Maritime Research and Development Opportunities

Report to Congress
December 2022

United States Department of Energy
Washington, DC 20585

Message from the Secretary

This report responds to legislative language set forth in section 3001(a) of the Consolidated Appropriations Act, 2021 (Pub. L. 116-260, Div. Z, Title III, codified at 42 U.S.C. § 17214(b)). It is an examination of the opportunities for research and development in the maritime industry, including those relevant to marine energy. The following report identifies research and development opportunities that could support the maritime industry transition to low-carbon fuels and technologies and ultimately reduce its greenhouse gas emissions and other criteria air pollutants.

This report is being provided to the following Members of Congress:

- **The Honorable Joe Manchin**
  Chair, Senate Committee on Energy and Natural Resources

- **The Honorable John Barrasso**
  Ranking Member, Senate Committee on Energy and Natural Resources

- **The Honorable Eddie Bernice Johnson**
  Chair, House Committee on Science, Space, and Technology

- **The Honorable Frank Lucas**
  Ranking Member, House Committee on Science, Space, and Technology

If you have any questions or need additional information, please contact me or Ms. Becca Ward, Deputy Assistant Secretary for Senate Affairs or Ms. Janie Thompson, Deputy Assistant Secretary for House Affairs, Office of Congressional and Intergovernmental Affairs, at (202) 586-5450.

Sincerely,

Jennifer M. Granholm

Executive Summary

The maritime industry is the domestic and international network of ships and ports that makes the global economy possible. While there are numerous factors that are rapidly changing the industry, the threat of climate change is the most pressing. The maritime industry is currently undergoing a once-in-a century energy transition to reduce its emissions of greenhouse gases (GHG), which will have profound effects on fuel markets, the environment, and global trade. This energy transition is being driven largely by pressures from regulatory bodies and market forces via customers and shareholders. The maritime industry is fortunate in some respects to have a single international regulatory body—the International Maritime Organization (IMO)—which has set industry-wide goals to cut annual GHG emissions by at least half by 2050, though some member countries, including the U.S., are pushing for more ambitious action.

The maritime energy transition will happen both at sea and onshore. New technologies and fuels must be deployed at scale, which will require substantial investments over the next several decades. Research, development, demonstration, and deployment (RDD&D) can help accelerate the adoption of these fuels and technologies by buying down risk, improving performance, and reducing costs. The United States was founded as a seafaring Nation and has a tremendous maritime legacy. To this day, it operates some of the largest ports in the world and has tens of thousands of commercial vessels both big and small. The United States has a pivotal role to play in the global maritime energy transition through regulation, standards development, rules enforcement, and supporting RDD&D.

This document outlines a variety of emissions reduction measures (ERMs) and suggested areas of research and development (R&D) that the U.S. Government might support to accelerate emissions reduction in the maritime industry. While this document is comprehensive in scope, the collection of ERMs is not exhaustive. The ERMs included represent the numerous technologies, fuels, and methods that can be used to reduce emissions in the maritime industry. As an example, marine energy derived from waves and currents could be harvested by vessels to reduce overall fuel consumption as is discussed in the R&D Needs

R&D opportunities for fuel treatments and reforming include:

- Continued analysis and modeling of novel low-cost fuel additives and their effects on fuel properties, combustion, engine thermal efficiency and fuel consumption, and emissions would be beneficial. As new alternative marine fuels, such as some biofuels, are adopted, new additives may be required to help control some certain types of GHG emissions, improve fuel lubricity, or prevent accelerated wear of engine and fuel system components, as examples.

- Analysis and identification of commercially relevant formulations, with emphasis on understanding reaction kinetics, transport limitations, and catalyst cyclability and stability. Multiscale modeling tools, spanning the molecular and reactor scales, should be developed to understand and predict the physics and chemistry of fuel reforming networks. Catalytic reforming presents opportunities for novel design concepts (e.g., 3Dprinted reactors or microreactors) for both mobile and stationary reforming applications. Technoeconomic and life cycle analyses that consider various trade-offs such as space, weight and energy, are crucial to assess and down-select viable reforming scenarios and operational strategies.

Energy Sources and Carriers – Clean Energy section of this report.

Within this report ERMs are grouped into nine sections that cover ship design and operations; energy sources and carriers; machinery energy efficiency; exhaust treatment; as well as port infrastructure and operations. Some of the research needs identified for each ERM are already being addressed by agencies such as the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy and the U.S. Maritime Administration, but some research needs remain unaddressed. The collection of R&D opportunities identified in this report are applicable to multiple Federal agencies and offices. It is imperative that these entities work together in close collaboration to help the maritime industry meet U.S. and international goals for emissions reduction.

Maritime Research and Development Opportunities

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ACT	Automated container terminal
AF	Antifouling
ANL	Argonne National Laboratory
BDR	Bubble drag reduction
CARB	California Air Resources Board
CCS	carbon capture and storage
CHE	Cargo-handling equipment
CO_2 eq	Carbon dioxide equivalent
DF	Dual fuel engine
DOE	U.S. Department of Energy
ECA	Emission control areas
EEDI	Energy Efficiency Design Index
EEXI	Efficiency Existing Ship Index
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
ERM	Emission reduction measure
FRP	Fiber reinforced polymers
GHG	Greenhouse gases
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model
HPDF	High-pressure dual fuel engine
HFO	Heavy fuel oil
HVO	hydrotreated vegetable oil
IC	Internal combustion
ICE	Internal combustion engine
IMO	International Maritime Organization
MEPC	IMO Marine Environment Protection Committee
kW	Kilowatt
kWh	Kilowatt-hours
LCA	Lifecycle Assessment
LCC	Life Cycle Cost
LH2	Liquid hydrogen
LNG	Liquefied natural gas
LPDF	Low-pressure dual fuel engine
LWR	Light water reactor
MBD	Million barrels per day
MARAD	U.S. Maritime Administration
MDO	Marine diesel oil
MGO	Marine gas oil

MW	Megawatt
MWh	Megawatt hours
NO_X	Nitrogen oxides
NREL	National Renewable Energy Laboratory
OEM	Original equipment manufacturer
ORNL	Oak Ridge National Laboratory
PM	Particulate matter
PNNL	Pacific Northwest National Laboratory
PV	Photovoltaic
PWR	Pressurized water reactor
R&D	Research and development
RD&D	Research, development, and demonstration
RDD&D	Research, development, demonstration, and deployment
RNG	Renewable natural gas
RTG	Rubber-tire gantry crane
SCL	Seattle City Light
SCR	Selective catalytic reduction
SMRs	Small modular reactors
SMR	Steam methane reforming
SNL	Sandia National Laboratory
SO_X	Sulfur oxides
SVO	Straight vegetable oil
TRL	Technology readiness level
UK	United Kingdom
UN	United Nations
USCG	U.S. Coast Guard
VFD	Variable frequency drives
VSR	Vessel speed reduction
WEC	Wave energy converter
WES	Wet exhaust scrubbers
WHR	Waste heat recovery

Acknowledgements

This work was produced with help from contributors and reviewers across the U.S. Department of Energy, its National Laboratories, and the U.S. Maritime Administration. Contributing authors include David Hume, Pacific Northwest National Laboratory (PNNL); Nicholas Thornburg, National Renewable Energy Laboratory (NREL); Heather Kelly, PNNL; Kevin Schneider, PNNL; Emily Newes, NREL; and John Kopasz, Argonne National Laboratory. Their thanks and gratitude goes out to the reviewers and editors that also contributed.

I. Legislative Language

This report responds to legislative language set forth in section 3001(a) of the Consolidated Appropriations Act, 2021 (Pub. L. 116-260, Div. Z, Title III, codified at 42 U.S.C. § 17214(b)), wherein it is stated:

‘‘(b) STUDY OF NON-POWER SECTOR APPLICATIONS FOR ADVANCED MARINE ENERGY TECHNOLOGIES.—

(1) IN GENERAL.—The Secretary, in consultation with the Secretary of Transportation and the Secretary of Commerce, shall conduct a study to examine opportunities for research and development in advanced marine energy technologies for non-power sector applications, including applications with respect to—

> *‘‘(A) the maritime transportation sector;*
> *‘‘(B) associated maritime energy infrastructure, including infrastructure that serves ports, to improve system resilience and disaster recovery; and*
> *‘‘(C) enabling scientific missions at sea and in extreme environments, including the Arctic.*

(2) REPORT.—Not later than 1 year after the date of enactment of this section, the Secretary shall submit to the Committee on Energy and Natural Resources of the Senate and the Committee on Science, Space, and Technology of the House of Representatives a report that describes the results of the study conducted under paragraph (1).”

II. Introduction

This report is a response to legislative language set forth in section 3001(a) of the Consolidated Appropriations Act, 2021 (Pub. L. 116-260, Div. Z, Title III, codified at 42 U.S.C. § 17214(b)) requesting from the U.S. Department of Energy's Water Power Technologies Office a study of non-power sector applications for advanced marine energy technologies with respect to the research and development (R&D) needs for the maritime transportation sector and its associated maritime energy infrastructure. It was drafted by the U.S. Department of Energy and its National Laboratories in consultation with the U.S. Department of Transportation's Maritime Administration. This report focuses on maritime transport, a separate report examines research opportunities for marine energy in the Arctic as requested in the legislative language.

The maritime industry is undergoing a dramatic shift due to numerous factors such as automation, digitalization, and globalization. Chief among these is the threat of climate change and an ever-growing demand from investors, customers, regulators, and communities for rapid reduction in greenhouse gases (GHG) emissions from maritime activities. This report therefore focuses on the R&D needs and opportunities for reducing the energy consumption and GHG emissions that stem from maritime activities aboard ships and within ports.

There are several decarbonization pathways available to the industry including electrification, low-carbon fuels, energy efficiency, operations optimization, and exhaust treatment. Each of these pathways has a variety of emissions reduction measures (ERM) which are unique fuels, technologies, or other methods that are known to reduce energy consumption or GHG emissions. The technological maturity of each ERM varies, some are conceptual while others are proven in commercial settings and widely used. This report provides a comprehensive overview of the most important ERMs and presents useful R&D activities for each that would improve their effectiveness or accelerate their adoption within the maritime industry. Harvesting marine energy from waves and currents is one of many ERMs that could be used to reduce GHG emissions in the maritime industry and is included in this report as requested. However, it is important to consider marine energy in the context of the broader set of solutions that the industry is actively investigating to reduce emissions.

The sections within this report provide an overview of the maritime industry, and then descriptions of more than twenty-nine ERMs grouped into ten different sections. Each ERM includes a description of the technology, its energy or emissions impacts, and its associated R&D needs. The information in this report was collected through in-depth literature review and interviews with subject matter experts in industry and the Department of Energy's National Laboratories.

III. Maritime Industry Overview

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. This section provides a brief overview of the maritime industry in terms of its size and energy impacts from global and domestic perspectives.

III.1 Maritime Industry – Size and Economic Impact

The maritime industry is the domestic and international network of ships and ports that makes the global economy possible. In 2017, marine vessels and seaports handled 80 percent of all international trade by volume and more than 70 percent by value (Hoffmann and Sirimanne 2017). Our global trade networks cannot function without ships.

The domestic maritime industry can be sized in several ways. In terms of U.S. registered vessels, there are approximately 12 million privately owned recreational boats (USCG Office of Auxiliary and Boating Safety 2019); 375,000 vessels over 5 tons , including 41,000 commercial vessels, of which 9,000 are self-propelled, like tugboats and ferries (USCG Maritime Information Exchange 2021; Transportation and Statistics 2018), and 180 are ocean-going cargo ships over 1,000 tons (Maritime Administration 2020). The U.S. military fleet owns and operates approximately 6,500 boats and ships of varying sizes from small river boats to ocean-going Destroyers. The domestic fleet are not the only vessels that operate in American waters. Despite laws that restrict foreign vessels from transporting cargo between U.S. ports (see the Merchant Marine Act of 1920, also known as the Jones Act), an estimated 10,000 foreign vessels complete approximately 50,000 port calls each year, out of an estimated 291,000 total arrivals (UNCTAD STAT 2019). These ships vary tremendously in shape, size, and power requirements (see Figure 1 and

Table 1).

