and resilient.

In implementing the action plans, utilities and transportation planners—working with their regulatory authorities and public and private sector entities, and in coordination with DOE and the Department of Transportation (DOT)—should incorporate local, regional, and national multimodal mobility goals into energy infrastructure plans by:

- ***Extending planning horizons.*** Utilities and states can continue to implement EV-charging programs, specifically considering more recent technology assessments and the associated energy demanded by long-term decarbonization goals, thereby identifying cost-effective electricity system investments that support timely service to and energization of customers.
- ***Expanding end-use forecasts.*** Utilities can plan for and serve anticipated electricity demand from non-road transportation end uses, including maritime, rail, and aviation—and associated efficiency measures.
- ***Contributing to the national network.*** State DOTs and utilities can coordinate to better understand and serve the electricity demand associated with inter-utility, interstate, interregional transportation to deploy electricity delivery infrastructure that meets the needs of regional and national interest mobility corridors in a timely and cost-effective manner.
- ***Improving efficiency of capital investments.*** Utility and transportation planners can seek information from stakeholders to understand needs, priorities, and issues to maximally leverage private sector financing and other means to reduce the marginal costs of delivering electricity to transportation end uses.

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[l] 23 U.S. Code § 151 established the Joint Office of Energy and Transportation to facilitate collaboration between DOE and DOT to study, plan, coordinate, and implement zero-emission transportation and related infrastructure. Among other responsibilities, the Joint Office is charged with technical assistance related to the deployment, operation, and maintenance of electric vehicle supply equipment (EVSE) and hydrogen fueling infrastructure; vehicle-to-grid integration; data sharing to inform the network build-out of EVSE and hydrogen fueling infrastructure; studying national and regional needs to support the distribution of grants; and electric infrastructure and utility accommodation planning in transportation rights-of-way; studying, planning, and funding for high-voltage distributed current infrastructure in the rights-of-way of the Interstate System and for constructing high-voltage and or medium-voltage transmission pilots in the rights-of-way of the Interstate System; among other activities.

[m] Multi-state freight corridor planning, authorized under 49 U.S.C. § 70204 recognizes the right of states, cities, regional planning organizations, Indian Tribes, and local public authorities (including port authorities) that are regionally linked with an interest in a specific nationally or regionally significant multi-state freight corridor to enter into multi-state compacts to promote the improved mobility of goods. These compacts allow for project along corridors that benefit multiple states, assembling rights-of-way, performing capital improvements, and employing a variety of financing tools to build projects, including with support of DOT.

[n] 16 U.S.C. § 2621 amended PURPA to establish a requirement wherein each state's utility rate-making authority, electric utilities, and nonregulated electric utilities shall consider measures to promote greater transportation electrification. The standard describes measures that states and utilities could pursue, including the establishment of rates that promote affordable and equitable options for light-, medium-, and heavy-duty EV charging; improving the customer experience including by reducing charge times; accelerating third-party investments; and appropriately recovering the marginal costs of delivering electricity to EVs and charging. The provision allows states with existing EV rate standards to be exempt from the standard, and permits states that decline to implement the standard to publish a statement of reasons.

4.4.3.2.2 Microgrids, On-Site Generation, and Storage

Technologies to modernize the grid and provide local power and management strategies can help alleviate some demand constraints by addressing one of the major reasons so much supply is required. Microgrid technology, with complementary on-site generation and storage, can provide two major benefits that allow limited supplies to be stretched much further. First, microgrid technology allows a subset of activities and demand to be treated and managed as its own system. This allows a portion of overall demand to reduce peaking loads and balance demand so that limited supply is used more consistently and efficiently. A theoretical port microgrid can be designed that considers all the loads within it and manages power distribution in real time so that large draws, like high-speed charging, are staggered and complementary—perhaps even allowing some vehicles connected to chargers to act as batteries that capacitate demand for other activities when not in use.

Adding dedicated storage into a microgrid environment creates similar benefits. When demand is abnormally high, batteries or other storage devices can provide supplementary power to reduce peaks. These batteries are then charged when demand is low or while intermittent supply (as from wind or solar) is more available. Batteries have the added benefit of helping to “clean” reactive power from regenerative loads while also enabling faster DC-DC charging for equipment.

To add to the benefits of a locally managed grid environment, many ports around the world are installing on-site renewable energy generation with wind turbines or solar panels. Even though the port environment can be constrained for adding new facilities that require dedicated land allotments, some renewable generation can be integrated with existing facilities. Smaller wind turbines can be installed with minimal footprint or on existing equipment. Solar panels can be integrated onto the roofs of warehouses or added to new coverings above storage for cars or refrigerated containers.

4.4.3.2.3 Charging Infrastructure for Harbor Craft and Midsized Vessels

For many smaller and shorter-range vessels, particularly those with highly variable energy demand and duty cycles, electrification will be a compelling option in a low-carbon economy. Vessels that meet these characteristics and have regular berths for hoteling will be the first to require charging facilities as their regular berths. As with other port equipment where operational demand requires minimizing downtime, fast charging will be crucial.

With the multi-megawatt (MW) scale batteries likely required for many types of harbor craft, the charging facilities will need to supply more power in similar time compared to other types of port equipment. Despite this, the actual total power required for charging vessels' fleets may be lower than for larger fleets of cargo-handling equipment of heavy-duty trucks. Also, unlike other port equipment, MW–scale charging for harbor craft is still in the process of being standardized.

Current efforts to standardize charging across multiple industries[82] have already started and U.S. government-led efforts to develop those standards have started as well, so development and deployment of electrified vessels at this scale may need to occur in parallel. To meet vessel electrification targets described in this plan, all the complementary measures—from microgrids to utility planning—must be engaged as soon as possible.

4.4.3.3 Other Port Activities, Infrastructure, and Accommodations to Support Decarbonized Vessels

While fuel and electricity supplies are the core strategy for decarbonizing vessels in the port environment, other facilities and accommodations at a port can also contribute. In broad terms, any measures that allow vessels to be technically or operationally more efficient will contribute to vessel decarbonization by reducing the amount of expensive alternative energy required to operate. In some cases, port facilities can encourage or enhance a vessel’s ability to be more efficient.

4.4.3.3.1 Wind Equipment Accommodation

Wind propulsion is a nascent technology for medium-sized vessels that has been proven on large vessels and in concept over hundreds of years. Modern wind propulsion technologies range from cylindrical Flettner rotors that may be moved or lowered from where they are attached on the deck of a vessel to fixed wing sails that provide more optimal power with less flexibility. Some aspects of port environments may create barriers for wind-power technologies on vessels due to height constraints or other operational conditions. Working with vessel operators, particularly during early stages of terminal development or redesign, may allow vessel operators to consider wind propulsion opportunities that would not have been available when serving traditional ports.

4.4.3.3.2 Shore Power

Shore power is an effective strategy to reduce local air pollution resulting from docked OGVs and harbor craft while contributing to acceleration of decarbonization of maritime activity at ports. While at berth, maritime vessels run auxiliary diesel engines that contribute to air pollution in ports and near port communities. Shore power infrastructure enables vessels to instead connect to the electric grid and turn off onboard engines, significantly reducing emissions. The decision to install shore power and retrofit vessels can be especially practical at ports with a high percentage of frequently returning vessels, such as harbor craft and cruise ships. As shore power requires a significant cost investment and adequate power supply to the vessels, there are important considerations for stakeholders, including local utilities and port operators, to collaborate on to ensure these projects can be operated in a timely and consistent manner.

As the nation’s electric grid decarbonizes over time, investments in shore power infrastructure will result in substantial reductions in GHG emissions, enabling OGVs and harbor craft to achieve decarbonized operations while in port. Portside grid infrastructure installed to enable near-term zero-emissions berth operation by OGVs can also strategically benefit zero-emissions harbor craft charging as technology for those vessels matures. Ports should work with their local electric utilities to identify strategies to ensure there is sufficient grid capacity to support shore power infrastructure alongside rising electricity demand necessary to support other types of electrified port equipment, such as cargo-handling equipment and drayage trucks, in addition to maritime vessels. These clean energy solutions will come in many ways, from the aforementioned decarbonization of grid-based electricity to on-site fuel cells use and even floating nuclear power plants[83, 84] near ports as safety and security concerns are addressed.

4.4.3.3.3 Hull Cleaning and Reception Facilities

U.S. ports can also support vessel decarbonization by offering services that enhance the efficiency of vessels. While there may be other services that can be offered at a terminal to support efficient operations, regular hull, propeller, and rudder cleaning can be done relatively inexpensively and with minimal shoreside resources to support the services. More frequent hull cleaning can improve fuel efficiency by roughly 5% in many types of vessels, particularly those that travel in waters that are prone to biological fouling. Many top vessel operators will have a hull cleaning regime in place, but offering more and more competitive services will allow more frequent cleaning of top performers and more access to services from vessels that may not participate to the same degree.

4.4.3.3.4 Communications and Data Sharing

The worldwide maritime system is complex, with thousands of ports spread across hundreds of countries serving millions of vessels. This complexity has slowed the adoption of modern tools for data management and communication. Passive technologies, like the automatic identification system (AIS), used to track vessels, have revolutionized some aspects of how the industry is able to manage fleets and improve safety and security. More active data sharing, particularly between vessels and ports, has been more elusive. Each harbormaster has limited scope and resources for managing traffic and operations only within the immediate vicinity of the port environment.

Being able to expand the scope of communication beyond the immediate vicinity of the port—by days or miles—has the potential to improve efficiency for both the port and vessel. On the port side, understanding incoming vessel delays or conditions at precedent ports that may affect local scheduling can improve a port's ability to plan and react to better manage all the landside resources that are needed to support a cargo ship. This type of communication also helps in the event of a natural disaster or major incident that takes a port or waterway out of service. Broad, real-time communication makes the freight system more resilient as well as more efficient.

More data and better approaches to sharing data will also improve policy and regulatory development by providing a clearer picture of systemic activity and needed improvements. For decarbonization, improved data sharing will be fundamental to the emerging context of "green corridor" initiatives. These corridors seek to partner with vessels dedicated to the routes and fuel types. Improving communication and data sharing in the context of green corridor development will allow ports to optimize (initially) limited supplies of alternative fuels for these vessels and match supply chain requirements with activity in a way that ensures availability and optimizes price.

4.4.3.4 Related Programs

The port sector in the United States has been a central focus of support programs and funding in recent years. This is partially because ports are a crucial part of the nation's freight movement infrastructure. Above-average demand during the COVID-19 pandemic strained the system and led to systemic slowdowns and bottlenecks that focused resources on ports and related systems. Improvements to the aging infrastructure at ports may help to alleviate some of these issues in the future as freight volumes vary.

Ports are also a hub for many types of industry and freight transportation activity. This makes them an ideal focus for deploying SMFs, renewable electricity supplies, and other technologies and strategies that support clean energy. While many of the equipment and transportation modes (e.g., rail, medium- and heavy-duty) that use port resources have their own federal funding streams to support energy transition, maritime does not. This disconnect makes matching shoreside improvements and facilities that would support a decarbonized maritime industry much more difficult.

4.4.3.4.1 MARAD Port Infrastructure Development Program (PIDP)

The PIDP is a discretionary grant program administered by MARAD to help ports improve safety, efficiency, and reliability of goods in and around the port area. PIDP grants are primarily aimed at developing and improving infrastructure for freight movement to ensure that it can meet anticipated growth in freight volumes. The grants support both planning and capital projects, seeking to balance support for large and small ports in both rural and urban areas. To achieve this balance, PIDP has a dedicated amount of funding for smaller ports to improve and expand capacity, reliability, and efficiency. From its inception in 2019 through 2023, grant applications for PIDP have totaled over $9 billion. For those years, funding was available for only one-fifth of the meritorious projects despite available funds being tripled in 2022 under the Bipartisan Infrastructure Law (BIL). As a result, there were still substantial projects left unfunded.

4.4.3.4.2 EPA Ports Initiative and Clean Ports Program

The IRA established several new funding programs for EPA, including to reduce emissions at U.S. ports. This new direction from the IRA leverages EPA's Ports Initiative to invest $3 billion to fund a wide range of energy, climate, and air quality initiatives at ports. The EPA Ports Initiative has long been a central tool for planning and policy related to health and climate impacts. This new and substantial infusion of funds will allow for grants in two important areas that set the groundwork for major changes to how ports are powered and how they can develop more sustainably in the context of the environment and communities around them. The two sets of funding (Clean Ports Program: Climate and Air Quality Planning Competition) announced approximately $2.8 billion in selected projects in October of 2024.

4.4.3.4.3 Department of Energy Hydrogen Hubs Initiative

Also funded by the BIL, the Regional Clean Hydrogen Hubs Program (H2Hubs)[51] provides $7 billion in government cost share, catalyzing billions in private sector investment to establish 10 Regional Clean Hydrogen Hubs across the United States. These hubs are intended to be the foundation of a national clean hydrogen network that will help to decarbonize multiple major economic sectors, including heavy industry and transportation. H2Hubs will not just be for fueling facilities but support an entire system, from production, distribution, and demand, to accelerate the use and availability of hydrogen as a clean energy source. DOE sees scaling up hydrogen in this way as critical to making hydrogen and a range of other hydrogen-based clean fuels developed, demonstrated, and available in the market as soon as possible.

The Sea Change, the world's first hydrogen-powered ferry, operating in the San Francisco Bay. Image courtesy of SWITCH Maritime.

5. MARITIME DECARBONIZATION NON-TECHNICAL CONSIDERATIONS

The maritime industry connects people to the goods and services that support their lives and livelihoods. These connections are part of a complex system of transportation, infrastructure, and energy. The journey of decarbonizing maritime, therefore, will not only happen aboard vessels. It will occur in shipyards, at ports, and at industrial hubs around the country. In addition, maritime decarbonization will employ mariners, naval architects, scientists, engineers, planners, steelworkers, and many other professionals.

For the maritime sector, decarbonization can also mean revitalization. International competitors have strengthened their position relative to the U.S. maritime economy in recent decades. Growing global momentum toward decarbonization provides an opportunity to reinvigorate domestic industry. Without accelerated action in the United States, the gap between the United States and international maritime industries could grow. Some countries are announcing bold goals for how their domestic maritime industry will compete in the marketplace for new vessels, energies, and technologies. This action plan can help strengthen U.S. competitiveness and position the United States to lead the way globally.

Decarbonizing maritime supports job creation throughout the national economy. If the United States is successful in achieving net-zero emissions and expanding maritime capacity by 2050, there will be new jobs in shipyards to construct advanced ships, new jobs at bunkering facilities to provide zero and near-zero emissions fuel, and new jobs on vessels to navigate them safely, cleanly, and efficiently. And the U.S. maritime economy can also grow to support foreign demand for vessels, positioning the United States as a global leader in the design and construction of new domestic-manufactured vessels and the development and distribution of clean fuels.

Maritime can support and benefit from the broader clean energy transition. Fuel and technology development for the maritime sector are linked to energy needs in other sectors, and cross-cutting initiatives like DOE's Hydrogen Hubs illustrate the benefits of an integrated approach. By building and strengthening relationships between maritime and other sectors, we can spur innovation and investment to collectively build a decarbonized economy.

Innovation in vessel design and manufacturing, in addition to clean fuels, will be critical. Leveraging our world-class research and development capabilities, the United States can become a global leader in the marketplace with the appropriate investment and policy environment. Onboard technology is likely to grow in prevalence, and there is a trade competitiveness and national security imperative for supporting U.S.-made technology and markets.

5.1 Workforce Development/Transition

Maritime decarbonization will not be possible without the maritime workforce, which is the foundation of the maritime economy. The mariners are depended on every day for their specialized skills, expansive knowledge, and resiliency. Adoption of new fuels and technologies must prioritize workforce safety, including through supporting training and skills development. This is an opportunity to strengthen maritime academies and other institutions, e.g., trade schools, community colleges, and mariner training facilities, that are educating the next generation of the maritime workforce, contributing to a stronger and cleaner maritime economy. A focus on the human element is the only way to achieve a net-zero future.

The U.S. maritime industry directly employs nearly 650,000 Americans across the country. This figure includes merchant mariners, port operators, longshoremen, stevedores, and other essential personnel that work on the waterfront. Decarbonization will require new technologies and fuels, and this will require a workforce that is trained in their safe handling and operation.

In addition to the direct mariner and port-related jobs, there is an opportunity to maintain and increase high-quality manufacturing jobs within the United States. To increase the fleet of zero and near-zero emission vessels, U.S. shipbuilding will need to increase. To support the production of these new vessels, jobs will be needed to support the technology supply chain. Lastly, an increase in jobs will be needed to produce the new fuels presented in the Sustainable Maritime Fuel Grand Challenge and beyond.

Gain experience with new technologies during at-sea training to prepare the maritime workforce.

MARAD and DOE should work together to equip U.S.-flagged commercial vessels as demonstration platforms for novel SMFs and technologies. Not only would this provide researchers with a relatively low-cost platform to de-risk technologies, it would also provide valuable early exposure to the future mariner workforce through collaboration with labor and other forward-leaning maritime partners. Additionally, this could offer experience aboard commercial vessels for maritime academy cadets as part of the at-sea training through working with commercial operators to make sure cadets and others receive exposure to and experience with new and emerging systems either as part of demonstration projects or as these new technologies are fully integrated into commercial operations.

Develop new decarbonization curriculum for maritime academies and other institutions.

Target the incoming workforce by working with the seven U.S. maritime academies and other institutions (e.g., trade schools, technical colleges, Historically Black Colleges and Universities, Minority Serving Institutions, community colleges, and mariner training facilities) to integrate new and emerging SMFs and technology information into academic discourse, where practicable. This could include providing training aids for students on topics such as hydrogen fuel cells, U.S. government-sponsored capstone projects, or business plan competitions for students that focus on zero-emission technologies.

Create a new environmental Standards of Training, Certification, and Watchkeeping requirement for commercial mariners.

The Unites States' interest in making changes at the national and international level to the current mariner training standards, including new requirements for certifications and training on environmental protection and emissions reduction technologies, falls under the authority of the USCG and its participation in the IMO Sub-Committee on Human Element, Training, and Watchkeeping. This training would be an additional endorsement on the mariner's Merchant Mariner Credential, which is a pre-requisite for working on commercial vessels. An internationally accepted baseline training framework for seafarers in decarbonization must first be issued by the IMO. The training course should be developed in partnership with key stakeholders, including maritime unions, environmental justice organizations, MARAD, EPA, and DOE. The training would be administered by the maritime academies and maritime training institutions.

5.2 Safety and Standards

Several technical, operational, and regulatory aspects require discussion while transitioning to a decarbonized maritime sector.

- **Alternative fuel handling** – A decarbonized maritime future will certainly include alternative fuels. Some of these fuels require different handling practices. For example, a hydrogen storage and delivery system is not the same as for residual fuel or MDO and requires different standards and practices. Ammonia is shipped by vessels; however, using ammonia as a fuel will require additional safety practices because its storage and bunkering practices will be different.
- **Workforce health and safety standards** – As part of the workforce development during the maritime industry's decarbonized transition, safety and health standards will be needed so mariners and support workforce remain safe and healthy while working with and around these new fuels and vessels.
- **New-build vessel construction and operation** – As more vessels use alternative liquid fuels or are electrified (hybridized or fully electrified), constructing and operating these vessels will require additional safety standards. Design standards will need to address vessels' structural integrity, ease in operation, and vessel stability.
- **Infrastructure safety** – Shore-based infrastructure such as bunkering facilities for methanol, ammonia, hydrogen, and LNG need to ensure that their construction is safe, and maintenance equipment is up-to-date. Electric vessels will require charging infrastructure, and for some vessels, charging cables will be extremely heavy and operated by machinery. Safety protocols should be developed for such operations.
- **Foreign-flagged OGVs** – Most of the OGVs that will visit U.S. ports will be foreign-flagged, meaning they fall under another nation's law-making authority. However, while at berth in a U.S. port and operating within U.S. waters, the United States may exercise jurisdiction over these foreign-flagged vessels.[85] As such, the safety and security of these vessels are held to the same standards of U.S.-flagged vessels.

5.3 Regional Considerations

Due to the immense diversity in the United States, a one-size-fits-all approach to maritime decarbonization is likely to be less effective than tailored approaches. There are many regional or local decarbonization strategies announced or underway in the North American region. In 2010, the North American Emission Control Area was established by the IMO, which applied stricter SO_x and NO_x emission standards in those areas.[86] MARAD funded a project to identify and evaluate alternative fuel and propulsion technologies to reduce GHG emissions in Great Lakes Shipping.[87] Pacific Coast Collaborative, a collaborative effort between states and cities along the Pacific coast, released their first Pacific Coast Action Plan on Climate and Energy in 2013, revised in 2016, and set a target of 80% GHG reduction in the region by 2050. Regional strategies for electricity are also relevant in this discussion for upcoming electric vessels. In the Long-Term Strategy of the United States, Pathways to Net-Zero Greenhouse Gas Emissions by 2050, the goal of 100% clean electricity by 2035 was announced.[54]

5.4 International Efforts/Commitments

Many parts of the maritime industry are inherently global. OGVs, in particular, which are a focal point of this plan, are almost all international vessels by nature. Decarbonization of ports, fuels, and ships must all be coordinated to make ocean-going voyages possible. The United States is committed to working with international partners to lead in this space. As such, the United States has collaborated in or led numerous international missions, strategies, and initiatives, and the U.S. government has committed to a variety of maritime initiatives and declarations. These commitments strengthen the United States' ability to decarbonize the domestic sector while strengthening international cooperation. Below is a list of many of those initiatives and high-level commitments:

- **Mission Innovation Zero-Emission Shipping Mission (ZESM)** – International public-private partnership focused on innovation gaps that limit the adoption of zero-emissions fuels for OGVs. Three goals of the mission for 2030 are to enable: (1) at least 600 large ships to use zero-emissions fuels; (2) the production of 16 Mt of HFO equivalent WTW zero-emission fuels by 2030; (3) 20 key ports covering at least three continents to supply zero-emission fuels. DOE is a co-lead of the mission on behalf of the U.S. government.
- **Mission Innovation Clean Hydrogen Mission** – International public-private partnership focused on increasing the cost-competitiveness of clean hydrogen by reducing end-to-end costs to $2 per kilogram by 2030. This effort is also addressing heavy-duty end-use technical challenges, including hydrogen fuel cells for maritime applications. DOE is a co-lead of the mission on behalf of the U.S. government.
- **The Clydebank Declaration for Green Shipping Corridors** – A U.K.-led declaration that commits signatories to establish at least six[o] green shipping corridors by 2025. The U.S. government published the U.S. Framework for Green Shipping Corridors in April 2022 that builds on this commitment and outlines the United States' desired ambition and how to build these routes. The Clydebank Declaration engagement is being led by the U.S. Department of State (DOS).
- **Green Shipping Challenge** – In 2022, the United States partnered with Norway to launch the Green Shipping Challenge at a high-level event during the World Leaders Summit of Conference of the Parties (COP) 27. The Green Shipping Challenge is designed to encourage countries, ports, companies, and other actors in the shipping value chain to prepare commitments to spur the transition to green shipping and help place the shipping sector on a path this decade that is aligned with the goal of limiting global temperature rise to 1.5°C. Countries, ports, and companies have made over 60 major commitments on issues such as innovations for ships, expansion in low- or zero-emissions fuels, and policies to help promote the uptake of next-generation vessels.
- **The Green Shipping Corridor Initiation Project** – This project supports feasibility studies for green shipping corridors involving developing countries. The project brings together country representatives and non-state actors, including ports and companies, on green shipping corridor opportunities and implementation. The DOS contributed $2.5 million to this effort.
- **Declaration on Zero-Emission Shipping by 2050** – At COP26, the U.S. government co-led with Denmark and the Republic of the Marshall Islands and issued a declaration, along with 12 other nations, with the stated goal to strengthen global efforts to achieve zero emissions from shipping by 2050, including at the IMO.
- **First Movers Coalition** – First Movers Coalition is a global initiative harnessing the purchasing power of companies to decarbonize seven "hard to abate" industrial sectors that currently account for 30% of global emissions, including shipping. The U.S. government is working with the World Economic Forum on organizing the First Movers Coalition.
- **International Maritime Organization (IMO)** – On July 2023, the IMO unanimously adopted the 2023 IMO GHG Strategy on Reduction of GHG Emissions from Ships (2023 IMO GHG Strategy), which superseded the 2018 Initial IMO GHG Strategy on Reduction of GHG Emissions from Ships. The 2023 IMO GHG Strategy includes: (1) a long-term goal to reach net-zero GHG emissions by or close to

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[o] More recently, G7 countries pledged to support the establishment of at least 14 green shipping corridors involving G7 members by the middle of this decade.

2050; (2) intermediate GHG reduction goals of 20%, striving for 30% by 2030, and 70% reductions, striving for 80% by 2040; and (3) a new 2030 target on the uptake of zero or near-zero GHG emission technologies, fuels, and/or energy sources used by the international shipping sector. The U.S. delegation to the IMO is composed of members from DOS, EPA, DOE, DOT, NOAA, and the USCG.

- **International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI** – Annex VI of the MARPOL instrument is the main international treaty addressing air pollution prevention requirements from ships. It was implemented in the United States through the Act to Prevent Pollution from Ships, 33 USC §§ 1901 et. seq. (APPS). Annex VI requirements comprise both engine-based and fuel-based standards and apply to U.S.-flagged ships wherever located and to foreign-flagged ships operating in U.S. waters.[88]

5.5 Intermodal Optimization

For a given freight route in the U.S. freight transportation system, maritime transportation is often one option of several different modes, including trucking and rail. In many cases, maritime services provide a more effective, energy-efficient, and less carbon-intensive way of transporting similar goods over similar distances. For example, tugs and barges use waterways for heavy products that would otherwise congest highways. When maritime transportation is a feasible option, it is often the most cost-effective and efficient method of moving goods.

For many products, especially bulk commodities, waterborne transportation is one of many modes that can be used during the transit of goods from source to market. Products that are generated inland will have to move by trucks and rail before even arriving at a port. Then they may travel by barge along rivers and coastal waterways before they arrive at larger ports to be transferred to larger ships. Goods movement often self-optimizes around factors such as commodity type and value, distance, timing, reliability, access to markets, and cost. Often, this favors modes like trucks for short, flexible routes on land and last-mile deliveries, rail for longer overland transit, and maritime routes where capacity and routes are compatible with the overall transportation needs. Private companies aiming to minimize the emissions across their supply chain may opt to include GHG emissions and carbon intensity as a factor by which to optimize a given route.[89] As they do so, maritime freight transportation may increasingly be considered as an alternative to trucking for certain routes. Continued investment in maritime freight movement, including in the U.S. marine highway system, can help to strengthen the value proposition of this mode and improve optionality for shippers and logistics managers to leverage lower-carbon, more efficient freight transport.

Preserving and expanding modal choice is essential to ensuring a resilient, reliable, efficient, and flexible national freight system. Maritime freight contends with several factors limiting its role in domestic freight movement. A major barrier is geography: while the nation's 31 designated Marine Highway Routes encompass more than 20,000 miles of navigable waterways, routes that are prohibitively distanced from these waterways will be serviced by other modes. Other factors include environmental factors (e.g., persistent regional drought leading to record-low channel depth in portions of the Mississippi River), costs and logistical requirements for changing modes (i.e., from maritime to trucking), and an overall lack of investment, especially for inland ports. Focused investments in resilience, inland port infrastructure and modernization, and terminal facility technology and logistics can help to alleviate some of these concerns.

