PATHWAYS TO NET-ZERO 2050 IN THE NORTH AMERICAN MARINE SHIPPING INDUSTRY:

Vessel Inventories and Emissions – Pathways and Challenges

A Report of the Blue Sky Maritime Coalition

Prepared for Blue Sky Maritime Coalition
by the Vanderbilt University Climate Change Initiative

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TABLE OF CONTENTS

I. ABOUT THIS REPORT

Blue Sky Maritime Coalition (BSMC or Blue Sky) launched in June 2021 with a goal to facilitate needed collaboration across the entire North American marine shipping value chain in order to achieve commercially viable net-zero carbon emissions by 2050. Recognizing the unique challenges to decarbonization that exist in the United States and Canadian markets, BSMC brings together industry leaders representing the wide range of businesses that are integral to marine shipping: from vessel builders, operators, and port authorities to fuel providers, finance institutions, engine manufacturers, customers of marine shipping, classification societies, and more. Blue Sky emerged from the reality that no one of these stakeholders can achieve decarbonization without concerted, targeted, and collaborative efforts between them all.

As a non-profit, Blue Sky's mission is action-oriented and membership based, and we engage across four topical workstreams to identify pathways, opportunities, and barriers to decarbonization. Blue Sky's work encourages innovation and acceleration of needed investments in vessels, infrastructure, and pilot projects to deliver near- and long-term greenhouse gas (GHG) emission reductions. Our members recognize the value of this collaboration to their customers, their operations, and to their ability to thrive in an increasingly carbon-constrained economy. Each member stands to benefit from collective knowledge sharing and a better understanding of the long-term decarbonization pathways likely to be supported within the value chain each depends on.

This Report on "Vessel Inventories and Emissions—Pathways and Challenges" is the second in a series of three reports aimed at identifying the pathways and approaches that Blue Sky has initially identified as most likely to accelerate significant GHG emission reductions and serve the North American marine shipping sector in achieving net-zero—measured on a life-cycle emissions basis from "well-to-wake"—by 2050.

The first Report, "Fuels and Propulsion Systems," was published in April 2022 and examined and identified the marine fuels and propulsion systems that Blue Sky expected to most effectively accelerate the transition to net-zero emissions by 2050. Importantly, the Fuels and Propulsion Systems Report recognized that due to significant inherent differences in vessel categories and their operating conditions, there is no "one-size-fits-all" approach to future low- and zero-carbon marine fuels. Rather, flexibility and a range of fuels and propulsion systems will be appropriately adopted. Technology advances or adoption of new regulatory incentives that facilitate particular fuel or propulsion system pathways may impact the choice of selected fuels and propulsion systems over time.

This Report builds on the understanding of the future fuel and propulsion system pathways presented in the initial Report. It sets forth a more detailed assessment of the currently operating vessel categories, their operational constraints and related emissions profiles, and the implications for decarbonizing the marine shipping value chain by 2050.

II. INTRODUCTION

Blue Sky recognizes that marine shipping is uniquely situated as a transportation mode with respect to the goal of achieving net-zero GHG emissions by 2050. Water-borne transportation is already one of the most sustainable modes of freight transport, but within the marine shipping sector, the vessels and their operational needs are far from uniform. Unlike other freight modes, such as trains or truck, this wide variety (in vessels and operational constraints) have a substantial impact on the path and feasibility of decarbonizing the marine shipping sector. Vessels vary from small fleet boats of less than 1,000 horsepower to ocean going vessels of over 100,000 horsepower, with many vessel types in-between. The operating conditions and fueling requirements within this large variety of vessels also differ substantially. Large, ocean-crossing vessels have fewer constraints on size and weight but must operate over long distances without access to refueling infrastructure. Small river fleet boats operate in limited geographic areas near shore infrastructure and typically operate on 12-hour shifts. Some river tugboats must traverse a complex systems of locks and dams (with the locking infrastructure that dates back nearly a century in some cases), while other larger river tugboats must navigate tortuous river bends and potentially shallow waters. Vessels that operate in coastal harbors are similarly variable—some large coastal vessels operate on much shorter routes than similarly sized ocean-crossing vessels. Offshore support vessels have a number of different service roles, often related to the energy sector, that range from dive support vessels to emergency standby vessels to conducting drilling operations and more, with consequent variation among the tonnage, fuel capacity, speed, and capacity for modifications.

The wide variety in the types and operational parameters between vessel categories is directly related to the potential for decarbonization. For example, a decarbonization pathway that may be achievable now within the small, low horsepower river "fleet boat" category may not be applicable to large, ocean-going vessels or coastal and harbor tugboats. Accordingly, this Report first categorizes vessels according to criteria relevant to greenhouse gas (GHG) emissions, and then estimates current GHG emissions per vessel category based on vessel inventories. Next, drawing on the first Blue Sky Report's discussion regarding alternative fuels and propulsion systems, this paper identifies potential decarbonization pathways likely to be applicable to each vessel category.

III. VESSEL CATEGORIES AND CHARACTERISTICS: DECARBONIZATION POTENTIAL

A. VESSEL DESIGN AND OPERATIONAL PARAMETERS RELEVANT TO DECARBONIZATION PATHWAYS

While a number of different vessel design and operating conditions are relevant to the potential for successful implementation of decarbonization pathways, this section identifies and discusses some of the most salient factors. These characteristics within each vessel category will need to be evaluated as alternative fuels, propulsion systems, and retrofitting are considered.

1. Vessel size and weight distribution

Vessel size is related to the volume of cargo a ship can carry (or push), but size is also relevant to the constraints applicable to the installation of alternative fuels or propulsion systems in existing vessels, and the commercial viability of new vessel builds. Studies have found that larger vessels within all vessel categories tend to emit less carbon dioxide on a per-ton-mile basis (assuming, of course, that the extra capacity is used), but the pathway to net zero requires reducing overall emissions. More important to selection of alternative fuels and propulsion systems, however, are the weight and balance constraints that are directly related to a vessel's size. Certain vessel categories, especially those that operate on U.S. inland waterways, are exceptionally size, balance, and weight constrained. Inland river depths in the U.S. require operating with a maximum vessel draft of nine feet in many locations, and many vessels must also be small enough to push large assemblages of barges through the existing lock and dam river infrastructure, leaving little leeway to retrofit, or even newly design, vessels that require greater size or weight, or even a redistribution of existing weight.