Figure 1. Large container ship being escorted by smaller harbor tugboats; note the difference in vessel sizes. (Photo: EPA)

Table 1. Select vessel specifications; note the differences in dimensions and engine ratings. (Source data from MarineTraffic 2021.)

Vessel Type	**Vessel Name**	**Length** (m)	**Breadth** (m)	**Draft** (m)	**Gross Tonnage** (tons)	**Design Speed** (knots)	**Main Propulsion Engine Size** (hp)
Container	*M/V Emma Maersk*	397	56	16	100,000	25.5	108,920
LNG Tanker	*LNGRV Explorer*	291	43	12	102,777	19.2	36,024
Car-Passenger Ferry	*M/V Tacoma*	134	27	5	3,246	18	11,500
Offshore Platform Supply	*M/V SEACOR Atlas*	84	18	7	3,370	14	5,520
Harbor Tug	*M/V Delta Audrey*	30	12	6	194	14	6,712

There are approximately 360 commercial seaports in the U.S. that handle every type of cargo, from containers to cattle and everything in between. These ports are located not just in coastal cities and towns, but along inland waterways as well. The U.S. is home to some of the largest ports in the world. For example, over the last two decades the Port of Los Angeles has been the busiest container port in the Western Hemisphere (The Port of Los Angeles 2020).

The maritime industry is essential to many other industries and their supply chains. In an analysis from 2011, vessels were found to carry 53 percent of U.S. imports and 38 percent of exports, the largest share of any mode of transport (Chambers and Liu 2013). In terms of economic contributions, as of 2019 the U.S. maritime industry *directly* employs nearly 650,000 Americans across all 50 states and contributes $154 billion to the nation’s economic growth annually (Transportation Institute 2019). The Port of Los Angeles contributes nearly three million jobs (direct and indirect) nationwide (The Port of Los Angeles 2020).

III.2 Energy and Emissions

Ports and ships need energy for a variety of purposes, including cargo-handling equipment and ground transport, vessel propulsion, and electrical power generation (see Figure 2 and Figure 3). Ports meet their energy needs using locally generated power sources or the regional electric grid. Vessels most often carry their energy within them in the form of fuels such as heavy fuel oil (HFO), marine gas oil (MGO), or marine diesel oil (MDO). As an example of energy needs, the MOL Triumph is a container ship operated by Mitsui O.S.K. Lines that carries 20,000 twenty-foot containers and is fitted with a large diesel propulsion engine rated at more than 82 megawatts which can consume more than 300 tons of fuel each day. In 2012, the Port of Los Angeles collectively consumed approximately 250,000 megawatt-hours of electricity at a cost of $30 million annually (Matulka et al. 2013). For context, this is roughly equivalent to the same electrical energy consumption as 23,400 American homes (EIA 2020). Ports and vessels come in many shapes and sizes however, and smaller vessels and ports may have substantially less demand for energy.

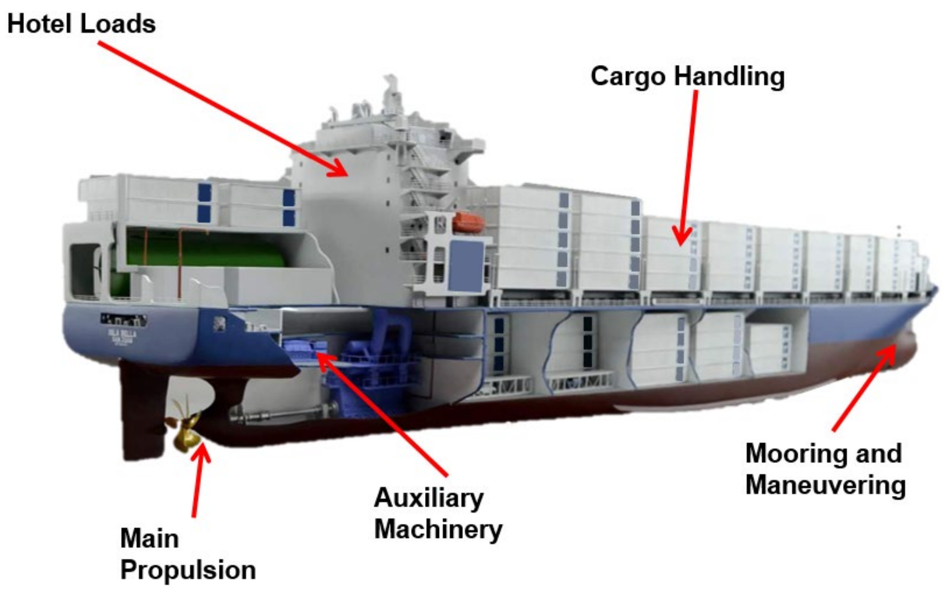

Figure 2. Common energy consumers on a ship.

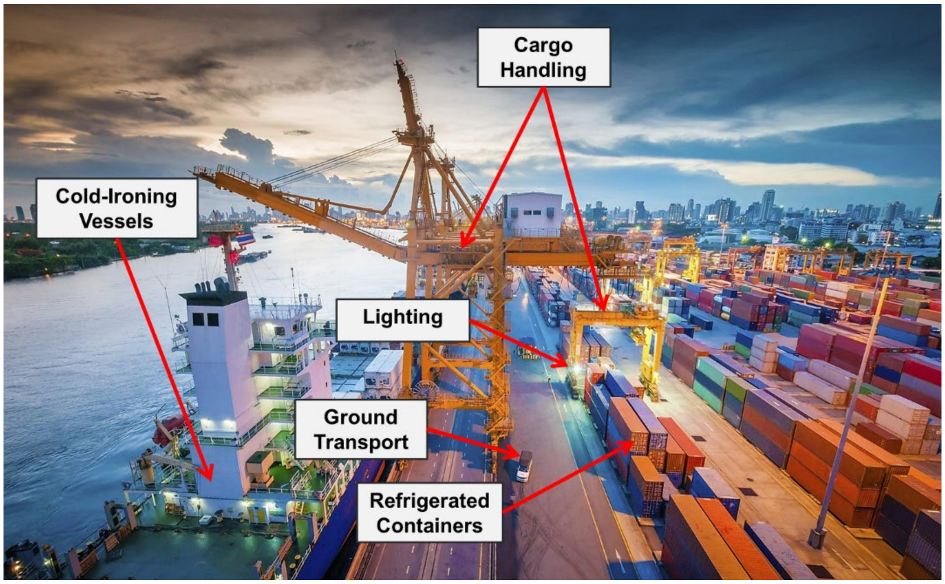

Figure 3. Common energy consumers in a port.

According to the U.S. Energy Information Administration, marine vessels account for about four percent of global oil demand, or about 4.3 million barrels per day (MBD) collectively (EIA 2019). Annually, this equates to roughly 330 million metric tons of fuel across the global fleet (Faber et al. 2020; see Figure 4). According to the EIA, in 2018 U.S. bunker fuel[1] consumption represented about 3 percent of total transportation energy use and 2 percent of total U.S. petroleum and liquid fuel use. Of the 4.3 MBD of *global* marine sector demand, about 10 percent of those sales originated at U.S. ports (EIA 2019).

[1] Bunker fuel is an expression commonly used to refer to a variety of fuels used aboard vessels

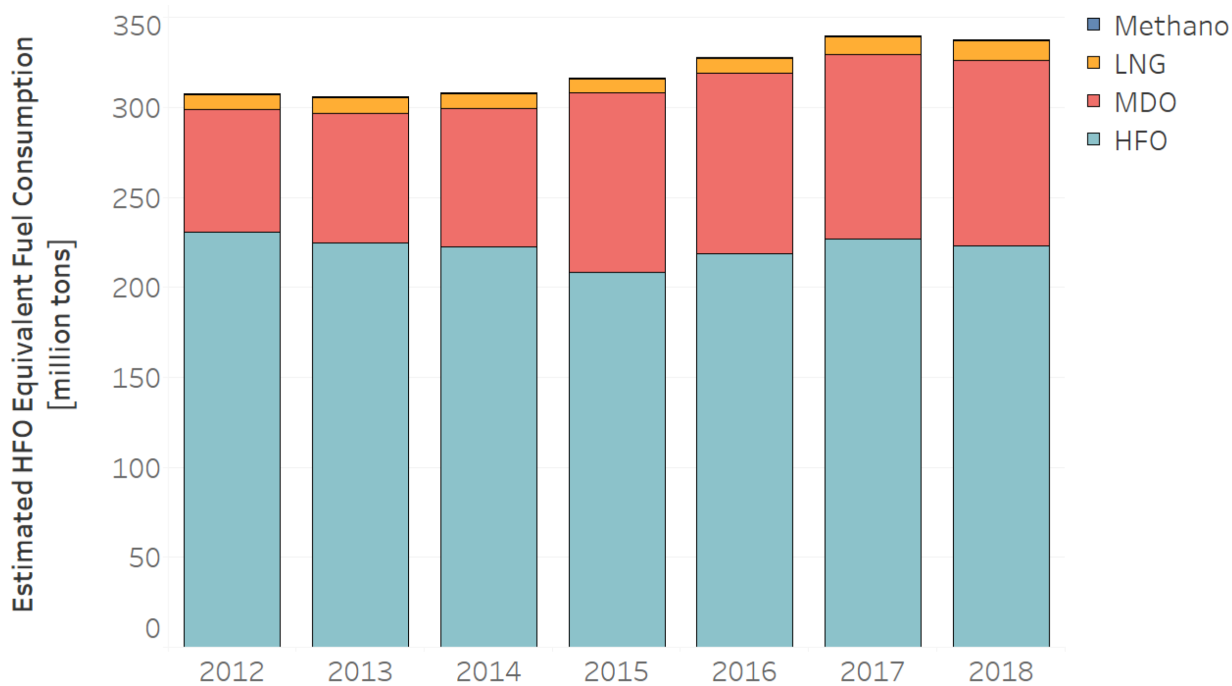

Figure 4. Estimated fuel consumption by international shipping. (Source data from Faber et al. 2020.)

The GHG emissions of all global shipping (international, domestic, and fishing) are more than 1 billion tons of carbon dioxide equivalent (CO_2eq) per year as of 2018, according to the most recent International Maritime Organization (IMO) GHG study (Faber et al. 2020). Maritime emissions have increased approximately 9.6 percent from 2012 levels and the percentage of global emissions attributed to shipping has likewise increased from 2.76 percent to 2.89 percent of total GHG emissions, indicating a trajectory in the wrong direction. To put this number into perspective, 1 billion tons is approximately three times the emissions of France in 2018. The global maritime industry is also responsible for approximately 13 percent of the emissions of global nitrogen oxides (NO_X), 12 percent of sulfur oxides (SO_X) (GEF-UNDP-IMO GloMEEP Project and IMarES 2018), and large amounts of particulate matter (PM) and black carbon each year. Additionally, since 2012 there has also been a 150 percent increase in methane emissions, which have a global warming potential much greater than CO_2 (Faber et al. 2020).

In the U.S., the U.S. Environmental Protection Agency (EPA) emission inventories for 2019 determined that gasoline, distillate fuels, and residual fuels consumed by commercial and recreational vessels accounted for 35.9 million metric tons of CO_2eq (MMT CO_2eq) emissions, or about 2.1 percent of total domestic transport emissions ((EPA 2021a) see Table 2). International marine bunker fuels consumed by cargo or passenger-carrying marine vessels are not typically included in emissions inventories but are included here for context purposes.

Table 2. U.S. CO_2 emissions from fossil fuel combustion of select transportation end-use sources (MMT CO_2eq.). Not all transport modes are displayed, military vessels excluded. Source data from EPA (2021a).