The U.S. government is already taking steps to support these long-term investments and improvements, which will generate benefits broadly across the economy. MARAD's United States Marine Highway Program (USMHP)[90] highlights and supports the use of major river and coastal routes in the context of the broader national freight movement system. DOT has also recently established an Office of Multimodal Freight Infrastructure and Policy (as directed by Congress in the IIJA), which will continue the advancement of DOT's Freight Logistics Optimization Works[91] tool and seeks to further improve coordination on freight infrastructure implementation and planning, while ensuring digital tools maintain hands-on human oversight and workforce protections. DOT will designate a National Multimodal Freight Network[92] in 2024 that supports the use of and shift to lower-carbon modes. In addition to these efforts, the level of support and investment in strategic maritime infrastructure beyond major ports must increase significantly to be commensurate with the level of need and potential long-term benefits.

Improving the Maritime Transportation System (MTS) to meet current and growing demands will require building on these initiatives and seeking a better, more coordinated approach to freight planning, which includes not only the federal government, but state departments of transportation, port authorities and other governmental bodies, civil society, labor, and the private sector. Considered holistically at the freight system, maritime routes are a key and essential resource, supporting the efficiency, resilience, and vitality of freight movement more broadly, while creating opportunities to reduce GHG emissions.

5.6 Equity and Justice

Ports operations and shipping produce air emissions that can have significant environmental and human health impacts. More than 39 million people[93] in the United States currently live near ports, and near-port communities are more likely to be low-income or minority populations; these populations are exposed to air pollution from diesel engines at ports and are at disproportionately high rates of and increased risk of developing asthma, heart disease, and other health problems.[94] Port and maritime operations also create areas of intense industrial activity, including truck and rail movement and associated pollution, port construction and expansion, and linkages to fuel, pipelines, and other supply chain elements that are often located adjacent to and in some cases bisect low-income and underserved communities.

Near-port communities, which are often overburdened and historically underserved communities, continue to bear the economic and health burdens of higher emissions, noise, and worsened air quality. It is critical that these communities are not left behind in the transition to a decarbonized economy. These impacts are not distributed equally, not only due to the disproportionate siting of ports in low-income communities. Research indicates that the negative health outcomes contributed by port pollution disproportionately impact Black near-port residents.[95] The Justice40 Initiative, made it a goal that 40% of the overall benefits of certain federal climate, clean energy, affordable and sustainable housing, and other investments flow to low-income communities that are marginalized by underinvestment and overburdened by pollution.[96] Reducing or eliminating GHG emissions and criteria pollutants associated with the use of conventional fossil fuels for port and maritime operations will reduce climate impacts and improve overall air quality for low-income communities, lowering health-related risks from exposure to air pollution derived from these operations.

The Justice40 Initiative is a key component in federal efforts to confront and address decades of underinvestment, which has contributed to the lack of economic opportunity in communities across the country. The U.S. government is committed to addressing these by increasing safe and affordable transportation options, connecting Americans to good-paying jobs, making communities more resilient, improving access to resources, and enhancing quality of life. In addition to Justice40, Executive Orders on Tackling the Climate Crisis at Home and Abroad (EO 14008), Revitalizing Our Nation's Commitment to Environmental Justice for All (EO 14096), Worker Organizing and Empowerment (EO 14025), Ensuring the Future Is made in All of America by All of America's Workers (EO 14005), and others prioritize the widespread creation and retention of high-quality jobs with the choice to join a union as an integral part of strategies to build an equitable clean energy future. Other key enablers include robust engagement with community and labor stakeholders and formal partnerships and agreements that secure, create, and expand access to good jobs and deliver community benefits.

Section 2.3 outlined several possible impacts that ports can have on local communities, including air pollution, noise and vibration, displacement of local communities, and a disproportionate impact on jobs and opportunities. In addition, communities with environmental justice concerns often experience stressors beyond health disparities such as neighborhood disinvestment, income inequality, public safety concerns around truck routes and rail crossings, and coastal-related threats from extreme weather events and climate change. The industrial super blocks, rail lines, and highways surrounding ports can create barriers between residents and necessities such as grocery stores, health services, pharmacies, retail centers, transit, and recreation spaces. Industrial features in near-port areas mean that near-port neighborhoods often lack adequate sidewalks, street trees, safe intersection crossings, and other basic infrastructure.[97] Actions taken to decarbonize the maritime sector and ports under this plan should make every effort to manage and improve environmental impacts of the maritime sector on low-income communities.

Many disproportionate impacts on near-port communities are the result of long-term policy and siting decisions across various levels of decision-making. Community engagement and education are an important component of ensuring that changes at ports lead to a positive environmental justice outcome. To support these dialogues, EPA's Ports Initiative is working to support effective communication and engagement between the port industry, communities, Tribes, and port stakeholders. To promote community-port collaboration for effective planning and engagement, EPA's Ports Initiative developed the Community-Port Collaboration Toolkit,[98] which includes the Ports Primer for Communities document,[99] the Community Action Roadmap,[100] and the Environmental Justice Primer for Ports.[101] All these tools, along with descriptions of pilot projects, case studies, and other resources, can be found on the Clean Ports' Community-Port Collaboration webpage.[102]

EPA's Clean Ports Program[103] has a goal to help ensure that meaningful community engagement is a port industry standard practice. The Clean Ports Program has been designed to ensure that near-port community engagement and equity considerations are key elements of the program. In considering applications, selection criteria favor projects that take place in low-income communities experiencing poor air quality. In addition, applicants are strongly encouraged to engage with local communities to inform their project, and EPA will evaluate applications on the extent and quality of meaningful engagement activities before applying, during the project, and after project completion to ensure that community concerns are considered in proposed projects and beyond.

6. MARITIME DECARBONIZATION STRATEGY

The U.S. maritime sector encompasses a diverse set of vessels, that vary in energy efficiency, application, and use, from large vessels such as bulk carriers and tankers (often referred to as OGVs), and harbor craft like tugboats, commercial fishing boats, and ferries, to non-commercial vessels. Each of these vessel types requires unique decarbonization solutions ranging from more efficient operations to the use of electrification and fuel cells as well as the use of SMFs. As such, the U.S. maritime industry will need to employ multiple fuel and propulsion system types to reduce its GHG emissions. This section recommends four general strategies for maritime decarbonization.[26, 56]

1. Increase vessel, engine, and operational efficiency to the extent possible (e.g., hull design, exhaust treatment).[32, 56, 80]
2. Electrify and hybridize where feasible.
3. Implement use of SMFs (e.g., clean hydrogen, clean methanol, clean ammonia, and RNG/e-methane).
4. Reserve drop-in fuels (e.g., RD, renewable gasoline) for legacy vessels that are not easily replaced or vessels that are most sensitive to fuel energy density.

The following presents the strategies assigned to each vessel category (see section 4.4.2 Sustainable Vessel Developments for definitions):

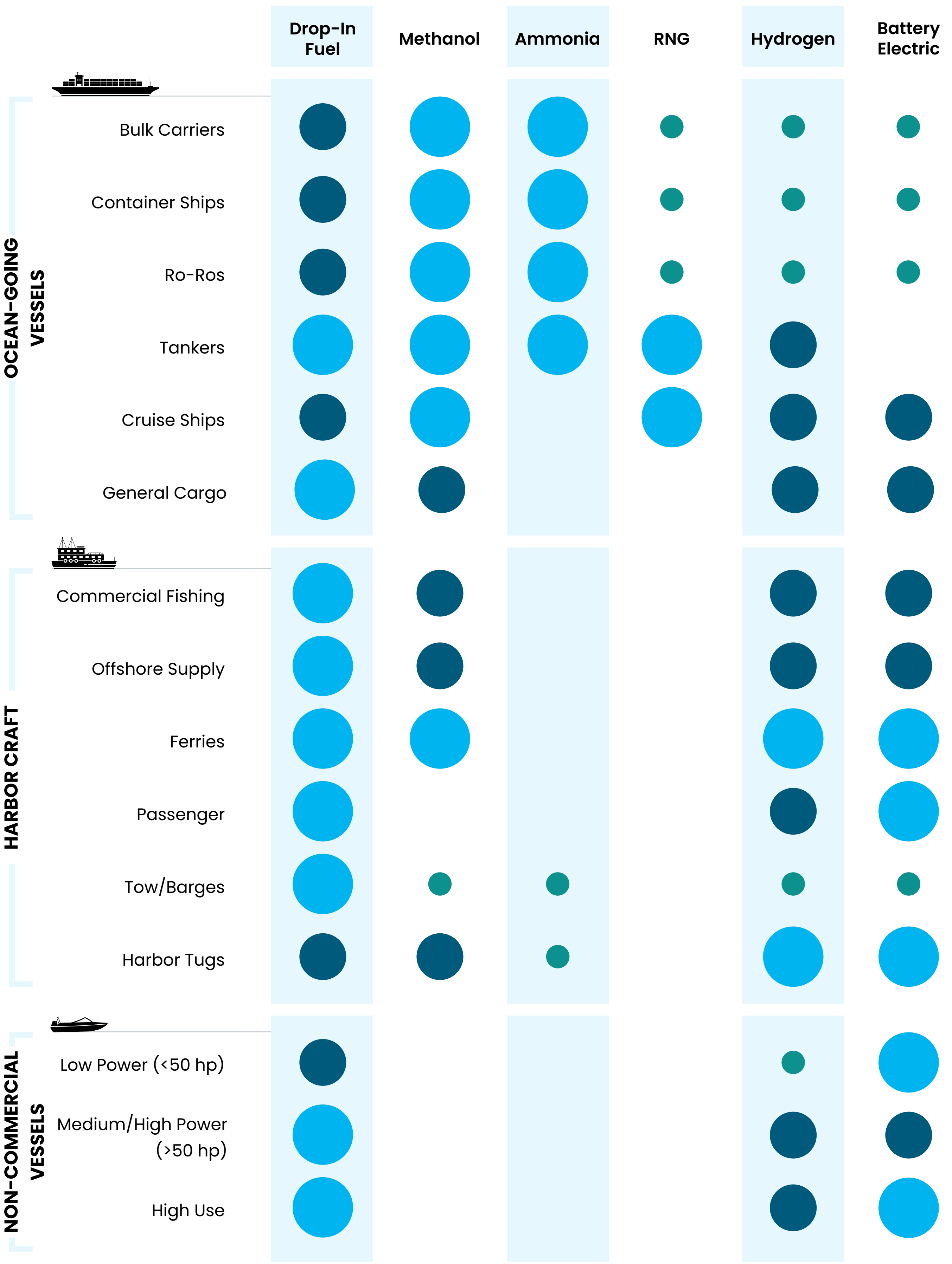
1. **Ocean-Going Vessels**: Prioritize implementation of clean methanol and ammonia fuels by 2050 while integrating sustainable biofuels as direct drop-in and pilot fuel as appropriate.[56, 104, 105]
2. **Harbor Craft**: Prioritize low- to zero-emission vessel technology—hybrid electric, battery electric, and hydrogen fuel cell by 2050 while integrating biofuels where route and vessel characteristics dictate.[43, 58, 106–110]
3. **Non-Commercial Vessels**: Prioritize sustainable drop-in fuels while focusing on advancing efficiency improvements such as hull designs, hybrid electric, battery electric, and hydrogen propulsion systems by 2050.[26, 111, 112]

This action plan considers the importance of infrastructure development for sustainable fuel production, bunkering, vessel charging, and technologies that reduce criteria air pollutant emissions of OGVs while at berth through application of SMFs, shore power, or other available technologies. Without these infrastructure improvements, a decarbonized fleet would not be able to operate. It should be noted that while this plan accounts for the fuel and energy needs of the DOD, it does not include a strategy for decarbonization of the DOD fleet.

Combining the above factors and overarching strategies, and informed by publicly available analyses, the following projection describes which fuels, energies, and technologies are anticipated to be most used for each vessel class in the U.S. maritime sector in 2050.

Figure 18: Conceptualization of the predominant, supporting, and niche fuels and powertrain technologies of the U.S. maritime sector in 2050 by vessel type. (Note: Hybridization and partial electrification will be important to improving vessel operational efficiency and decarbonization.)

⬤ Predominant ● Supporting • Niche



		Drop-In Fuel	Methanol	Ammonia	RNG	Hydrogen	Battery Electric
OCEAN-GOING VESSELS	Bulk Carriers	●	⬤	⬤	•	•	•
	Container Ships	●	⬤	⬤	•	•	•
	Ro-Ros	●	⬤	⬤	•	•	•
	Tankers	⬤	⬤	⬤	⬤	●	
	Cruise Ships	●	⬤		⬤	●	●
	General Cargo	⬤	●			●	●
HARBOR CRAFT	Commercial Fishing	⬤	●			●	●
	Offshore Supply	⬤	●			●	●
	Ferries	⬤	⬤			⬤	⬤
	Passenger	⬤				●	⬤
	Tow/Barges	⬤	•	•		•	•
	Harbor Tugs	●	●	•		⬤	⬤
NON-COMMERCIAL VESSELS	Low Power (<50 hp)	●				•	⬤
	Medium/High Power (>50 hp)	⬤				●	●
	High Use	⬤				●	⬤

There are several limitations to the 2050 maritime decarbonization projections and the fuel use scenario (Figure 18). The projected propulsion systems per vessel type in 2050 is dependent on what technologies are either showing promise of commercialization or already commercialized at the present time, which could change with potential technology breakthroughs. Currently, methanol-ready OGVs lead in new ship orders compared to ammonia and hydrogen. However, this could change between now and 2050 if, for example, the global maritime industry converged on a specific SMF. Retrofitting existing maritime vessels with alternative propulsion systems was not considered in detail for the strategy but could become a cost-effective means of converting the U.S. maritime fleet if other options are cost prohibitive.

The availability and accessibility of clean energy is a prerequisite for the maritime sector to reach net-zero GHG by 2050. Without clean energy, even the transition to electrification and SMFs will not lead to a net-zero GHG sector. This underscores the importance of coordinating decarbonization strategies across transportation sectors.

To achieve these goals, the action plan is organized across five actions with distinct objectives, targets, and activities supporting each (Figure 19).

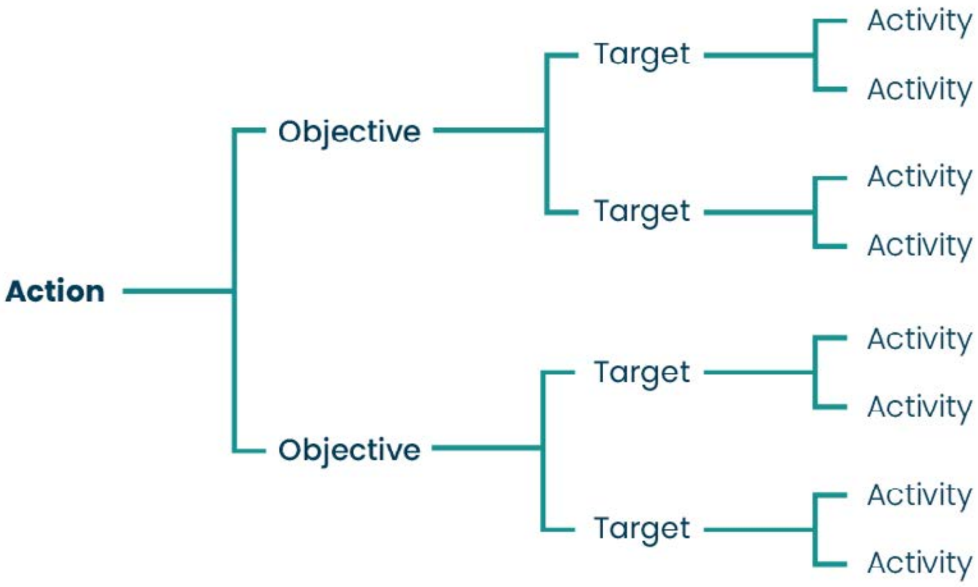


Figure 19: Breakdown of U.S. maritime decarbonization strategy organization

The actions include:

- ✓ **Action**: Decarbonize maritime vessels and operations through efficiency improvements, clean fuel and energy sources, and technology integration.
- ✓ **Action**: Adopt sustainable, emerging maritime fuels and energies by increasing their development, production, and use.
- ✓ **Action**: Support U.S. maritime ports by advancing infrastructure development and shipbuilding to enable systemwide maritime decarbonization.
- ✓ **Action**: Strengthen and expand the maritime workforce by prioritizing safety, security, and training.
- ✓ **Action**: Build partnerships and collaborations through strategic planning.

These actions, as well as the activities and associated targets, align with U.S. policy. Though not exhaustive, the following highlights actions that need to occur to achieve our goals. The targets included in this section are intended to fully leverage solutions highlighted within the three Blueprint strategies (convenient, efficient, and clean) to yield near-term energy efficiency improvements and reductions in criteria pollutant and GHG emissions. These activities also identify areas where the United States can position itself to achieve medium- and long-term zero emissions by spurring U.S. innovation and developing the necessary SMFs and technologies at scale, while ensuring that new fuels and zero-emissions solutions will not increase emissions of criteria pollutants. The activities within this document implicitly include the need for equitable development, community engagement, and environmental justice throughout the U.S. maritime decarbonization effort. Along with the overall goal to fully decarbonize the U.S. maritime sector by 2050, there are several high-level ambitions with which the action plan is aligned, including the U.S. goal to achieve a net-zero emissions economy by 2050 and the IMO levels of ambition. Further, the action plan aims for more ambitious interim targets to reduce total annual GHG emissions from international shipping by 37% by 2030 and 96% by 2040 compared to a 2008 baseline and achieve zero GHG emissions from international shipping by 2050 to align the sector with the goal to limit global temperature rise to 1.5°C.

Washington State Ferry (harbor craft) operating in Elliott Bay, WA.

6.1. Action: Decarbonize maritime vessels and operations through efficiency improvements, clean fuel and energy sources, and technology integration.

Achieving near to zero emissions from maritime operations is complex and includes both technical and operational measures, while technical measures on ships can include engine refit and retrofit, waste heat recovery, and hull design or coatings. Measures also include optimizing the technical efficiency of the fleet and improving operational and systemic efficiency and using sustainable fuel across all harbor craft and shoreside port operations. Each of these independently or in combination can produce immediate emission reductions if practices and technologies are upgraded to incorporate these measures. Getting to zero will require actionable, strategic, and impactful zero and net-zero emissions solutions for the U.S. domestic and international fleet.

These objectives include targets for a range of vessels—OGVs, harbor craft, and non-commercial vessels—and operational profiles and applications, such as inland waterways, fixed routes, and variable use, to promote fit-for-purpose decarbonization approaches. The implementation requires deployment of vessel efficiency technologies, improved data resources that support planning, and improved integration among vessels and shoreside facilities.

6.1.1 Objective: Decarbonize ocean-going vessels.

TARGETS

- ▶ By 2030, increase operational efficiencies to reduce intensity of GHG emissions by 40%, consistent with the IMO goal for cargo- and passenger-carrying vessels.
- ▶ By 2030, at least 15% of all OGV port calls at U.S. ports have net-zero GHG emissions while at berth through application of SMF, shore power, or other available technologies, reaching 50% by 2040 and 100% by 2050.

ACTIVITIES

- Support the development of green shipping corridors allowing for the early demonstrations of near- to zero-emissions OGVs between domestic and international ports.
- Support multiple pilot/demonstration programs for the adoption of SMFs, including green shipping corridors.
- Provide technical assistance to freight users and shippers on deployment of SMFs and electrification.
- Hold a workshop with cargo owners and shippers to further understand policies and regulations that affect the increase of operational efficiencies and GHG emissions reductions.
- Promote implementation of virtual arrival and other communication improvements to support operational efficiencies in the port area, including just-in-time queueing.
- Study onboard carbon capture and integration with a host terminal or port with coordination with nearby carbon capture, use, and storage infrastructure.

6.1.2 Objective: Decarbonize harbor craft including coastwise inland waterways vessels.

TARGETS

- By 2027, standardize and increase access to charging/refueling infrastructure at ports for harbor craft consistent to support all new build electrified vessels and existing harbor craft.
- By 2030, at least 10% of harbor craft (by number) are running entirely on SMFs, reaching 70% by 2040 and 100% by 2050.
- By 2030, at least 25% of all new-build harbor craft are hybrid electric, battery-electric, or hydrogen fuel cell, reaching 50% by 2040 and 75% by 2050.
- By 2035, significantly and measurably expand the U.S. retrofit, rebuild, and replacement capacity of harbor craft to use hybrid electric, battery-electric, and hydrogen fuel cell and SMF options.

ACTIVITIES

- Build or upgrade harbor craft to near-zero or zero-emissions through coordination with existing interagency grant and finance programs like EPA Clean Ports Program and Federal Ship Financing Program (Title XI).
- Increase RD&D on criteria pollutants of SMFs, on marinized batteries, and on marinized fuel cells for harbor craft.
- Provide technical assistance for decarbonization of harbor craft via the use of SMFs and electrification where possible.

6.1.3 Objective: Decarbonize non-commercial vessels.

TARGETS

- By 2030, at least 10% of marine gasoline consumption is from SMFs (e.g., green gasoline or e-gasoline), reaching 88% by 2040 and 100% by 2050.
- By 2030, at least 15% of new non-commercial vessels sold annually are hybrid electric, battery electric, or hydrogen fuel cell powered or designed exclusively for operation on SMF, reaching 35% by 2040 and 50% by 2050. Boats with higher use should be the priority for electrification and hydrogen.
- By 2030, identify up to 10 green boating regions to focus development of fast-charging infrastructure or hydrogen refueling stations and incentivize deployment of alternative energy vessels.

ACTIVITIES

- Support the development of industry standardized life cycle assessment models specific to non-commercial vessels.
- Focus on renewable gasoline and RD, along with hybrid vessel technologies, to support non-commercial vessels as part of broader efforts to increase RD&D related to maritime drop-in fuels.
- Enable SMF distribution to marinas and key refueling areas.
- Increase support for RD&D to improve energy density and to reduce the cost of marine electric vessel batteries, focusing additionally on co-development with non-commercial vessel manufacturers to accelerate adoption.
- Encourage the purchase of new electric, hydrogen (ICE and fuel cell), and hybrid non-commercial vessels that use comprehensive life cycle assessments to prove reduced carbon footprint based on typical annual hours of operation.
- Study and define areas of high demand for fast-charging infrastructure and align deployment of fast chargers accordingly.

Bulk carrier (left), a type of OGV, taking on fuel from a bunkering barge (right), which is a type of harbor craft.

6.2. Action: Adopt sustainable, emerging maritime fuels and energies by increasing their development, production, and use.

The development, production, and use of or near-zero emission fuels on a life cycle basis is necessary for long-term maritime decarbonization. But no single energy source will meet the needs of a diverse and resilient maritime sector. Multiple alternative and renewable fuel and technology types must be identified and evaluated for technology readiness to support near- and long-term deployment, and sector-specific use for ocean, inland, and landside applications. As the industry transitions to a multi-fuel future, stronger integration with the broader energy system will help increase availability and decrease cost. Doing this will require increases in zero and net-zero emissions fuels and energy RD&D to de-risk and accelerate integration of new technologies into the market.

6.2.1 Objective: Facilitate greater coordination among U.S. agencies to strengthen cooperation on technology development, demonstration, and other RD&D activities/policies, including establishing mechanisms for cross-coordination with rail, road, and port operations to undertake sector-wide strategic actions for maritime decarbonization.

TARGETS

- By 2026, establish two or more federal interagency agreements that coordinate RD&D efforts on maritime decarbonization.
- By 2026, assess decarbonization opportunities for cross-cutting areas such as multimodal freight.
- By 2030, initiate at least 20 new demonstration projects, across maritime sectors, to support deployment of alternative energy.

ACTIVITIES

- Conduct a study to determine cost and strategies to decarbonize the U.S. fleet.
- Assess the current U.S. technology and manufacturing capabilities to address RD&D; grow these applications in ways that can inform targets and capacity requirements, and recommend how federal financing and expertise can expedite their development.
- Engage relevant ports, maritime operators, and related government agencies to identify low- and zero-emission operations along ports and coastal and inland waterways, especially marine highways, that could be good candidates for demonstration projects.
- Leverage current and emerging governmental programs, such as MARAD's Maritime Environmental and Technical Assistance[113] program and the U.S. Center for Maritime Innovation, to accelerate demonstration projects of alternative maritime energy and fuels in partnership with industry.

6.2.2 Objective: Promote development and availability of SMFs and energy sources to meet the needs of the maritime sector.

TARGETS

- In 2025, launch a Sustainable Maritime Fuel Grand Challenge that works with industry to quickly deploy SMFs in the near term while building long-term capacity.
- By 2030, support the annual domestic production of SMFs to at least 700 million heavy fuel oil gallon equivalent or HFOGE (the amount of SMF it takes to produce the same energy content of 1 gallon of HFO). This equates to roughly 10% of fuels bunkered in the United States.
- By 2030, support the annual domestic production of green gasoline to at least 80 million gasoline gallon equivalent, while simultaneously distributing a majority to U.S. marinas for use in non-commercial vessels. This equates to roughly 10% of gasoline these non-commercial vessels use in the United States in this segment.
- By 2030, at least 15% of all energy requirements for vessels at port are met by zero-emissions solutions, reaching 50% by 2040 and 100% by 2050.
- By 2030, begin implementation and infrastructure build-out and conversion for alternative fuels and energies through use of PIDP, USMHP, and Title XI programs.

ACTIVITIES

- Conduct a gap analysis of different low- and zero-emissions technologies for different vessel types to prioritize RD&D support.
- Ensure that WTW LCAs are available for all existing and new SMF pathways and are regularly updated.
- Support RD&D projects that improve energy density and reduce the cost of marine batteries and to ensure safety of battery systems in all marine environments.
- Support RD&D projects that optimize production and use of all SMFs.
- Accelerate the development of informed and actionable strategies to complete and implement clean electrification focused master plans and emissions inventories to benchmark and reduce GHG emissions for U.S. ports, terminals, and vessel operations.
- Integrate U.S. Hydrogen Hubs with ports to make hydrogen available for fuel cell powered vessels.
- Work through collaborative opportunities such as the U.S. Center for Maritime Innovation to identify and demonstrate emerging efficiency improvement technologies.
- Leverage available funding authorities and programs, like EPA's Clean Ports Program: Climate and Air Quality Planning Competition and MARAD's PIDP and USMHP, to work with ports, terminal operators, and utilities to identify needs and pathways towards greater electrification and alternative fuels infrastructure for zero-emissions vessels to support electric charging and alternative fuels infrastructure for the U.S. domestic fleet and maritime and inland waterways in such a manner that can be scaled up to meet U.S. and global decarbonization targets.

- Optimize the decarbonization and electrification of ports and port equipment in parallel with harbor, coastal, and OGVs, including through technical assistance, to identify gaps and challenges and develop emissions inventories and master plans through existing programs.
- Continue international leadership through bilateral and multilateral discussions and cooperations on issues like port infrastructure, SMF production, and interoperability standards for SMFs.