Certain fuels also will have regulatory constraints likely to mandate additional heavy or large equipment that the vessel will have to accommodate. For example, existing diesel fuel tanks cannot be used to store any alternative fuel that requires pressurization—such as LNG, hydrogen, or ammonia. Classification societies are developing design, safety, and fuel system requirements for the various options.

The use of ammonia, as another example, will require larger tanks—both to account for pressurization needs and the lower energy density relative to marine diesel—but also additional safety equipment such as emergency ventilation and gas-absorption systems, double-walled piping, and safety barriers such as cofferdams in the event of a leak, fire, or explosion. A Japanese ship classification society, ClassNK, has recently issued new safety requirements for ammonia-fueled vessels, but regulatory approvals and specifications are still being determined and developed in the U.S. and Canada. LNG similarly requires additional pressurized, cooling, and safety equipment that may impact space and weight distribution, or impact commercial viability (e.g., a reduction of commercial cargo to accommodate needed fuel equipment).[1] The American Bureau of Shipping recently issued a report examining the design, safety, and fuel system arrangements required with the use of LNG fuel and potential impacts on operational parameters.

Overall, vessel categories that have greater flexibility regarding weight, space (above or below deck), and balance constraints are more likely to be candidates for retrofitting to accommodate alternative fuels. New-build vessels can of course be

1 Safety regulations for LNG-fueled ships from both the International Maritime Organization and the U.S. Coast Guard were developed based on the IGC Code and have been in place for a number of years. In 2017, the U.S. Coast Guard issued an Update to Policy Letter 01-12, Ch-1 - Design Criteria for Natural Gas Fuel Systems (Change-1) (July 12, 2017).

designed to accommodate a new fuel, but must be economical to build and operate. Certain fuels, even with new designs, may be difficult to accommodate in particular vessel categories simply based on the size, weight, or balance constraints inherent to that vessel category and its operations (such as some inland river vessels as discussed below).

2. Life span of engine and vessel

Marine transport vessels in the U.S and Canada have long life spans relative to other transport modes, especially road-based transportation, and relative to the average global fleet (see Table 1 below). The long life span of these vessels, together with the expense of new-builds, means that replacing old ships with alternative-fuel ready designs is not likely to be economically feasible within a time frame that aligns with our climate-related decarbonization goals.[2]

According to reports by SAE International, the average age of the global merchant fleet (all ship categories; currently operating vessels) is 13 years, substantially lower than the average age of the U.S. and Canadian fleets (see Table 1 below). Table 1 excludes the inland sector, but studies by the American Bureau of Shipping and Vanderbilt University report that the average age of the U.S. inland fleet is 36 years, with many inland vessels substantially longer lived given the fresh water (less corroding) environment in which those vessels operate. Although the U.S. and Canadian fleet make up a small percent of global shipping, unique regulatory requirements also make U.S. flagged ships some of the longest lived in the industry. For example, the U.S. Merchant Marine Act of 1920 (also known as the Jones Act, 42 U.S.C. §§ 861-889) requires that vessels that move from one U.S. port to another U.S. port must be U.S.-built, -crewed, and -maintained. Building Jones Act-compliant vessels in the U.S. is more expensive than building vessels outside the U.S., and the higher initial capital investment results in an economic incentive to extend vessel-life rather than upgrade. In addition, a large portion of the total U.S. fleet operates in fresh, inland waterways or lakes, and is not exposed to the more-corrosive characteristics of salt water. Finally, stringent regulatory standards in the U.S. result in well-built, maintained, and operated vessels, further contributing to the longer average life-span of U.S. vessels.

Table 1.

Canadian and United States Merchant Fleet - 2022

	Canadian	Canadian	United States	United States
Ship Type	Average Age of Vessels (years)	Number of Vessels	Average Age of Vessels (years)	Number of Vessels
Oil Tankers	29.04	15	17.97	70
Bulk Carriers	20.47	21	15.98	4
General Cargo	37.80	65	45.58	99
Container Ships	16.58	1	19.34	58
Other	39.61	587	32.8	3,405

Source: Knoema data, from United Nations Conference on Trade and Development Statistics.
Note: Data exclude inland waterway, fishing vessels, military vessels and yachts.

2 The U.S. has made a Paris-Agreement commitment to achieve 50-52% reduction of GHG emissions from 2005 levels by 2030 and to reach net-zero (economy wide) by 2050. Canada has pledged a reduction of 30% below 2005 levels by 2030 and to achieve net-zero by 2050.

Diesel engines also have very long lifespans,[3] which presents economic challenges to incentivize upgrades. Even if new, alternative fuel engines were available that could meet size, weight, and operational requirements of a vessel, it is rarely economical to replace a fully functioning engine with a brand new one, and incentives and subsidies will be needed to do so.

Although the U.S. Environmental Protection Agency (EPA) has rules applicable to marine diesel engines to reduce certain pollutants (primarily those with health-related impacts, the rules are not focused on greenhouse gas emission reductions), EPA's tiered approach to imposing more stringent pollution control requirements over time only applies to the manufacture of *new* (and certain retrofitted) engines. A vessel owner is not required to scrap old (even high CO_2 emitting) engines simply based on the availability of newer technology. Thus, EPA rules aimed at phasing out older engines over time have less impact in the maritime sector where engines are especially long-lived, than in the on-road sector, where vehicles and their engines do not last nearly as long.[4]

Accordingly, for nearly all vessel categories, alternative fuels that can be used in existing or minimally retrofitted diesel engines are likely to be adopted earlier, assuming it is commercially viable to do so.