Transport Mode	1990	2005	2015	2019
Ships and Non-Recreational Boats	29.4	27.7	17.4	22.3
Recreational Boats	17.0	16.6	13.1	13.6
International Bunker Fuels	65.4	53.1	39.0	35.3
Rail	38.5	50.8	40.5	40.8
Passenger Cars	612.2	641.4	729.1	748.3
Transportation Total (Including Bunkers)	1,575.6	1,976.6	1,834.4	1,938.0

Maritime emissions are not just a global issue, they are also a local issue. In a 2016 report, the EPA estimated that about 39 million people in the U.S., or roughly 12 percent of the total population, then lived near seaports (EPA 2016). Many of the communities in which these people lived were disproportionately affected by emissions from maritime activities. Port-affected communities exhibit higher rates of poverty, higher rates of respiratory and cardiovascular disease, and poorer health outcomes than surrounding regions. The health outcomes of these community members are exacerbated by the concentration of emissions from marine vessels, cargo-handling equipment, commercial trucks, and trains that move goods to and from the ports (Delaware Valley Regional Planning Commission 2015; Gilmore 2017). Indeed, harmful pollutants from maritime activities contribute to death (James J. Corbett et al. 2007), serious respiratory illnesses (EPA 1999; Gilmore 2017), as well as water and soil acidification. A 2018 study published in *Nature* estimated that ship emissions contribute to around 400,000 premature deaths from lung cancer and cardiovascular disease and around 14 million childhood asthma cases each year globally. The study projected that these premature mortality and asthma rates could fall by 34 percent and 54 percent, respectively, with the adoption of cleaner maritime fuels (Sofiev et al. 2018).

These emissions figures and trends highlight the need for accelerated deployment of technologies, fuels, and operational measures that can reduce emissions from maritime activities. Under business-as-usual scenarios it is predicted that maritime emissions may increase to approximately 30 percent *above* 2008 levels if no action is pursued (see Figure 5; Faber et. al 2020). A rapid transition to lower-emitting fuels and technologies is required.

III.3 Energy Transition Drivers

Several high-level trends are currently reshaping the maritime industry and bringing about the maritime energy transition. These include digitalization and automation, more stringent pollution regulations, societal pressures from consumers demanding cleaner modes of transportation, and market forces from an increasingly globalized economy. Of all these important trends, climate change appears to be the most pressing issue for the industry. One industry survey conducted in 2020 by Shell, Deloitte Netherlands and Deloitte UK found that 95 percent of shipping executives interviewed worldwide viewed decarbonization as “important, or a top-three priority," and nearly 80 percent noted its importance had increased significantly over the past 18 months (Sahu 2020).

Given the inherently international nature of the maritime industry and the challenge with attributing emissions from activities at sea to a country, the United Nation's (UN's) IMO specifies how the industry should limit its GHG emissions. In April 2018, the IMO established goals, referred to as the Initial IMO GHG Strategy, to reduce the carbon intensity of international shipping by at least 40 percent by 2030 and to cut total GHG emissions by at least 50 percent by 2050 relative to a 2008 baseline (IMO MEPC 2018).

Many environmental groups, nongovernmental organizations (NGOs), and IMO members, including the U.S., believe that these non-binding goals are not ambitious enough (Degnarain 2020). Multiple scenario-modeling efforts predict that industry is not even on track to meet the IMO's initial 2050 GHG reduction goals (see Figure 5; (DNV-GL 2019b; Faber et al. 2020), and international shipping emissions are modeled to increase throughout the next several decades. To address this challenge, in April 2021, Special Presidential Envoy for Climate Change John Kerry announced that the U.S. will be working with countries at the IMO to adopt a goal of zero emissions from international shipping by 2050. The U.S. is also working through the Mission Innovation collaboration to co-lead the Zero-Emission Shipping Mission, an international public-private partnership to accelerate the deployment of zero-emission ocean-going vessels by 2030.

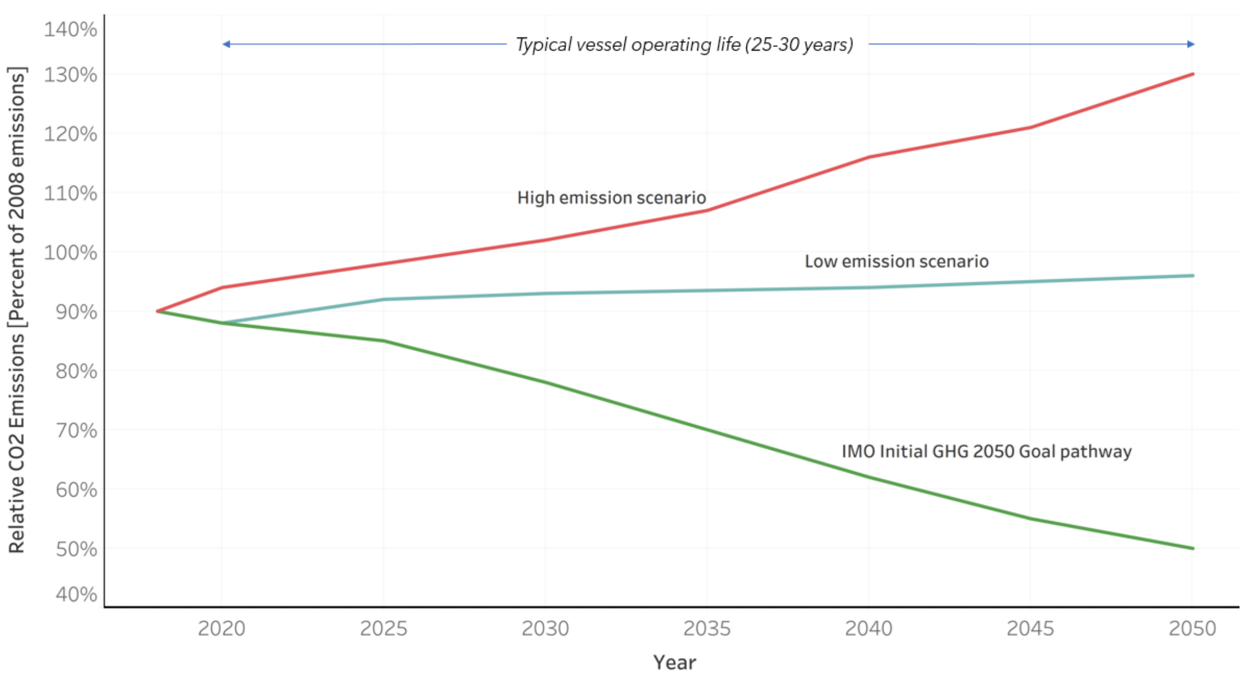

Figure 5. The IMO scenario modeling for international shipping GHG emissions from 2018–2050. Note that the IMO Initial GHG 2050 Goal pathway is provided by the authors for reference purposes as one possible pathway toward achieving at least a 50 percent emissions reduction by 2050. (Source data from (Faber et al. 2020)

Other IMO regulations and standards are influencing energy efficiency measures, designs, and operations, such as: the Energy Efficiency Design Index (EEDI), the Ship Energy Efficiency Management Plan, the IMO 2020 Sulfur Cap, the Energy Efficiency Existing Ship Index (EEXI), Nitrogen Oxides Emission Standards, Emission Control Areas, and others.

There are many technologies, fuels, and operational measures that could be used to reduce emissions; examples include the following:

- alternative fuels such as ammonia, methanol, hydrogen, and biofuels produced using sustainable feedstocks and renewable energy (Section VII);
- ship hybridization or full electrification with batteries (Section IX);
- speed optimization (Section VI); and
- cold-ironing of ships when in port (Section XIII).

At the same time, ports will also need to have clean electric grids and adopt new technologies and infrastructure (Section XII), such as the following:

- refueling infrastructure for new fuels;
- recharging infrastructure for multi-megawatt fast charging of electric vessels; and
- electric or hybrid cargo-handling equipment.

Many of these technologies and fuels are not yet available at the cost and scale needed for deep and rapid emissions reduction. Meeting international and national emissions reduction goals will require a rapid increase in investment to support technology research, development, and demonstration (RD&D) projects to lower costs, assess full lifecycle emissions, increase production volumes, and buy down risk.

The rest of this document focuses on the RD&D opportunities that could accelerate maritime emissions reductions for ships, fuels, and ports.

IV. Research and Development Opportunities for Maritime Emissions Reduction

Meeting IMO 2050 goals, U.S. commitments, as well as other local, state, and national regulations, will require the rapid deployment of emission-reduction measures (ERMs), which encompass technologies, fuels, and other operational practices. There is no one single solution that can be applied to all vessels and ports; multiple fuels and technologies will need to be stacked upon one another to achieve the emissions reductions needed (see Figure 6).

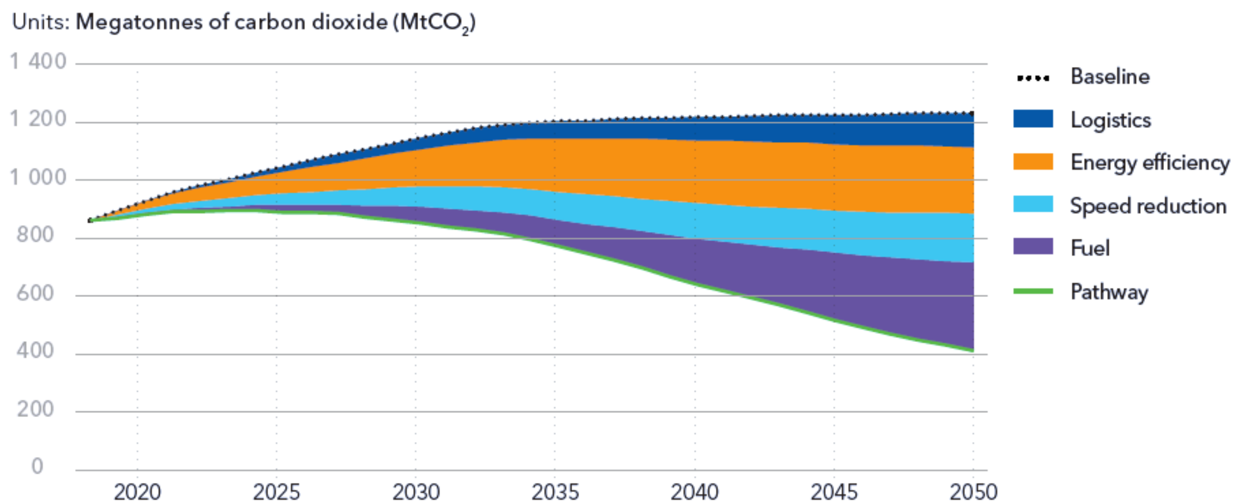

Figure 6. Shipping emissions reduction by measure 2018–2050 (DNV-GL 2019b).

Myriad methods exist to reduce emissions from ships and ports. To effectively cover the breadth and scope of the space in a methodical way, a structured approach that groups ERMs is used. A method of categorization was developed, which was informed by other frameworks used in the literature (Caughlan and Reynolds 2016; Faber et al. 2020; Bouman et al. 2017), a series of Federal interagency meetings, as well as a research and development (R&D) workshop (Washington Maritime Blue 2019), and the related ERMs are listed in Table 3.

Table 3. Emission-reduction measures in this report.

Section	Emission Reduction Measure
Vessel Hull Design	Hull Size, Shape and Design
	Lightweight Materials
	Drag Reduction Measures
Vessel Operations	Voyage and Speed Optimization
	Hull Cleaning
Energy Sources and Carriers - Liquid and Gaseous Fuels	Biofuels
	Natural Gas
	Methanol
	Ammonia
	Hydrogen and Fuel Cells
	Fuel Treatments
Energy Sources and Carriers - Renewable Energy	Wind Energy
	Solar Energy
	Wave and Current Energy
	Nuclear Energy
Energy Sources and Carriers - Hybrid and All-Electric	Batteries, Hybrid, and All-Electric
Energy Efficiency	Waste Heat Recovery
	Shipboard Power Management
	Engine Design
	Auxiliary Machinery Efficiency
Exhaust Treatment	NOx and SOx Control Measures
	Particulate Matter Control
	Onboard Carbon Capture and Sequestration
Port Infrastructure	Cargo Handling Equipment
	Microgrids and Smartgrids
	Bunkering Infrastructure
Port Operations	Automation and Capacity Optimization
	Cold Ironing
Systems Integration	Systems Engineering and Integration

This framework, while not exhaustive, allows for a more methodical consideration of the various methods and pathways for emission reduction in maritime transportation. Although these technologies are considered in isolation for this report, it must be noted that many of these technologies can be integrated to achieve even greater emissions reductions. Each ensuing section discusses the technology, its energy or emission impacts, and identifies R&D opportunities as identified in literature or through subject matter expert interviews.