6.2.3 Objective: Identify and remove barriers to uptake of SMFs and energies.

TARGETS

- ▶ By 2026, identify communities and other local stakeholders in at least 10 key regions and open regular engagements to facilitate fast-charging and electrification infrastructure and shore power.
- ▶ By 2027, convene a summit open to the public, including relevant agencies and stakeholders, to discuss permitting and approval processes, challenges, and barriers, and produce a comprehensive plan to address these issues, considering input from the community and stakeholder outreach process.
- ▶ By 2028, establish a centralized resource for information on permitting processes, safety regulations, training, and other standard practices around SMFs.

ACTIVITIES

- Increase the speed of approval processes such that vessels and fuels can safely be approved to achieve 2030 goals.
- Support RD&D projects related to SMF safety, safe handling, and spill analysis, including storage and delivery systems, maintenance requirements, and new safety protocols.
- Link land use assessments to broader maritime decarbonization initiatives.
- Convene maritime stakeholders along with interested members of the public to identify constraints and concerns in siting and permitting for sustainable fuel and energy projects, including bunkering.
- Conduct workshops and develop solutions to port electrification solutions with utility providers, regulators, and electric grid and port stakeholders.
- Conduct workshops and develop solutions to increase sustainable fuel production.

6.3. Action: Support U.S. maritime ports by advancing infrastructure development and shipbuilding to enable systemwide maritime decarbonization.

There is a large opportunity to transform the U.S. maritime sector, allow the sector to thrive in a low-carbon economy, and help the sector become more resilient overall. Achieving this includes bolstering port and infrastructure development and expanding the use and capabilities of smaller ports to support more domestic shipping and waterborne freight movement while advancing U.S. technology, shipbuilding capacity, and workforce development. These steps will enhance U.S. shipyards as a potent strategic asset while providing the ability to build and operate the next, low-carbon generation of the U.S.-flag fleet.

6.3.1 Objective: Lead transformative change in ship design and construction.

TARGETS

- ▶ By 2028, support the incorporation of GHG reduction strategies and technologies in new vessel designs to meet 2030 targets and the incorporation of technology pathways to meet future targets. Such vessel designs should emphasize technologies with environmental co-benefits such as reductions in underwater noise and criteria air pollutants.

ACTIVITIES

- By 2026, pursue opportunities with domestic and international forums to discuss opportunities and challenges for integrating decarbonization into vessel design standards.
- By 2030, lead transformative, measurable change in ship design and construction to build a zero-emission U.S.-flagged commercial fleet and accelerate the pace of transition to low- and zero-emissions technologies.
- Address RD&D hurdles for maritime applications and enable rapid development of technologies for commercial applications to meet decarbonization goals.
- Increase RD&D for vessel design efficiencies and operation optimization.
- Enhance coordination with the U.S Coast Guard to identify needs and gaps for type approval for new equipment and design basis review process to support the build of new vessels and approval of retro and refit appliances and systems.
- Support programs that design and build or otherwise convert U.S.-flag commercial vessels to low- and zero-GHG emissions.

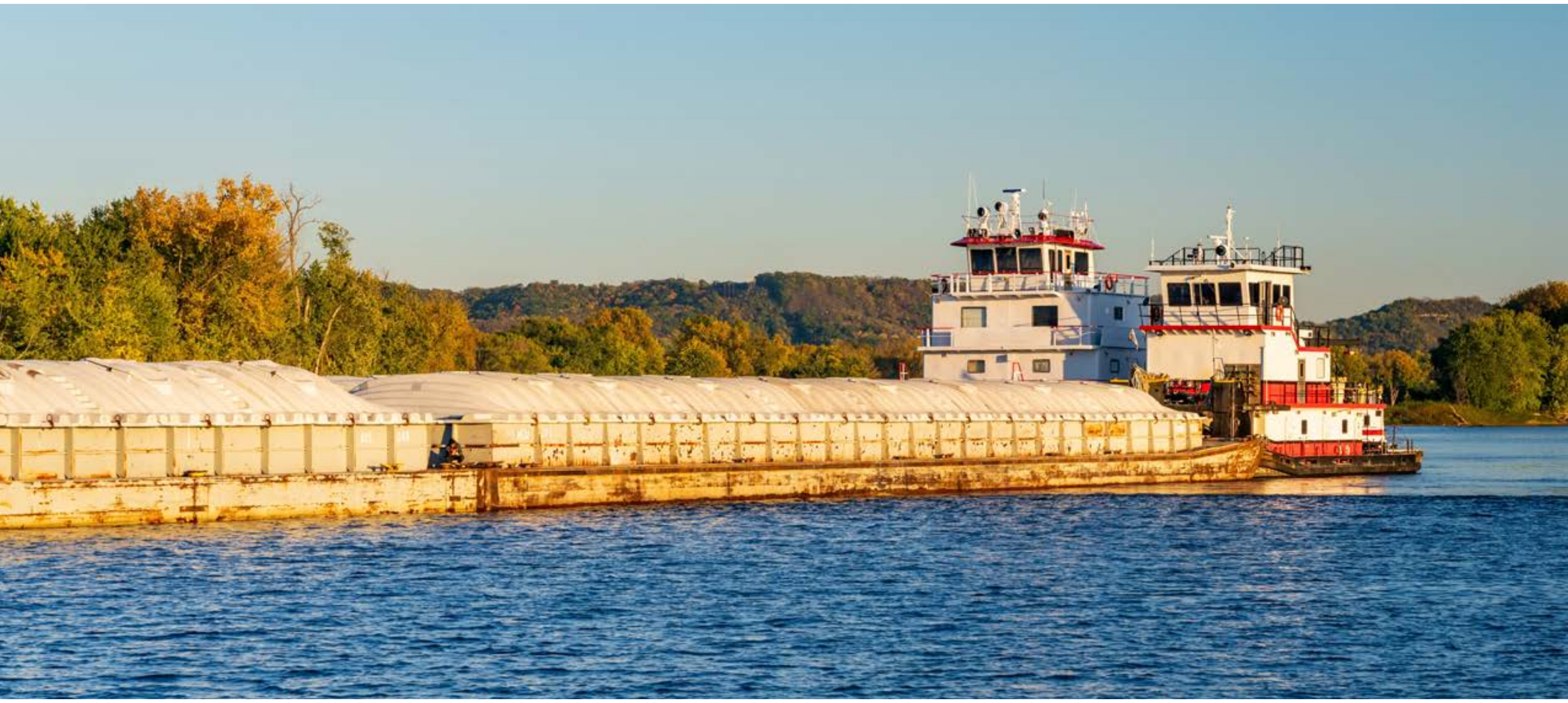
6.3.2 Objective: Revitalize U.S. shipyards.

TARGETS

- By 2026, convene a stakeholder workshop to discuss expanding U.S. shipyards to build and maintain vessels for a decarbonized economy and develop a strategy to achieve the U.S shipyard revitalization targets.
- By 2030, increase U.S. commercial vessel yearly production rate by 10%.
- By 2030, increase infrastructure capacity and availability to enable 10% of existing harbor craft to run on SMFs and to enable 25% of all vessels repowered/retrofit in the United States to run on hybrid electric, battery electric, and hydrogen fuel cell vessels.

ACTIVITIES

- Hold a series of workshops for key stakeholders, including private industry and nongovernmental organizations (NGOs), on what is needed to modernize and expand shipyards to meet future requirements, including RD&D needs.
- Expand support for small shipyard grants and Title XI programs while exploring ways to leverage and incentivize U.S. companies to use funding in the Capital Construction Fund and Construction Reserve Fund to invest in low- and zero-emissions vessels.
- Encourage increased U.S. shipyard use to reinforce national security while increasing the U.S. ability to retrofit, rebuild, and replace U.S. vessels.



A pair of towboats, a type of harbor craft, pushing grain barges up the Mississippi River.

6.3.3 Objective: Expand from existing green shipping corridors and continue to develop low- and zero-emissions port and shipping corridors to demonstrate and deploy established, evolving, and new technologies and infrastructure.

TARGETS

- By 2030, accelerate the transition to low- and zero-emission technologies through the deployment of fuels and technologies along green shipping corridors by bunkering SMFs at a minimum of three U.S. ports.
- By 2030, have the proper infrastructure in place to support Action 1's target of achieving at least 15% of all OGV port calls at U.S. ports having net-zero GHG emissions while at berth through application of SMFs, shore power, or other available technologies, reaching 50% by 2040 and 100% by 2050.

ACTIVITIES

- Support efforts to establish coastal and inland domestic green shipping corridors, including by advising on next steps for planning and infrastructure investments.
- Advance existing international green shipping corridors under the Clydebank Declaration, the Green Shipping Challenge, and the Green Shipping Corridor Initiation Project.
- Advance the goal of expanding green shipping corridors to encompass ports and coastal and inland waterways, where applicable, and identify partners for collaboration and establishment of these more inclusive green corridors.
- Use the USMHP to fund projects that will advance the establishment of domestic green corridors.
- In coordination with other agencies, identify U.S. industry partners to work toward establishing green corridor product identification and incentive programs such as EPA's SmartWay[114] program.

6.4 Action: Strengthen and expand the maritime workforce by prioritizing safety, security, and training.

The maritime workforce, whether on land or on water, will power the decarbonized transportation system. The MTS employs hundreds of thousands of people within the country, and many more globally. Decarbonizing the maritime sector is an opportunity to expand the maritime workforce. Engineers, scientists, and the maritime trades will be needed to develop and install shoreside and shipboard systems that promote decarbonization. These highly technical systems will also require technical experts specifically trained to maintain and repair the equipment. Modernizing the MTS through a climate lens is an opportunity to educate and train a larger and more diverse workforce; ensure the maintenance and growth of high-quality jobs; promote a just transition, including for impacted workers; and work to make inclusive economic growth a priority. Prioritizing safety, security, education, and training alongside growing and promoting the workforce is integral to advancing decarbonization. Through a coordinated, innovative approach to decarbonizing the maritime shipping industry, we can ensure the United States is a leader for the workforce of the future by investing in a more efficient, safer, cleaner, and just future.

6.4.1 Objective: Prepare and educate current and future generations of engineers, scientists, and technical specialists in decarbonization, achieving the net-zero goals by 2050.

TARGETS

- By 2026, work with the Accreditation Board for Engineering and Technology (ABET) accredited institutions to encourage a focus on decarbonization elements into the curriculum that meet ABET-required outcomes related to environmental factors and context during the next six-year review cycle.
- By 2026, identify existing university and apprenticeship programs addressing decarbonization, including Maritime Academies and MARAD-designated Centers of Excellence.[115] Work to expand current and develop new programs and curricula to enhance maritime decarbonization education and training opportunities.
- Beginning in 2028, increase investment in colleges with engineering programs with a focus on maritime studies to purchase lab and technology equipment to support student understanding of green systems and enable education and training of stakeholders to develop a decarbonization curriculum.
- By 2034, introduce elements related to decarbonization into existing engineering and science curriculum.

ACTIVITIES

- Work though ABET and the National Council of Examiners for Engineering and Surveying to include decarbonization-related content in engineering programs and follow on engineering licensure exams.
- Work with the USCG within maritime academy approved curriculum for both the navigator (DECK) and engineer (ENGINE) sides, to identify opportunities to integrate new guidance on decarbonization fuels, technologies, and vessel operations, as they become available and appropriate.
- Accelerate maritime decarbonization by making best practices information available, including lessons from domestic and global workforce as well as IMO initiatives that can be used in education and training settings.
- Support decarbonization research and development (R&D) at colleges and universities with a maritime-related program, including and beyond the U.S. Merchant Marine Academy and State Maritime Academies.
- Support training programs to introduce current trends toward new fuel standards as an add-on to the existing curriculum and, as appropriate, develop training plans for future mariners once the Secretary of Transportation has determined that appropriate fuel(s) are available to facilitate decarbonization in shipping.

6.4.2 Objective: Promote greater diverse, STEM-focused maritime workforce development for the rapid and just transition and operation of zero-emissions vessels and port equipment and coordinate training for advanced technology systems as the industry starts to implement such technologies at scale throughout the maritime sector.

TARGETS

- ▶ By 2030, develop remote diagnostic pathways for decarbonization systems so that technicians may work on the systems without traveling to specific vessels.
- ▶ By 2030, establish and build on existing union training infrastructure and encourage partnerships to provide technical assistance for labor unions and small business owners around safely working on and with new, high-tier engines, clean fuels, or zero-emissions systems through dedicated engagement workshops and opportunities.

ACTIVITIES

- Support projects that provide significant benefits to the national workforce and economy.
- Enable greater U.S. technology development, expanding U.S. market presence and competitiveness for U.S. companies.
- Support workforce development, training, and modernization of equipment and practices to prepare for a surge in advanced, green technologies and future vessel designs.
- Support innovative workforce programs, including maritime academies and other institutions (e.g., trade schools, community colleges, and mariner training facilities), and MARAD's Centers of Excellence for Domestic Maritime Workforce Training and Education Program,[115] and provide additional funding to programs like small shipyard grants that support programs and grants for domestic maritime workforce training and education.
- Increase use of the Small Shipyard Grant Program at required levels to support workforce development, training, and modernization of equipment and practices to prepare for a surge in advanced, green technologies and future vessel designs.
- Continue to support development of an IMO framework on training for emerging emission control technologies and alternative fuels under the Sub-Committee on Human Element, Training, and Watchkeeping.

6.5 Action: Build partnerships and collaborations through strategic planning.

The maritime industry is built on many layers of partnerships, from commercial agreements that govern the transfer of freight across global supply chains and oceans, to large-scale, billion-dollar investments in port facilities that require complex interactions among terminal operators; cargo owners; federal, state, and local regulatory entities; labor, communities, and NGOs; and other public interest groups. Decarbonization needs to happen across the entire industry and will require new collaborations. This includes all aspects of the maritime community from shipyards to shippers to energy providers and entrepreneurs, as well as environmental justice organizations. Doing so creates partnerships and generates opportunities and investments that can leverage innovative financing and partnering mechanisms that reach beyond traditional, locally oriented strategies by including non-traditional and/or multi-sector and multi-modal entities. This plan identifies opportunities for collaborations to develop innovative solutions, grow markets, and create the policies, standards, and regulations that promote stability. The urgency to advance decarbonization technologies highlights the need for collaborations designed to rapidly bring solutions to market. The United States supports new collaborations that are inclusive, transformational, and actionable.

6.5.1 Objective: Establish mechanisms for collaboration with portside communities and stakeholders for informed technical and policy decision making.

TARGETS

- By 2026, engage with networks of regional portside community advocacy working groups to facilitate equitable energy transitions. Focus on addressing concerns with safety, air pollution, displacement of local communities, disproportionate impact on jobs and health, and noise incursions.

ACTIVITIES

- Develop a stakeholder engagement plan to identify the best methods to support collaboration.
- Engage communities surrounding new and retrofit SMF production facilities to support safe and equitable operations.
- Work with portside communities to make sure their concerns surrounding maritime decarbonization (emissions, safety, noise, etc.) are not only heard but are addressed accordingly.
- Host webinar series aimed at port stakeholders (and in the broader intermodal freight, electric utility, landscape, etc.) across sectors, including highlighting a diverse set of steps that ports are taking to decarbonize.
- Continue to engage with ports and maritime stakeholders to better understand the challenges for alternative fuels and green technology implementation while working with them to fully leverage existing technologies to yield near-term reductions in criteria air pollutant and GHG emissions and promote greater energy efficiency.

6.5.2 Objective: Provide tools and models for calculating GHG emissions and potential reductions based on alternative fuels, repowering/retrofitting, and operational changes.

TARGETS

- By 2025, complete the SAFE-T and work to integrate into industry and stakeholder best practice approaches to reducing GHG emissions.
- By 2026, complete the first phase of a maritime energy, noise, and emissions model and provide baseline information on U.S. maritime GHG emissions and underwater noise.
- By 2026, complete the Global Routing Energy and Emissions Network for Transportation (GREEN–T) and make publicly available.
- By 2026, develop monitoring and data collection plans.
- By 2026, develop an intermodal port fuel optimization tool to identify priority fuels for infrastructure development and market deployment.
- By 2027, implement a public dashboard of indicators to track progress toward goals.
- By 2027, establish the ability to calculate baseline emissions from vessels operating in U.S. waters and understand emissions implications of measures such as fuel switching, electrification, and operational changes (routing) on total maritime GHG emissions in U.S. waters.
- By 2027, conduct emissions and energy usage inventories on 25% of U.S. ports and associated terminal operations. By 2030, encourage all U.S ports and associated terminal operations to complete annual emissions and energy usage inventories.

ACTIVITIES

- Provide bottom-up emissions calculation capabilities for vessels engaged in both domestic and international voyages to help operators make informed decisions about implementation of new technology and fuels.
- Collaborate among federal agencies to gather and publish additional vessel activity and emissions data, spanning more years with greater granularity, to understand and define the complex and changing sources of emissions in the U.S. fleet and intermodal port operations.
- Work to align federal and state government agency characterizations of the U.S. fleet of vessels to facilitate consistent baselines for energy consumption, emissions, and fleet size.
- Enable scenario testing for users to enter information about their vessels or fleets as well as current fuels, routes, etc. The program will provide analysis, including costs, on various potential options for reducing harmful emissions.

6.5.3 Objective: Actively engage to maintain ambitious short- and long-term strategic targets on SMF standards and potential GHG reduction measures, domestically and internationally, through interagency groups and international venues to achieve U.S. and international climate goals.

TARGETS

- By 2027, identify current and potential low- and zero-emission demonstration projects along coastal and inland waterways and ports that can serve as building blocks for scalable decarbonization operations in the next year.
- By 2027, identify cross-modal initiatives or high-impact projects that could benefit and possibly leverage funding across modes and agencies' grant/financing programs for more rapid decarbonization.

ACTIVITIES

- Leverage existing multimodal stakeholder consortia to identify regional needs and effective incentives to decarbonize maritime operations.
- Support upgrades to port and intermodal equipment to zero-emission technologies through coordination with interagency grant and finance programs like EPA Clean Ports Program and MARAD PIDP.
- Explore opportunities for supporting oversubscribed programs at required levels such as the USMHP, Title XI, and Small Shipyard Grant Programs in support of greener infrastructure improvements and near-zero or zero-emissions vessels and cargo-handling equipment.
- Comprehensively assess regulatory and policy opportunities, including aligning domestic GHG measures and goals with IMO (as applicable), developing a GHG maritime fuel standard for domestic vessels, incentivizing the use and production of SMFs, incorporating GHG reduction technologies into new U.S. vessel construction guidance, crafting GHG reporting and inventory guidance, and developing a national e-fuel strategy incorporating maritime fuels.
- Co-lead interagency efforts around port decarbonization coordination and issue elevation by contributing to vision/action documents for ports.

7. NEXT STEPS – GETTING TO 2030 AND BEYOND

7.1 Actions Now Through 2030

Putting the country on a course of action will be critical to achieve the action plan's net-zero goal by 2050. The action plan puts forth the near-term targets that will then feed into mid- and eventual long-term targets facilitating the U.S. maritime industry's decarbonization efforts through 2030, 2040, and into 2050. The objectives are developed based on the high-level fleet categories discussed throughout the document, OGVs, harbor craft, and non-commercial vessels, as well as infrastructure and overarching goals. Other considerations were also included in the development of the near-term targets, including existing and relevant overarching, economy-wide goals for the United States as it relates to this maritime decarbonization strategy, namely, the goal to achieve a carbon-free electricity sector by 2035 and to equitably transition America to net-zero GHG emissions.[54]

7.2 Funding and Financing Development

U.S. investments in the maritime sector will help ensure national competitiveness and stability of trade flows, promote American manufacturing, and improve public health for port communities.

To help advance clean technologies and related fueling infrastructure, the IIJA and the IRA provide billions of dollars in funding to support the development, demonstration, and deployment of low- and zero-emissions technology solutions. These historic investments support the goal of reaching net-zero emissions by 2050 by employing efficient and cost-effective strategies.

The IIJA provided substantial investment in hydrogen through the $8 billion hydrogen hub program. H2Hubs administered by DOE includes up to $7 billion to establish RCHHs across America. Additionally, up to $1 billion is dedicated to the Clean Hydrogen Hubs Demand-Side Initiative. The IIJA also significantly expanded the PIDP[116] administered by MARAD, which funds improvements of the infrastructure needed to move cargo to, through, and around ports, including projects that help reduce or eliminate criteria pollutants and GHG emissions associated with port operations. The IIJA provided $250 million, through the Electric or Low-Emitting Ferry Program to support the transition of passenger ferries to low- or zero-emission technologies.[81]

The IRA made several new tax credits available for clean energy projects. The Clean Hydrogen Production Tax Credit (45V)[117] created a new 10-year incentive for clean hydrogen of up to $3/kilogram that can help reduce the cost of hydrogen-based fuels. The level of the credit is based on carbon intensity, up to a maximum of 4 kilograms of CO_2e per kilogram of hydrogen.[118]

DOT, DOE, and EPA administer several funding programs to help maritime operators, public and private ports, and private maritime operators deploy low- or zero-emissions technologies and related fueling infrastructure for vehicles, vessels, and equipment.

DOE's Loan Programs Office (LPO) works with the private sector to finance the deployment and scale-up of innovative clean energy technologies, build energy infrastructure and domestic supply chains, create jobs, and reduce emissions in communities across the United States. The office works across multiple innovative clean energy and advanced transportation sectors, including advanced vehicles and components, biofuels, hydrogen, and renewable energy. In July 2024, LPO's long-standing Advanced Technology[120] Vehicles Manufacturing Loan Program was updated with new authorities to finance the manufacturing facilities for additional types of advanced vehicles, including maritime vessels. In addition, LPO can finance projects in the United States that support clean energy deployment and energy infrastructure reinvestment to reduce GHG emissions and air pollution through the Title 17 Clean Energy Financing Program (Title 17).[121] As amended by IIJA and the IRA, Title 17 has tens of billions in available loan authority that can be leveraged for port-related projects.

MARAD offers long-term financing through the Federal Ship Financing Program[122] to encourage U.S. shipowners to obtain new vessels and recondition existing vessels with U.S. shipyards. MARAD also assists U.S. shipyards with modernizing their facilities for building and repairing vessels.[123]

NGOs have also begun to work together to further zero-emissions shipping. For example, the Zero Emission Maritime Buyers Alliance, an initiative of the Cargo Owners for Zero Emission Vessels, announced in April 2024[124] the successful conclusion of its inaugural tender for ocean shipping that achieves at least a 90% reduction of GHGs on a life cycle basis relative to fossil fuel powered service. Other interested parties like the Global Maritime Forum are investigating different models for aggregating fuel demand, including entering consortia that could help support economies of scale.[125] The Beneficial Cargo Owners have also started their own commitments to decarbonize.[126]

Despite the aforementioned programs and considering that the maritime industry is critical to national and economic security, the maritime industry still struggles to secure access to capital for the maritime sector. There are major hurdles to the creation and adoption of alternative fuels and emissions reduction practices in the maritime domain, including the costs associated with retrofitting existing vessels or building new "greener" vessels. Vessel owners/operators who want to move towards hybrid solutions, battery electric, or fuel cells often face costs drastically exceeding the cost of a status quo vessel. These costs vary depending on the technology, engine, fuel type, and whether a retrofit/repower or new build is required as well as whether a new vessel design is incorporated. Such variability can range from as little as 10%–20% premium to 100%–200% increase depending on vessel type and the extent of the shoreside infrastructure required.[P]

When factoring in new build domestic and international vessels, new port equipment, and the required expansion of U.S. innovation and manufacturing, costs can easily be justified in the multibillion USD range. Currently, the cost to build workboats for the domestic sector ranges from $1 million to $25 million; offshore support vessels range from $25 million to $175 million depending on specifications; and U.S. flag internationally trading vessels range between $200 million to $600 million to build.[127] Across the approximately 10,000 domestic and 100 internationally operating Jones Act vessels, required investment is expected to be significant to transition the existing U.S. fleet to new zero-emissions vessels as the technology becomes available and existing vessels age out and need to be replaced. Accelerating this process will require additional significant investment in our shipyards and workforce to provide appropriate infrastructure and expertise to build these next-generation vessels. Focusing on near-shore coastal and inland waterway operations provides the opportunity to move the U.S. fleet towards a low/zero-emission future, increase uptake of future zero-emission fuels and technologies, and support a safe and efficient domestic maritime sector.

However, federal funding does not currently match these needs. Annual MARAD funding and financing programs are oversubscribed by millions to billions depending on the program. Importantly, this estimate only represents the current annual funding requests to meet the sector's immediate needs. It does not reflect the additional financial requirements the sector will have to meet decarbonization goals.

The lack of tailored programs for ships and vessels as well as the exclusion of ships and vessels from other funding and incentive programs (for example, the RFS) has created a barrier to multimodal collaboration. While there are a number of existing

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[P] Personal communication with MARAD Office of Shipyards and Marine Engineering and members of industry.

programs that can address portions of maritime decarbonization needs, there are other needs not addressed within current authorizations. The programs below could leverage existing financial programs like the Construction Reserve Fund and the Capital Construction Fund, as well as Title XI to address vessel design and construction needs and implement low- and zero-emission operations along coastal and inland waterways that can serve as building blocks for scalable operations.

7.3 Data and Research Needs

A critical component of decarbonization is undertaking necessary research to identify technology gaps and opportunities, developing the technologies required to meet the needs across the sector, demonstrating their efficacy in the field, and reporting out on lessons learned and next steps.

7.3.1 ADDRESSING INFORMATION AND ANALYSIS GAPS

Thirteen large U.S. ports (of the 57 ports continuously tracked by EPA's Ports Initiative) have undertaken various forms of energy and emission inventories over the last 10–15 years, with just a handful updating them annually. These inventories contain a range of information that may cover emissions from vessel operations, port equipment, and trucks, rail, and on-road operations. Most smaller ports have not historically had the capacity, financial or otherwise, to take on the complex task of coordinating an emissions or energy inventory. However, EPA’s Clean Ports Program in 2024 announced $150 million in grant funding to support climate and decarbonization planning and GHG inventorying.[103]

The U.S. maritime sector would benefit from the collection and access to more reliable data (including fueling and energy information) through a uniform approach to inventories and central data repositories. Across the sector, these efforts can establish common benchmarks, build relationships, and provide additional opportunities that accelerate decarbonization in the sector. Examples of specific actions include:

- Focus research and data gathering programs to enable a wide range of ports and operators to undertake inventories using uniform data gathering approaches and metrics to address information gaps and support consistent and coordinated information sharing about sector emissions, energy use, and maritime activities.
- Gather additional vessel activity, fuel consumption, and emissions data, spanning more years with greater granularity, to understand and define the complex and changing energy types and sources of emissions in the U.S. fleet and to address significant data and methodological gaps in current baseline energy and emissions inventories for vessel activity in U.S. waters.
- Further develop and harmonize practices for LCA and techno-economic analysis to holistically evaluate the effects of various decarbonization options on decarbonization and vitality of the U.S. maritime sector.
- Gain a more granular understanding of the freight information driving port and maritime operations by investment in freight data gathering and analytical tools, and research to enhance the abilities of state, regional, and local agencies to evaluate and address freight movement issues and reduce associated GHG emissions.