3. Refueling needs and infrastructure availability

The length of time a vessel needs to travel between refueling, and its proximity to potential refueling supply infrastructure, directly impacts the type of alternative fuel or propulsion system that are the ideal candidates to support that vessel's operations. Some vessels, such as harbor assist vessels, operate for very short durations and remain in close proximity to port infrastructure when they are not working. Thus, these vessels may be candidates for electrification because they are frequently waiting at port where they could charge between assisting ocean-vessels into port. However, one of the key roles of harbor assist vessels is to assist ships during emergencies, such as extreme weather events (e.g., hurricanes), groundings, and other navigational issues. Thus, these vessels must have multi-day power capabilities even if such capabilities are only used periodically.

In addition, electrification always will require consideration of whether the port infrastructure has the required capacity to support the needed electrification demand. By contrast to harbor assist vessels, vessels that traverse the ocean must remain under power for many hundreds or thousands of miles before they can refuel. The amount of battery power and storage required to fully support the power needs for that kind of voyage is currently not practical, so fuels such as ammonia, hydrogen, or bio-fuels (including methanol) may be more feasible solutions for these types of voyages. Thus, the specific operational bunkering conditions that are currently supported by marine diesel must be considered in determining the most appropriate and cost-effective low- and no-carbon fuels.

3 Diesel engines are larger and primarily rely on larger (sturdier) parts such as gears, rather than timing belts or chains found in gasoline engines that are more likely to bend or break. Diesel fuel itself is also more lubricating and less corrosive to the engine than gasoline, and is also less volatile and reactive to the engine components (igniting through compression rather than a spark). Diesel engines also typically operate at lower rotations per minute (RPMs) putting less wear-and-tear on the engine. With proper maintenance it is not uncommon to find diesel engines in operation for many decades (nearly as long as the vessels themselves).

4 EPA's marine diesel engine rule is aimed at reducing "criteria pollutants" (six pollutants selected based primarily on their health impact and regulated by EPA pursuant to the federal Clean Air Act—ground level ozone, particulate matter, carbon monoxide, lead, sulfur dioxide, and nitrogen dioxide). The rule does not directly regulate GHG emissions; however, because fuel efficiency is an important component of reducing pollution emissions, the rules and engine control requirements have some limited GHG emissions reduction impacts as well. Because fuel is the largest cost-driver in marine shipping, the availability of engines that achieved even ten-percent more fuel efficiency would be economically advantageous and likely incentivize the move to new engine technologies.

4. Vessel power requirements

A central challenge to adoption of alternative fuels and propulsion systems is the lower energy density of nearly all alternative fuels. Ships are designed so that they are economically viable to operate. Each category of vessel described below in Section III.B is designed to meet the speed, range, and power requirements for the transport or functional needs of that vessel category. Alternative fuels must meet safety criteria and existing operational needs or they are not likely to be adopted. Fuels that meet or exceed those needs *and* are cost effective (including through the offset of costs elsewhere) are likely to be adopted.

As shown in Table 2, lower energy density of the alternative fuels as compared to marine diesel (the amount of energy available in one gallon of diesel versus one gallon of the alternative fuel) means that to achieve the vessel's need for speed, engine power (both propulsion and auxiliary energy), idling capacity, etc., the vessel will have to carry a substantially higher fuel volume, in addition to the new tanks, fuel systems, and safety equipment, that certain fuels will require. Extra weight means additional power required to move the vessel. Batteries must also be considered within this context and offer high power (energy density) and efficiency to provide performance for an adequate duration between charging. Recharging time represents an unavailable (non-operating) vessel, and must be considered as compared to current refueling times, with the potential for battery exchanges to reduce such charging time.

Table 2.
Energy Density of Alternative Fuels as % of Marine Diesel Fuel

Fuel	Energy Density as a Percentage of Marine Fuel
Marine Diesel	100%
Biofuel	95%
LNG	54%
Methanol	39%
Ammonia	39%
Hydrogen	23%

For some vessel categories and alternative fuel combinations, the volume of fuel that would be necessary (or the needed battery stacks) to achieve the desired speed and range may not be achievable without reducing cargo carrying capacity, making commercial viability difficult. But other combinations may now, or with expected technological improvements, have the capacity to meet vessel speed and power needs.

5. Navigation conditions

Navigational considerations are also central to power and range needs of a vessel, and the viability of alternative fuels and propulsion systems. For example, inland river vessels in the U.S. and harbor assist vessels in many ports must navigate shallow waters and confined operating areas. Inland waterway vessels additionally must contend with challenging river bends and a system of locks and dams. Even new-build vessels for harbor assist and inland-river operations are size, weight and balance constrained given this environment, and may not be able to accommodate certain new fuels or propulsion systems. This constraint is magnified when onboard fuel infrastructure must be positioned in certain locations on the vessel (for safety or other reasons) if that positioning does not align with the vessel's buoyancy and trim needs. In contrast to the inland sector, ocean-going vessels may have fewer space constraints, but must have long ranges and power reserves to navigate long distances, open ocean weather, and waves. Some vessels, such as harbor assist boats, or ferries that traverse a single river or lake from shore to shore, have much lower range and power needs. Vessels that typically operate for short durations may be required to operate for longer durations during emergencies, during transit to other ports or harbors for routine maintenance, or when reassigned to a new geography. These vessels may require more than one fuel/power approach. Additionally, it can be easier in some cases to assure alternative fuel access for vessels that only serve a particular route.

These factors, when taken together, create complex challenges to implementation of alternative fuels and propulsion systems. Given the range of constraints, it is likely that multiple solutions will be required as we develop viable decarbonization strategies for the North American shipping industry.

B. POTENTIAL DECARBONIZATION PATHWAYS BY VESSEL CATEGORY

Although other maritime organizations and associated reports categorize commercial maritime vessels,[5] Blue Sky considers the categorizations discussed in this section appropriate when considering fuel and decarbonization pathways. Despite some variation within each category, the majority of the vessels in each category share characteristics and operating conditions that are most relevant to the adoption of alternative fuels and propulsion systems. Accordingly, this section discusses, within each vessel category, the primary relevant characteristics and resulting fuels and propulsion systems that are likely to offer decarbonization potential.