V. Vessel Hull Design

Vessel hull design is a broad category that includes several different types of ERMs; included here are vessel size, hull shape and design, lightweight materials, and drag reduction measures, including air lubrication and hull coatings. Generally speaking, most of these ERMs are associated with reducing the frictional drag of the vessel, by making the ship either more slender or smoother, thereby allowing it to move through the water with less resistance, which therefore requires less power.

V.1 Hull Size, Shape, and Design

The size, shape, and the addition of other design elements (e.g., appendages) can have substantial effects on a vessel's lifecycle emissions. This section covers a wide range of ERMs or energy-saving devices for vessels, but this list should not be considered exhaustive.

Technology Description

Size and Shape

The interplay between vessel shape, size, and speed can be complex. A basic principle in vessel propulsion is that the power (and fuel) required is a function of vessel speed to the power of three. While many factors affect speed, size and shape of the vessel are two of the most important parameters. Historically, most ocean-going vessels have been designed and optimized to operate at or near their boundary speeds, which are based on the hydrodynamic elements and dimensions of the ship. The boundary speed can be defined as the speed range where the resistance coefficient goes from a nearly constant value to rapidly increasing making any further increases cost prohibitive (H. Lindstad, Sandaas, and Steen 2014; E. Lindstad and Bø 2018). The boundary speed increases with vessel length therefore enabling larger vessels to operate at lower power consumption per freight unit than shorter ones at similar speeds. Larger ships are generally more efficient on a per freight unit than smaller ones. For example, if a ship's cargo-carrying capacity is doubled, the required power and fuel use typically increases by about two thirds, so fuel consumption per freight unit is reduced (Bouman et al. 2017; H. Lindstad and Eskeland 2015).

The shape of a vessel's hull is sometimes expressed in terms of its block coefficient. This ratio relates the length and width of the vessel to a rectangular prism that encloses the hull; vessels with block coefficients closer to one resemble a shoebox while ships with block coefficients closer to 0.5 are more streamlined. Traditionally bulk vessels have been designed to maximize cargo carrying ability at the lowest building cost and not on reducing energy consumption (H. Lindstad et al. 2014). Yet by increasing the beam and/or length of the vessel and making it more slender it can reduce their block coefficients and the energy required for propulsion without affecting cargo carrying capacity (H. Lindstad et al. 2014; Stott 2012; H. Lindstad and Eskeland 2015).

Hull Design Elements and Appendages

Hull appendages are usually stationary devices that modify fluid flow direction around the vessel (Tacar et al. 2020). By some accounts, hull-mounted energy-saving devices are the cheapest options available for improving the energy efficiency of a ship (Hemanth Kumar and Vijayakumar 2020), but not all of these are easily retrofitted to existing vessels. Some design elements and appendages include the following:

- Bow and stern bulbs - When a vessel moves through the water, waves are produced that originate at the bow and stern. This wave-making resistance is more noticeable at the bow than the stern and is considered an energy loss for the propulsion system. Modifications to the bow and stern shape can reduce this wave making resistance. For example a bulbous bow is a protruding bulb at the front of the ship that has led to reductions in total resistance up to 15 percent (Gillmer and Johnson 1982) and is now commonplace on most large ships. Other newer bow designs such as the X-bow (bow raking backwards instead of forwards) or Ax-bow also reduce wave-making resistance and are starting to be utilized more widely in commercial work boats such as research ships, offshore wind service vessels, or offshore supply boats (Nordas 2012).

- Twisted rudders and rudder gates - The propeller and rudder of a ship are used to propel and maneuver a vessel, respectively. A ship's propeller creates residual swirl energy which does not typically contribute to the vessel's propulsion. This lost swirl energy can be recovered by using twisted rudder designs. Twisted rudders are asymmetric and have variable geometries that allow them to better match the flow of water coming from the ship's propeller. Such designs decrease losses and cavitation erosion damage while also providing additional thrust by recovering swirl energy, which improves the vessel's speed performance (J. H. Kim et al. 2014; Cusanelli et al. 2012). These designs have been shown to increase propulsion efficiency by 2-3 percent. A gated rudder system is a patented design that includes two asymmetric foils on either side of the propeller that can rotate their angular position in relation to the propeller to increase thrust applied to the vessel. An at-sea trial of a gated rudder on a containership led to fuel savings of 14 percent (Tacar et al. 2020).

- Stern flaps - Stern flaps are extensions of the ship's hull bottom surface created by a relatively small appendage fixed to the transom, behind the propellers. These energy saving devices modify the way water flows under the hull and create a relatively small amount of thrust which reduces drag and turbulence, thus reducing energy and emissions. Stern flaps can be easily incorporated into new builds or retrofitted onto existing ships and may lead to power reductions ranging from 4-19 percent (Hemanth Kumar and Vijayakumar 2020; Cusanelli et al. 2012).

- Advanced propeller designs - Propellers provide the thrust necessary to move a vessel. The most basic and common design is a screw propeller, which consists of a hub and number of fixed blades that extend out radially from the hub (Gillmer and Johnson

1982; Harrington 1992). There are variations on these basic propeller design such as adjustable pitch propellers, contrarotating propellers, tandem propellers, and more. Propeller selection depends on a number of parameters, including: ship type, speed, cost, materials, etc. There has been substantial research into modeling and designing efficient propellers; one such research focus is large area propellers (LAPs). LAPs are further aft and larger in size than other designs indicate potential for power reduction, modeling work has indicated potential reductions ranging from less than 1 percent (Cusanelli et al. 2012) to more than 20 percent (Knutsson and Larssson 2011; Horizon 2020 2015).

- Wave foils (see discussion in Section VIII.3, Marine Energy).

Energy Impacts

Many of the hull design ERM discussed here have moderate energy savings, yet some can be more substantial. It is important to note that even small fuel cost savings, say $300K per ship or approximately 3 percent, represent an immense cost savings on the order of hundreds of millions of dollars when applied to a fleet of dozens of vessels for their entire operating life, which may be 30 years or more (Cusanelli et al. 2012). In addition to the fuel savings potential noted above for different energy saving devices, Bouman et al. 2017 noted that the potential CO_2 reduction from vessel size measures could lead to reductions ranging from 4–83 percent, hull shape 2–30 percent, and appendages 2–15 percent.

R&D Needs

Some R&D opportunities relating to hull size, shape, and design include:

- Operational data from full-scale, at-sea demonstrations of these technologies are still lacking, which creates uncertainty about their performance across different vessel types. Operational data for some of the newer bow designs is often proprietary and the designs may be protected as Intellectual Property, which makes it difficult to assess their energy performance improvement and limits their adoption. Stern flaps have been used in high-speed displacement hulls (such as U.S. Navy surface combatants), but their applicability to slower-moving commercial vessels is worth investigating. Moreover, the design and modeling process of these devices involves complex fluid dynamics, which may benefit from recent advances in computing power and simulations.
- Modeling the hydrodynamic forces on rudders and propellers is complex (Gillmer and Johnson 1982) and an ongoing area of research. Advanced fluid hydrodynamic modeling will likely lead to new insights in rudder and propeller designs that will improve propulsion efficiency. Twisted rudders are relatively new design elements that may have a large impact on future vessel designs.

V.2 Lightweight Materials

Technology Description

Reducing the weight on a vessel helps to reduce its drag and increase its cargo-carrying capacity, all else being equal. Low-carbon steel is the standard material for building most commercial vessels, and while it is relatively cheap and strong, it is heavy, prone to corrosion, and easily conducts heat. Other materials such as aluminum, titanium, reinforced concrete, and fiberglass-reinforced polymers (FRPs) have also been used to varying degrees depending on the vessel type, application, cost, and operating environment. Lighter structural materials may allow for capacity increase and reduced emissions without affecting stability (Job 2015).

Using composites for recreational boats and leisure craft is common, but rare in larger commercial vessels, sometimes even prohibited for certain materials (Job 2015). This is due in part to IMO Safety of Life at Sea (SOLAS) requirements that specify structural materials to be noncombustible (Equipment, Construction, and Materials: Specifications and Approval, 46 C.F.R. § 164 2022). FRP and other similar composite materials have low fire-resistance due to the polymers used in their construction, which can prevent their use in commercial vessels that have high risk of fires (Hertzberg 2009).

Energy Impacts

The FIBRESHIP project claims that "some of the benefits of using composite materials can be the reduction of up to 30 percent in the weight of ships, a decrease in fuel consumption of between 10 percent and 15 percent, an increase in recycling ratio from the current 34 percent for steel structures to 75 percent, a substantial reduction of GHGs, less noise pollution and an increase in cargo capacity by roughly 12 percent" (University of Limerick 2017; CORDIS 2020). Some researchers note that the payback period for using FRP composite materials may be shorter than other energy-saving measures because the structural weight savings allow for an increase in cargo payload capacity (Job 2015). Bouman et al. 2017 notes that using lightweight materials for vessel construction could result in fuel savings of approximately 22 percent when compared to vessels using more traditional materials like steel.

R&D Needs

Some R&D opportunities relating to lightweight materials include:

- Overcoming the technical challenges of FRP or other composite materials that can meet the marine structural requirements specified by international and national regulatory bodies (e.g., IMO SOLAS and the U.S. Coast Guard [USCG] respectively), particularly in regard to fire safety. The findings of the European Commission-funded FIBRESHIP project are a good example of how this challenge might be overcome, yet further research is needed (CORDIS 2020) to help inform IMO regulatory changes.

V.3 Drag Reduction Measures

Technology Description

Approximately 40 to 85 percent of a ship's propulsive power is used to overcome frictional drag (ABS 2019; Mäkiharju et al. 2012; Jang et al. 2014), therefore measures that reduce a ship's frictional drag can have a significant effect on its operating cost and emissions. Drag reduction measures can be grouped into passive and active measures. Passive measures are methods such as coatings that smooth the hull or reduce fouling from marine organisms. Active measures, such as air lubrication, reduce the density or viscosity of the water near the hull (Mäkiharju et al. 2012).

Hull Coatings

Inevitably, any structure placed in the marine environment accumulates marine species that have the tendency to permanently attach themselves and then grow and multiply on the structure's surface. This is referred to as biofouling. Biofouling affects ships and over time can add a significant energy expense to the vessel due to increased weight and drag, which must be overcome to maintain the vessel's desired speed. For example, an unprotected ship's hull can accumulate up to 150 kg of fouling per square meter of underwater hull area in less than 6 months at sea (Buskens et al. 2013). The added resistance from biofouling varies based on a number of factors. Munk et al. 2009 proposed a range from 6 percent to 80 percent in the worst cases; on average it can be estimated to be approximately 30 percent for a typical ocean-going vessel.

Figure 7. Significant biofouling on a ship's hull. (Photo: Office of Naval Research, Duffie 2016)

Mitigating the effects of biofouling through design is accomplished through hull antifouling (AF) coatings and periodic cleaning.[2] There are two main types of AF coatings (Michelis and Gougoulidis 2015): biocidal AF coatings and non-biocidal AF coatings. There has been a trend away from the biocidal coatings due to their negative impact on the environment and, increasingly, their use is becoming banned or prohibited in certain regions. Much attention has been shifted toward non-biocidal foul-release coatings, which typically rely on vessels moving

[2] Periodic hull cleaning as an emission reduction measure is discussed in the Vessel Operations section.

at certain speeds to function properly. Coating longevity is of critical importance to prevent biofouling for as long as possible. Commercial vessel hulls are cleaned infrequently, sometimes going up to 60 months or more between cleanings (Munk et al. 2009).