7.3.2 TECHNOLOGY RESEARCH, DEVELOPMENT, AND DEMONSTRATION (RD&D)

Many of the technologies, fuels, and operational improvements that will make a decarbonized maritime sector possible are in a relatively early stage of maturity. Some still require field demonstration. A focus on the following RD&D-related areas can help address existing gaps:

- Research current practices and technologies that can contribute to reducing GHG and criteria pollutant emissions from ships, such as ship design, hull coatings, propeller and bow design, voyage route and logistical optimization, propulsion and auxiliary power technologies, fuels, exhaust aftertreatment systems (including onboard carbon capture), electrification, shoreside power, and retrofits, as well as combinations of these approaches.
- Ground-truth, test, refine, and update emissions models and assumptions for the application of one or a suite of the available measures in the field under varying conditions aboard different vessel types.
- Accelerate demonstration and reporting of actual reductions, benefits, costs, and challenges of emerging technologies, operational approaches, fuels, and energy sources to inform ongoing decarbonization efforts.
- Perform in-depth analysis of the potential technologies and market drivers to decarbonize the non-commercial vessels, given that non-commercial vessels contribute to the majority of U.S.-flagged vessel GHG emissions.

7.3.3 U.S. TECHNOLOGY AND MANUFACTURING

- Enhance understanding of necessary upgrades to the electric grid, infrastructure build-out, and conversion of existing infrastructure for accelerated uptake of alternative fuels and electricity by ports and vessels.
- Enhance understanding through review of data and in situ demonstration of various operations optimizations practices, such as reduction of congestion at ports and just-in-time arrivals to evaluate levels of success and applicability for wider implementation.
- Assess the readiness of U.S. port and terminal operators, design firms, shipyards, and vessel owners to implement these technologies for new and existing vessels and assets and the current U.S. technology and manufacturing capabilities to address RD&D needed to grow these applications through outreach and engagement with the sector at varying points in their decarbonization process.
- Systematically assess U.S. capabilities, challenges, and opportunities as well as research so federal agencies can determine how federal financing and expertise can expedite their development.

7.3.4 ALTERNATIVE MARITIME FUELS

- Research alternative maritime fuels to understand their requisite refueling infrastructure, storage, bunkering equipment, safety considerations, and other aspects. No one fuel or technology will suffice for all maritime applications, and there is a need to investigate several alternative and renewable fuel/technology types.
- Better understand alternative fuel feedstock availability, energy density, storage, and use limitations to facilitate implementation of large-scale production and development of distribution infrastructure.
- Support development and use of appropriate life cycle assessment methodologies and standards to ensure that GHG reductions are measurable in ways that facilitate accurate accounting of emissions along its entire life cycle from production to consumption.

7.3.5 ECONOMIC BARRIERS AND INCENTIVE STRUCTURES

Preparing the U.S. fleet to thrive in a low-carbon economy will be expensive. The capital cost premiums of vessels and systems, the added costs of alternative fuels, the cost of insurance or inability to insure vessels, and risks associated with deploying new technology are poorly understood for the U.S. fleet and must be accounted for if the fundamental goals of maintaining a robust domestic fleet remain. Costs can be manageable if considered systemically. How they could be borne by the system is the crux of the problem and where substantial investigation is needed. In particular, the following research needs to be done to clarify the economic pathway to decarbonization:

- What sectors of the economy bear disproportionate costs associated with goods movement and how added costs of decarbonization may further bias these impacts.
- What financial tools are available, through both public and private mechanisms or funding, to bridge the gaps in decarbonization costs.
- How the rate of existing fleet turnover is expected to contribute or detract from fleet decarbonization.
- Costs, timing, and potential of retrofits compared to fleet turnover.
- Sources of risk in fleet decarbonization and mechanism to de-risk the transition through financial, technical, or commercial mechanisms.
- Evaluation of how emerging regulations and initiatives at the international level will affect the U.S. fleet’s decarbonization and what additional or tailored measures may be necessary to support the transition.

7.3.6 U.S. SHIPYARD AND SUPPLY CHAIN CAPABILITIES

As discussed above, the cost to decarbonize the maritime sector is significant, as is the cost of inaction or inadequate action.[128] The proportion of that total cost needed to decarbonize the U.S. maritime sector and the U.S.-flagged fleet has not been quantified, nor has the capacity of U.S. shipyards and the U.S. supply chain to meet those needs been assessed.

- Review funding and financing programs already in place for other sectors that can be applied to the maritime sector.
- Identify existing maritime programs that should be expanded financially or legislatively to enable maritime decarbonization.
- Conduct a study to determine cost to decarbonize the U.S. fleet.
- Conduct a study to determine U.S. shipyard current capacity to meet the decarbonization new-build requirements and what finances, technology, critical materials, labor, etc., it would take to meet those demands.
- Conduct a study to determine how to improve shipyard capacity that increases decarbonization technological capabilities while strengthening the critical workforce.

7.4 Policy/Regulatory Opportunities/ Gaps

There is no single regulatory agency for the U.S. maritime sector nor are ports regulated by the federal government, except channels and harbors as outlined below in the excerpt. As outlined in the U.S. Committee on the Marine Transport System (CMTS) Compendium of Federal Programs in the MTS, over 35 U.S. departments and agencies have regulatory roles and responsibilities as part of U.S. maritime operations.[129] Very broadly, EPA sets U.S. regulatory environmental and emissions standards, and international environmental standards found within Annex VI of MARPOL have been integrated into U.S. law by the APPS. The USCG handles enforcement of these regulations, domestic and international, as well as safety regulations,[130] and Department of Justice is responsible for prosecuting any violations.

The Federal Maritime Commission (FMC) is an independent federal agency responsible for regulating the U.S. international ocean transportation system for the benefit of U.S. exporters, importers, and the U.S. consumer.[131] Also related to imports and exports, the Customs and Border Protection (CBP) enables fair, competitive, and compliant trade and enforces U.S. laws to ensure safety, prosperity, and economic security for the American people.[132] CBP also has the responsibility of enforcing the coastwise laws, including the Jones Act,[17] and can impose fines and penalties on violators.

Constitutional Parameters

"The U.S. Constitution does grant the federal government exclusive jurisdiction over the navigable waters of the United States, including its deepdraft channels and harbors—authority delegated primarily to the Coast Guard and the U.S. Army Corps of Engineers. But federal jurisdiction over harbors stops at the water's edge. Port authorities in the United States are instrumentalities of state or local government established by enactment or grants of authority by the state legislature. Neither Congress nor any federal agency has the power, or even the right, to appoint or dismiss port commissioners or staff members, or to amend, alter, or repeal a port authority charter. Certain port activities are, of course, subject to federal law and jurisdiction, particularly those pertaining to foreign and interstate commerce."[q]

[q] https://www.aapa-ports.org/files/pdfs/governance_uscan.pdf

Given the diverse responsibilities and regulatory roles across the federal government and considering the many additional agencies who help to craft policies, plans, and programs that support the maritime sector, there are economic, technical, and policy challenges and opportunities for maritime decarbonization. These include:

- **Scalability:** The technologies and fuels proposed in this strategy must be deployed at scale to have a meaningful impact. Prior to at-scale deployment, new fuels must be demonstrated from the proof of concept up through various technology readiness levels (TRLs). Policy support for RD&D will be crucial for increased scalability and successful implementation of such novel fuel and energy technologies.
- **New-Generation Vessels:** First-of-kind vessels with novel power trains or new technologies present a challenge for design approval because they have little precedent, and U.S. regulations do not account for all acceptable design and construction methods for first-of-kind vessels. Because the design basis agreement process is considered on a case-by-case basis, it can sometimes take

years to complete. Modernizing compliance regimes without compromising environmental and human safety and health would help accelerate the deployment of the fuels and technologies for emissions reduction.

- **Incentive for Low-GHG Energy Sources**: Unlike sustainable aviation and on-road fuels, as well as EVs, which have been eligible for federal tax credits, no such programs are available for the maritime sector. This absence of financial incentives limits the economic feasibility for rapid uptake of low-GHG fuel production and adoption of battery electric vessels energy technologies and infrastructure.
- **Federal Carbon Regulations and Voluntary Programs**: There currently exist regulations for specific criteria air pollutants such as oxides of sulfur and nitrogen (SO_x and NO_x) from marine engines. Only recently, voluntary federal transportation GHG emission goals that will impact the maritime sector were announced in the Blueprint. However, there are gaps in how to achieve such ambitious goals. This report is the first attempt to provide a path forward.

In an integrated approach to emissions reductions, policy and regulatory levers would complement other approaches, such as R&D and market incentives, and would be calibrated to emissions reduction targets. These levers would also incorporate workforce development, environmental justice, and economic development priorities. Aligning domestic policies and regulations with international approaches, as relevant and appropriate, and in coordination with state and local policies and regulations would help maximize their effectiveness and reduce uncertainty.

Like other transportation sectors, a combination of requirements and incentives would help create a balanced regulatory environment. These should be crafted to amplify impacts that maximize policy and regulatory efficiency and effectiveness. There are several potential policy and regulatory opportunities that could incorporate incentives, RD&D, and social and economic considerations while supporting maritime decarbonization. Some of these opportunities are outlined below and should be considered as potential steps that could be taken, where appropriate, in tandem with the actions discussed in section 6 to achieve decarbonization targets.

Align domestic GHG measures and targets with IMO where applicable.

In June 2021, the IMO adopted two near-term measures to reduce GHG emissions from international shipping by 2030, EEXI, and the Carbon Intensity Indicator (CII).[133]

In addition, the 2023 IMO Strategy on Reduction of GHG Emissions from Ships[10] sets a longer-term target of net-zero GHG emissions from international shipping by or close to 2050 as well as three supporting near-term targets:

1. Reduce carbon intensity of international shipping (to reduce CO_2 emissions per transport work), as an average across international shipping, by at least 40% by 2030.
2. Increase uptake of zero or near-zero GHG emission technologies, fuels, and/or energy sources to represent at least 5%, striving for 10% of the energy used by international shipping by 2030.
3. Reduce GHG emissions by at least 20%, striving for 30% in 2030, and by at least 70%, striving for 80% by 2040.

EEXI and CII currently apply to larger vessels on international voyages for vessels with a gross tonnage over 5,000 GT. To bring the U.S. domestic sector into alignment, the United States could explore mechanisms to adopt similar measures and targets with respect to domestic, non-OGVs as relevant and appropriate. The IMO is currently considering additional measures to reduce GHG emissions from ships in line with the levels of ambition of the 2023 IMO GHG Strategy. The measures under development are expected to emphasize sustainable fuels, energies, and technologies.

Develop a national GHG maritime fuel standard for domestic vessels.

The maritime economy in 2050 will employ a variety of fuels, owing to the diversity of maritime vessel types, use-cases, and fuel attributes. Zero and near-zero fuels, energies, and technologies are critical to achieving net-zero GHG targets. A U.S. maritime fuel standard for domestic vessels could allow for progressive reductions in life cycle fuel or energy GHG intensity over time and will aid in achieving the next steps of this action plan. Setting a maritime fuel standard to regulate the GHG intensity of maritime fuels sold in the United States and used in the U.S. exclusive economic zone (EEZ), which extends 200 nautical miles from the U.S. coastline,[q] could be a key instrument for leveling the playing field and providing market certainty.

Incentivize SMFs.

Reducing the cost of zero and near-zero fuels, energies, and technologies would complement potential regulations in accelerating the uptake of SMFs and reduce the use of carbon-intensive fuels. State and regional bodies can incorporate SMF into Low-Carbon Fuel Standards (LCFS). And there could be a federal LCFS-like mechanism to incentivize the producing low-carbon fuels for the maritime sector. In addition, maritime fuels could be incorporated into EPA's existing RFS, allowing Renewable Identification Number (RIN) credits to be eligible for approved fuel used in maritime vessels.

Incorporate GHG reduction technologies into new U.S. vessel construction guidance.

The United States could explore existing or new standards for vessel construction that could incorporate emerging fuels, energy solutions, and energy efficiency technologies into new vessel design and construction. These standards would take into consideration projected fuel and energy availability, including SMFs. This could be accompanied by incentives to help strengthen the shipbuilding industry in the United States.

Craft GHG reporting and inventory guidance.

Guidance for reporting and calculating GHG emissions from U.S.-flagged domestic vessels not currently covered by the IMOs' Ship Oil Consumption System would help provide a more granular understanding of GHG emissions distributions across the U.S. domestic maritime sector. Consistent reporting and analysis of these data could inform any future mandatory reduction measures by providing clarity on where GHG reduction needs and opportunities are the most significant.

Develop a national e-fuel strategy incorporating maritime fuels.

Several industries, including maritime, rail, and heavy-duty trucking, are expected to use renewable-generated e-fuels as a significant source of carbon-free energy, especially for use-cases in which batteries are not viable. Major investments in hydrogen technology and expected cost declines have made these fuels a strong candidate to power these sectors, but their supply entails complex processes across sectors, and with several competing uses. Additional research and modeling would help scale up a national e-fuel industry while maximizing systemwide GHG emissions reductions. An interagency national e-fuel strategy (building upon the U.S. Clean Hydrogen Strategy and Roadmap) would help to identify gaps and opportunities and provide analytical grounding for government policies.

7.5 Indicators of Progress (Metrics)

To measure the advancement towards the United States' maritime decarbonization efforts indicators of progress will need to be developed and tracked. This section provides a list of potential metrics to begin tracking progress. Some of these data are already collected and some will require new data collection methods. EPA supports fuels sales data collection, including bunker fuel and distillate sales as well as the sales of renewable fuels via RINs, i.e.,

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[q] 33 C.F.R. §§ 2.20, 2.30; U.N. Convention on the Law of the Sea, 1833 U.N.T.S. 31363, arts. 5, 57

RINs (although RINS do not account for maritime fuels). The DOE Alternative Fuels Data Center (fuel production numbers, charging stations, etc.) may also have potential to allow for public tracking of progress toward fuel use and availability targets. It is envisioned that these data and collection methods may be able to serve as a basis for broader data collection. Additionally, MARAD is currently developing a maritime emissions estimation tool. When fully realized, this tool will enable the calculations of GHG emissions for all vessel activity in the U.S. EEZ and use an array of metrics and/or regions or sub-regions to report results. Other potential data sources include the USCG (e.g., Coast Guard Maritime Information Exchange), the vessel AIS, U.S. drydock and shipyard order books, trade organization data from organizations like the National Marine Manufacturers Association (NMMA), and the ZESM Green Shipping Corridor Route Tracker. Proposed high-level, overarching progress indicators to track U.S. maritime decarbonization include:

Strategy	Indicator	Cadence	Sources
Ocean-Going Vessels	Volume of sustainable maritime fuel sold/bunkered in the United States and associated emissions	Quarterly	EPA and EIA
	Number of U.S. ports involved in a green shipping corridor	Annually	Mission Innovation Green Shipping Corridor Hubs
	GHG emissions for OGVs in U.S. waters	Annually	EPA and MARAD collaboration; model and port reporting based
Harbor Craft, Coastwise, and Inland Waterways Vessels	Number of maritime fast charging stations, hydrogen refueling stations, and amount of SMFs sold at ports	Ongoing	DOE – Alternative Fuels Data Center (expanded reporting from light-duty vehicles [LDV])
	Total GHG emissions and GHG emissions reductions for harbor craft in U.S. waters	Annually	EPA and MARAD collaboration; model and port reporting based
	Number and type of harbor craft on order in the United States capable of running on SMF and/or that are electric	Annually	Industry partner
	Number and type of harbor craft sold in the United States capable of running on SMF and/or that are electric	Annually	USCG vessel registrations
Non-Commercial Vessels	Volume of renewable gasoline sold at marinas	Quarterly	EPA and EIA
	Number and type of non-commercial vessels sold in the United States capable of running on SMF, or are hybrid electric, battery electric, or hydrogen	Annually	Mission Innovation Green Shipping Corridor Hubs
	Number of maritime fast charging stations and hydrogen refueling stations at marinas	Annually	DOE – Alternative Fuels Data Center (expanded reporting from LDV)

8. CONCLUSION

A Holistic, Comprehensive Approach

Transportation is the largest source of GHG emissions in the United States. Decarbonizing the transportation sector is integral to achieving a net-zero emissions economy that benefits all communities. Moving toward zero transportation GHG emissions is not only critical to tackling the climate crisis, but the accompanying transformation of the passenger and freight mobility systems toward sustainable solutions and technologies will save lives and improve quality of life for all Americans. It will increase U.S. competitiveness, decrease household costs, increase economic growth, reduce pollution, and increase accessibility and community opportunities.

The historic Memorandum of Understanding signed by DOE, DOT, EPA, and the Department of Housing and Urban Development (HUD) in September 2022, initiated collaboration across the federal government to rapidly decarbonize transportation. The agreement recognizes the unique expertise, resources, and responsibilities of each agency, setting the foundation for solutions that are more innovative and far-reaching than any of the agencies could achieve independently.

The Blueprint, the first step in this collaboration, created a national vision for a decarbonized transportation system. The Blueprint embraced five core principles (initiate bold action; embrace creative solutions across the entire transportation system; ensure safety, equity, and access; increase collaboration; and establish U.S. leadership) to serve as the foundation for all strategies.

The Blueprint's Five Principles

- Initiate bold action
- Embrace creative solutions across the entire transportation system
- Ensure safety, equity, and access
- Increase collaboration
- Establish U.S. leadership

The Blueprint provided a holistic, system-level approach to decarbonizing the transportation sector, proposing actions that address all aspects of transportation GHG emissions, from land-use patterns and development to design of individual vehicles. The Blueprint focused on three key strategies to increase convenience, improve efficiency, and transition to clean options, which will support and complement each other in achieving the goals of the Blueprint (see Figure 20).

1

Increase Convenience

by supporting community design and land-use planning at the local or regional level that ensure that job centers, shopping, schools, entertainment, and essential services are strategically located near where people live to reduce commute burdens, improve walkability and bikeability, and improve quality of life …

… Because every hour we don't spend sitting in traffic is an hour we can spend focused on the things and the people we love, all while reducing GHG emissions.

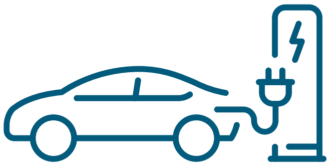
2

Improve Efficiency

by expanding affordable, accessible, efficient, and reliable options like public transportation and rail, and improving the efficiency of all vehicles …

… Because everyone deserves efficient transportation options that will allow them to move around affordably and safely, and because consuming less energy as we move saves money, strengthens our national security, and reduces GHG emissions.

3



Transition to Clean Options

by deploying zero-emission vehicles and fuels for cars, commercial trucks, transit, boats, airplanes, and more …

… Because no one should be exposed to air pollution in their community or on their ride to school or work and eliminating GHG emissions from transportation is imperative to tackle the climate crisis.

As part of the clean strategy, the Blueprint committed to developing specific mode-based action plans for the LDV, medium-/heavy-duty vehicle, rail, maritime, off-road, and aviation sectors to chart pathways to accomplish this complex task over the next three decades. The modal action plans propose near-, mid-, and long-term actions to achieve net-zero emissions in each of the different modal sectors by 2050. This phased approach leverages the historic federal IIJA and the IRA funding; encourages deployment of scalable, market-driven technologies; provides industry and stakeholders with certainty about transforming the transportation sector; recommends planning and proposes policy opportunities at multiple levels of government; and promotes expanded research, development, demonstration, and deployment (RDD&D) to support innovative approaches to decarbonize the transportation sector, including new technologies and fuels. The phased actions across all modes are summarized below.

Actions over the near term (initiated before 2030) involve **leveraging IRA and IIJA incentives** to support the deployment of zero-emissions vehicles in early medium- and heavy-duty markets and expand their market share in passenger (light-duty) vehicles. Billions of dollars in transportation tax credits, infrastructure, and supply chain investments are currently being made throughout the United States through IIJA and IRA funds. The Blueprint outlined the critical need to **develop energy refueling infrastructure**, particularly critical freight hubs. Since the release of the Blueprint, the U.S. freight corridor strategy was developed and released. This strategy outlined the phased approach of critical EV charging and hydrogen fueling networks. Work must continue with **utilities, utility regulators, and other grid stakeholders** to ensure **that integrated transportation and energy planning is conducted so electricity infrastructure and fueling systems are constructed in advance of deploying maritime vessels**. This could include extending planning horizons, expanding end-use forecasts, contributing to the national network, and improving efficiency of capital investments. There is a critical need to **scale up component manufacturing and fuel production** incentivized by IRA tax credits, including biofuels and hydrogen production for legacy vehicles, and domestic tax credits for the manufacture of batteries. The United States will need to expand production of biofuels and hydrogen to further support the harder to decarbonize sectors of rail, maritime, and off-road. **Engaging in further research, data collection, demonstrations, and outreach** for future zero-emissions vehicle deployments, hydrogen fuel cell technologies, and biofuel production and deployment will be essential for emerging markets. **International leadership** will continue to play a critical role in building out international infrastructure and standards for aviation, rail, and maritime. These actions will set the foundation for future actions to fully decarbonize the transportation system by 2050.

Mid-term actions (beginning before 2035) will need to focus on finalizing and ensuring IIJA and IRA investments are fully leveraged. **Transitioning demonstrations to market technologies** will be essential during this timeframe. The United States will need to **expand zero-emission vehicle adoption** from early market to full-scale production and new market segments. This will include **further establishing regional and international corridors and intermodal infrastructure networks** for passenger, freight, maritime, off-road, and rail fueling networks; and **scaling and supporting investments** in zero- and low-emissions vessels and vehicles. **Implementing EPA's Multi-Pollutant and Phase 3 Greenhouse Gas Emissions Standards, and the National Highway Traffic Safety Administration's Corporate Average Fuel Economy Standards**, through model year 2032 will continue the deployment and adoption of zero-emissions vehicles in the light- and medium-/heavy-duty sectors. Mid-term actions may also involve future rulemaking and legislative efforts in these sectors.

Long-term actions (2035 and beyond) will be responsive to market developments and will likely include **expanding zero-emissions vehicle and low-emissions vessel and vehicle adoption to all market segments**, as well as achieving **full build-out of corridor energy infrastructure** for all modes, both domestically and internationally. Realizing **cost reductions in zero-emissions vehicles** to reach parity with ICE vehicles, and supporting **sustainable liquid fuel adoption for legacy vehicles**, will be essential. **Production and bunkering of zero- and low-emissions fuels** will need to expand and scale for use in the aviation, maritime, and off-road sectors. Long-term actions may also involve future rulemaking and legislative efforts in these sectors.

The Action Plan for Maritime Energy and Emissions Innovation

The action plan for maritime proposes actions to demonstrate, scale, and support low- and net-zero emissions technologies and solutions to reduce and ultimately eliminate emissions in the U.S maritime sector. The maritime sector consists of a diverse set of vessels, which vary in energy efficiency, application, and use, from non-commercial vessels, ferries, and tugboats to OGVs. Over the near term, we must make advancements in vessel and operational efficiencies, invest in U.S. ports and bunkering infrastructure, and scale the production of low-carbon fuels. Over the long-term, solutions must focus on a full transition to net-zero emissions vessels across the U.S. maritime fleet, along with deployment of critical infrastructure. The United States must continue international leadership in the maritime sector by promoting and deploying low- and zero-emissions fuels and technologies. We also need to implement solutions and actions to reduce or eliminate emissions of GHGs and criteria pollutants, especially in overburdened communities near port facilities. In addition, there are several cross-cutting actions across all action plans in support of the Blueprint: develop a framework to collect the data necessary to track progress with the decarbonization objectives; support development of the workforce needed to manufacture and maintain new vehicle technologies and infrastructure; and decarbonize the national electricity grid.

Call to Action

Transforming the maritime sector, other transportation modes, and the entire national transportation system over the next three decades will be a complex endeavor, but by taking a comprehensive and coordinated approach it is a challenge that we can, and must, solve. The strategies presented in these action plans identify unique opportunities and will be most effective if decision makers, acting quickly and in concert, continually increase the ambitions of their actions, collaboration, and investments. There is no one technology, policy, or approach that will solve our transportation challenges unilaterally; we need to develop, deploy, and integrate a wide array of technologies and solutions to ensure we achieve our goals.

In addition to leadership at the federal level, reaching these ambitious climate goals will require collaboration with all levels of government, industry, communities, and non-profit organizations. The action plans are intended to send a strong signal to our partners and other stakeholders, to use the documents as guideposts and frameworks to support and complement their own planning and investments, and to coordinate actions in each sector. We will continue to set bold targets for improving our transportation systems and transitioning to zero-emissions vehicles, vessels, and fuels on a timeline consistent with achieving economy-wide 2030 and 2050 emissions reduction goals. As we decarbonize our transportation system, we can create a more affordable and equitable transportation system that will provide multiple benefits to all Americans for generations to come. It will be important to continually evaluate and update our actions as technology and policy continue to evolve, and to continue strengthening the collaborations between DOE, DOT, EPA, HUD, and all our partners. Together, we must act decisively now to provide better mobility options, reduce inequities, and offer affordable and clean mobility solutions to ensure the health of the planet for future generations. **It is up to all of us to make that vision a reality and move forward with creative and innovative solutions toward a better future for all.**

LIST OF ACRONYMS

ABET	Accreditation Board for Engineering and Technology
AIS	automatic identification system
APPS	Act to Prevent Pollution from Ships
BD	biodiesel
BI	bio-intermediates
BIL	Bipartisan Infrastructure Law
Blueprint	U.S. National Blueprint for Transportation Decarbonization
Btu	British thermal units
CBP	Customs and Border Protection
CCS	carbon capture and storage
CH_4	methane
CII	Carbon Intensity Indicator
CMTS	Committee on the Marine Transport System
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
COP	Conference of the Parties
DOD	Department of Defense
DOE	Department of Energy
DOS	Department of State
DOT	Department of Transportation
EEXI	Energy Efficiency Existing Ship Index
EEZ	exclusive economic zone
e-fuels	electrofuels
EPA	Environmental Protection Agency
EV	electric vehicle
FAME	fatty acid methyl ester
FIRST	Foundational Infrastructure for Responsible Use of Small Modular Reactor Technology
FMC	Federal Maritime Commission
FOG	fats, oils, and greases
ft	foot (feet)
ft^3	cubic foot (feet)
GDP	gross domestic product
GGE	gasoline gallon equivalent
GHG	greenhouse gas
GREEN-T	Global Routing Energy and Emissions Network for Transportation
GREET	Greenhouse gas, Regulated Emissions and Energy use in Technologies
GWP	global warming potential
H2Hubs	Regional Clean Hydrogen Hubs Program
HB	Haber-Bosch process
HFC	hydrofluorocarbon
HFO	heavy fuel oil
HFOGE	heavy fuel oil gallon equivalent
HUD	Housing and Urban Development
HVO	hydrotreated vegetable oil
ICE	internal combustion engine
IIJA	Infrastructure Investment and Jobs Act
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IRA	Inflation Reduction Act
lb(s)	pound(s)
LCA	life cycle analysis
LCFS	Low-Carbon Fuel Standard
LDV	light-duty vehicle
LHV	lower heating value
LNG	liquified natural gas

LPG	liquid petroleum gas
LPO	Loan Programs Office
LWR	light-water reactor
MARAD	Maritime Administration
MARPOL	International Convention for the Prevention of Pollution from Ships
MDO	marine diesel oil
MGO	marine gas oil
MMT	million metric ton
MSW	municipal solid waste
MTS	Maritime Transportation System
MW	megawatt
MWh	megawatt hour
N_2	nitrogen
N_2O	nitrous oxide
NBBI	National Biotechnology and Biomanufacturing Initiative
NGO	nongovernmental organization
NMMA	National Marine Manufacturers Association
NOAA	National Oceanic and Atmospheric Administration
NO_x	nitrogen oxides
NREL	National Renewable Energy Laboratory
OGV	ocean-going vessels
OSV	offshore supply vessel
PCTC	pure car and truck carrier
PIDP	Port Infrastructure Development Program
PM	particulate matter
RCHH	regional clean hydrogen hub
RD	renewable diesel
RD&D	research, development, and demonstration
RDD&D	research, development, demonstration, and deployment
RFS	Renewable Fuel Standard
RIN	Renewable Identification Number
RNG	renewable natural gas
Ro-Ro	roll-on/roll-off
SAF	sustainable aviation fuel
SAFE-T	Ship Alternative Fuel and Emissions Toolkit
SMF	sustainable maritime fuels
SMR	steam methane reforming
SO_x	sulfur oxides
TEU	twenty-foot equivalent unit
TRL	technology readiness level
TTW	tank-to-wake
U.S	United States
UCO	used cooking oil
USCG	U.S. Coast Guard
USMHP	United States Marine Highway Program
VLSFO	very low sulfur fuel
WASP	wind-assisted ship propulsion
WSF	Washington State Ferries
WTW	well-to-wake
ZESM	Mission Innovation: Zero-Emission Shipping Mission

APPENDIX A: RELEVANT GOVERNMENT STAKEHOLDERS

U.S. regulatory responsibilities with regard to maritime is divided across multiple agencies. As outlined in the CMTS Compendium of Federal Programs in the MTS, over 35 U.S. departments and agencies have regulatory roles and responsibilities as part of U.S. maritime operations. Very broadly, EPA sets U.S. regulatory environmental and emissions standards. International environmental standards are integrated in the Act to Prevent Pollution from Ships. The USCG handles enforcement of these regulations, domestic and international, as well as safety regulations.[130] The Department of Justice is responsible for prosecuting any violations. The FMC is the independent federal agency responsible for regulating the U.S. international ocean transportation system for the benefit of U.S. exporters, importers, and the U.S. consumer.[131] CBP enables fair, competitive, and compliant trade as well as enforces U.S. laws to ensure safety, prosperity, and economic security for the American people.[132] CBP also has the responsibility of enforcing the coastwise laws, including the Jones Act,[17] and can impose fines and penalties on violators.