Relevant to every vessel category, and as discussed in more detail in the first Blue Sky Report (Fuels and Propulsion Systems), are fuels that can be used now, or with slight adaptations, in existing engines and fuel storage infrastructure in place of marine diesel. These include bio-fuels that could be true net-zero fuels if sourced and processed sustainably (that is, taking into account the full lifecycle of the feed-stock growth, harvesting, fuel production, and transport involved). If supplies were sufficient, many vessels could currently utilize biofuels. Consequently, this section primarily addresses the considerations and fuel-types likely to be most relevant within each vessel category identified below.

1. Offshore Supply Vessels

Offshore supply vessels (OSVs) primarily consist of vessels designed to service offshore energy platforms.[6] These vessels provide transport for crew, equipment, power generators, piping, drilling supplies, diesel fuel, and other consumables needed in the offshore energy sector. Regulations also require standby vessels at floating or fixed platforms for emergency evacuation or other needs. There are also OSVs that provide anchor-handling services, assisting vessels to place up to eight anchors in offshore waters of less than 500 feet. In deeper waters, while on standby, OSVs may need continuous power, including to power dynamic positioning systems where anchoring is not possible. OSVs may also assist in towing heavy equipment, and can include large tugs well over 10,000 horsepower.

5 See e g., UMAS, Future Maritime Fuels in the USA: Options and their Potential Pathways, January 2022 (categorizing vessel types); and U.S. Environmental Protection Agency, EPA National Emissions Inventory, report prepared for EPA by ERG (Eastern Research Group), Draft 2020 Report (May 2022) (categorizing vessel types).

6 U.S Coast Guard regulations formally define OSVs at 46 C.F.R. § 125.160.

OSVs often operate for long durations and may service drilling platforms for many weeks, with fuel needs to operate for several days between refueling. Some newer OSVs (less than 20 years old) have hybrid diesel electric engines designed to drive electric motors that can support power needs while on standby or for dynamic positioning systems.

Nearly all OSVs currently operate with marine diesel, but there are an increasing number of LNG-powered OSVs. Harvey Gulf International Marine has built and converted existing OSVs to LNG and dual-fuel capability (these can operate on marine diesel or LNG, and may be considered "tri-fuel" as they also consume electric battery power). The company is currently sourcing bio-LNG (sourced from animal and farming waste, not fossil fuels) and is achieving net-zero emissions while operating on the renewable LNG. Although the current cost of bio-LNG is high, it can be blended with fossil-LNG and still achieve carbon neutrality given the negative carbon intensity value of bio-LNG (Harvey Gulf obtained a certified carbon intensity value for Swine-waste derived LNG fuel of -449.66 gCO_2-e/MJ). Investments and incentives that increase supply and drive costs down are needed to achieve commercial viability at scale for these types of proven technologies.

During dynamic positioning, Harvey Gulf also has realized approximately 25 percent fuel savings by using one engine to power the dynamic positioning system supported by an electric battery backup. Combining electric battery power with the bio-LNG achieves even more GHG emission reduction. Harvey Gulf has also invested in sophisticated, real-time emissions monitoring equipment and software that has provided valuable data and challenged many assumptions often made regarding emission estimations. Indeed, the company learned methane slip actually *increased* when engines were running at lower loads, whereas the emissions profile was improved by running at higher loads. Small changes to operations—such as running one engine at a higher load rather than two engines at lower loads—reduced overall emissions.[7]

Ammonia or hydrogen are also likely candidates for OSV conversion if safety considerations are addressed and supply infrastructure develops. OSVs are currently a poor candidate for electrification (as a sole or primary power source) because existing battery technology (power, range, and recharging requirements) would require large battery banks that would displace needed cargo space.

2. Inland River Tug Boats

Inland river boats have a range of operating conditions that make battery electric suitable in some limited inland river applications, and make the use of fuels requiring pressurized and larger tanks difficult to adopt on board. As described in a recent report on the inland river sector by ABS and Vanderbilt University, boats in the inland river system have some of the longest life-spans in the marine shipping industry (due in part to their operation in fresh water) and most were constructed when diesel fuel was inexpensive. Accordingly, diesel fuel also serves as ballast in these vessels which will need to be addressed in any transition to alternative fuels.

The U.S. Army Corps of Engineers maintains river channel depths on the inland system to a minimum depth of nine feet, and towboats routinely must navigate such shallow depths. Towboats also must be able to navigate the locking system and sharp river bends while pushing large assemblies of barges, which limits both the maximum length and width of these vessels. Accordingly, inland river vessels are weight and size constrained, and rely on precise onboard placement of tanks, engines, and other vessel infrastructure to maintain trim in the water. These considerations, together with the lower energy

7 The third Blue Sky Report will focus on developments in technology and approaches to operational efficiency, such as use of real-time data and information, which can have substantial impacts on overall GHG emissions, including in the near term.

density, make existing alternative fuels difficult to adopt on the inland sector while maintaining commercial viability. Two important exceptions exist.

First, the use of Portable Energy Modules (PEMs)—an arrangement where the space on a single barge is dedicated to carry and generate the power supply that is then transferred to the towboat as electricity—have potential to facilitate the use of nearly any alternative fuel. Cost is the primary barrier to use of this model as constructing the PEM is expensive, in addition to the reduction of barge capacity required to accommodate the PEM. Second, smaller "fleet boats" that assemble the barges into a "tow" for the larger tug boats to push up and down river, operate continuously in 12-hour shifts. The lower power requirements of fleet boats and operational duration needed between charging, together with their continuous proximity to shore infrastructure, make them potentially good candidates for electrification with current battery technology.

3. Coastal and Harbor Tugs

Coastal and harbor tug boats, unlike tug boats on the inland rivers, are built for operations in ocean and near-ocean conditions. They are designed to operate safely during periods of significant wave heights, strong currents, and the generally rough conditions that can be experienced in an ocean environment. Coastal tugs push or pull cargo up and down the coastal areas of the United States. Some states, such as California, are looking to decarbonize harbor tugs, which are typically less focused on commercial cargo and instead assist ocean-going vessels in and out of ports. Harbor tugs can range from 1,000-10,000 horsepower. Harbor tugs in some harbors are actively at work only a few hours within a 24-hour period, and in other ports operate 12-15 hours per 24-hour period. These tugs are usually near port infrastructure, and therefore could be candidates for electrification, recharging during idle periods in between ship-assists. Foss Maritime has built a hybrid electric harbor tug, and retrofitting existing tugs to adopt hybrid propulsion systems is possible on existing vessels. Crowley has also designed and is currently building the first fully electric U.S. harbor tug, which will operate in California.