Air Lubrication

Air lubrication reduces the frictional drag of a ship by pumping air beneath its hull to either minimize the amount of hull in direct contact with water, or by changing the average density in the boundary layer along the hull. The continuous injection of pressurized air along the ship's outer hull does require energy input to compress the air, but so long as the energy required to produce and deliver this air is less than the energy saved through reduced drag, this ERM can lead to a net reduction in fuel use and emissions. There are three main types of air lubrication: bubble drag reduction, air layer drag reduction, and partial cavity drag reduction.

Energy Impacts

Reducing drag through air lubrication or antifouling coatings allows ships to operate at higher efficiencies, thus reducing fuel consumption and GHG emissions. For example, the environmental performance and relative cost of a 300,000 deadweight ton very large crude carrier using antifouling coating to an uncoated vessel resulted in overall fuel savings of 39,420 metric tons over a period of 15 years which equates to approximately $28.5 million US dollars (at a price of $723 per metric ton of fuel) (Buskens et al. 2013). The overall reduction in CO_2 emissions was 125,000 metric tons over the same time period. In general, ocean-going cargo vessels may consume approximately 100 tons of fuel per day, and avoiding a ten percent efficiency penalty translates to at least 10 tons per day in savings or 31.9 tons of avoided CO_2 emissions (Munk et al. 2009). Bouman et al. (2017) notes that the potential CO_2 reduction from vessel hull coatings range from one to ten percent.

The net reduction in energy consumption due to air lubrication depends on the method and numerous other ship-specific factors. However, at-sea trials and modeling tests have shown reported savings of 4 to 22 percent (Mäkiharju et al. 2012; ABS 2019; Jang et al. 2014).

R&D Needs

Some R&D opportunities relating to drag reduction measures include:

- Improving the economics and durability of foul-release coatings is a persistent goal. For example, a recent survey noted that hull coatings are one of the most widely used ERMs, yet financial considerations continue to be among the largest barriers to their widespread adoption (Dewan et al. 2018). There is an ongoing need to constantly improve the performance of antifouling coatings and mitigate their environmental impacts, particularly in light of more stringent environmental protection legislation. More durable coatings are highly desirable. Fouling often starts with development of a slime layer; researchers have noted that the development of fouling release coatings with improved resistance to slime is the focus of academic and industrial research (Michelis and Gougoulidis 2015).
- Progress in the development of AF coatings based on natural biocides is slow. Some of the difficulties faced by researchers regarding the incorporation of natural AF compounds into coatings is the identification of suitable naturally produced materials

that offer a wide-ranging protection against many organisms and provide a practical operational life, while also being easily integrated into a coating (Michelis and Gougoulidis 2015).

- Researching the suitability of different air lubrication technologies for more complex hull forms and various ship types and sizes. The mechanisms behind bubble drag reduction (BDR) are not completely understood or agreed upon at a theoretical level (ABS 2019). Moreover, maintaining stable air layers on variable geometry hull shapes while vessels are in motion and encountering waves (heaving, yawing, pitching, etc.) is an area of interest.

VI. Vessel Operations

This section covers operational measures or behavior changes that ship owners or operators can employ to reduce energy impacts and GHG emissions. Topics included are voyage and speed optimization as well as hull cleaning.

VI.1 Voyage and Speed Optimization

Technology Description

Voyage planning involves plotting the intended course of the vessel. It has evolved over the years from a simple exercise done on paper charts to find the shortest path between two points to a more thorough risk management process that is commonly used today (Caughlan and Reynolds 2016). When planning a voyage, vessel operators need to take into account numerous factors, including weather (prevailing winds, waves, and ocean surface currents), cargo, draft and trim, time available, fuel costs, bunkering availability, and more (Lee et al. 2018). From an emissions standpoint, the ultimate objective of the optimization problem is to minimize fuel consumption for a vessel on a predefined route, while maximizing the service level, or duration of transportation and/or meeting time windows. These two objectives are at odds with one another, which creates a multi-objective optimization problem that requires trade-offs between operational costs and service levels. Among the multiple optimization strategies, two of the most prevalent are speed optimization and weather routing. Other optimization strategies include trim optimization, capacity optimization, and just-in-time arrival.

Route optimization is usually most concerned with weather and speed along a ship's route because these two variables can significantly affect arrival times in port and fuel costs. Weather routing involves adjusting the intended to course to avoid bad weather or to take advantage of favorable conditions, which may reduce fuel consumption. It requires reliable weather data and forecasts throughout the voyage of the ship. Access to these datasets is becoming increasingly more prevalent with the advent of low-cost sensors and wireless communications. Weather-routing algorithms take into account local or regional weather data, as well as historical trends in surface currents and waves, to determine a voyage path that is most optimal and to avoid bad weather, which can slow down a vessel and create dangerous operating conditions.

Speed optimization is concerned with adjusting vessel speed throughout the voyage to maintain desired service levels while maximizing profits and minimizing emissions (see Figure 8). The power required to propel a vessel is roughly proportional to the cube of the speed; this means that when a ship reduces its speed it can lead to nonlinear reductions in fuel consumption (see Figure 9). Slow steaming, or deliberately operating vessels at reduced speeds, is a common practice used today by vessel operators to reduce fuel consumption and save costs, but the practice does tend to fluctuate with freight rates and fuel costs; i.e., higher freight rates and lower fuel costs tend to encourage faster speeds (L. H. Liang 2014). Speed reduction can also be required or incentivized by ports by using established zones within which vessels must operate at or below a defined speed limit; for instance, the ports of Los Angeles, San Diego, and New York/New Jersey have established speed-reduction zones with limits between 10 and 15 knots (EPA 2021c). While speed reduction can reduce fuel consumption (and therefore GHG emissions) most diesel engines are less efficient when operating below their rated loads.

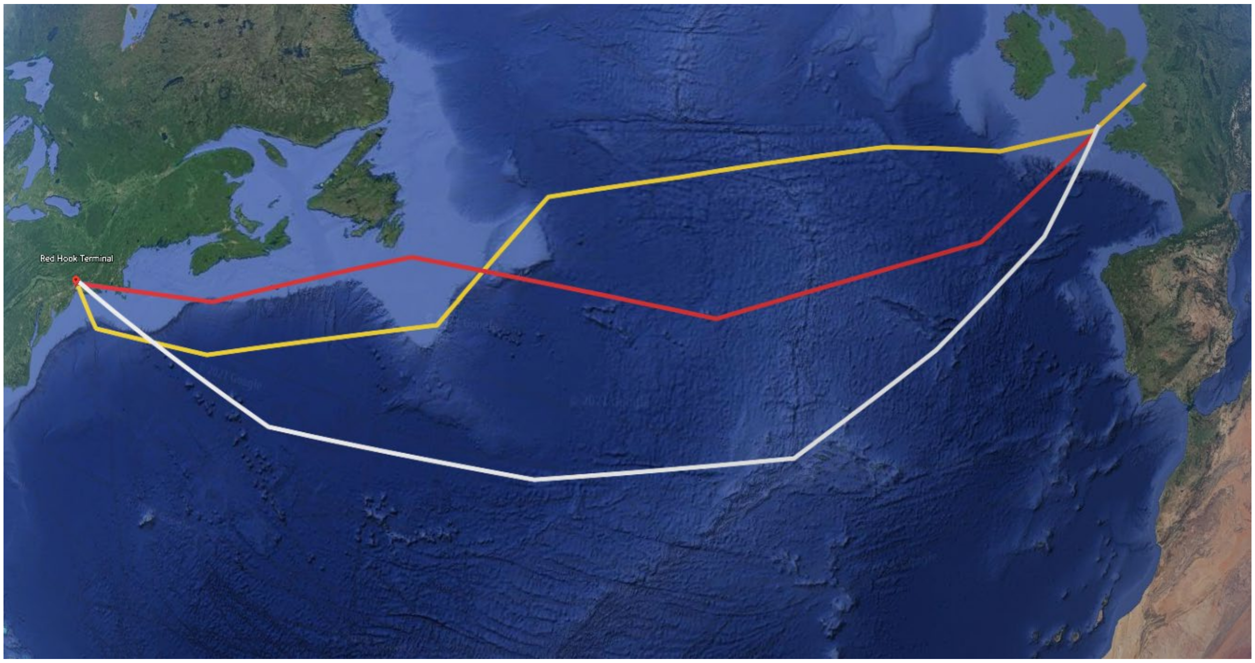

Figure 8. Example of different route options between New York and Northern Europe.

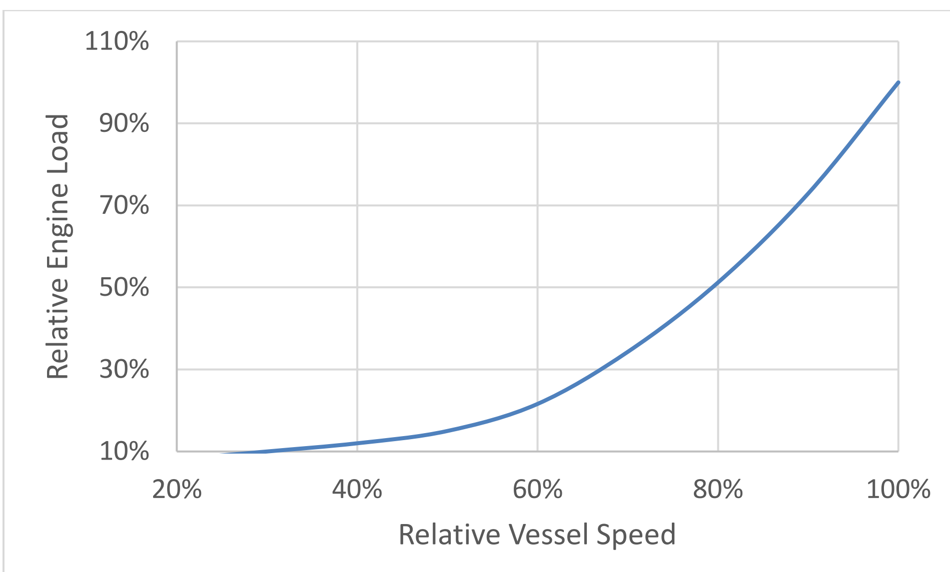

Figure 9. Nominal power curve for a typical vessel. Note the relationship between speed and power is nonlinear: the engine load is roughly proportional to the cube of vessel speed.

Energy Impacts

Voyage optimization has been shown to lead to reductions in fuel consumption between 3 and 10 percent, typically (Armstrong 2013; Hongchu Yu et al. 2021; Lu et al. 2015; Bouman et al. 2017). In a thorough literature review performed by Bouman et al. (2017), the researchers found that speed optimization showed a likely potential CO_2 reduction between 12 and 37 percent with a median value of 19 percent, but note that there appears to be low agreement among the higher values claimed in the literature. Vessel speed reduction (VSR) zones can also lead to substantial emissions reductions. The VSR program operated by the Port of Long Beach was estimated to reduce NO_x emissions by 747 tons and CO_2eq emissions by 28,600 tons in 2008, based on 2,477 vessel entrances per year (OECD International Transport Forum 2018).

R&D Needs

Some R&D opportunities relating to voyage and speed optimization include:

- There is a persistent need for faster and more accurate algorithms that are able to solve multi-objective optimization problems for speed and voyage optimization across multiple ship types operating on either liner (pre-determined route) or tramp (undetermined route) schedules. This would be beneficial for future autonomous or semi-autonomous ships as well.
- Weather data can be used with big data analytic techniques to help estimate the impact of weather on vessel fuel consumption for various times of the year and different routes. However, most of these archived data are not easily used due to their inconsistent format, volume, and data structure. Efforts to blend these data into more easily digestible formats for algorithms would be beneficial (Lee et al. 2018). In addition, increasing the availability of this data on both temporal and spatial scales through more widespread deployment of ocean sensors would be beneficial.
- Optimization models cannot take into account every possible variable and therefore their outputs often differ from reality. There is a clear need for enhancing the performance verification and evaluation through additional real-world experiments with multiple transoceanic routes to help improve the accuracy of these models (Yu et al. 2021).
- Ports in recent years have moved to establish VSR zones. Determining the impact of these zones requires the compilation of data about the number and types of vessels that visit each port, often using ship-tracking satellite data such as those generated using automatic identification system (AIS) transceivers. Developing specialized tools for ports to easily determine the emissions impacts of these zones would be beneficial (EPA 2021c; OECD International Transport Forum 2018).