While the U.S. government regulates deep water areas and harbors through the USCG and Army Corps of Engineers, the U.S. government does not manage the ports themselves. These ports are run by state or local authorities, independent of federal control. However, federal laws still apply to port activities related to international trade and commerce between states.[134]

A.1 Department of Transportation (DOT)

A.1.1 DOT OFFICE OF THE UNDER SECRETARY FOR POLICY

The Office of the Secretary of Transportation serves central functions within DOT to integrate the nation's transportation resources, including the development of national transportation policy, budget formulation, and oversight of regulatory initiatives across all modes of transportation. The under secretary for policy serves as a principal advisor to the secretary. By statute, the under secretary is third in the Department's order of succession.

The Office of the Under Secretary for Policy includes the Office of Transportation Policy and the Office of International Transportation and Trade, and each contributed to this action plan. The Office of Transportation Policy coordinates domestic transportation policy across the Department. The Office of International Transportation and Trade represents the Department at global transportation and trade organizations, including the IMO.

A.1.2 MARITIME ADMINISTRATION (MARAD)

MARAD was established to foster, promote, and develop the maritime industry to meet U.S. economic and security needs. MARAD supports the technical aspects of America's maritime transportation infrastructure such as ships and shipping, port and vessel operations, national security, environment, and safety. MARAD has the ability, within the authorities granted by Congress, to tailor requests for proposals, notices of funding, and other solicitations to include linkages to reducing GHG emissions from the sector in support of climate goals. MARAD, across its grant and financing programs, successfully awarded millions of dollars to the maritime sector in 2022 and 2023, supporting a range of projects that will advance the nation's decarbonization goals. These included projects that reduce GHGs, support the deployment of clean energy, and avoid adverse environmental impacts such as projects that procure battery electric yard equipment and associated charging infrastructure, installation of microgrids and solar panels, and the development of scalable plans for transitioning the port and local maritime industry to zero-emissions technologies.

A.2 DEPARTMENT OF ENERGY (DOE)

As the lead for alternative energy development and co-lead on the ZESM, DOE is a key maritime decarbonization partner in the discussions and actions relevant to developing alternative fuels, fueling infrastructure, and distribution systems that will support the decarbonization of the maritime sector. DOE works on these technologies through RD&D, bringing them from initial conception (TRL 1-2) through demonstration (TRL 8-9). Continued dedication and agency collaboration for technology development and exploration of partners to implement the use of alternative fuels and technologies are key actions required to reach overall departmental goals.

A.3 ENVIRONMENTAL PROTECTION AGENCY (EPA)

As the regulatory arm for much of transportation emissions, EPA, and the emissions reduction programs it administers, can help to drive the fuels and technologies across the transportation sectors that will be key to supporting maritime decarbonization, particularly around ports as important intermodal connectors. EPA programs are key to advance emissions reductions linked to new and emerging fuels and technologies as well as exploration of financial and regulatory levers that can be used to advance action on decarbonization.

A.4 U.S. COAST GUARD (USCG)

The USCG is the primary maritime regulatory authority in the United States and has responsibility for coordinating with interagency stakeholders, the public, and third parties in developing, revising, and promulgating regulations. In this role, the USCG serves as a lead agency for the U.S. government to the IMO. MARAD and EPA, as well as other federal agencies, support the USCG's role at the IMO as subject matter experts and U.S. delegates to ensure U.S. maritime interests are well represented. The USCG implements MARPOL domestically through the APPS. MARPOL is the main international convention covering prevention of pollution of the marine environment by ships from operational or accidental causes. Air pollution is addressed in MARPOL Annex VI and covers both U.S. ships, and foreign ships calling on U.S. ports or operating in U.S. waters. The USCG and EPA share authority to implement and enforce Annex VI under APPS.

A.5 U.S. DEPARTMENT OF STATE (DOS)

The Department of State is also a lead agency for the U.S. government to IMO and is responsible for implementing and managing the U.S. diplomatic engagement on maritime decarbonization and develops and coordinates USG policy on international GHG reduction efforts. By crafting and joining ambitious international partnerships and declarations, DOS sets, maintains, and implements the priorities and targets of the U.S. government. DOS is the bridge between U.S. policy goals and the international community. This connection is crucial in the maritime industry because domestic and international maritime policy homogeneity will be imperative to a worldwide transition by 2050.

A.6 MARITIME DECARBONIZATION WORKSHOP

On December 11, 2023, DOE, National Renewable Energy Laboratory (NREL), and Argonne National Laboratory hosted a virtual workshop with 243 maritime stakeholders from port authorities, ship owners, environmental justice groups, fuel producers, and classification societies regarding the state of the maritime industry, future projections for the U.S. fleet, and barriers to decarbonization. The participants' individual feedback emphasized the need for long-term policy to incentivize alternative fuels for maritime, align with international policies, and bolster U.S. shipbuilding capacity. The participants also spoke of the importance of a just transition through port community engagement and local safety considerations with new fuels and refineries. The stakeholders expressed high regard for pilot programs and green corridors as testing grounds for alternative fuels, ships, and port energy structure. Finally, we heard many discussions regarding the importance of recognizing the effects of a modal shift from truck and aviation to ship and rail as more efficient modes of transport.

The Hornblower Hybrid ferry operates in the San Fransico Bay and uses 75% less fuel than similar non-hybridized vessels.

APPENDIX B: SUSTAINABLE MARITIME FUELS

B.1 Sustainable Maritime Fuels (SMFs) Introduction

SMFs are the quickest strategy to reduce the GHG emissions from the maritime sector by replacing GHG-intensive fossil fuel. Depending on the primary feedstock of sustainable fuels, GHG reductions can be at least 50% (e.g., biomass) and up to over 100% (e.g., waste). This section covers the major SMFs as alternatives to the HFO, MDO, and renewable gasoline. The advantages and limitations of the fuels will be discussed and their scope in the maritime sector will be examined.

B.1.1 BIOFUELS

Biofuel (see Appendix D for additional biofuel information) is a type of fuel derived from organic matter, also known as biomass. Unlike fossil fuels that take millions of years to form, biofuels can be replenished on a human timescale, making them a renewable energy source. Biomass, acquired for biofuels, sequester carbon directly from the atmosphere opposed to releasing otherwise trapped carbon in fossil fuels. Besides being renewable, most biofuels are also sustainable, depending on their feedstock and conversion processes. This organic matter can come from various sources including purpose grown energy crops (e.g., short-rotation woody crops, herbaceous crops, intermediate energy crops, and algae) and from more traditional commodity crops (e.g., corn [maize], sugarcane, and soybeans). This organic matter can also come from waste sources such as used cooking oil (UCO), manure, agricultural residues, and forest residues. When blended with HFO, biofuels offer potential synergistic benefits by reducing sulfur content, improving overall engine lubricity, and lowering emission profiles, especially for PM.[135] Depending on the biomass feedstock and processing conditions, biofuels can be low in sulfur and nitrogen (N_2) while also providing a low carbon intensity. In fact, some biofuels exhibit close to net-zero emissions, because the GHG emissions from combustion are offset by carbon uptake during biomass growth. However, energy required to produce biomass and convert biomass into fuels add GHG emissions, which are not offset by the carbon sequestration by biomass. With projected decarbonized grid and other net-zero energy inputs, some biofuels have the potential to be a net-zero energy source. Some types of biofuels are considered drop-in replacements of petroleum-based fuels for most engines, which makes them an appealing candidate fuel. A few examples of major biofuels are discussed below.

Research on the combustion characteristics of biofuels and biofuel blends (particularly with HFO) is needed to ensure proper engine operation. This includes studies of lubricity, viscosity, pour point, HFO compatibility, and impacts on fuel injection equipment.[136] Biofuels, excluding hydrotreated vegetable oils (HVOs), generally have relatively high oxygen concentration that leads to their degradation through the formation of peroxides, acids, and other insoluble compounds over time. These compounds can damage the vessel's engine and fuel systems through abrasion, blockage, or poor combustion efficiency. Further research on low-cost stability additives or other methods to reduce the rate of degradation, and thus avoid unnecessary wear, would be beneficial.[137]

B.1.1.1. BIODIESEL (BD)

BD, also known as fatty acid methyl ester (FAME), is produced by transesterification, which converts organic fats and oils into fatty acid alkyl esters by reacting them with alcohols and catalysts (AFDC, 2022a). About 40 lbs of feedstock are required to produce one gallon of BD.[30] Feedstock and capital cost requirement for BD production is lower compared to RD production. However, unlike RD, it's not a drop-in biofuel that can readily replace conventional diesel in traditional diesel engines. Most current engine manufacturers allow BD to be blended with fossil-based or RD, and there is ongoing work to increase the blend.[135] In 2023, total BD production capacity in the United States was 2.1 and 3 billion gallons, respectively.[138, 139] LHV of BD is approximately 32.54 MMBtu/ton. GHG intensity of BD is approximately 73 lbs/MMBtu, which translates to 67% GHG reduction compared to HFO.[30]

B.1.1.2. RENEWABLE DIESEL (RD)

RD or green diesel is a drop-in ready biofuel that can potentially replace conventional fossilized diesel completely in marine diesel engines. It is produced by hydroprocessing or hydrotreating, in which renewable feedstock and hydrogen reacts over a bed of solid particulate catalyst. The hydrotreating process is like the process used to crack crude oil into gasoline, diesel, and other petroleum products. Since crude oil refining technology is used in this process, capital cost is higher than BD. Feedstock requirement for RD production is higher than BD because more material is lost during conversion, and it varies on both feedstock choices and desired final coproduct ratio. Typical coproducts during RD production are fuel gas, LPG, and/or naphtha. While naphtha has a lower octane rating than what is required to be used as a renewable gasoline drop-in fuel for current gasoline engines, it could be upgraded to the desired octane level by blending with high octane blendstocks (e.g., isooctane, alcohols, etc.) produced from green pathways (either from biomass or e-fuels). Typically, about 43 lbs of feedstock produces 1 gallon of RD and a minor amount of naphtha and LPG.[30] The LHV of RD is approximately 37.82 MMBtu/ton. GHG intensity of RD varies between feedstock choices, e.g., GHG of RD from yellow grease is approximately 34 lbs/MMBtu, which translates to 85% GHG reduction compared to HFO.[30] However, GHG intensity of RD from oil seeds (soybean, corn, camelina, canola, carinata, pennycress, jatropha, etc.) could be higher. Besides oil seeds, RD can be produced from various feedstocks such as wet wastes (sludge, manure, FOG), MSW, woody biomass, purpose grown energy crops, etc. The cost of RD is higher than traditional MDO, which poses a challenge for wider adoption of RD as a maritime fuel.

B.1.1.3. BIO-INTERMEDIATES (BI)

BI refer to intermediate products derived from biomass or bio-based feedstocks that serve as key components in the production of biofuels, biochemicals, or other bio-based materials. These intermediates are essential in various bio-refining processes, where biomass undergoes conversion into different value-added products. However, some of these BI can be used as maritime fuel without further bio-refining processes. According to EPA, biocrude, BD distillate bottoms, biomass-based sugars, digestate, free fatty acid feedstock, glycerin, soapstock, and undenatured ethanol are considered as BI.[140] BI enable specialization for facilities where different facilities can focus on their areas of expertise, leading to more efficient production processes. Partially processed BI are often easier and cheaper to transport than raw biomass. BI, which may be cheaper to produce than typical RD, may be able to be blended with traditional fossil fuels or used as neat fuel in some instances.[141, 142] Further, BI can be hydrotreated directly into RD as discussed above or may be partially hydrotreated to result in more favorable performance than raw BI but are less expensive than RD.

B.1.1.4. RENEWABLE GASOLINE

Renewable gasoline, also known as green gasoline or bio-gasoline, is a type of gasoline produced from renewable feedstocks rather than traditional fossil fuels. It's a drop-in ready biofuel that has the potential to replace 100% gasoline in traditional gasoline engines. Currently, 20% blend limit is approved by the EPA.[143] It can be produced from woody biomass, agricultural residues, algae, or other organic materials. The primary benefit of renewable gasoline is reduced GHG emissions compared to conventional fossilized gasoline. According to the California Energy Commission, 61% to 83% GHG emissions can be reduced by using renewable gasoline depending on the feedstock used.[144] Blending renewable gasoline with conventional gasoline can provide at least 40% GHG reduction.[145] Non-commercial vessels in the United States, still existing in 2050, will depend on renewable gasoline to replace conventional fossil-based gasoline.

B.1.2 Methanol and Other Alcohols

Alcohols such as methanol, ethanol, and butanol can provide a low-carbon alternative compared to their fossil counterparts. Especially, methyl alcohol or methanol is gaining traction as a potential alternative to traditional, high-polluting maritime fuels. Methanol can be used in an ICE and potentially in fuel cells. There are several advantages of methanol as an SMF. Methanol can be produced from renewable sources like biomass, RNG, or captured CO_2 using renewable electricity. Currently, almost all of the globally produced methanol—approximately 110 MMTs—are produced from fossilized natural gas because it is the most economical.[50, 146] Renewable methanol from biomass feedstock or waste CO_2 offers an option to significantly reduce GHG emissions, which is crucial for the industry's decarbonization efforts. It can virtually eliminate SO_x and PM emissions and reduce NO_x emissions by up to 80% compared to traditional maritime fuels.[30] This aligns with stricter air quality regulations for the maritime industry. The significant interest in methanol can be observed by the recent order of methanol-ready ships, establishment of clean methanol production facilities across the United States, and the recent efforts for establishing bunkering standards for methanol. Existing infrastructure for storing and transporting methanol can be adapted for marine use, lowering the initial investment, which is one of the advantages over some of the other alternative fuels such as ammonia or hydrogen. It is a liquid in ambient conditions, which makes storage and transportation easier than for LNG, hydrogen, or ammonia.[147] Methanol is reported to dissolve and biodegrade quickly in the event of a surface water spill, which makes it less toxic compared to traditional maritime fuels.[148] While the upfront cost of methanol-powered ships could be slightly higher, the fuel itself can potentially be cost-competitive with traditional fuels.

However, there are a few disadvantages of methanol as a maritime fuel. Methanol has a lower energy density than HFO, meaning ships would need to carry more fuel for the same journey. This could necessitate larger fuel tanks or more frequent refueling stops and reduced cargo capacity. Additionally, methanol is a volatile liquid with a lower flashpoint than HFO. It burns with a clear and invisible flame, which adds another layer of complexity in the event of a fire. This requires additional safety precautions during storage, handling, and bunkering. Moreover, while larger ports may adapt to methanol bunkering, smaller ports may not adequately support methanol bunkering compared to the same level as traditional fossil fuels. This could limit its use on certain routes or regions. Another technical difficulty may arise from engine technology. While methanol-compatible engines are available, they are not yet as widely adopted as traditional marine engines. This could lead to higher costs and longer wait times for newbuilds. Using methanol in marine engines requires the use of pilot oil for easy ignition and efficient combustion. The ratio is approximately 7% pilot oil and 93% methanol by volume. Renewable methanol availability may also present issues on large-scale adoption. Like other fuels considered in this action plan, renewable methanol production is limited to the biomass and CO_2-based feedstocks availability. Directly captured carbon quantities are not adequate to replace the fossilized methanol production estimates as well.

GHG intensity of methanol primarily depends on the major feedstock to produce it (Figure B1). Methanol produced from natural gas has higher GHG intensity than HFO. But biomass or RNG can provide significant GHG reduction. Methanol can be produced through biochemical and thermochemical conversion pathways,[149] the latter being more common for industrial-scale production. It relies on production of synthesis gas, or syngas, which is a mixture of carbon monoxide and hydrogen produced through gasification or fast pyrolysis of any one of several feedstocks, including biomass, coal, natural gas, and RNG. The resultant syngas can then be used in catalyzed reactions to produce methanol. When biomass (wood, MSW, etc.) is used as a feedstock to produce biogas, the resultant product is commonly referred to as bio-methanol. Currently, much of the globally produced methanol is produced from reforming syngas obtained from natural gas[150] or in the case of China, coal.[151] If the hydrogen is sourced from electrolysis and reacted with CO_2, the resultant methanol is often referred to as e-methanol (where "e" indicates electricity was used in its production), one of several electrofuels or e-fuels.

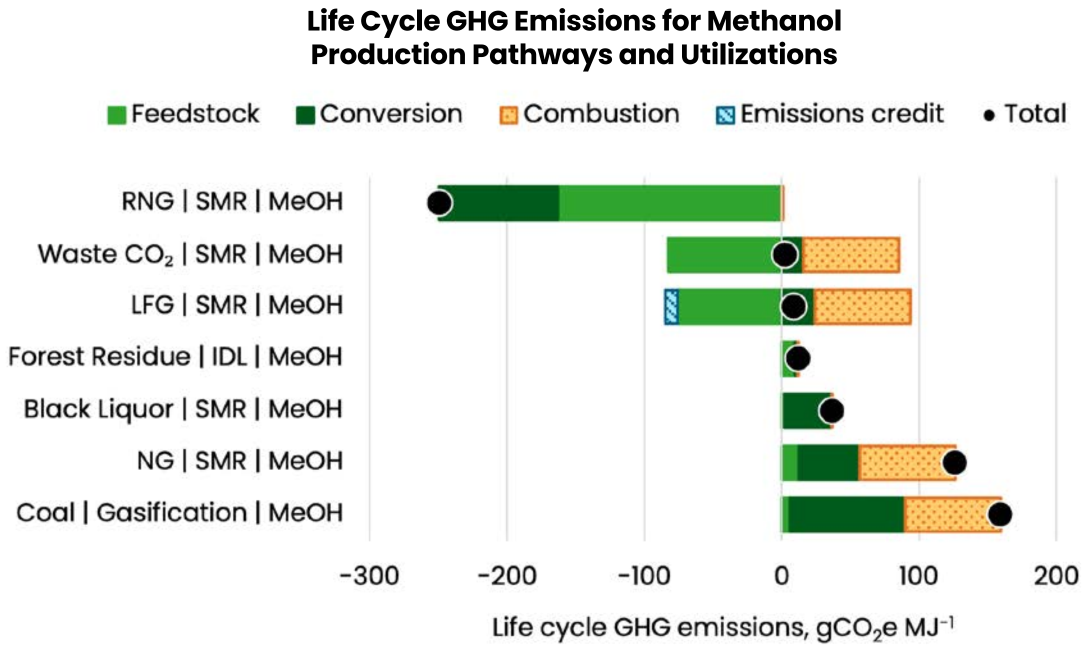


Figure B1: GHG intensity of methanol,[30] RNG = renewable natural gas, SMR = steam methane reforming, LFG = landfill gas NOTE: (1) Biomass is 100% logging residue; (2) Source of RNG is manure, which receives counterfactual credit of avoiding CH_4 emissions from conventional manure management. As conventional waste management becomes more efficient in avoiding CH_4, this credit will change; (3) LFG pathway results may incur fugitive CH_4 emissions and CH_4 slip from ship engines, which vary widely in practice. CH_4 is another potent GHG involves potentially significant use phase CH_4 slip and fugitive emissions (GWP of 29.8 gCO_2-eq./g CH_4 based on IPCC AR6).

Overall, methanol presents a promising alternative for cleaner shipping with its significant emission reductions and potential for renewable production. However, challenges like energy density, bunkering infrastructure, and engine technology need to be addressed for wider adoption. The future of methanol in maritime transportation will depend on overcoming these challenges and capitalizing on its potential. With continued effort and collaboration, methanol has the potential to play a significant role in decarbonizing the maritime industry.

B.1.3 Ammonia

Ammonia (NH_3), a compound composed of N_2 and hydrogen, is a colorless gas with a pungent odor, commonly used in fertilizers and refrigeration. Like methanol, ammonia can be used in an ICE and potentially in fuel cells. Besides direct combustion, ammonia has also gained interest as a hydrogen carrier. It is increasingly being recognized as a promising alternative fuel for the shipping industry due to its potential to reduce GHG emissions. The primary interest is because the ammonia molecule contains no carbon atom and produces no CO_2 during the combustion stage. However, there could be higher N_2O emissions, which is about 300 times more potent than CO_2 as a GHG. There could also be higher NO_x emissions, but those are industrially mitigated using a scrubber. Research is ongoing to verify the emissions produced when using ammonia in an ICE.

Besides zero-carbon emissions during the use phase, ammonia has other advantages. As a globally traded commodity for agricultural purposes, supply, and distribution of ammonia in the maritime industry can be easily incorporated. Approximately 240 million tons of ammonia are produced worldwide (2023 data), about 10% of which are transported by sea.[152, 153] Currently there are about 200 gas tankers that can take ammonia as cargo and typically 40 of them are deployed with ammonia cargo at any point of time. These are potential early adopters. Therefore, it is obvious that the maritime industry does have experience with ammonia; it is carried as a cargo, used as a refrigerant, and used in selective catalytic reduction in its aqueous form. Major engine manufacturers such as Caterpillar, Wartsila, Japan Engine Corporation, and MAN[154, 155] have already begun developing and testing ICEs using ammonia as a fuel, with ships rolling out in this decade.

The GHG intensity of ammonia, as with methanol, depends on the feedstock and production processes (Figure B2). Ammonia can be produced through many different pathways using different feedstocks such as natural gas, coal, biomass, and water through a variety of conversion steps such as steam methane reforming (SMR), gasification, or electrolysis that all rely on energy inputs. The two key elements—hydrogen and N_2—are used to form ammonia via the HB process, which combines the gases at high pressures and temperatures.[154, 156] Approximately 100% of commercial ammonia is exclusively produced by the HB process, which is responsible for 1%–2% of global energy consumption and around 1.2% of CO_2 emissions.[19]

Furthermore, between 75% and 90% of ammonia produced is used in fertilizer, which suggests that new markets such as maritime transportation will require a major increase in global ammonia production capacity.

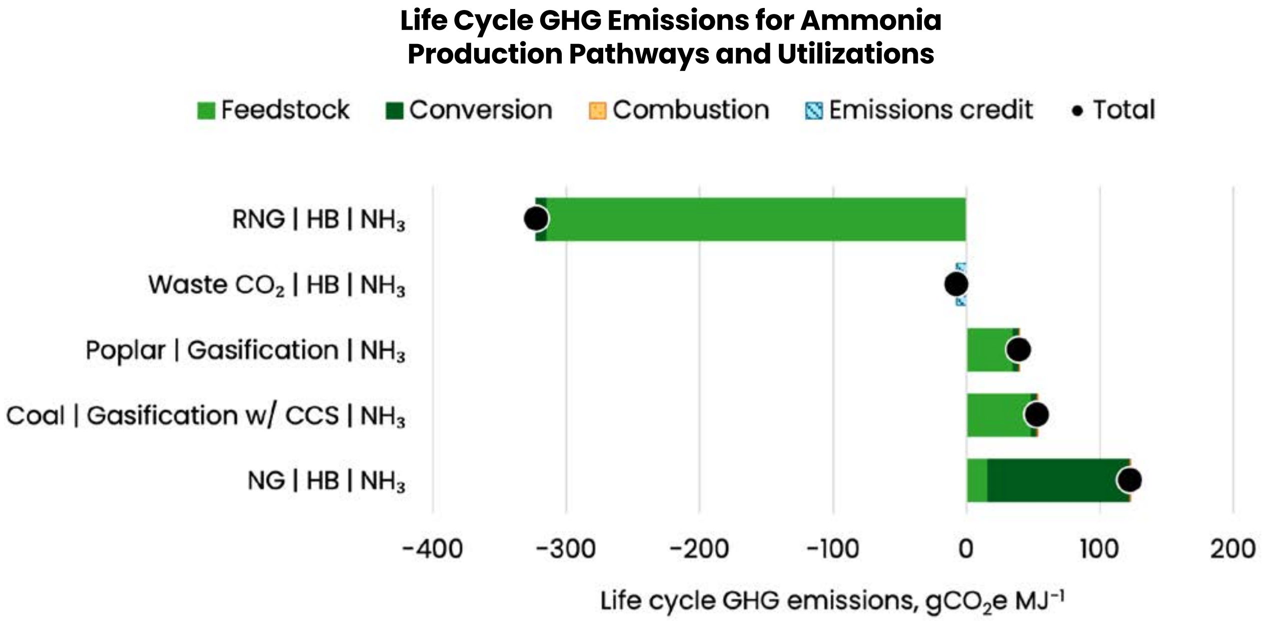


Figure B2: GHG intensity of ammonia, RNG = renewable natural gas, HB = Haber-Bosch process
Note: (1) Waste CO_2 is captured from ethanol processing plant. (2) Source of RNG is manure, which receives counterfactual credit of avoiding CH_4 emissions from conventional manure management. As conventional waste management becomes more efficient in avoiding CH_4, this credit will change.