Hydrogen also has medium and long term potential for harbor tugs, but at only 25 percent of the energy density of diesel (in liquid form), adoption of hydrogen will be challenging. It is likely that liquid hydrogen will be a challenge to implement in a harbor tug; gaseous hydrogen (stored in high pressure tanks) is a more likely solution but implies a fairly limited operating range. Some states, especially those focused on coastal air pollution such as California, are already making investments to encourage the design and deployment of hydrogen fuel-cell harbor tugs. With respect to hydrogen in particular, the existing projects will begin to address challenges associated with supply, transport, and storage of liquid hydrogen. These early projects are critical for understanding cost and operational successes, and to the ultimate scaling of the adoption of electric and alternative fuels across the maritime sector.

4. Cruise Vessels and Ferries

Cruise vessels and ferries have important differences with respect to size and operational durations, but both typically operate within relative proximity to shore infrastructure. In the U.S. and Canada, ferries tend to provide transportation for people and their vehicles to cross bodies of water typically over relatively short distances. However, there are a considerable number of ferry operations that transit longer distances, with transit times of one to 24 hours. Cruise vessels operate for longer, multi-week journeys, but typically stop frequently at ports where refueling and other infrastructure could be available. Cruise vessels also expend significant fuel loads providing hotel services for passengers.

Cruise ships tend to be larger ships capable of carrying extra weight and with more options to distribute that weight than smaller vessels. Most cruise-line companies operating in the U.S. and Canada have set decarbonization targets. For example, Carnival Cruise has set a goal of 40 percent carbon intensity reduction relative to its 2008 baseline by 2030. Based on currently available technologies and the size and operational needs of cruise vessels, a number of approaches to achieve decarbonization goals are likely to be increasingly pursued in this vessel category. This includes increasing the capability of cruise vessels to connect to electric shore power, and expanding use of LNG, batteries, fuel-cell technologies, and biofuels.

Ferries typically operate for shorter distances between ports and may remain at shore terminals for shorter durations than cruise vessels. The short operational distances and ability to quickly exchange (rather than recharge) batteries, or to recharge during non-operational times (e.g., at night) make some ferries good candidates for electrification. For example, the Washington State Department of Transportation, through its Washington State Ferries (WSF), is investing in electrification of the ferry system through retrofits, new vessels, hybrid electric technology, and terminal electrification. The cost, however, is substantial and requires public investment. WSF reports that over $1.3 billion was secured to electrify fewer than 10 vessels (both new build and retrofits) and certain terminals. The size and operational needs of ferries also make LNG a viable alternative fuel option.[8]

5. Bulkers, Containers, and RoRos

Bulkers (vessels that carry bulk cargo such as grain), container ships, and RoRos (vessels that carry cargo such as vehicles that roll on and roll off the vessel) typically transport heavy cargos over long, ocean-going voyages and are not likely to be good candidates for electrification. Although these vessels may have fewer relative constraints related to weight and storage space (for onboard propulsion and fuel infrastructure), current battery technology would not realistically provide sufficient power or operational range for the needs of these vessels. However, other low- and no-carbon alternative fuels are viable options. Cost, supply, availability, and transportation and storage infrastructure are current challenges to commercial viability.

Like other vessel categories, projects that demonstrate cost, viability, and operational efficiency of new approaches are critical. Both TOTE Maritime and Crowley Maritime Corporation successfully operate at least two LNG-fueled containerships between Florida and Puerto Rico. The first U.S. flagged LNG bunker barge, the Clean Jacksonville, is operated by TOTE Maritime and refuels these LNG vessels. Having a dedicated route has facilitated the use of this alternative fuel. In addition, Matson announced they will undertake the conversion of a large containership from conventional diesel power to LNG when retrofitting work begins on the Daniel K. Inouye in 2023; and TOTE expects to be running vessels on dual-fuel LNG propulsion in the Alaska trade by 2023.

8 Although LNG is a fossil fuel that produces greenhouse gas ("GHG") emissions when combusted, natural gas emits nearly 30 percent less GHG emissions for the same energy output (in addition to a reduced volume of other air pollution constituents) as compared to diesel. Accordingly, the U.S. Department of Energy's Alternative Fuels Data Center recognizes that the Energy Policy Act of 1992 defines an alternative fuel to include "Natural gas and liquid fuels domestically produced from natural gas." See Alternative Fuels Data Center, available at https://afdc.energy.gov/fuels/.