VI.2 Hull Cleaning

Technology Description

Inevitably, any material placed in the marine environment will attract and accumulate marine organisms (see the discussion in Section V.1 on Vessel Hull Design). The accumulation of marine organisms on the wetted area of a ship's hull creates additional drag, which increases the power required to maintain a ship's operating speed (see Figure 10), thereby increasing fuel consumption and emissions. While there are coatings that can be used to slow the growth of marine organisms on the ship's hull, regular cleaning is still required. Typically, every four to five years ships are taken out of service to perform periodic maintenance that cannot be done while the vessel is in normal operation. Such maintenance involves bringing the ship out of the water, known as dry-docking, to access those parts of the ship that are normally under water. Part of this regular maintenance includes cleaning the hull and propeller to remove rust and biological growth that affect the structural integrity and hydrodynamic efficiency, respectively, of the vessel. The emissions reduction opportunity for improving the cleaning process lies in monitoring and scheduling hull cleanings based on observed vessel performance, as well as using robotic systems to perform in-water cleanings to maintain peak efficiency.

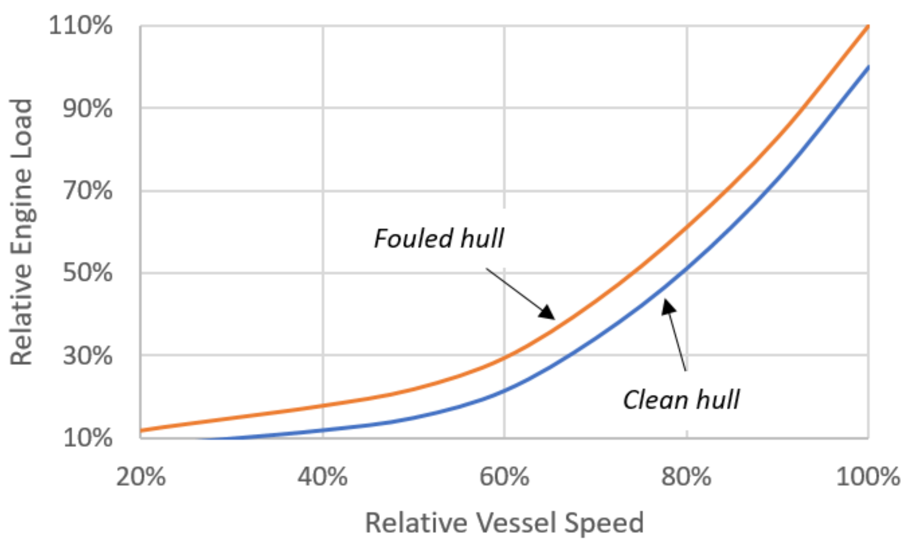

Figure 10. Nominal power curve demonstrating the efficiency penalty due to biofouling. Biofouling leads to increased engine loads to achieve the same speeds as a clean hull.

Energy Impacts

As noted in the Drag Reduction Measures discussion, reducing drag allows ships to operate at higher efficiencies, thus reducing fuel consumption and GHG emissions. Likewise, hull and propeller cleaning can have significant effects on the energy efficiency of ships. Left untreated, a vessel's overall efficiency is likely to experience up to 30 percent decrease over time (Munk et al. 2009). Regular cleanings can prevent this; some naval vessels have exhibited a 15 percent decrease in fuel consumption derived from hull and propeller cleanings, for example (Munk et al. 2009). On average across the world fleet, deterioration in hull and propeller performance due to biofouling is estimated to account for nine to 12 percent of current world fleet GHG emissions (Clean Shipping Coalition 2011). For context, a 30 percent increase in resistance caused by the moderate biological contamination of a 100,000 deadweight ton tanker hull will increase the ship's fuel consumption by up to 12 tons/day (Song and Cui 2020).

R&D Needs

Some R&D opportunities relating to hull cleaning include:

- Tools and methods, such as leveraging digital twins, to better predict the time-dependent penalties of hull and propeller fouling with respect to various physical and environmental factors need to be developed (Song et al. 2020; Coraddu et al. 2019). Such condition-based maintenance policies can lead to more efficient operations.
- The performance of robots that can be used for hull cleaning and inspections, both while in port and under way, need to be advanced. It has also been noted that developing robotic systems that use fleets of robots to service or inspect a hull is an area of interest, which requires additional research in autonomy and cooperative work (Iborra et al. 2010).

VII. Energy Sources and Carriers – Liquid and Gaseous Fuels

Since the 1960s, HFO, also known as residual fuel oil, has been the primary fuel for the very large diesel engines and marine boilers used in the commercial maritime industry, because it is energy dense, cheap, and widely available. In 2018, it accounted for 79 percent of fuel consumption for international shipping (Faber et al. 2020). Unfortunately, the combustion of HFO and other marine fossil fuels emits several pollutants that are harmful to human health and the environment, such as CO_2, SO_X, NO_X, black carbon, PM, and others. Total emissions from the use of these fossil fuels are sizable and the maritime industry is currently investigating alternative fuels, or those not widely used, that have low or zero emissions.

Alternative fuels of interest to the maritime industry include certain types of biofuels, ammonia, hydrogen, liquefied natural gas (LNG), and methanol. Each alternative fuel has relative strengths and weaknesses compared to HFO, including energy density, which can affect the amount of cargo on a vessel as well as the distance traveled between refuelings (see Figure 11). Note that some of these fuels have multiple production pathways (Figure 12), each of which produces different emissions, as shown in Figure 13.

When considering emissions from alternative fuels, it is important to consider their full lifecycle emissions from production to transportation to storage to consumption, often referred to as well-to-wake. This allows for a fairer comparison across fuels. Some fuel types may appear to offer emissions reductions when considering their combustion emissions only, but when production is also considered, these fuel types are worse than HFO or MDO. As an example, methanol synthesized from natural gas has greater lifecycle GHG emissions than MDO, but e-methanol produced using waste CO_2 and electrolysis-produced hydrogen is nearly zero. There are several lifecycle assessment (LCA) tools available, such as the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) Model developed by Argonne National Laboratory. For each of the fuels presented, additional research investigating each of the production pathways and the associated well-to-wake emissions is needed to help inform the LCA models.

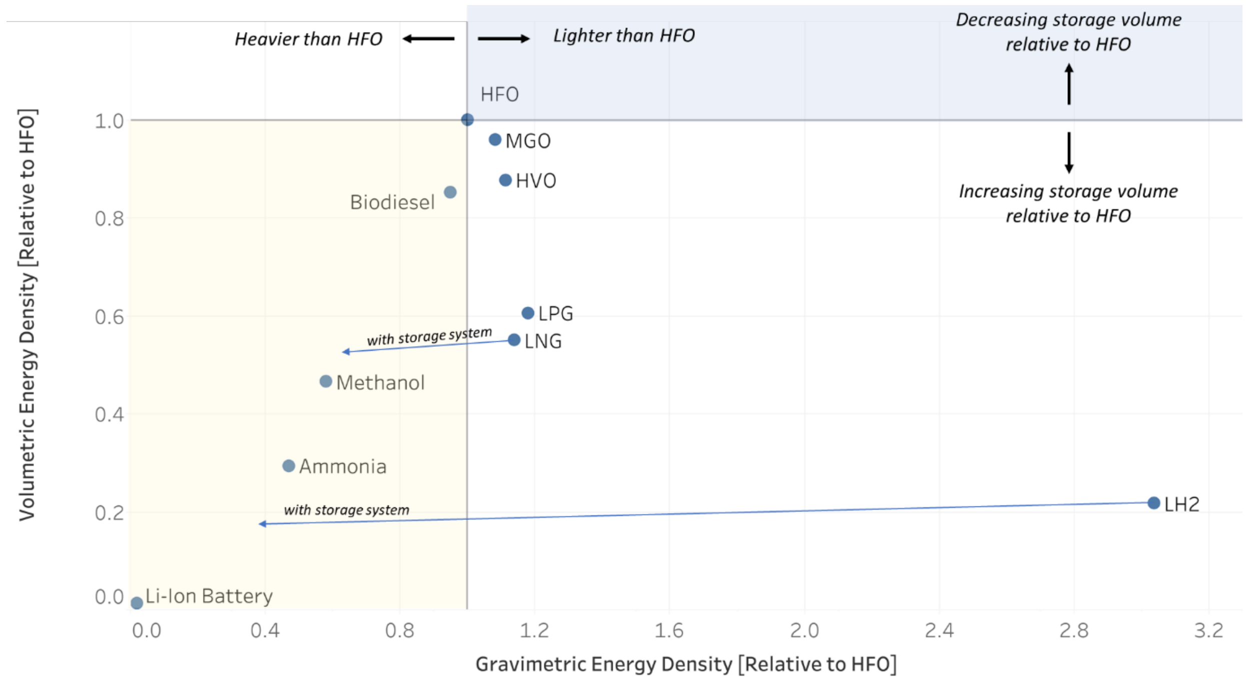

Figure 11. Volumetric vs. gravimetric energy density of select marine fuels. LH2 represents liquid hydrogen, LPG represents liquid petroleum gas, and Li-Ion represents lithium-ion battery (Foretich et al. 2021; DNV-GL 2019b).

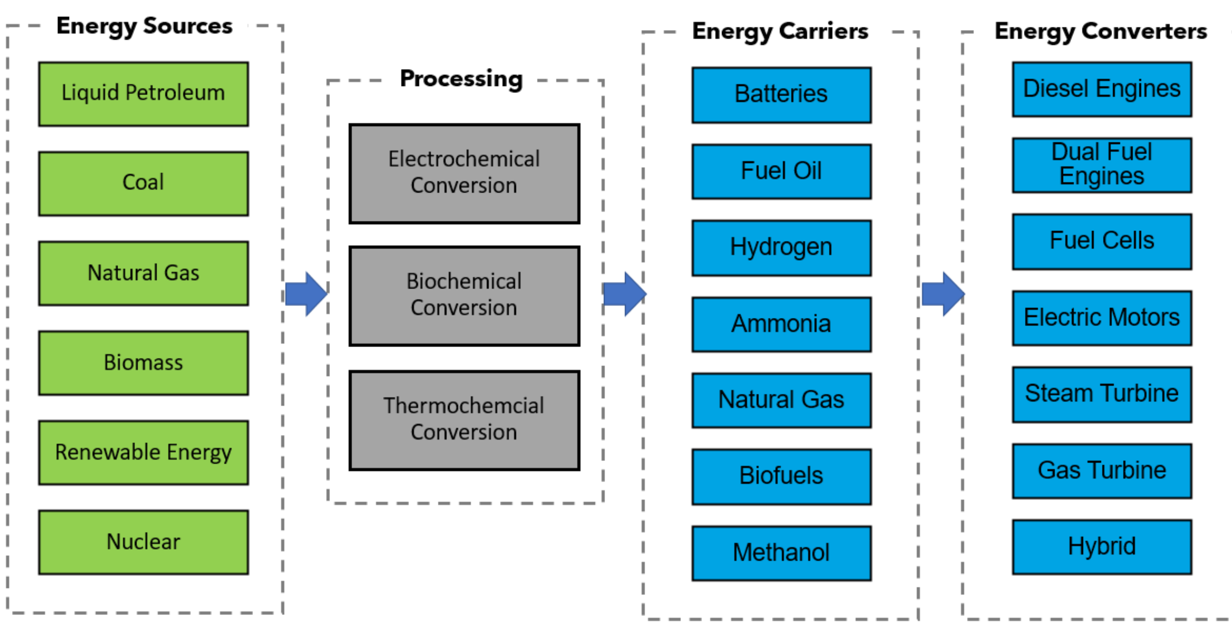

Figure 12. Simplified energy pathways for vessels. Note the diversity of the low-carbon options available. Figure created by the report authors.