Along with the advantages, there are some disadvantages in realizing ammonia as a maritime fuel. Ammonia is toxic and flammable and poses safety challenges in terms of handling, storage, and transportation. Robust safety measures and regulations would be essential. However, ammonia is transported worldwide for agricultural purposes, and some of the existing transportation and distribution infrastructures can be used for maritime use. Even though the first-generation ammonia-fueled engines are rolling out, existing ships would need modifications to use it as a fuel. Like methanol, ammonia has lower energy density compared to HFO. Therefore, more fuel by volume will be required for the same trip. Also, similar to methanol, ammonia requires pilot oil for easy ignition and efficient combustion. It may require a higher ratio of pilot oil than in the case of methanol; fuel blends use could be up to 30% pilot oil. Further limitation for ammonia as a maritime fuel comes from the fact that the bunkering standard for ammonia is yet to be developed. Global agricultural ammonia demand is already likely to increase to keep up with the food demand. Ammonia demand for maritime fuel production will impose further supply constraints. Therefore, supply of adequate renewable ammonia will be a challenge.

Overall, ammonia presents both opportunities and challenges as a maritime fuel. Overcoming the technical, safety, and economic hurdles will be crucial for its successful adoption and contribution to a cleaner maritime industry.

B.1.4 Hydrogen

Hydrogen is emerging as a promising candidate for the maritime industry as a clean and sustainable fuel option to reduce GHG emissions. When produced from renewable sources or with thermal sources with carbon capture and storage (CCS), hydrogen can reduce GHG emissions significantly. Like ammonia, hydrogen molecule does not contain carbon atoms and is carbon-free at the use phase. There are no PM emissions and very low NO_x emissions when ammonia is used in ICEs (no NO_x in fuel cells).

Decarbonized maritime sector needs to shift away from fossil-based hydrogen and focus on clean hydrogen. According to H2Hubs, clean hydrogen is produced with equal to or less than 2 kgCO_2e per kg of hydrogen.[157] Currently, most of the hydrogen produced worldwide (approximately 70 million tons annually) comes from fossil fuel sources such as natural gas (48%), oil (30%), and coal (18%).[157] The most common hydrogen, produced currently, is from fossil sources—generated from natural gas through SMR. Introducing carbon capture process to fossil-based hydrogen production reduces the GHG intensity of hydrogen by 60%.[30] However, it still does not meet the criteria of clean hydrogen without CCS, as defined by the IRA and IRS 45V guidance. Hydrogen produced from electrolysis of water where water is electrolyzed with renewable electricity from nuclear, solar, or wind can meet the criteria and provides significant GHG reduction (Figure B3).

Well-to-Gate (WtG) GHG Intensity of Hydrogen

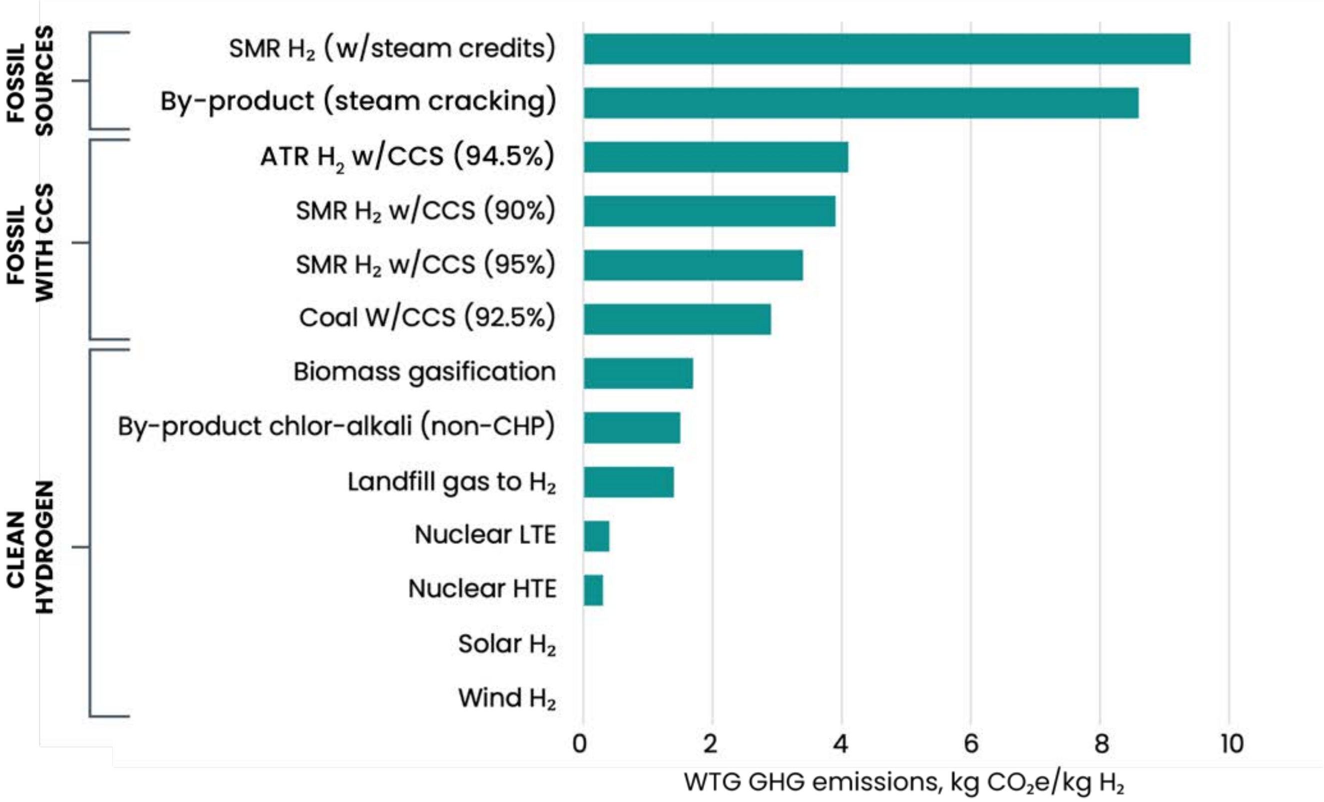


Figure B3: Well-to-Gate (WtG) GHG intensity of hydrogen[30]
Note: SMR: steam methane reforming, CCS: carbon capture and storage, CHP: combined heat and power, LTE: low-temperature electrolysis, HTE: high-temperature electrolysis.

Besides zero GHG emissions during the combustion stage, hydrogen has other advantages. With water electrolysis with zero-emission renewable electricity, WTW GHG emissions of hydrogen can be completely carbon neutral. Hydrogen has a high energy density by mass, approximately 0.05 MMBtu/lbs,[159] which provides an advantage in load or carrying capacity of maritime vessels in which volume is not an issue. However, because hydrogen's energy density per volume is low, only 290 Btu/ft^3, it presents challenges in smaller vessels especially over long distances. Refueling hydrogen is relatively quick, which offers higher operational efficiency.

However, there are challenges and considerations associated with using hydrogen as a maritime fuel. The cost of producing hydrogen is currently 100% higher compared to the traditional HFO[160] and needs significant subsidies to become competitive with conventional fuels to drive widespread adoption in the maritime sector. Hydrogen has a low volumetric energy density, which poses challenges for storage and distribution. Advanced production, storage technologies, and infrastructure are needed to address these issues. While ammonia is suggested as a hydrogen storage solution on a weekly or monthly basis, compressed and liquefied hydrogen was deemed as more economic in most storage situations, i.e., in shorter time frame.[161] The United States has announced $7 billion in funding to establish RCHHs to address issues related to production, processing, delivery, storage, and end use of clean hydrogen.

Despite these challenges, several pilot projects and initiatives are exploring the use of hydrogen as a maritime fuel. Around the world and in the United States, several hydrogen-powered ferries and tugboats have been deployed or ordered.[162] In the United States, a hydrogen-powered tugboat is under development and expected to be launched in 2024. It will be used for harbor operations in San Pedro, California. It will be powered by a 0.85 MMBtu fuel cell module and will use compressed hydrogen stored in onboard tanks.

Ongoing research and technological advancements are crucial for overcoming hurdles and making hydrogen a viable and sustainable option for decarbonizing the maritime industry. Collaboration between industry stakeholders, governments, and research institutions will be essential in realizing the full potential of hydrogen as a maritime fuel.

B.1.5 Electrofuels (E-Fuels)

E-fuels, also known as electrofuels, refer to a group of synthetic fuels created using provide significant CO_2 reduction opportunities if the source of electricity is renewable because the primary feedstock for the e-fuels—CO_2—are captured from the atmosphere or industrial emissions. These carbon atoms are combined with clean hydrogen produced, for example, by electrolyzing water with renewable electricity generated from wind, solar, hydro, or nuclear sources. A few e-hydrogen options are discussed in sections B.1.2. Methanol and other alcohols through B.1.4. Hydrogen.

The major benefit of e-fuel is its GHG reduction potential. However, it needs to be ensured that the source of electricity is decarbonized and not displacing renewable electricity already being used for other purposes such as EV charging. Another benefit of e-fuels is that it has the potential to be a 100% drop-in fuel that can replace its fossilized counterpart completely for effective decarbonization. As the grid decarbonizes in the United States, e-fuels are becoming increasingly of interest. However, e-fuels require a significant additional availability of green electricity due to the power-to-fuel conversion efficiency (Table B1).

Table B1:
Conversion efficiency of e-fuel production[163]

e-Fuel	Energy Efficiency (DAC)	Energy Efficiency (SMR)
e-Hydrogen	75%	
e-Ammonia	59%	
e-Methane	52%	61%
e-Methanol	48%	51%
e-FT Diesel	42%	51%

DOE's Bioenergy Technology Office has a consortium consisting of five national laboratories, called the CO_2 Reduction and Upgrading for e-Fuels Consortium. The major goal of this consortium is to support BETO's goals to generate cost competitive fuels, incentivize CO_2 use, and enable efficient CO_2 conversion to intermediate streams via renewable electricity. There are three major challenges in wide-scale adoption of e-fuels—adequate and extraneous renewable electricity, high production cost, and stability. Currently, e-fuels are more expensive than conventional fuels. Additionally, large-scale production requires a considerable amount of captured carbon and production infrastructure.

B.1.6 Renewable Natural Gas

Natural gas is a colorless, odorless, nontoxic combustible mixture of hydrocarbon gases, predominantly CH_4 (typically 80% or higher). RNG, also known as biomethane or biogas, is CH_4 produced from organic sources such as agricultural waste, landfills, wastewater treatment plants, and organic residues. Once produced, RNG can be treated the same as traditional fossil-based LNG, which is a natural gas that has been cooled to a liquid state at approximately -162°C using liquefaction plants. The volume of natural gas in its liquid state is about 600 times smaller than its volume in its gaseous state, which makes transportation and storage much more practical. Natural gas can also be stored in compressed form, but this is less common in larger volumes. When LNG reaches its destination, it is turned back into a gas through a regasification process. When combusted, natural gas produces approximately 20% less CO_2 emissions than other fossil fuels like HFO, MDO, or MGO, but CH_4 slip, a common phenomenon in which unburned natural gas escapes through an engine's exhaust system, can negate these benefits.[164] CH_4 is 25 times more potent compared to CO_2 in its GWP. Depending on feedstock, using RNG can reduce up to 300% GHG emissions when compared to traditional gasoline.[30]

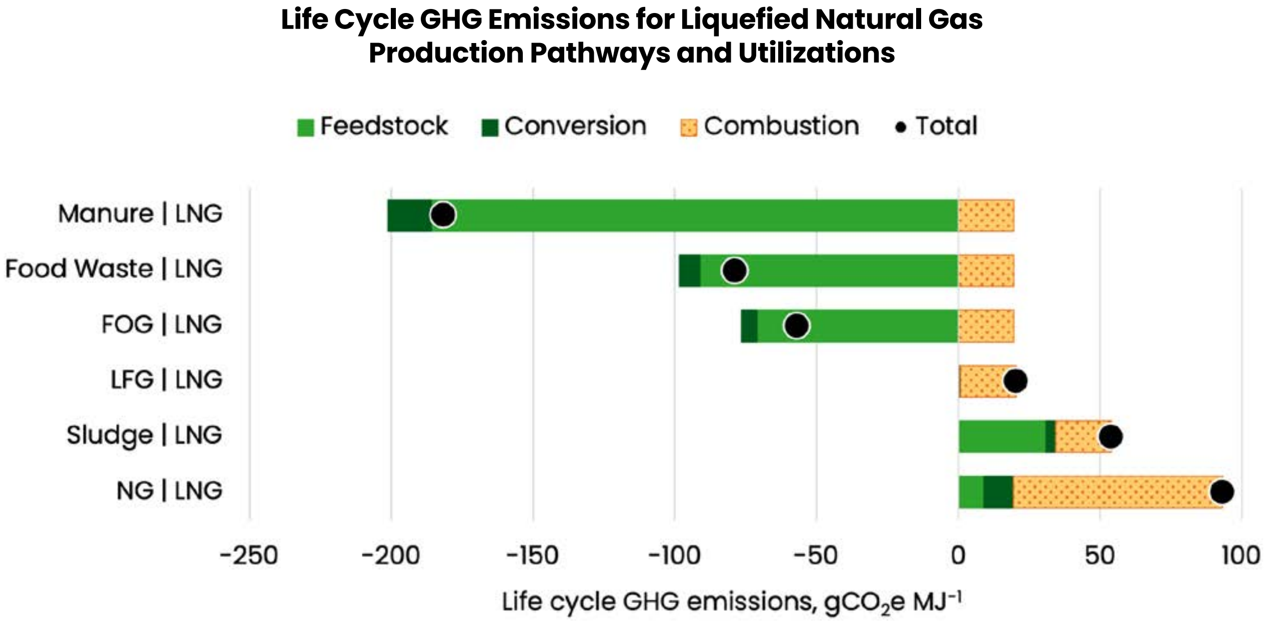


Figure B4: Life cycle GHG emissions of liquefied natural gas,[30] FOG = fats, oils, and grease, LFG = landfill gas, NG = natural gas NOTE: (1) LNG from waste-based pathways—manure; food waste; FOG; LFG; and sludge—receives counterfactual credit of conventional waste management, included in the feedstock category. As conventional waste management becomes more efficient in avoiding CH_4 and other GHG agents, this credit will change. CH_4 is another potent GHG involves potentially significant use phase CH_4 slip and fugitive emissions (GWP of 29.8 gCO_2-eq./g CH_4 based on IPCC AR6). (2) Waste-based pathways use RNG as a process fuel, which provides credit in the conversion category.

Biogas comes from various biomass sources like landfills, agricultural waste, manure, etc., and through a biochemical (anaerobic digestion) or thermochemical (gasification) process followed by conditioning or upgrading to remove impurities, it is converted to RNG.[165, 166] Waste feedstocks offer some of the best potential for emissions reduction using RNG on a life cycle basis, and depending on feedstock and production methods, RNG can have low or net-zero carbon emissions (Figure B4).

RNG is chemically similar to conventional natural gas, enabling its use in existing maritime LNG engines and infrastructure with minimal modifications. This facilitates easier adoption and avoids major investments in new technology. According to DNV, one of the biggest challenges for LNG fueled vessels is its energy density and associated storage issues. Because LNG has lower energy density, onboard storage or tank size requirement is higher compared to fuel oil. Additional space is required for tank installation and required gas handling system because of the low temperature of LNG. The availability of RNG is also a major concern due to feedstock availability. In 2020, U.S. LNG production was approximately 36,172 billion cubic feet,[167] but RNG production amounted to approximately 0.059 billion cubic feet.[168]

Although only recently approved to operate by the USCG, LNG carriers have been transporting LNG since 1959 and using it as a fuel since the 1960s.[19] At the turn of the century, four-stroke gas engines (dual fuel or gas only) became more common than steam turbine propulsion systems, which can burn LNG as well as other traditional maritime bunker fuels. In 2011, high-pressure injection two-stroke dual fuel (HPDF) engines were introduced, allowing use of either LNG or HFO/MGO.[169] Currently, the most popular LNG engine technologies are low-pressure injection dual fuel, four-stroke, medium-speed engines.[170]

Despite these challenges, investment in RNG for the maritime industry is increasing. The LNG ecosystem (fossil) has matured rapidly in recent years because it is now available globally and in large volumes.[169] Of the alternative fuels considered within this report, it has seen the most adoption, and both the supply and demand is expected to grow significantly in the coming years according to the IMO.[164] In 2013, there were 44 vessels operating internationally (not including LNG carriers) using LNG as a fuel and an equal number on order awaiting construction. As of 2021, there are 198 LNG-fueled ships across multiple vessel segments (not counting around 500 LNG carriers), and approximately 277 are slotted for construction.[164, 171] Despite this recent growth, and the fact that LNG has been used as a maritime fuel since the early 1960s, it still only represents about 1%–2% of global fuel consumption for international shipping.[55] Given LNG's muted GHG benefits, many organizations believe that LNG cannot be a substantial part of the future fuel mix if the maritime industry is to achieve the GHG emissions reductions required by the IMO GHG Strategy.[172] RNG can be made from wet wastes such as wastewater sludge, animal manure, food wastes, and FOG. However, scalability remains an issue for wet wastes to biofuel production.

B.1.7 Electricity

Electricity is increasingly being explored as a source of renewable energy in the maritime sector, offering a cleaner alternative to traditional fossil fuels. Electrically powered vessels produce no emissions at the point of operation, directly contributing to cleaner air and healthier marine ecosystems. Electric motors are significantly quieter than combustion engines, reducing noise pollution and minimizing disturbance to marine life. Electric power can be used for various onboard functions beyond propulsion, like powering auxiliary equipment and reducing overall reliance on fossil fuels. Using electricity for cold ironing at the shore reduces the need for liquid fuel or onboard battery storage, which could be an important strategy in decarbonization with a decarbonized grid.

The adoption of electricity as a renewable source in the maritime sector, or its scalability, depends on several factors, which will be discussed with more details in Appendix C. Current battery technology limits range and storage capacity, often restricting electric vessels to shorter routes or requiring frequent charging stops. Combining electric propulsion with traditional engines or other alternative fuels like hydrogen can offer a viable option for longer distances or specific operational needs. Additionally, building and maintaining a network of charging stations in ports and at sea remains a significant challenge, requiring substantial investment and collaboration. Electric vessels and supporting infrastructure are often more expensive upfront compared to traditional options, although long-term operational costs could be lower. Regulatory frameworks and safety standards for electric vessels are still evolving, requiring adaptation and harmonization across different maritime jurisdictions.

The WTW GHG emissions of electric powered vessels primarily depend on the source of electricity, i.e., how renewable the primary energy source is. Electricity can be produced from fossil sources such as coal and natural gas or renewable sources such as hydro, wind, solar, and nuclear. Each state has their own grid mix, which makes the emissions from electricity varied by location (Figure B5). As previously mentioned, U.S. grid mix is getting cleaner and the U.S. government has a goal of 100% clean electricity by 2035.[54]

Currently, there are several major ports in the United States that can use electricity with lower-than-average GHG emissions such as the ports in New York, New Jersey, and California.[173] However, many of the largest ports by tonnage, such as in Texas, Louisiana, West Virginia, Ohio, and Kentucky, will require electricity with lower GHG emissions. The grid mixes are becoming increasingly cleaner in terms of lowering GHG emissions, and the United States has a goal of 100% electricity with net-zero GHG by 2050. When produced from zero-emissions sources, electricity vessels can eliminate WTW GHG emissions.

Variation in GHG Emissions of Electricity in Different States, 2023

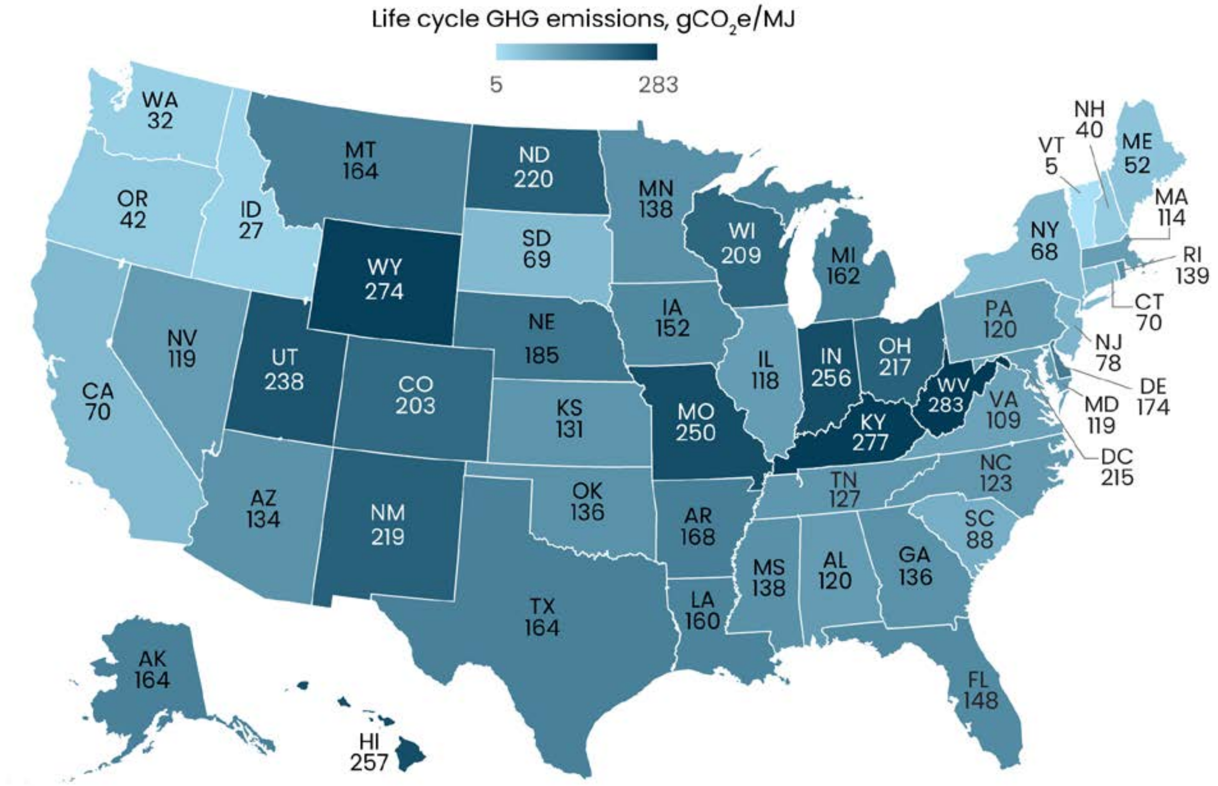


Figure B5: Variation in GHG emissions of electricity in different states in the year 2023[30]

B.1.8 Nuclear (Including Small Modular Reactors at Port)

According to the Maritime Research and Development opportunities Report,[19] the extreme mission requirements of some power-intensive vessels, such as those used for military and defense as well as icebreaking, makes refueling difficult if not impossible. Nuclear power provides an alternative to the frequent refueling needed for traditional fossil fuels; it occurs perhaps every five to ten years[174] instead of monthly and has been successfully used aboard icebreakers and military vessels around the world for more than half a century. To date, about 700 traditional nuclear reactors have operated at sea on a variety of vessels, though mostly military.[175, 176]

A nuclear reactor is a system designed to start and control a continuous nuclear chain reaction. Reactors can be classified based on the type of coolant they use, generation technology, reaction type, fuel, and other factors. Most maritime reactors currently operate using nuclear fission with uranium fuel. In a sustained chain reaction, the heat generated can superheat water, creating steam to drive a turbine in a Rankine cycle, providing power for propulsion or electricity. Today, the majority of maritime reactors are pressurized water reactors (PWRs), a type of light water reactor (LWR) that uses water both to cool and manage the reaction heat. Advanced reactor designs may instead utilize alternative coolants, such as liquid metals, gases, or molten salts.[177] Small modular reactors (SMRs) are compact, advanced models that can use various coolants and are known for their smaller size, power capacities from tens to hundreds of megawatts, lower capital costs, flexibility in location, and scalable power options. Microreactors are even smaller than SMRs and can be portable, factory-assembled, and serve both civilian and military sectors. They provide a resilient and clean energy supply for electricity and heat applications, such as in remote communities, industrial operations, forward-deployed military sites, and disaster relief.[178] Typical microreactors generate around 20 MW, SMRs can produce up to 300 MW, and large LWRs usually deliver around 700 MW.[179, 180] For comparison, a commercial ocean-going vessel (OGV) would generally need about 10–80 MW of propulsion power.

Traditional nuclear reactors and their support systems are larger and more expensive, occupying significant space on a ship, compared to traditional internal combustion power system. For military ships or icebreakers, this trade-off is acceptable due to the reduced need for refueling. However, for traditional ocean-going vessel (OGV), which docks frequently, the high costs of a nuclear system and the space it occupies are harder to justify economically. In contrast, modern small modular reactors (SMRs) and microreactors are designed to be more compact and cost-effective than traditional reactors, making them potentially more attractive to the commercial maritime industry for use on ships or in ports. Some SMRs are reportedly small enough to fit within a standard shipping container,[181] which could present an alternative to batteries in electric-powered vessels.

Nuclear reactors produce no greenhouse gas (GHG) emissions during their operation, allowing them to potentially cut vessel emissions by nearly 100%. While some emissions are generated during the fuel's mining and processing stages, the total lifecycle emissions of a small modular reactor are estimated to be comparable to or even lower than those of renewable energy sources like wind and solar.[19]

There are two major R&D needs that will help integration of small modular reactors - safety/security and end-of-life cost reduction. Regarding safety, protocols for safely incorporating nuclear reactors in commercial vessel design are still in their early days.[175] To ensure people and environmental safety, new design standards and regulations are needed keeping small modular reactors in maritime vessels in mind. Special safety considerations are needed for nuclear powered vessels in territorial waters. New vessel designs should include separation of nuclear propulsion module from the cargo module.[176] Enhancing the security features of small modular reactors for commercial maritime applications will also be essential. The other major R&D need is to minimize the end-of-life expense for nuclear powered vessels, especially costs related to reactor dismantling. These costs are currently high and optimizing for these costs by improving recyclability and reusability will enhance their economic resilience.

APPENDIX C: VESSEL TYPES

This section discusses all major vessel types in terms of their economic significance to the United States (and the world), their primary fuel consumption, and opportunities and challenges for their decarbonization, and current market trends towards vessels and their alternative fuel choices.

C.1 Ocean-Going Vessels

C.1.1 TANKERS

A tanker vessel (depicted on page 35), often simply called a tanker, is a ship specifically designed to transport liquids in bulk over long distances without the use of barrels or any other containers.

Relevance

They play a crucial role in the global economy, carrying a wide range of liquid cargo such as crude oil, LNG, chemicals, and food. Crude oil tankers are the most common type of tankers. Tanker spills can have devastating environmental consequences. Therefore, strict regulations and safety measures are in place to minimize the risk of such incidents. There are approximately 9,000 tankers worldwide. In the United States, there are 92 tankers as of 2019.

Overview

Tanker size can vary significantly, between a few thousand to a few hundred thousand tons. Many modern tankers are constructed with a double hull to enhance safety and reduce the risk of oil spills in the event of a collision or grounding. Tankers are designed with stability in mind, considering the challenges posed by carrying liquid cargoes. Ballast systems are often used to maintain stability during different phases of the voyage. Liquid cargo carrying tankers have advanced pumping systems for efficient loading and unloading of liquid. Special protocols are followed to prevent accidental spills related to environmental incidents.

Decarbonization Options

MDO is the primary fuel used in the maritime industry for tankers. However, there are several LNG-powered tankers in operation and it's gaining popularity worldwide. According to FrieghtWaves, 2% of the existing tankers and 20% of new-builds are LNG-ready.[182] Tankers can be powered by a host of renewable fuel options, including LNG, renewable hydrogen, and RD, green methanol, and green ammonia. Tankers are typically used to transport all these fuels. Infrastructure to load these fuels into tankers already exists. With minor modifications, those infrastructures can support bunkering of these fuels as well.