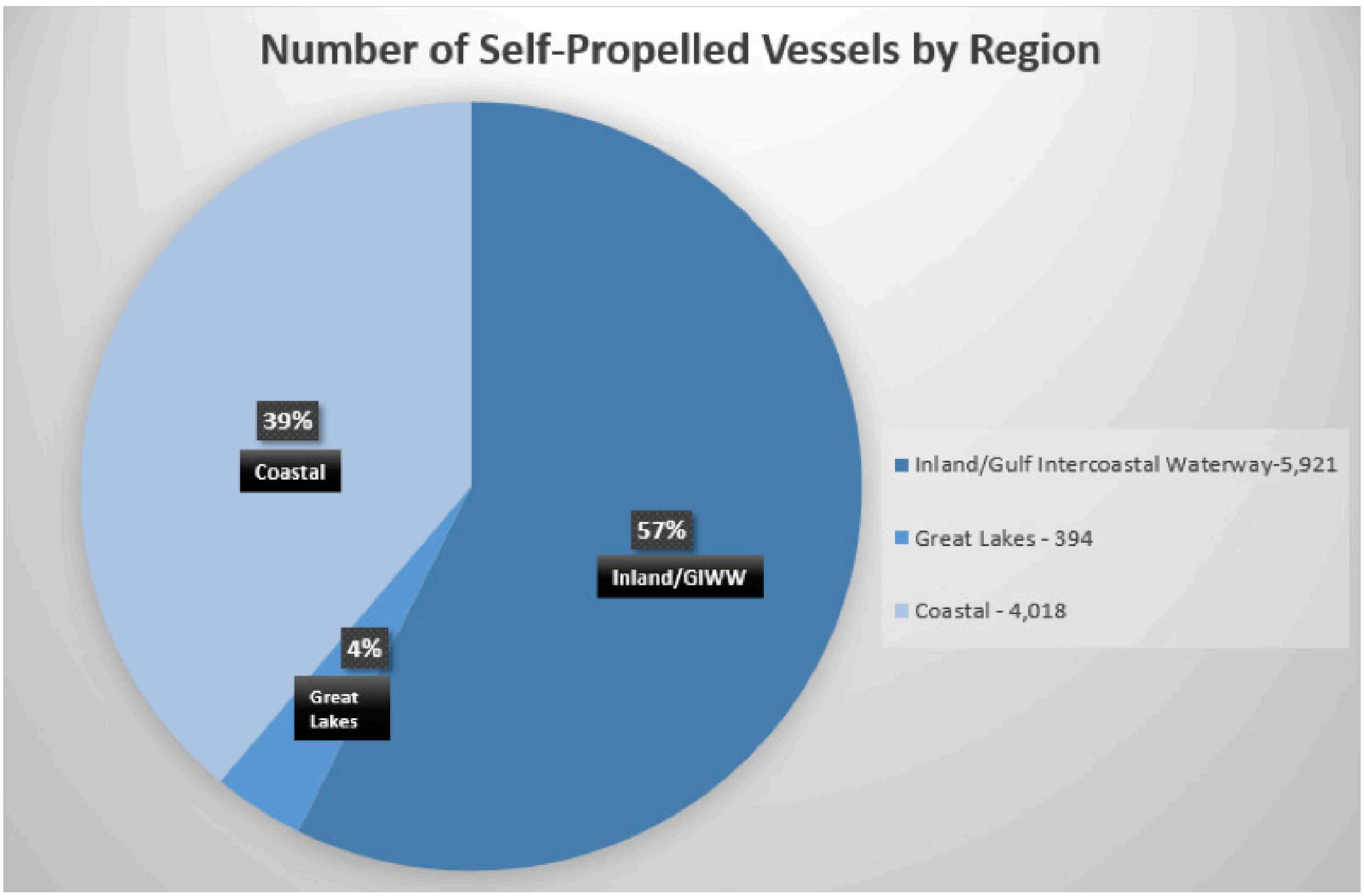
IV. NORTH AMERICAN MARINE VESSEL INVENTORIES AND GHG EMISSIONS

A. VESSEL INVENTORIES

The number of vessels operating in each vessel category discussed above is relevant to decarbonization potential. In addition, inventories can serve to provide important information regarding where allocation of resources may be most effective in reducing overall sector emissions. The Institute for Water Resources of the U.S. Army Corps of Engineers (USACE or Corps) annually publishes national summaries of U.S. flagged vessels transporting freight and people, including ferries. This USACE report divides vessel inventories into three regions, with the inland sector representing the largest number of vessels as shown in Figure 1. The Corps' numerical inventory of vessels relevant to this report is shown in Table 3, and utilizes the following categories: container ships, off-shore supply vessels, ferries & passenger, dry cargo (not container) and towboats.

Figure 1.

Vessel Inventory (U.S. Flagged) by Region



Data source: USACE Waterborne Transportation Lines of the United States, 2020.

Table 3.
U.S. Flagged Vessels by Type - Self Propelled

Type	Number
Container	70
OSV	1,846
Ferries and Passenger Vessels	1,804
Dry Cargo (not container)	152
Towboats	6,385
Tankers	76

Data source: USACE Waterborne Transportation Lines of the United States, 2020.

Within each vessel category inventoried, vessels vary by size, horsepower, and other characteristics discussed in Section III.A. Thus, while the vessel categories set forth in this Report are relevant to decarbonization pathways, there are likely to be multiple fuels or propulsion systems that are appropriate even within a single vessel category.

B. SUMMARY OF EXISTING STUDIES OF U.S. MARINE SHIPPING GHG EMISSIONS

The differing characteristics between vessel categories discussed in this Report translate to likely differences in the GHG emissions profiles for each vessel category. However, there are few studies accounting for GHG emissions by vessel group. Table 4 compares GHG total emissions for U.S. flagged ships by vessel category from a recent study by UMAS as compared to a recent similar estimation completed by Blue Sky. The total number of vessels in each category were similar, yet the total CO_2 emissions calculated by the two approaches varied substantially. This is not unusual because standardization regarding carbon accounting for GHG emissions inventories is not developed and presents a challenge to nearly all economic sectors seeking to better understand current emissions.

Table 4.

Comparison of UMAS and Blue Sky Maritime Estimation of GHG Emissions by Vessel Category (vessel category identified by BSMC noted if different from UMAS categorization)

Vessel Category (from UMAS report)	CO_2 Emissions (Mt)	
	UMAS (*Maritime Fleet of the USA*)	Blue Sky Maritime Coalition
Offshore Supply Vessels	3.46	13.0
Inland Tugs and Towboats	3.49	9.3
Coastal & Harbor Tugs		6.8
Ferry	1.11	6.4 (Cruise Vessels and Ferries)
Tankers and Articulated Tug Barge	0.83	
Other Deep Sea	7.5	3.8 (Bulkers, Containerships, RoRos)
Fishing	5.6	
Other	4.0	3.0 (Other U.S. Flag)
		3.0 (Tank Vessels)
		1.7 (Canadian Flag)
Total	**26.0**	**47.0**

Irrespective of vessel categories, there is also no single standardized approach to accounting for GHG emissions within the North American marine shipping sector or globally. This is a potential barrier to comparability when such values are reported because methodological approaches can vary significantly. In addition, the cross-boundary nature of maritime shipping can make accounting for emissions that are appropriately attributable to the United States or Canada or another country or region extremely challenging. If a vessel purchases its fuel in the U.S. but then departs for China, which portion of that voyage should be considered to be U.S. emissions? Similarly, should the purpose or destination of the cargo on board the ship be considered in attributing the vessel's direct emissions (i.e., which country is benefitting from the voyage?).