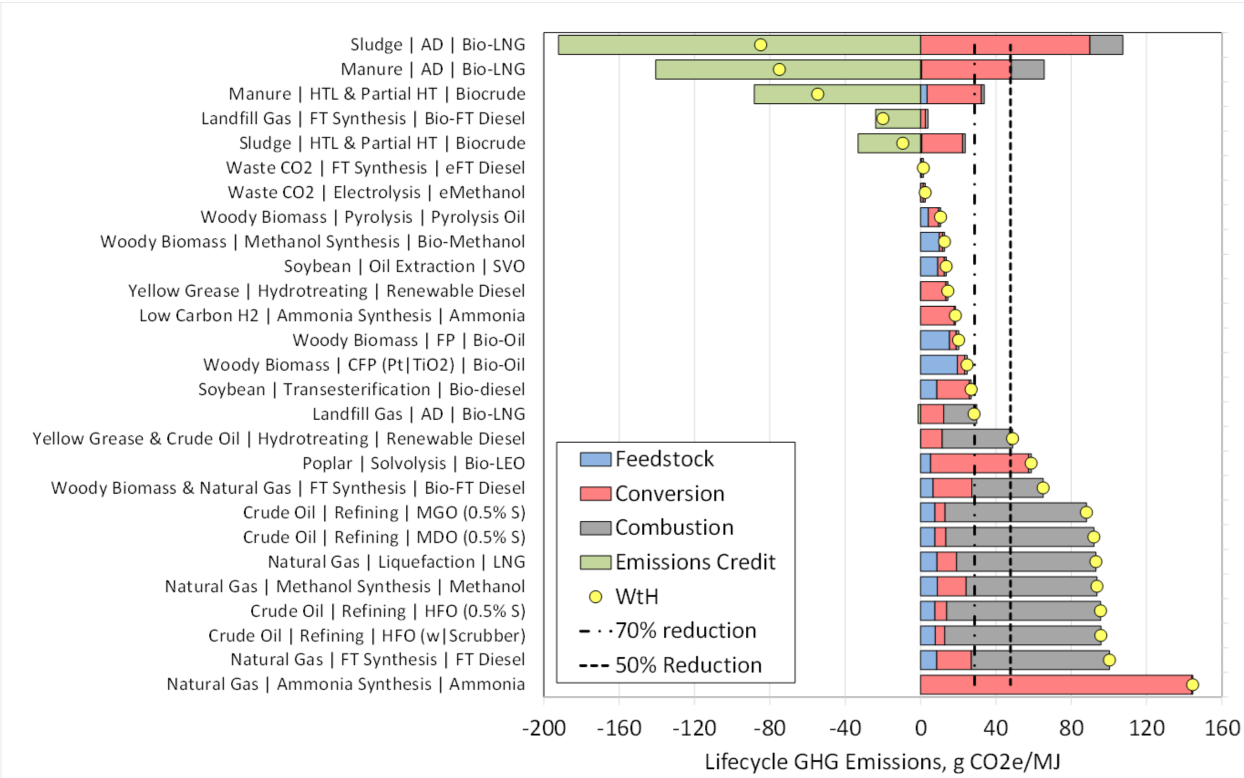

Figure 13. Lifecycle GHG emissions from select marine fuels, production methods, and feedstocks. Note that a single type of fuel can have very different lifecycle emissions depending on how it is produced, and the feedstocks used. Source data from Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) Model developed by Argonne National Lab. CFP: Catalytic Fast Pyrolysis; HT: Hydrotreating; HTL: Hydrothermal Liquefaction; FT: Fischer-Tropsch; S: Sulfur; LEO: Lignin Ethanol Oil; AD: Anaerobic Digestion; SVO: Straight Vegetable Oil; WtH: Well-to-hull

VII.1 Biofuels

Technology Description

Biofuels are any number of liquid or gaseous fuels derived from virgin or waste biomass (plants, algae, municipal solid waste, etc.). They can be produced from a wide range of cheap biomass sources and thus their specific properties will vary with the feedstock and production method. When blended with HFO, biofuels offer potential synergistic benefits by reducing sulfur content, improving overall engine lubricity, and lower emission profiles, especially for PM and SO_X (Kass et al. 2018). Depending on the biomass feedstock and processing conditions, biofuels can be low in sulfur and nitrogen while also providing a low carbon intensity. In fact, some biofuels exhibit net-zero emissions, because the GHG emissions from combustion are offset by carbon uptake during biomass growth (Foretich et al. 2021). However just because a biofuel is produced from a plant-based feedstock, it is not safe to assume that the fuel is always carbon-neutral. Some types of biofuels are considered drop-in replacements of petroleum-based fuels for most engines, which makes them appealing candidate fuels.

Biofuels can be grouped into two categories: oxygenated biofuels and hydrocarbon biofuels. Oxygenated biofuels include straight vegetable oils (SVOs), biodiesel, fast-pyrolysis bio-oil, and hydrothermal liquefaction (HTL) biocrude. Hydrocarbon biofuels include renewable diesel, hydrotreated vegetable oils (HVOs), Fischer-Tropsch (F-T) diesel, fully upgraded (deoxygenated) bio-oil, and biocrude (Kass et al. 2018). Biofuels can also be characterized as first-, second-, and third-generation based on the technology and raw materials used to produce them (Tyrovola et al. 2017). In first-generation fuels the carbon source comes from a sugar, lipid, or starch extracted from a plant; second-generation fuels are produced biochemically or thermochemically using non-food crops (grass, trees, or other lignocellulosic feedstocks) or waste products (used cooking oil); third-generation fuels are produced from algae biomass. For maritime applications, SVO, bio-oil, biodiesel, HVO, and biocrude show promise as replacements for traditional petroleum-based fuels because of their similar volumetric energy densities, reduced sulfur and total lifecycle emissions, and potential for economic competitiveness (Foretich et al. 2021; Kass et al. 2018; DNV-GL 2021). In 2019, Maersk fueled a large ocean-going containership for 25,000 nautical miles on biofuel blends alone, using up to 20 percent sustainable second-generation biofuels (Maersk 2019).

Energy Impacts

According to Bouman et al. (2017), biofuels could reduce vessel CO_2 emissions by between 25 and 84 percent, one of the highest of the ERMs considered by the researchers. However, the true emissions impact depends on two main factors: the feedstock and how the fuel is produced, as well as how the emissions are calculated (e.g., land-use changes, credits). Research performed by Foretich et al. (2021), indicates that all the biofuel pathways they examined resulted in at least a 50 percent reduction in GHG emissions relative to HFO. See Figure 13, which shows lifecycle GHG emissions for some biofuels as determined with the GREET model.

R&D Needs

Some R&D opportunities relating to biofuels include:

- 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, for example (Kass et al. 2018). Biofuels, excluding 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 (Foretich et al. 2021).
- Minimally processed biofuels, such as bio-oil and biocrudes, hold promise as maritime fuels but they have not been appropriately evaluated for maritime applications. Future research should investigate the technical, economic, and environmental potential of catalytic fast pyrolysis and hydrothermal liquefaction biofuels for maritime applications (Foretich et al. 2021).
- Some biofuels such as HVOs and bio-oils can be produced at existing oil refineries, using hydrotreating capital, and can be combusted using conventional engines;

however, construction of new production facilities or additional unit operations and organization of feedstock collection systems are required for production scale-up (DNV-GL 2019b).

- Fueling infrastructure relies not only on physical capital but also on the availability of standards for fuel quality and production. Fuel standards ensure that fuels are safe for purchase, and fuels that lack standardization may vary in quality and thus be less attractive to purchasers. Of particular importance to biofuels such as SVO, biocrude, and bio-oil, is a lack of standardization that may present significant barriers to their adoption. Standardization can also help reduce potential issues with engine manufacturers and their reluctance to allow warranties on fuels other than those recommended (Foretich et al. 2021).

VII.2 Methanol

Technology Description

Methanol (MeOH, or CH_3OH), also known as methyl alcohol or wood alcohol, is a low flash point fuel that is very low in sulfur content, but toxic, corrosive, and bears a pungent odor. It is a colorless liquid at ambient conditions, which makes storage and transportation easier than for LNG, hydrogen, or ammonia (Ammar 2019), but it does have a lower energy density when compared to traditional fossil fuels, which equates to larger fuel tanks on a ship to store the same quantity of energy (see Figure 11). Given this energy density, a methanol fuel storage tank on a ship will need to be roughly twice the size of a diesel fuel storage tank for the same energy content. Methanol has a relatively low cetane number (an indicator for the quality of combustion), which can create problems with ignition. One strategy to help improve the ignition of methanol is to use a small amount of diesel, biodiesel, or similar fuel as a pilot fuel within the engine combustion chamber.

Methanol can be produced through biochemical and thermochemical conversion pathways (Gautam et al. 2020), 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, or natural gas. The resultant syngas can then be used in catalyzed reactions to produce methanol. When biomass (wood, municipal solid waste, etc.) is used as a feedstock to produce biogas, the resultant product is commonly referred to as bio-methanol. Currently, the majority of the globally produced methanol is produced from reforming syngas obtained from natural gas (Gautam et al. 2020) or in the case of China, coal (Andersson and Salazar 2015). If the hydrogen is sourced from electrolysis (a very energy-intensive process) 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.

Most modern marine engines can reportedly can be adapted to run on methanol in dual fuel mode with some modifications, such as higher fuel injection pressure and enhanced leak prevention in fuel piping (i.e., doubled-wall piping) (Andersson and Salazar 2015). Major engine manufacturers such as Wartsila and MAN have been working on designing these engines for the last decade (Andersson and Salazar 2015; ABS 2021) and a number of demonstrations have been carried out since 2015, most notably the Stena Germanica ferry, which was the world's first ship to use methanol as a fuel in a Wartsila dual fuel engine. As of this writing, there are approximately a dozen methanol-fueled ships in operation. In July 2021, Maersk announced that they would be purchasing the world's first container ship using e-methanol as a fuel in a low-speed, dual fuel engine, manufactured by MAN (MAN Energy Solutions 2021). For this single vessel, Maersk will source approximately 10,000 tons per year of e-methanol from the companies REintegrate and European Energy (Maersk 2021). In August 2021, Maersk announced that they will buy eight additional methanol-fueled ships. In 2018, methanol was assessed as the "fourth most significant fuel" in for international shipping, behind HFO, MDO, and LNG (Faber et al. 2020), but it still has very low adoption.

Methanol affords unique maritime emissions reduction opportunities, particularly when co-optimized with onboard reforming and combustion strategies. As a standalone fuel, renewable methanol significantly reduces NO_x and PM, and eliminates SO_X. Methanol can also be reformed in an electrochemical conversion process to produce H_2 and CO_2. The H_2 product and any unreacted MeOH carrier then serve as low-temperature combustion fuels, while the CO_2 could be diverted to an onboard carbon capture and sequestration (CCS) system. This isolated CO_2 could also be used to produce additional MeOH via the reverse reaction with fresh H_2, enabling a potentially closed-loop carbon cycle. High capital and spatial requirements of onboard reformers and CCS units are drawbacks of this approach, but further R&D may demonstrate promising cost and energy reductions as the technology matures. Fuel reforming is discussed in more detail in the Fuel Treatments subsection, while onboard CCS is discussed in the Exhaust Treatment section.