If the distance covered is short and predictable, electrification of tankers is also possible. In 2022 and 2023, Japanese shipping company Asahi Tanker launched two electric tankers, powered by 3,480 kWh battery.[183] Their gross tonnages are 499 tons each, and they can reach approximately 10 knots of speed and can be recharged in 10 hours. If electrification is not feasible for instances such as longer routes, then hybridization can also provide opportunities for increased fuel efficiency and reduced CO_2 emissions. Tankers are also good candidates for onboard CCS because they have deck space available for carbon storage tanks. LNG carriers are also good candidates because they typically have higher waste heat that can be used for the carbon capture system, and the amine solution that participates in the carbon extraction from the engine exhaust is able to last longer before needing to be regenerated and cleaned from exhaust contaminants.

C.1.2 CONTAINERS

Container ships (depicted on page 33) are specialized vessels designed for the transport of standardized cargo containers, facilitating efficient and secure shipping of goods between ports worldwide.

Relevance

These ships play a crucial role in global trade and the logistics industry by providing a standardized and streamlined method for loading, unloading, and transporting cargo containers. Net income from the container shipping industry was $13 billion in the first quarter of 2023, which emphasizes the economic importance of this sector.[184]

Overview

According to FreightWaves, the average size for container ships is 4500 TEUs.[185] However, container ships can be as big as 24,000 TEUs. As of 2019, there are 50 container ships in the United States. The container sizes can be of 8 ft., 10 ft., 20 ft., and 40 ft. However, 20 ft. is considered standard unit for containers.

Decarbonization Options

HFO is the primary fuel for container ships. However, methanol and LNG are gaining popularity as an alternative fuel for this type of vessel. According to DNV, 251 container ships worldwide operate on LNG, and 104 vessels operate on methanol. According to Clarksons Maritime and Shipping Research Services, 475 of total container ships in service and on order are either LNG-capable or LNG-ready. That constitutes 3.6% of the existing in-service fleet and 29.4% of newbuilds. Hydrogen has also been of interest for container ships. In 2023, Switzerland-based engineering and sustainability company ABB announced two hydrogen-powered container ships.[186] Each of these ships are 443 ft. in length, will be powered by an 11 MMBtu hydrogen fuel cell system, and are predicted to reduce 25,000 tons of CO_2 emissions annually.

Because container ships operate on longer distances and they are usually large in size, electrification options of container ships are currently limited. On the other hand, the route predictability provides opportunity for electrification. In 2023, two 700 TEU containerships were run entirely by electricity.[187] Each of these vessels is 393 ft. long, 10,000 tons in weight, powered by 900 KW propulsion motors, and designed to run more than 600 miles along the river and to the sea.

Onboard CCS is possible on container ships. New build container ships can be designed in a way in which the lower platform supports the CO_2 storage tanks and containers can stack on top of it.

C.1.3 BULK CARRIERS

According to Wartsila,[188] a bulk carrier (depicted on page 69) is "a vessel designed to carry dry cargo, loaded into the vessel with no containment other than that of the ship's boundaries, as distinguished from the liquid bulk carrier or tanker." It is also known as bulk freighter or simply bulker. According to Dfreight, a bulk carrier "is a merchant ship specially designed to transport unpackaged bulk commodities such as grains, ores, coal, cement, steel, and forest products."[189]

Relevance

Bulk carriers play a significant role in global trade by transporting essential raw materials and commodities. Understanding their design, capabilities, and operational profile allows one to appreciate their significance in the maritime industry. As of 2019, there are 140 bulk carriers registered in the United States.

Overview

Bulk carriers can vary broadly by size, which can range from under 10,000 DWT to over 365,000 DWT. Typical bulk carriers have cargo holds, which are covered by hatches that open outward from the deck. The deck space is also claimed by cranes that help load or unload cargo. These characteristics play a role in deciding which decarbonization options are feasible in a bulk carrier.

Decarbonization Options

HFO is historically the most dominant fuel for bulk carriers. However, alternative fuels are making their entries to replace HFO. According to Clarkson's Maritime and Shipping Research Services, there are 169 LNG-ready or LNG-capable dry bulk carriers in operation or on order.[182] Between hydrogen and ammonia, ammonia was reported to be the best renewable alternative for bulk carriers even though the technology to use it is still limited.[190] Renewable methanol is a promising option for decarbonizing bulk carriers. There is considerable interest in methanol powered bulk carriers. Japan's Tsuneishi Shipbuilding Co., Ltd. has ordered three methanol engines for their three bulk carriers for Danish shipping company J. Lauritzen.[191] Each vessel will have the capacity of 81,200 DWT.

Electrification in bulk carriers presents a challenge because of its very large size and long trip durations between ports, which means a very large battery requirement. Because the deck space is essentially used for cargo hatches, options for installing CO_2 storage tanks are limited. However, new build or future bulk carriers can be designed by installing storage tanks in a way that does not impair the functionality of the crane.

C.1.4 ROLL-ON/ROLL-OFF (RO-RO)

Ro-Ro vessels (depicted on page 41) are specialized ships designed for the transportation of wheeled cargo, such as automobiles, trucks, trailers, and railroad cars, that can be rolled on and off the ship.

Relevance

Ro-Ro vessels contribute to the global economy by facilitating the trade of vehicles and other wheeled cargo, supporting industries such as automotive manufacturing and international trade. Ro-Ro vessels operate on international shipping routes, connecting major ports and facilitating the movement of vehicles and goods between countries.

Overview

It can be a pure car carrier or pure car and truck carrier (PCTC) or a general Ro-Ro vessel. These vessels are equipped with ramps or stern doors that facilitate the efficient loading and unloading of the cargo without the need for cranes or other lifting equipment.

Decarbonization Options

In 2023, there were at least three LNG-fueled PCTC, launched by NYK Line, Japan.[192]

In December 2022, European multinational aerospace corporation Airbus started running a test campaign for 18 months in which they tested RD fuel, made from HVO, on one of its vessels to reduce its carbon emissions.[193] Approximately one-third of the total diesel requirement is supposed to come from the renewable source, reducing CO_2 emissions by 20% compared to purely fossilized fuel.

C.1.5 CRUISE SHIPS

A cruise vessel, also known as a cruise ship (seen on the following page), is a large passenger ship designed for leisure and entertainment voyages. They differ from traditional passenger ships, like ocean liners, in their primary purpose and operational style.

Relevance

Currently, there is only one major cruise ship, NCL America's Pride of America, registered in America. However, there are many cruise lines that bunker in the United States. Global cruise capacity is forecast to grow 19% (from 625,000 to 746,000 lower berths) between 2022 and 2028. Global cruise liner economy is valued at $75 billion, supporting 848,000 jobs.[24]

Overview

Most cruise ships embark on round-trip journeys from a home port, returning passengers to the same location after the itinerary is completed. However, some cruises offer one-way itineraries, disembarking passengers at a different port from the embarkation point, often facilitating multi-destination travel plans. In both cases, the routes are predefined or predictable. Predictable routes help in identifying options for electrification.

Decarbonization Options

According to Cruise Hive,[194] MDO is the primary fuel for cruise vessels. However, LNG vessels that could then run on other carbon sources such as RNG, e-methane, and methanol fuel are becoming popular for powering cruise ships. The first cruise ship to completely operate on LNG was AIDAnova,

Cruise ship departing from the Port of Miami.

which made its maiden voyage in December 2018.[195] In the United States, Carnival Mardi Gras was launched in 2020. It has dual-fuel engines that can operate on LNG or traditional MGO, and it's the largest LNG-powered cruise ship in North America[196, 197] and can be retrofit to run on methanol. According to Cruise Lines Industry Association,[24] 38 LNG-powered ships are planned to be in service by 2028.

C.2 Harbor Craft

According to the California Air Resources Board, the definition of harbor craft "means any private, commercial, government, or military maritime vessel including, but not limited to, passenger ferries, excursion vessels, tugboats, ocean-going tugboats, towboats, push boats, crew and supply vessels, work boats, pilot vessels, supply boats, fishing vessels, research vessels, barge and dredge vessels, commercial passenger fishing vessels, oil spill response vessels, USCG vessels, hovercraft, emergency response harbor craft, and barge vessels that do not otherwise meet the definition of ocean-going vessels or non-commercial vessels."[198] In this report, the classifications of harbor craft considered are ferries, commercial fishing vessels, OSVs, passenger vessels, and towboats. This section will provide the relevance, an overview, and decarbonization options for each of these sub-types of harbor craft.

Harbor craft are commercial vessels (workboats) that are used to provide a service and (for private companies) make a profit for those services. Different from non-commercial vessels, they are typically operated 1,000 to 4,000 hours annually and operate on distillate (diesel) fuel. Harbor craft are responsible for approximately 30% of the energy consumption and GHG emissions of the U.S. fleet.

Harbor craft operate on U.S. in-land waterways, coasts, and the Great Lakes. They typically operate from a base port or marina and return to their home port after a particular mission. Some operate on predictable routes (e.g., ferries), while others have less predictable activity (e.g., fishing vessels and towboats). The duration of time between instances of berth could be on the order of minutes to days.

Drop-in low carbon fuels for harbor craft could be RD, e-diesel, or blends of BD (at this time, up to 20 vol%). For vessels that operate in and around international ports, methanol may be a potential fuel available, although methanol-fueled operation would require either a vessel retrofit or newbuild.

Battery-powered and hydrogen fuel cell powered vessels have no direct emissions, making them very attractive to port communities for their reduction in portside emissions. They can also potentially reduce life cycle emissions, offsetting the higher production GHG burdens from battery or fuel cell and hydrogen storage component manufacturing when operated on low carbon electricity or hydrogen. With short predictable missions, the range reductions from battery- and hydrogen-powered propulsion can be managed prior to installation. Given the nature of commercial harbor craft operations, the additional capital expenditure of these advanced propulsion systems could be offset by reduced operating expenses.[199] However, the additional infrastructure cost for vessel battery charging or hydrogen refueling should be considered.

For less predictable routes, battery-electric hybridization could be a way to offer greater versatility and decarbonize at the same time. While vessels can't recover energy from their motion (like regenerative braking in on-road vehicles), battery-stored energy could help supplement auxiliary power demands, such as hotel electrical loads, maneuvering thrusters, pumps, air compressors, or

An offshore supply vessel, a type of harbor craft, docked at the Port of Tampa Bay.

other work machinery. Battery hybridization could also assist the main engine(s) in the propulsion system to operate more efficiently.

C.2.1 HARBOR TUGS AND TOWS/BARGES

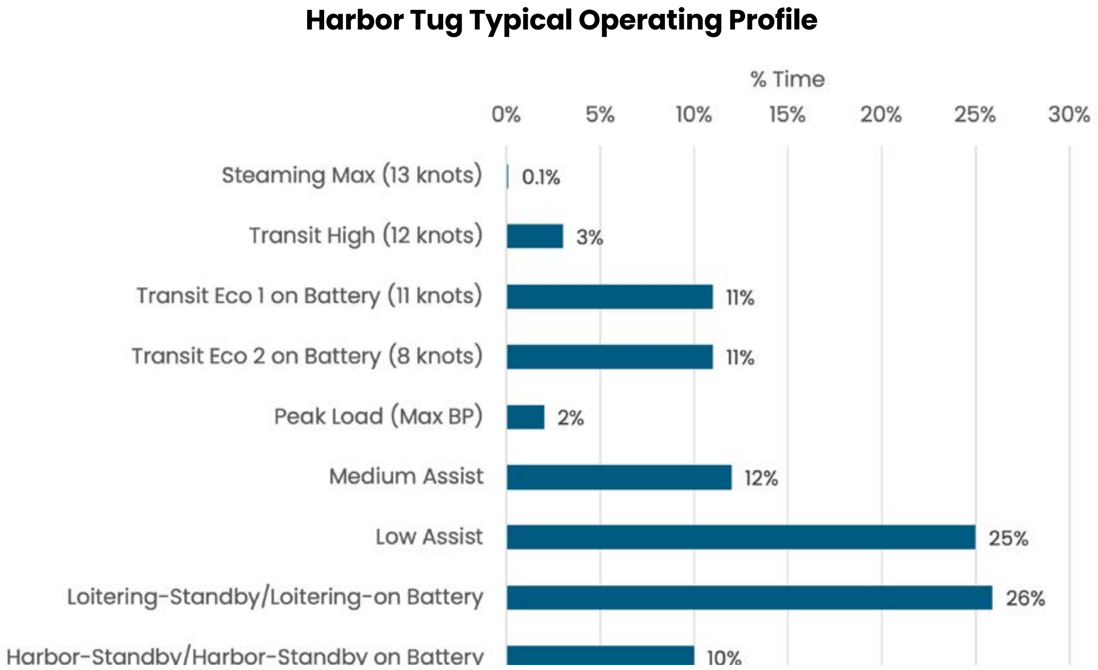
Title 46 of the United States Code defines a towboat as "a vessel in commercial service that pushes, pulls, or tows alongside and includes what is traditionally known as a tug."

Towboats (depicted on page 74) are vessels used to transport barges in harbors and inland water ways. Tugboats (depicted on page 47) guide large OGVs when they enter harbors or depart from berth. Combining tow/push-boats and tugboats generally as "towboats," they represent approximately one-fifth of harbor craft in the U.S. fleet and contribute 40% of the GHG emissions from U.S. harbor craft vessels.

Overview

On average, harbor tugboats have two propulsion engines with approximately 1,275 hp each and one or two auxiliary engines with approximately 100 hp each. However, larger ocean tugboats can have well over 10,000.[200] Towboats that pull or push barges around ports or on inland waterways have two smaller propulsion engines that on average are approximately 500 hp each and an auxiliary engine with on-average approximately 100 hp. Tugboats have exceptionally high power-to-tonnage ratios, ranging 2.2-9.5:1 kW/GT. In comparison, the power-to-tonnage ratios of cargo ships are 0.35-1.2:1 kW/GT.

The following operation profile (Figure C1) was prepared by Wartsila based on 260 operational days (3,120 hours) per year, including harbor standby. The rest of the year is in cold standby and is not relevant for the comparison due to the minor power need and its supply from shore. This shows that harbor tugboats spend a small portion of their operation at high or max power, with significantly more time spent at low assist, medium assist, and standby. It is also important for tugboat propulsion systems to have fast transient response. Electric-hybrid propulsion systems have improved low load torque and are already employed in tugboats to both reduce energy consumption (by approximately 30%) and transient response time.



Harbor Tug Typical Operating Profile

Figure C1: Harbor tug typical operating profile (Source: Wartsila 2018[74])

Decarbonization Options

As mentioned, tugboats and towboats are very power dense vessels, have high power-to-tonnage ratios, and have limited (if any) extra space (for cargo, passengers, etc.) for lower density energy carriers. Tugboats can operate on HFO, but the primary fuel of choice is MGO diesel as diesel-mechanical propulsion system technologies are commonly preferred systems. Drop-in biofuels, such as BI, BD, and RD, have similar energy density as conventional HFO and MGO. Because tugboats operate out of major international ports, they would have access to low-carbon energy infrastructure used by OGVs, potentially including methanol, ammonia, electricity, and hydrogen. Towboats, mostly used for transporting barges on rivers or along coastlines, may not have ready access to such new decarbonized energy infrastructure, but rather to drop-in low carbon fuels. Methanol and ammonia require approximately 2.4 times or 2.8 times, respectively, larger fuel storage volume than diesel fuel. Hydrogen system storage (including tanks, etc.) requires approximately 13 times more volume than MGO (for 700 bar gas storage); however, this can be reduced to eight to nine times more than diesel for a hydrogen fuel cell powered vessel when taking higher conversion efficiency into account. The storage volume of hydrogen can be further reduced when storing hydrogen as a liquid (at −253 °C) to approximately four to eight times that of diesel fuel, or 3–5.5 times when considering the higher efficiency of a fuel cell. However, liquid hydrogen storage requires additional energy for maintaining cold storage temperature and has boil-off losses. Marine battery storage systems (including cooling and safety equipment) take up approximately 100 times more volume than diesel fuel and approximately 150 times more weight (affecting vessel displacement).

While electric-hybrid propulsion systems are already commercially available, full electric propulsion options for tugboats will be available in the near future. The first fully electric tugboat in the United States, the eWolf, is expected to go into operation in 2024.[108, 201] It's powered by 6.1 MWh (21 MMBtu) of main propulsion battery and two electric motors; it is capable of a top speed of 12 knots.

In 2021, a hydrogen fuel cell river towboat (push boat), "Elektra," went into service around Berlin, Germany (including to Hamburg, Germany).[202] When solely powered by its 2.5 MWh (0.009 MMBtu) battery system, it can travel 40 miles over an eight-hour period before recharging. It is capable of 62 miles range with its parallel hybrid fuel cell battery electric propulsion system. When operating on its 1,650 lbs of hydrogen, it can operate at least 62 miles or 16 hours before refueling.

In 2023, the Port of Antwerp-Bruges and CMB.TECH launched the first hydrogen-powered tugboat.[203] It uses two 2 MW (2682 hp) hydrogen-diesel dual-fuel engines for propulsion and has 915 lbs of compressed hydrogen storage. It boasts a 65% reduction in diesel consumption and GHG emissions.

Barges are flat-bottomed boats or vessels that are designed for inland waterways, rivers, canals, and other shallow or calm navigable waters. They are typically used to transport goods and cargo, and their design is optimized for stability and the efficient movement of bulk commodities. Their flat bottom enables navigation in shallow waters, accessing ports and waterways inaccessible to larger ships. Diverse barge types cater to various cargo needs, offering adaptability for different applications. Barges are cost-effective for bulk transportation. However, the lack of self-propulsion means they rely on other vessels such as river tugs, limiting their independent movement and maneuverability.

Operational Profile

Barges can typically range from 100 ft. to 300 ft. in length, 30 ft. to 60 ft. in width, and carry between 500 to 3,000 tons. For example, Fuel Barge 0—a single-hull liquid tank barge—is 150 ft. long, 44 ft. wide, and capable of a net tonnage of 665 tons.[204] Their operational profile is typically characterized by sustained periods of high load when traversing upstream as opposed to low load periods when traveling downstream. When fully loaded, the draft of such vessels can range between 4 ft. to 12 ft.

Fuel Types (Fuel Competition, Infrastructure, Technical Gaps)

The primary fuel for tugs towing barges is diesel. The alternative fuel choices mentioned can be applied here. However, tugboats staying near harbors are different in their operational profile compared to the ones towing river barges. The routes for barges are long and will require frequent stops for charging if powered by electricity, which makes it less ideal.

"The study shows that barges can move a ton of cargo 647 miles with a single gallon of fuel, an increase from an earlier estimate of 616 miles. In contrast, trains can move the same ton of cargo 477 miles per gallon, and trucks can move the same ton of cargo 145 miles per gallon." – U.S. National Waterways Foundation, 2017.[205]

Dredgers are defined as the specialized vessels designed to excavate and remove sediments, debris, or other materials from the bottom of bodies of water, such as rivers, harbors, canals, or coastal areas. They are included in the towboat/barge classification because they require a powered vessel to position them.

C.2.2 COMMERCIAL FISHING VESSELS

Commercial fishing vessels are defined by the Title 46 of the United States Code as "a vessel that commercially engages in the catching, taking, or harvesting of fish or an activity that can reasonably be expected to result in the catching, taking, or harvesting of fish."[r]

Relevance

Commercial fishing vessels represent approximately half of harbor craft in the U.S. fleet by vessel number and contribute approximately one-third of the GHG emissions from the harbor craft segment.

Overview

Commercial fishing vessels typically operate out of ports of a variety of sizes on the coasts, as well as in the Great Lakes. Vessel types include trawlers, crab/lobster boats, etc. Typically, these vessels are

A commercial fishing vessel, which is considered a type of harbor craft, docked in southern California.

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[r] 46 USC 2101: General definitions

powered by a single engine (some may have two propulsion engines) that have an average of 230 hp. Auxiliary engines have an average of 71 hp. The furthest a fishing vessel might sail from its home port is one to three days.[11]

Decarbonization Options

Commercial fishing vessels consume energy through propulsion, onboard equipment, and refrigeration of the ship's hold where fish are stored. Almost all fishing vessels are suitable for hybrid propulsion because they will generally have variable loads during non-transit operations. Likewise, powered gear and equipment on vessels that require intermittent energy also lend well to hybrid power. The wide variety of vessels, with varying number of gensets for auxiliary power loads, also vary widely in their trip lengths and time at sea. Many vessels just stay out for several days while some may stay out for months at a time.

Decarbonization options for energy used by these vessels could focus on propulsion and auxiliary power separately or combined. Subject to the common limitations of the technology, batteries could be used to augment auxiliary power demands (e.g., refrigeration) if they are not too detrimental on the weight (displacement) of the vessel or hold capacity. Battery electrification may even replace the propulsion system for short range vessels.

To the latter, a lobster fishing vessel decarbonization project by Oceans North in Nova Scotia found that 60% of lobster boats consumed less than 400 kWh per day, and it would be possible to fully electrify those boats when the daily range was less than 20 km (12.4 miles) of the home port.[57] For vessels that needed longer range than 20 km, they proposed hydrogen fuel cell propulsion.

For commercial fishing vessels that operate out of large ports, it might be easier to gain access to vessel charging and hydrogen refueling infrastructure. Infrastructure already exists for drop-in fuels, and older fishing vessels could still decarbonize with low carbon drop-in fuels. New vessels or rebuilds that operate near large international ports could take advantage of other low carbon fuels, such as methanol.

Retrofitting older commercial fishing vessels is another option. Analysis at NREL of a small Alaskan fishing vessel has shown that retrofitting with a parallel diesel-electric hybrid propulsion system could reduce fuel consumption by 80%.[206] For small fishing operations, fuel costs can take away 30% of revenue, which makes fuel saving technologies attractive. By combining battery charging with green electricity at port and SMF, GHG reductions would be greater than 80%. The parallel hybridization technology will use the diesel engine while operating at high vessel speed and the electric propulsion system operating at lower speeds when fishing. Another retrofit project being explored is a series diesel-electric hybrid where the vessel would operate in 100% electric mode within 10 miles of home port but could use a diesel engine as a range extender.

C.2.3 FERRIES

In the United States, a ferry (depicted on page 42) is defined as a vessel carrying people and/or vehicles, across a body of water on a fixed route, which is less than 300 miles.[s]

Relevance

There are approximately 700 active vessels, ranging in capacity from carrying as many as 6,000 passengers to as few as two, using nearly 500 terminals and 350 routes in 37 states and three U.S. territories, and covering 7,877 nautical route miles (14,588 km).[207] New York state has the highest number of ferries (at 92), while the Washington state ferry system is the largest in the United States.[208, 209] Ferries comprise approximately 2% of the U.S. fleet of harbor craft but contribute 5%–10% of the GHG emissions from the harbor craft segment due to their high activity.

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[s] 46 USC 2101: General definitions (house.gov)

Overview

Ferries on average have approximately 3,500 annual operating hours per vessel, which is the highest in the harbor craft segment. As an example, ferries belonging to the Washington state ferry system operate for 344 days annually, and approximately 20 hours a day.[209] Ferries are prime candidate vessels for decarbonization technologies because they have predictable routes, and the significant up-time allows for offsetting GHG burdens from vessel propulsion system production.

Decarbonization Options

Currently, the primary fuel of the ferry fleet is diesel, and low carbon drop-in fuels could help the existing fleet decarbonize. There are ferries powered by natural gas, hydrogen fuel cells,[162] and batteries. In the United States, two small fully electric ferries (James V. Glynn and Nikola Tesla) were launched in 2020, providing tours at the Niagara Falls, New York.[210] These 90 ft. long ferries, each powered by two 316 kWh lithium-ion batteries, have a capacity of carrying 600 passengers each. For longer ferry routes, more battery capacity is required onboard, which challenges shoreside electrical infrastructure because of higher (up to 10–30 MW) level charging requirements during loading/unloading periods.

Washington State Ferries (WSF) revealed its plan towards an electrified future that includes hybridizing up to four existing ICE vessels, building five new Olympic class hybrid electric vessels, and electrifying the terminals.[211] WSF plans to invest $1.33 billion in the project.

Smaller ferries could be powered by hydrogen fuel cells, such as the Hydra (295 passengers, 80 vehicles) or the Sea Change (84 passengers). Another infrastructure challenge is to provide the clean hydrogen needed for complete decarbonization.

C.2.4 PASSENGER VESSELS

A passenger vessel is defined as a vessel of at least 100 gross tons (as measured under section 14502 of Title 46), or an alternate tonnage (measured under section 14302 of Title 46) as prescribed by the secretary under section 14104 of this Title 46 and a) carrying more than 12 passengers, including at least one passenger for hire, b) that is chartered and carrying more than 12 passengers, c) that is a submersible vessel carrying at least one passenger for hire, or d) that is a ferry carrying a passenger. While ferries are technically a type of passenger vessel, the category “passenger vessel” in this report will consider all other passenger vessels that do not have a fixed route less than 300 miles.

A passenger vessel named, "The Maid of the Mist" at Niagara Falls, NY.

Relevance

Approximately one-fourth of harbor craft in the U.S. fleet are passenger vessels other than ferries, and they are responsible for approximately 10%–15% of GHG emissions from U.S. harbor craft. They could be a variety of domestic passenger-carrying vessels, such as chartered fishing boats, entertainment vessels (like casinos, dinner cruise boats, etc.), combination cargo/passenger vessels, etc.

Overview

Passenger vessels are commercial business-operated vessels that operate for approximately 1,000–2,000 hours per year. When operating on low carbon energy, that level of use helps in offsetting the GHG burden of batteries, fuel cells, and hydrogen storage systems. If given a choice, some customers of these vessel services may opt for one that has reduced GHG emissions technology over a conventional fossil fuel powered vessel. This could be an incentive for some passenger vessel operators to invest in low carbon technology.

Decarbonization Options

In the case that passenger vessels cater to a particular experience for their passengers (dinner cruise, nature viewing, etc.), some customers may be willing to pay more for vessel propulsion that has lower noise, vibrations, and odors, such as battery-electric and hydrogen fuel cell powered vessels. Depending on the operations timetable, these vessels may have more time than ferries for battery recharging, which could ease charging infrastructure challenges. Lower vessel operating speeds would also be more accepting of technologies with lower energy storage than conventional engines and fuels.

For passenger vessels where high-speed operation is a selling point of the service and conventional vessel range is needed, ICE (or hybrid) propulsion with low carbon fuels may be a preferred option. Those fuels could be drop-in fuels (e.g., BD, RD, or e-diesel) or something that would require an engine retrofit or newbuild (methanol).

C.2.5 OFFSHORE SUPPLY

Offshore supply vessels or OSVs (depicted on page 117) are specialized ships designed to support offshore exploration, development, and production activities. It supports the oil and gas industry, renewable energy installations and maintenance, fisheries, and scientific research. These vessels provide logistical support, transportation of personnel, equipment, and supplies to offshore platforms, drilling rigs, and other offshore installations.[212] OSVs are limited by tonnage and are used by the mineral and oil industry, and while so employed are not considered a small passenger vessel. These vessels also support offshore renewable projects, like wind, wave, and even potential macro algae farms.