International agreements provide that voyages between two countries are governed by the International Maritime Organization and do not need to be accounted for in any individual country's emissions inventory that is required by the Paris Agreement and the United Nations Framework Convention on Climate Change (UNFCCC). Other approaches account for emissions only from fuel loaded at ports within certain boundaries, or calculate emissions based on vessel AIS data also within certain pre-selected boundaries. The accounting can become exceedingly complex and nearly always relies on certain estimations and emission factors.

Table 5 below summarizes the major, existing studies that have characterized what may be considered "United States" or "Canadian" total GHG emissions attributed to the marine shipping sector. The Table also identifies the boundary selected by the report and a summary of the primary methodology employed.

Table 5.

Summary of Total Marine Shipping GHG Emissions; Methodology from Identified Reports

Report/Study (*links provided in References)	Total GHG Emissions	Boundary	Methods
UMAS – Future Maritime Fuels in the USA: Options and their Potential Pathways, January 2022	13.3 $MtCO_2$ (2018)	U.S: Total calculated from "domestic shipping" (Jones Act vessels connecting ports within U.S. waters)	UMAS Fuel Use Statistics and Emissions (FUSE) model based on AIS data and vessel information to calculate fuel use.
U.S. Environmental Protection Agency (EPA) – *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, 1990-2020. EPA 430-R-22-003, April 14, 2022	23.3 $MtCO_2$ (2018)	U.S.: U.S. domestic "ships and boats" category.	Data from distillate fuel oil sales and residual fuel oil sales, *excluding* recreational boats and international bunker fuels.
U.S. Environmental Protection Agency (EPA) – *EPA National Emissions Inventory*, report prepared for EPA by ERG (Eastern Research Group), Draft 2020 Report (May 2022)	38.6 $MtCO_2$ (2020)	U.S.: Category 1, 2, and 3 vessel engines (displacement below 7 liters per cylinder, between 7-30 liters per cylinder, and over 30 liters per cylinder, respectively), operating in the U.S. Exclusive Economic Zone (EEZ)	Emissions were calculated using AIS vessel data based on location and engine information and activity duration, which translates to fuel burn.
American Bureau of Shipping (ABS): Decarbonization of the *Inland Waterway Sector in the United States*, September 2021	5.6 $MtCO_2$ (2018)	U.S.: U.S. Inland waterways only – vessels reported in the Inland River Record	Estimate based on Inland Waterways Trust Fund tax receipts, and confirmed using company data.
Blue Sky Maritime Coalition – Chartering, Finance, and Commercial Workstream: Report – Carbon Footprint of the North American Waterborne Fleet	47 $MtCO_2$ (45.3-US / 1.7-CA) (2018) Additional: Ports—19 $MtCO_2$	U.S and Canada: U.S. offshore support, inland, coastal, ferry, tankers/ containerships/RoRo, and Canadian flagged.	Estimates based on industry knowledge, published data from ports, and total vessel inventory of various classes and owner/ operator feedback for fuel usage and ranges by vessel type. Inland sector estimation methods are similar to those used by ABS/Vanderbilt (with notable difference in estimated percent of total inland fuel use that is *not* subject to Inland Waterways Trust Fund Fee (20%--ABS/ Vanderbilt vs. 50%--BSMC.
Environment and Climate Change Canada – *Marine Emission Inventory Tool*	8.7 $MtCO_2$ (2019)	Canada: All vessels that entered the Canadian EEZ from 2015 to 2020	AIS data, vessel characteristics, and emission factors along with other information such as course correction based on bathymetry or engine load based on currents.

As Table 5 demonstrates, the lack of consensus and coordination regarding approaches, data sets, and emission boundary present issues of comparability. The reports that are focused on U.S. emissions also did not have consistency regarding the emission boundary used. The primary data sources relied on across the six studies were (i) AIS data coupled with vessel operating information and (ii) fuel sales data. However, different approaches (methodology, models, emission factors, etc.) resulted in variation of total emissions calculated.

The lack of standardization is in part due to the lack of a mandatory reporting structure. While there are some entities that are required to report their GHG emissions under federal or state rules (such as the EPA GHG Reporting Rule or pursuant to the California Air Resources Board regulations), the majority of emissions associated with marine shipping are not required to be reported under a standardized structure, so different approaches are emerging as voluntary reporting has continued to increase.

Despite the lack of a standardized reporting structure, the United States is required, pursuant to its membership in the UNFCCC, to report the total human-made emissions that are attributable to the country, and does so annually through the publication of EPA's "Inventory of U.S. Greenhouse Gas Emissions and Sinks." This inventory represents the official United States government estimate of our nation's human-made GHGs, and contains a "ships and boats" category as noted in Table 5.

Blue Sky is developing recommendations to standardize GHG emissions reporting approaches and methodologies to allow for accurate, comparable (across vessel type) emissions calculations.

V. CONCLUSION

Decarbonizing marine shipping will require utilization of multiple fuels and propulsion systems, even within a single vessel category. Approaches that are currently viable on a fleet boat that operates in 12-hour shifts close to shore infrastructure may not be applicable to an ocean-going container ship that must traverse thousands of miles before refueling. However, as discussed in this Report, certain vessel categories are more or less suited to particular alternative fuels and propulsion systems based on vessel characteristics and operational requirements. Decarbonization potential within each vessel category will continue to expand as regulatory incentives drive adoption at scale of new and existing technologies, and pilot projects demonstrate commercial viability. We emphasize that for nearly all low- and no-carbon fuels, adoption is likely to require regulatory incentives, grants, and pilot projects to establish safety, realistic expectations of cost, and to demonstrate operational success applicable to each vessel category.

A better understanding of emission profiles—both within vessel categories and for the marine shipping sector in North America more generally—is also needed to prioritize resource allocation to the vessels that present the greatest opportunity to reduce emissions. However, the lack of standardization in emissions inventory accounting presents a challenge and serves to decrease confidence in, and comparability between, reported values. Nevertheless, emission inventories are a critical step in achieving net zero, and are likely to improve as more consistent frameworks and approaches emerge.

VI. REFERENCES

American Bureau of Shipping (2022). LNG as Marine Fuel. July 2022. Available at chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://ww2.eagle.org/content/dam/eagle/advisories-and-debriefs/sustainability-whitepaper-lng-as-marine-fuel.pdf.

American Bureau of Shipping (ABS), 2021. Decarbonization of the Inland Waterway Sector in the United States.

American Bureau of Shipping (ABS): *Decarbonization of the Inland Waterway Sector in the United State*s, September 2021.

Arioli, M. S., Márcio de Almeida, D. A., Amaral, F. G., & Cybis, H. B. B. (2020). The evolution of city-scale GHG emissions inventory methods: A systematic review. *Environmental Impact Assessment Review*, 80, 106316.

Azarkamand, S., Wooldridge, C., & Darbra, R. M. (2020). Review of initiatives and methodologies to reduce CO2 emissions and climate change effects in ports. *International journal of environmental research and public health*, 17(11), 3858.

Bhardwaj, S., Bhardwaj, N., Kumar, V., & Parashar, B. (2019). Estimation of lifespan of diesel locomotive engine. *Journal of Information and Optimization Sciences*, 40(5), 1097-1108.

Blenkey, Nick (2022). Lakers innovative diesel electric solution delivers emission savings. MarineLog, News, Technology, May 23, 2022.

Bloomberg, (2021). Chart Industries Reports 2021 First Quarter Results, April 22, 2021.

Blue Sky Maritime Coalition – Finance/Commercial Group Estimate.

Capital Reman, n.d. Why do Diesel Engines Last So Long? available at https://www.capitalremanexchange.com/why-do-diesel-engines-last-so-long/.

Cariou, P., Lindstad, E. (2021). Container Shipping Decarbonization Pathways. In: Ko, BW., Song, DW. (eds) New Maritime Business. WMU Studies in Maritime Affairs, vol 10. Springer, Cham. https://doi.org/10.1007/978-3-030-78957-2_5.

Carnival Corporation, Annual 10-K Report (2022). Form 10-K Filed with the United States Securities and Exchange Commission, available at https://www.sec.gov/edgar.

Chamber of Marine Commerce, Vessel Types.

ClassNK, (2022). Guidelines for Ships Using Alternative Fuels (Edition 2.0), Part C-1 Guidelines for the Safety of Ships Using Ammonia as Fuel, June 2022.

Cotta, W., Haugh, W., and Franklin, Lee, n.d. Liquefied Natural gas as Fuel Design Considerations, U.S. Coast Guard, Marine Safety Center.

Environment and Climate Change Canada – *Marine Emission Inventory Tool*.

Grzelakowski, A. S., Herdzik, J., & Skiba, S. (2022). Maritime Shipping Decarbonization: Roadmap to Meet Zero-Emission Target in Shipping as a Link in the Global Supply Chains. *Energies*, 15(17), 6150.

Gurney, K. R., Liang, J., Roest, G., Song, Y., Mueller, K., & Lauvaux, T. (2021). Under-reporting of greenhouse gas emissions in US cities. *Nature communications*, 12(1), 1-7.

ITF. Decarbonising Maritime Transport. Pathways to Zero-Carbon Shipping by 2035; International Transport Forum: Paris, France, 2018.

Kennedy, C., Steinberger, J., Gasson, B., Hansen, Y., Hillman, T., Havránek, M., ... & Mendez, G. V. (2010). Methodology for inventorying greenhouse gas emissions from global cities. *Energy policy*, 38(9), 4828-4837.

Larter, D. (2018). The US Navy's fleet is getting old. It might get a lot older. Defense News, June 7, 2018, available at https://www.defensenews.com/naval/2018/06/07/the-us-navys-ships-are-getting-old-they-might-be-getting-a-lot-older/.

Lindstad, E., Eskeland, G. S., Rialland, A., & Valland, A. (2020). Decarbonizing maritime transport: The importance of engine technology and regulations for LNG to serve as a transition fuel. *Sustainability*, 12(21), 8793.

Mallouppas, G., & Yfantis, E. A. (2021). Decarbonization in shipping industry: A review of research, technology development, and innovation proposals. Journal of Marine Science and Engineering, 9(4), 415.

Olmer, N., Comer, B., Roy, B., Mao, X., & Rutherford, D. (2017). Greenhouse gas emissions from global shipping, 2013–2015 Detailed Methodology. *International Council on Clean Transportation*: Washington, DC, USA, 1-38.

SAE International, Average Age of Ocean Going Ships, Department of Defense Maintenance Symposium presentation, available at https://www.sae.org/events/dod/presentations/aging-halsch-part3.pdf.

The White House, 2021. Press Release Fact Sheet: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies, April 22, 2021. Available at https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/ .

U.S. Army, Corps of Engineers, Waterborne Transportation Lines of The United States, Volume 1, 1995-2020: National Summaries (New Orleans, LA : Annual Issues), table 2, available at https://usace.contentdm.oclc.org/digital/collection/p16021coll2/id/7441.

U.S. Department of Energy and Pacific Northwest National Laboratory (2021). Ammonia as Maritime Fuel. David Hume, May 7, 2021. Available as of September 6, 2022 at https://www.energy.gov/sites/default/files/2021-08/9-nh3-maritime-fuel.pdf.

U.S. Environmental Protection Agency (EPA) – *EPA National Emissions Inventory*, report prepared for EPA by ERG (Eastern Research Group), Draft 2020 Report (May 2022).

U.S. Environmental Protection Agency (EPA) – *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, 1990-2020. EPA 430-R-22-003, April 14, 2022.

UMAS – Future Maritime Fuels in the USA: Options and their Potential Pathways, January 2022. Available at https://oceanconservancy.org/wp-content/uploads/2022/04/oc_fuels_final_report_20220117.pdf.

UMAS – The Maritime Fleet of the USA – the current status and potential for the future, January 2022.

Washington Department of Transportation, n.d. Ferry system electrification, Major project overview, Summer 2022 electrification update. Available at https://wsdot.wa.gov/construction-planning/major-projects/ferry-system-electrification.