Relevance

By vessel number, OSVs constitute approximately 5% of the U.S. harbor craft fleet, while producing approximately 10% of the GHG emissions. They are critical for work at offshore locations.

Overview

OSVs are used to transport crew and supplies to offshore worksites, such as oil platforms, wind power installations, ships at anchor, and coastal islands. Because workers depend on short transit times, these are high-speed vessels. Once the vessel reaches its destination, it requires complicated propulsion systems to maintain its location, even in dangerous sea conditions. For those reasons, OSVs can have a power to gross tonnage ratio 1–3 kW/GRT. According to Wartsila, a typical OSV spends 25% of its time in the harbor loading/unloading, 35% loading/unloading at sea, and the remaining 40% of its time in transport.[213]

Decarbonization Options

From the challenging work conditions of OSVs, high power-to-tonnage ratios are required. This means the propulsion system and energy onboard needs high energy density. In addition, these vessels require multiple levels of redundancy for dynamic position control. In addition to the main propellor and rudder, they also typically have electrically powered azimuthal and tunnel thrusters. Given the combination of electrically and mechanically driven propulsion systems, and the demands for high power-to-tonnage ratios, hybridized engine-electric propulsion seems like a potential decarbonization pathway if combined with low carbon SMF. Alternatively, several projects are ongoing to build full battery electric OSVs with up to 16 MWh of battery capacity.[213, 214]

C.3 Non-Commercial Vessels

Definition

For the purposes of this plan, non-commercial vessels are defined as any vessel or boat that is designed primarily for personal use, or leased, rented, or chartered to a person for personal use, including boats engaged in non-commercial fishing.

Relevance

In the U.S. fleet, the non-commercial vessel segment is the largest (11 to 12 million vessels as of 2019) and most complex in terms of vessel sizes, power ratings, materials of construction, hull design, and use profile.[26] Approximately 95% of those boats are less than 26′ in length, making it possible to carry them with a trailer. The regions of the United States with the highest number of boat registrations are Southeast (especially FL and the Carolinas), Great Lakes (MN, MI, WI, OH), CA, TX, and NY. Despite contributing to greater than 99% of vessels in the U.S. fleet, non-commercial vessels contribute to just under half of the energy consumption and GHG emissions from the U.S. fleet. This is largely due to the low average annual operating hours per vessel (35–48 hours per year),[26] with the exceptions of rental fleets have an average of 156 annual hours of operation.[23] The non-commercial vessel industry in the United States is a significant economic driver, with $32 billion in sales, $230 billion in economic impact, 812,000 jobs, and 36,000 businesses (of which 93% are small businesses).[216] Of the boats sold in the United States, 95% are American made. Approximately one-third of the United States goes boating annually, of which 61% have an annual household income of $100,000 or less.

Overview

Approximately 90% of the fuel consumed by non-commercial vessels is gasoline (Figure 5), with the

Water enthusiast operating a personal watercraft, a type of non-commercial vessel, in Sheboygan, WI.

remainder being diesel fuel that is typically used on larger non-commercial vessels. Non-commercial vessels have a long lifetime, with averages ranging from 30 years for a runabout to 50 years for a larger vessel, with exceptions for inflatable boats/tenders (10 years)[26] or rental personal watercraft (12.5 years). In 2021, approximately 80% of boat sales were used vessels. The average annual turnover rate for non-commercial vessels is only 1.7%, which will make integration of new decarbonized vessel technologies challenging. In 2020, nearly 50% of new powerboat sales were freshwater fishing and pontoon boats.

Decarbonization Options

In 2023, the International Council of Marine Industry Associations commissioned consulting firm Ricardo to evaluate the suitability of GHG reduction technologies for boating in the non-commercial sector. The study[26] explored drop-in SMFs (e-gasoline and HVO), hybrid-electrification, full battery electrification, and hydrogen fuel cells or ICEs across nine non-commercial vessel types. Hybridization and drop-in SMF ICEs allow these vessels to maintain similar range and performance without impacting vessel displacement or space onboard. Due to the lower energy density of batteries and hydrogen storage systems, vessel ranges can be reduced by as much as 65% (battery-powered pontoon boat, while allowing 36% higher vessel displacement) to 95% (battery-powered inland waterway vessel) for the same propulsion system power level. Derating of vessel power can allow for more reasonable range, but at the consequence of vessel maneuverability.

Due to low use rates (35–48 hours/year), life cycle GHG emissions of battery-powered non-commercial vessels (even with zero-carbon electricity) are similar (or higher) than conventional ICE powered vessels operating on fossil fuels, due to the GHG burden from the battery manufacturing process. The exception would be higher-use vessels like rental fleet personal watercraft, where the increased use of a lower carbon energy source offsets the battery manufacturing GHG burden. Another potential for battery-powered non-commercial vessels is when the vessel power requirement is very low (<20–50 hp), of which some battery electric commercial outboard motors already exist.[111] Low powered vessels would require a smaller battery and reduce the battery manufacturing GHG burden. Hydrogen energy, whether for a fuel cell or an ICE, also has on-vessel storage challenges because of its low energy density. Vessel range can be reduced almost as much as battery-powered non-commercial vessels (60%–95%). While this issue is less severe with other low carbon fuels (methanol, isobutanol, BD/FAME, etc.), it should still be a consideration.

Fueling/Bunkering

Building a decarbonized energy infrastructure for non-commercial vessels could have its challenges. Electric vessel charging points, SMF or hydrogen refueling stations, could be installed in marinas. Boats that are moored in, or launched from, marinas could use such a fueling/charging infrastructure, but a significant number of vessels are stored outside of marinas (at homes or storage facilities) and are used on waterways without a marina. For battery-powered boats in that situation, they could be charged during storage, but they would need to carry enough charge for a full day of boating activity, which (as discussed) could be a significant challenge. Currently, many vessels are fueled using roadside automotive fueling stations, while being trailered to the water, taking advantage of the automotive fueling network.
In areas of the country where non-commercial vessels and vehicles (ATVs, snowmobiles, etc.) are more popular, it is possible to see a premium 0% ethanol gasoline option for those engines. Perhaps this could be a method for distributing SMF outside of marinas. Likewise, potential roadside hydrogen refueling stations could also be used for refueling hydrogen-powered vessels.

The NOAA's Ronald H. Brown, a U.S. non-DOD global class blue-water research vessel operating near Charleston, SC.

C.4 GOVERNMENT FLEET

C.4.1 DOD Vessels

There are more than 2,680 vessels in the DOD fleet, mostly operated by the Navy and the USCG.[218] At least 1,900 of those vessels are DOD small vessels. The Navy has approximately 430 commissioned ships, such as carriers, cruisers, destroyers, submarines, amphibious craft, littoral combat ships, and hospital ships. The Navy also owns 130 non-commissioned ships used to transport military supplies. The USCG has a wide variety of vessels, including icebreakers, cutters, buoy tenders, tugboats, and several types of 12–64-foot-long boats. The Army's fleet consists of landing craft, tugs, barges, dredges, logistic support ships, and aircraft repair ships. The U.S. Air Force has two ships and several small boats, such as patrol boats and inflatables. All Navy ships operate on F-76 naval distillate fuel. Because the DOD has developed its own GHG reduction plan, this action plan will exclude DOD vessels.[32]

C.4.2 Non-DOD Vessels

The majority of the 6,220 vessels in the U.S. government fleet are not part of the DOD. NOAA operates include hydrographic survey, oceanographic research, and fisheries survey ships, as well as more than 40 small boats, from tenders and utility boats up to 85-foot regional class boats. The U.S. Customs and Border Protection operate vessels in the range of 33′ to 41′ in length.[219] MARAD operates 48 vessels in its Ready Reserve Force[220] that supports military logistics. It is anticipated that decarbonization measures appropriate to each vessel type and activity in the U.S. government non-DOD fleet will take similar actions as the non-governmental fleet.

APPENDIX D: BIOFUEL'S ROLE IN DECARBONIZING THE TRANSPORTATION SECTOR

Context

Historically, the U.S. transportation sector has overwhelmingly relied on liquid petroleum-based fuels, which supplied over 90% of its energy needs in 2022.[221] The U.S. Transportation Decarbonization Blueprint laid out a bold plan to move the transportation sector to net-zero emissions, utilizing a range of low GHG fuels, including electrification, hydrogen, and liquid fuels from biomass and other waste carbon resources, such as CO_2 and food waste (referred to here collectively as "biofuels"). Biofuels already contribute to on-road light-, medium-, and heavy-duty transportation on the order of billions of gallons, driven by decades of U.S. policy objectives such as energy security, clean air, lead-free octane enhancement of gasoline, climate change mitigation, and rural economic development. The Blueprint identifies aviation as the transportation sector with the greatest long-term opportunity for biofuels, as aviation is limited in low GHG options. Due to biofuel compatibility with existing fleets and fueling infrastructure, biofuels will play an important role in reducing carbon emissions across all modes during the transition to zero emission solutions. In particular, biofuels will be important in decarbonizing the legacy fleet in the rail, maritime, and off-road sectors due to long equipment lifetime and slow fleet turnover in these modes. The Blueprint also recognizes that biofuels will play a supporting role where electrification and hydrogen may not be as practical. Successfully managing these competing demands for biofuels will be a key challenge going forward. Converting bioenergy from one sector to another does not automatically reduce transportation GHG emissions unless the first sector is reduced or carefully replaced with another energy source. More biofuels beyond current production are needed. To avoid direct land use actions such as converting to more agricultural land for producing corn and soybeans currently used for biofuels, a critical near-term action within approximately 10 years for biofuels is to pivot to accessing unused and underused biomass already available, which is estimated at around 350 million dry tons per year, including over 130 million dry tons agricultural residues, over 170 million dry tons of a variety of wastes, and over 30 million dry tons forestland resources.[219]

The United States Aviation Climate Action Plan establishes a goal of net-zero emissions from U.S. aviation by 2050. The SAF Grand Challenge establishes a goal of, by 2030, 3 billion gallons of sustainable aviation fuel (SAF) that achieves at least a 50% reduction in emissions on a life cycle basis and 35 billion gallons by 2050.[4] The SAF Grand Challenge Roadmap,[222] which was developed by USG agencies with extensive input from researchers, NGO, and industry, outlines a whole-of-government approach with coordinated policies and activities that should be undertaken by federal agencies to achieve both the 2030 and 2050 goals. In the SAF Grand Challenge Roadmap, the vast majority of the policies and activities focus on the needs for innovation in feedstock and conversion technologies that are largely agnostic to fuel type. As discussed in the action plan, decarbonizing maritime freight may require large volumes of methanol, decarbonizing non-commercial vessels may require significant volumes of green gasoline, and decarbonizing the off-road, rail, and long-haul heavy-duty modes may require large volumes of biomass-based diesel. The Blueprint recognizes that biofuels will play a leading role for aviation decarbonization while playing a supporting role for decarbonizing other transportation sectors.

In addition to the Blueprint, the U.S. goals and strategies for biofuels are also driven by the National Biotechnology and Biomanufacturing Initiative (NBBI) and coordinated through the National Bioeconomy Board. This Appendix seeks to complement modal plans by summarizing USG goals and strategies for biofuels that are not specific to individual modes of transportation and thus not fully integrated within specific modal plans.

Biofuels background

The United States is the world's largest biofuels producer, producing 15 billion gallons of ethanol and over 5 billion gallons of biomass-based diesel in 2022.[138, 139] These fuels are typically blended into gasoline and diesel, respectively, for use in on-road transportation. Most U.S. ethanol is produced from fermentation of corn starch. U.S. biomass-based diesel is currently produced via either hydroprocessing, co-processing, or transesterification and use lipid feedstocks that include oilseeds (e.g., soy, canola) and waste FOG, such as UCO. While the United States has these domestic supplies of biofuels, the supply is far from sufficient to satisfy the energy needs of the entire U.S. transportation sector.

Maximizing the impact of biofuels in support of the Blueprint will require expanding biofuels production, primarily through new feedstocks and production pathways. Government support will continue to play an important role in developing technologies, building supply chains, and scaling up biofuels production to meet the need for low-carbon liquid fuels. Policy and regulation at the federal and state levels have played and will continue to play a critical role for biofuels production in the United States to drive down carbon intensity and expand production.

Domestic resource potential for biofuel production

Currently, most biofuels in the United States are produced from corn and soybean planted on agricultural land. It is important for the U.S. agricultural system to prioritize its most productive land to produce food, feed, and fiber. Therefore, there are limits to the amount of agricultural land that can be used for biofuel production to meet the energy demands of our transportation sector. While productivity improvements can increase the amount of biofuel feedstock produced from the same acreage, these gains are modest in comparison to the needs for biofuels expansion. USDA projects 2% annual yield improvements for corn and 0.5% yield improvements for soy over the next 10 years.[223] The deployment of intermediate oilseeds that are planted and harvested in between these cash crop rotations could also sustainably expand lipid feedstock supply that can be converted using commercially-ready technologies to increase production of SAF and biomass-based diesel with little impact on land use.[223] However, in order to support decarbonization, domestic biofuels production must expand primarily through the use of new feedstocks resources that are not grown on prime agricultural land.

The 2023 Billion-Ton Report (BT23) report[47] estimates United States has the capacity to sustainably and economically produce 1.3 to 1.5 billion tons of biomass and organic wastes per year in the future, over triple the amount the current U.S. bioeconomy utilizes today. These resources include:

- Agricultural residues (e.g., corn stover, wheat straw) from the production of food, grain, and fiber.
- Wastes including animal manure, wastewater sludge, inedible FOG, sorted MNW including unrecyclable paper/cardboard waste, yard waste and food waste, and landfill gas.
- Forest thinnings from small-diameter trees that need removal to increase forest health and reduce wildfire potential, and logging and mill processing residues.
- Purpose-grown energy crops (e.g., perennial grasses, fast growing trees) that can be grown on less productive land with improved environmental performance and lower carbon intensity than traditional agricultural production.

Because biomass production potential is contingent upon market pull, the BT23 presents production capacity by market scenario. One scenario presented in the BT23 is the "Near-term scenario," which illustrates resources that exist today[t] (and in 2030). This includes 350 million tons per year of unused biomass (including ~250 million tons per year of cellulosic biomass) in addition to the ~340 million tons of biomass currently used for energy and coproducts (Figure D.1). The mature-market scenarios, adding ~440-800 million tons more biomass, include energy crops, which will not be fully deployed by the 2030 SAF target. However, if the SAF Grand Challenge 2030 target of 3 billion gallons per year were met entirely through biofuels, that could require 50-60 million tons of biomass per year,[u] which is merely ~15% of the near-term scenario untapped production capacity. (See BT23 Figure ES-1 and Table ES-2.)

Roughly half a billion tons of new biomass is needed for the SAF Grand Challenge goal of 35 billion gallons per year by 2050. As the bioeconomy mobilizes to meet the SAF Grand Challenge, there will be opportunities for biomass utilization for other sectors. Approximately 1.3 billion tons of biomass is required to meet the goals of the SAF Grand Challenge and the Clean Fuels & Products Shot™, which collectively aim to produce sufficient low-carbon fuels to meet 100% of needs in aviation, and 50% of our projected liquid fuel demand for maritime, off-road, and rail. In addition to the biomass resources listed above, BT23 identifies other emerging feedstocks, including microalgae, macroalgae (seaweed), and point-source waste carbon dioxide, that could be used to produce low-carbon liquid fuels in support of these goals.

BT23 identifies scenarios with a maximum supply potential of 1.3 billion tons or more, suggesting that such supply may be technically feasible in the long run (i.e., by 2045 or later). The report makes clear, however, that attainment of these long-run supply potentials will require the development and maturation of feedstock supply sources that do not exist today and are not expected to exist in significant volumes in the near term (e.g., feedstock supplied from production purpose-grown energy crops). The report also makes clear that continued government action is essential to enact new policies and establish guardrails for biomass production at these levels to be achieved sustainably.

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[t] Near-term presents resources that are annually available (within specified environmental constraints, at specified prices, and available for collection).

[u] At an assumed average conversion rate of 55 gallons of biofuels per ton.

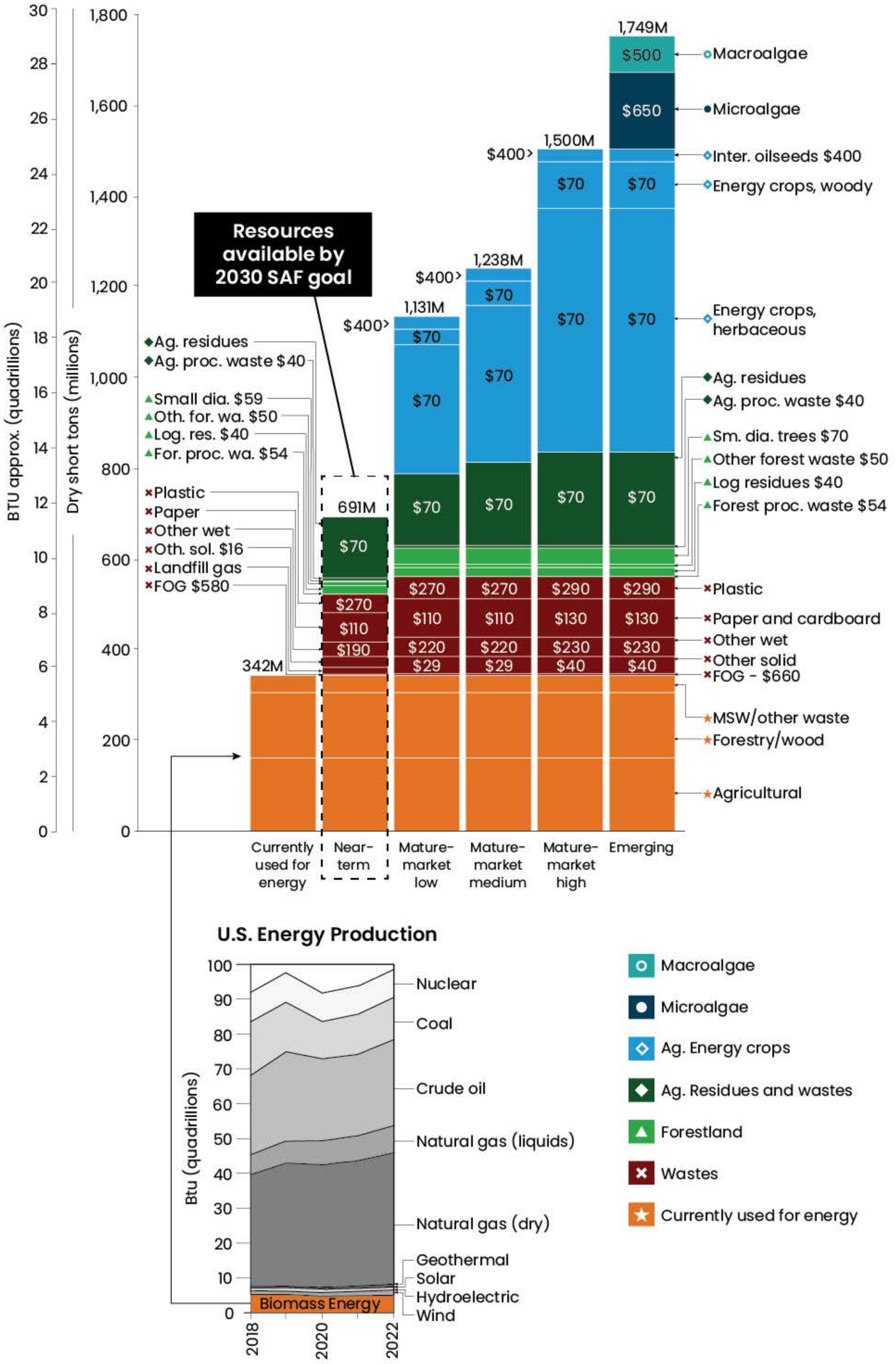

Figure D.1. Estimated biomass production capacity of the United States. The near-term scenario is highlighted, which identifies production capacity in 2030, including 235 million tons per year of unused cellulosic biomass resources. (Source: U.S. DOE 2023[47] Figure ES-1.) Underlying data for this figure and a version using alternate units can be found at https://bioenergykdf.ornl.gov/bt23-data-portal.

U.S. Government goals and strategies for biofuels:

The U.S. Transportation Decarbonization Blueprint prescribed five guiding principles to guide future policymaking and RDD&D in the public and private sectors, which are exemplified by the USG's coordinated approach and leadership on biofuels.

- Implement Bold Actions to Achieve Measurable Results
- Embrace Creative Solutions Across the Entire Transportation System
- Ensure Safety, Equity, and Access
- Increase Collaboration
- Establish U.S. Leadership.

The U.S. government has a long history of biofuels coordination since the Biomass Research and Development Act of 2000. Since then, the Biomass R&D Board has coordinated biofuels-related activities to advance a range of policy objectives, including climate change, energy security, domestic manufacturing, and competitiveness. In recent years, these efforts have been driven by the NBBI and the SAF Grand Challenge with the mutual objectives of increasing domestic production of biofuels and improving the carbon intensity of biofuels production.

Federal government agencies developed a series of Bold Goals for U.S. Biotechnology and Biomanufacturing R&D in March 2023 which include several goals that align with the U.S. Transportation Decarbonization Blueprint. These goals focus on expanding the availability and sustainability of feedstocks for the production of biofuels and increasing the production of SAF and biofuels for other hard-to-decarbonize modes of transportation.

Switchgrass, which is an herbaceous energy crop that can be used to produce biofuels, including sustainable maritime fuels.

2023 Bold Goals for U.S. Biotechnology and Biomanufacturing R&D that align with the U.S. Transportation Decarbonization Blueprint

GOAL
1.1

Expand Feedstock Availability – In 20 years, collect and process 1.2 billion metric tons of conversion-ready, purpose-grown plants and waste-derived feedstocks and utilize >60 MMT of exhaust gas CO_2 suitable for conversion to fuels and products, while minimizing emissions, water use, habitat conversion, and other sustainability challenges.

GOAL
1.2

Produce Sustainable Aviation Fuel (SAF) – In seven years, produce 3 billion gallons of SAF with at least 50% (stretch 70%) reduction in GHG life cycle emissions relative to conventional aviation fuels, with production rising to 35 billion gallons in 2050.

GOAL
1.3

Develop Other Strategic Fuels – In 20 years, develop technologies to replace 50% (>15 billion gallons) of maritime fuel, off-road vehicle fuel, and rail fuel with low net GHG emission fuels.

GOAL
3.1

Develop Measurement Tools for Robust Feedstock Production Systems – In five years, develop new tools for measurement of carbon and nutrient fluxes in agricultural and bioeconomy feedstock systems that contribute to a national framework.

GOAL
3.2

Engineer Better Feedstock Plants – In five years, engineer plants and manipulate plant microbiomes to produce drought tolerant feedstocks capable of growing on underutilized land with >20% improvement in N_2 and phosphorus use efficiency.

Strategies to Achieve Near-Term Biofuel Goals

BT23 estimates there are 350 million dry short tons per year of biomass above current uses that are near-term opportunities that could be accessible for biofuels in the next 5-10 years. Some of these resources, such as wastes, are already collected but then landfilled. Others, such as agricultural residues and timberland resources, exist in fields and forests but must be collected for use. Most of this near-term biomass is lignocellulosic. Technologies to produce liquid fuels from lignocellulosic biomass have not been fully derisked. Given the significant lead time required for biofuels production infrastructure to be built, the path to meeting near-term goals focuses on actions to scale the harvesting/collection and scaling of these resources and the production facilities to that can turn them into biofuels as quickly as practicable. These actions include:

- Demonstrate new biofuel pathways that can produce biofuels from additional feedstocks beyond lipids and starch.
- Build and support stakeholder coalitions through outreach, extension, and education to set the stage for biofuel feedstock and biofuel supply chains to develop and sustain themselves and replicate with continuous improvement.
- Increase deployment of alternative lipid feedstocks including intermediate oilseeds that can be readily converted to SAF and biomass based-diesel through commercially available conversion technologies.[v]
- Improve the carbon intensity of biofuels production using commercially available feedstocks and infrastructure.
- Develop improved environmental models and data for biofuels to support optimization of existing policies and implementation of new policies that could be enacted.
- Inform biofuels policy development with analysis of gaps and impacts of policies under consideration.
- Stakeholder outreach and engagement on sustainability to exchange data and information about best practices to reduce life cycle GHG emissions from agricultural and forest-derived feedstocks and optimize other environmental and social impacts.
- Enable use of drop-in unblended biofuels and biofuel blends up to 100% to simplify blending requirements, reduce cost of logistics, and facilitate supply.

Strategies to Achieve Long-Term Biofuel Goals

The path to meeting long-term biofuel and decarbonization goals requires a continuing focus on innovation, including RD&D of new feedstock and conversion technologies, increasing production capacity, with continued progress in cost reductions and carbon intensity. This effort occurs simultaneously with the near-term strategies above such that these innovations can be demonstrated and scaled by 2050. Technologies in this portfolio are expected to result in a dramatic build-out and expansion of alcohol, waste-based, lignocellulosic, and waste and captured carbon gas pathways.

- Conduct RD&D on scaling and sustainability of biomass, waste, and residue feedstocks to enable innovations in technologies and strategies that increase the availability of purpose-grown energy crops, wastes, and agricultural and forestry residues at reduced carbon intensity (CI) and cost. This includes addressing the social, environmental, and economic sustainability aspects of feedstock supply chains.
- Conduct RD&D on feedstock logistics and handling reliability to increase efficiencies and decrease cost and CI of supply logistics from the producer's field to the conversion facility door. De-risk scale-up through R&D and integrated piloting of critical pathways by 2030 to accelerate fuel conversion technology scale-up and improve financeability of critical conversion pathways that utilize the full potential of an expanded feedstock supply.
- Model and demonstrate sustainable regional supply chains for critical pathways by 2035 to promote commercialization of biofuel supply chains through process validation and risk reduction via access to critical data and tools that empower rapid, informed decision making when evaluating biofuel supply chain options.

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[v] The BT23 Near-Term scenario does not include intermediate oilseeds because these feedstocks are not currently widely available. However, this is a resource that has been prioritized under the SAF Grand Challenge as a near-term opportunity due to significant increase in demand for lipid feedstocks for the production of SAF and biomass-based diesel.

- Build and support regional stakeholder coalitions through outreach, extension, and education to continue to expand a biofuels industry that improves environmental and economic performance while supporting job creation and social equity in multiple regions of the country.
- Continue to invest in industry deployment to help overcome barriers to project financing through creative financing, government loans and loan guarantees, and outreach.
- Continue to inform biofuel policy development to enable aligned policy incentives that will support long-term biofuel deployment.

Conclusion

Biofuels will play an important role in reducing carbon emissions across all modes of transportation, whether as a long-term decarbonization strategy or as a transition to zero emission solutions. USG agencies have identified goals and strategies to improve carbon intensity and sustainability of biofuels and to expand biofuels production—particularly through developing supply chains and technology necessary to produce biofuels from purpose-grown energy crops, wastes, and agricultural and forest residues. While USG has placed a priority on producing biofuels for aviation due to the lack of alternative low-GHG options, it will be important to periodically assess fleet turnover and zero-emission vehicle adoption rates across various modes of transportation to inform the optimal allocation of biofuels across these modes to maximize the GHG benefits of biofuel use.

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