Energy Impacts

When methanol is combusted, it has very low emissions of sulfur, PM, and NO_x. It does produce aldehydes and CO_2, but these CO_2 emissions are approximately 60 percent less than those from diesel or HFO. When considering the full well-to-wake emissions, the emissions of the feedstocks such as natural gas and coal can negate the emissions benefits. However, if electrolysis powered by renewable energy is used to produce the hydrogen, and the carbon is sourced from CO_2 captured from the atmosphere or high concentration point sources of emissions, the resultant e-methanol would be net-zero emissions on a well-to-wake basis (Verhelst et al. 2019; see Figure 13). When a pilot fuel is used to enhance ignition and combustion in the engine, there are modest emissions associated with the use of this fuel, but these can potentially be minimized or eliminated through the use of some biofuels.

R&D Needs

Some R&D opportunities relating to methanol include:

- Reducing the production costs of e-methanol is a critical barrier to the adoption of the fuel. RD&D efforts that address price disparities between e-methanol and traditional fossil fuels would be beneficial, particularly those production processes that use biogenic or anthropogenic CO_2 as inputs in e-methanol production. Opportunity exists in co-locating methanol production plants nearby industrial facilities that produce large amounts of CO_2 (which can be used for e-methanol production), and research into optimal pairings of such facilities would be beneficial.

- RD&D on methanol engines to improve operating efficiency is an area of constant interest to some of the major marine engine manufacturers, particularly relative to improving the combustibility of methanol in large, slow-speed, two-stroke and four-stroke dual fuel diesel engines. Most methanol engines rely on a small amount of pilot fuel using traditional fossil fuels for better combustion; reducing this reliance and studying the best ways to blend the fuel, potentially using some types of biofuels, would be beneficial (Verhelst et al. 2019).
- Data about the well-to-wake emissions of methanol for maritime applications are sparse, which makes emissions comparisons with other fuels difficult for lifecycle assessments. Additional demonstration projects that result in robust data sets to inform lifecycle assessment modeling tools would be beneficial (Verhelst et al. 2019).

VII.3 Ammonia

Technology Description

Ammonia (NH_3) is a compound composed of nitrogen (N_2) and hydrogen (H_2) and can be used as a fuel in internal combustion engines or fuel cells, though in some cases it is difficult to use it in its pure form and it must be blended with other fuels (fuel blends use between 20 to 30 percent hydrocarbons according to some engine manufacturers) or reformed into hydrogen. Under ambient conditions it is a pungent, colorless gas with a boiling point of -33.3°C. When compared to traditional fossil fuels like HFO, the energy content of ammonia in its liquid state is less than half on a mass basis and roughly 30 percent on a volume basis (see Figure 11,) which translates into more frequent refueling or larger tanks (or both) for a vessel, all else being equal. Ammonia's lower heating value is less than that of hydrogen, but the density of the fuel means that less volume is required to store the same amount of energy compared to hydrogen. While ammonia is easier to transport and store than hydrogen, its volume requirement is higher than for traditional fossil fuels and it will still require specialized storage tanks. One of the major weaknesses of ammonia as a fuel is its toxicity and corrosivity to some materials that contain copper, nickel, and some plastics (DNV-GL 2021), which means additional safety systems will be required aboard vessels and refueling infrastructure to protect people and the environment.

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, gasification, or electrolysis that all rely on energy inputs. The two key elements, hydrogen and nitrogen, are used to form ammonia via the Haber-Bosch process, which combines the gases at high pressures and temperatures (Liu et al. 2020; Korean Register 2020). Approximately 170 million metric tons of ammonia are produced annually (DNV-GL 2021), almost exclusively by Haber-Bosch-type routes, which is responsible for one to two percent of global energy consumption and around 1.2 percent of CO_2 emissions. Furthermore, between 75 and 90 percent 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.

Ammonia does not contain carbon and can be produced using renewable or clean energy to power electrolysis to obtain the hydrogen, sometimes referred to as green ammonia or clean ammonia. If the hydrogen is sourced from water electrolysis (a very energy-intensive process), the resultant ammonia is often referred to as e-ammonia (where "e" indicates electricity was used in production), one of several electrofuels or e-fuels. Currently, most ammonia is produced using steam methane reforming (SMR) of natural gas to obtain the hydrogen; this is referred to as brown or gray ammonia. Sometimes SMR is integrated with carbon capture and storage to prevent CO_2 emissions, and during production, this is referred to as blue ammonia.

Given these various production pathways, it is important to account for the full lifecycle emissions of the fuel when considering its effect in reducing maritime emissions reductions (see Figure 13). When combusted, ammonia will result in emissions of NO_X, N_2O, CO, and potentially hydrocarbons (if a pilot fuel is used)—the amount of emissions will depend on the engine technology used (DNV-GL 2021; Hansson et al. 2020) and can be largely controlled with exhaust treatment measures. There is also the potential for unburned ammonia to escape from the engine combustion chamber, referred to as ammonia slip.

The maritime industry does have experience with ammonia; it is carried as a cargo, used as a refrigerant, and used in selective catalytic reduction. For example, of the roughly 170 million metric tons of global ammonia production, approximately 10 percent is transported by sea (Korean Register 2020) by roughly 200 different gas tankers (DNV-GL 2021). Major engine manufacturers such as Caterpillar, Wartsila, Japan Engine Corporation, and MAN (Korean Register 2020; K. Kim et al. 2020) have already begun developing and testing internal combustion engines using ammonia as a fuel, with ships planning to be operating by mid-century. In addition to internal combustion engines, ammonia can be used in fuel cells to produce electricity for electrified propulsion systems. For example, under the ShipFC project a number of companies (including Equinor, Eidesvik Offshore, and Yara) have partnered to test and eventually demonstrate a two-megawatt ammonia fuel cell system on an offshore supply vessel by 2023 (Equinor 2020).

Energy Impacts

The emissions benefit of ammonia relies on using renewable energy resources like wind, marine, solar, or hydro energy for production. If renewable energy is used for production, it will bring the GHG emissions close to zero. A small amount of an additional fuel is likely to be needed as a pilot fuel for proper combustion when using ammonia with internal combustion engines, but these emissions can potentially be offset by using a biofuel such as renewable diesel.

R&D Needs

Some R&D opportunities relating to ammonia include:

- Global production of ammonia in 2018 was roughly 170 million metric tons (DNV-GL 2021), the vast majority being produced from natural gas as the feedstock. Global fuel consumption from ships is approximately 330 million metric tons of fossil fuels (Kass et al. 2018), which would equate to around 700 million metric tons of ammonia on an energy basis and require more than 6,500 terawatt-hours of electricity. Ammonia separation and recovery from Haber-Bosch reactors is an energy-intensive unit operation, and further R&D is needed to identify more energy- and cost-efficient isolation strategies, especially those that leverage renewable energy inputs to drive molecular separations. Measured data about the emissions from these various production pathways are needed for modeling lifecycle emissions.

- Downscaled, modularized synthesis plants hold promise for distributed NH_3 production and enables economically viable scales for the utilization of fluctuating renewable electricity resources. Locational flexibility is also afforded by modularity, allowing miniaturized production plants to be co-located with H_2 refueling, electric vehicle charging stations, and other maritime applications.
- The current cost of green ammonia is nearly twice that of traditional fossil fuels, largely driven by the high price of water electrolysis. Efforts to reduce this fuel cost disparity through improvements to electrolyzer efficiency would be beneficial to fuel adoption—for example, by investigating the suitability of producing ammonia from seawater electrolysis and marine energy (Liu et al. 2020).
- A major R&D need for ammonia maritime fuel adoption is the development of efficient, thermally integrated catalytic reforming reactors to generate requisite hydrogen fuel onboard the vessel. Catalytic fuel reforming technologies are discussed in detail in the Fuel Treatments subsection. Along this vein, emission control technologies will also likely require step advancements to handle significantly higher NO_x and N_2O emissions resulting from NH_3 combustion, although new opportunities exist for exhaust gas recirculation and sensible heat recuperation for upstream NH_3 reforming reactors.
- Limited operating experience on ammonia engines and ammonia fuel cells creates uncertainty and reluctance to adopt the technology. Supporting the demonstration of ammonia engines provides valuable operating data about combustion characteristics, injection pressures, operating temperatures, engine wear, and numerous other engine design parameters.
- Given the toxicity of ammonia even in small concentrations, robust safety systems will need to be designed and tested to protect people and the environment. This may include ventilation systems, leak detection methods, novel sensors, and other safety mechanisms that will be critical to the use of ammonia as a fuel.

VII.4 Hydrogen and Fuel Cells

Technology Description

Hydrogen can be made through many different pathways from a variety of resources. Currently, most hydrogen is made from natural gas using the SMR process. When made this way, CO_2 emissions are associated with the hydrogen production. However, hydrogen can be made in other ways using feedstocks that provide hydrogen with low, zero, or even potentially negative carbon emissions. For example, hydrogen can be made from renewable feedstocks such as biogas or biomass in processes like SMR, and when coupled with carbon capture storage and sequestration, hydrogen made from biomass can lead to a low- or zero-carbon footprint.

Hydrogen can also be made by electrolysis of water with renewable or nuclear electricity to provide hydrogen that has a low- or zero-carbon footprint. Hydrogen is generally stored as a high-pressure gas at 5,000–10,000 pounds per square inch or as a cryogenic liquid at about -252°C. When stored as a compressed gas or cryogenic liquid, hydrogen provides a higher volumetric and gravimetric energy density than batteries, but lower volumetric energy density than diesel fuel. The combination of hydrogen storage and fuel cells can provide long-range and fast refueling times, similar to those provided by fossil fuels. Hydrogen as a fuel can be used in internal combustion engines, gas turbines, and most commonly in fuel cells.

Fuel cells are energy-conversion devices that take the chemical energy stored in fuels and convert it to electrical energy. They are similar to batteries and consist of two electrodes—a negative electrode (or anode) and a positive electrode (or cathode)—sandwiched around an electrolyte. However, fuel cells produce electricity and heat as long as fuel is supplied and do not run down or need recharging. A fuel, such as hydrogen or ammonia, is fed to the anode, and air is fed to the cathode. In a polymer electrolyte membrane fuel cell, a catalyst at the anode separates hydrogen molecules into protons and electrons, which take different paths to the cathode. The electrons go through an external circuit, creating a flow of electricity. The protons migrate through the electrolyte to the cathode, where they unite with oxygen and the electrons to produce water and heat. The process results in the production of electricity, heat, and water with no carbon or criteria pollutant emissions. Other fuel cells, such as solid oxide fuel cells, operate at higher temperatures and can use hydrogen as a fuel or convert hydrocarbon fuels like natural gas, methanol, and ethanol directly to CO_2, water, and electrical power. Fuel cells are believed to have several advantages over conventional diesel engines (especially when used with hydrogen), such as lower operating temperatures, reduced noise, fast start times, improved thermal efficiency, less vibration, and lower emissions (Minnehan and Pratt 2017). Fuel cells are often used in conjunction with marine batteries (see Section IX.1 Hybrid and All-Electric).

Initial applications of hydrogen and fuel cells are likely to be in coastal and inland applications where the onboard fuel storage requirements are less demanding than large ocean-going vessels and the fuel costs are a smaller fraction of the total cost of ownership. Tugboats and ferries are promising initial applications. Recent studies suggest that hydrogen-powered fuel cell ferries can be competitive with diesel ferries if developmental targets are met for fuel cell and hydrogen technologies and hydrogen fuel costs drop to $3.50/kg (Ahluwalia et al. 2021).

In the United States, construction of one of the first hydrogen fuel cell vessels in the world, *Sea Change*, is nearing completion and a demonstration is set for late 2021 (see Figure 14.; (Pratt and Klebanoff 2018)). Fuel cells have been investigated for research vessels, including via studies conducted at Sandia National Laboratories (SNL) establishing the technical and economic feasibilities of zero-emission hydrogen fuel cell research vessels, such as the *Zero-V* and a smaller research vessel targeted to be a replacement for the Scripps Institution of

Oceanography, the *R/V Robert Gordon Sproul* (Klebanoff et al. 2020). There have been projects initiated for fuel cell-powered cargo ships, including a recent announcement of a 2-year project bb the Australian-based Global Energy Ventures and Ballard Power Systems to design and develop a hydrogen fuel cell system for a proposed large-scale ocean-going hydrogen transport ship (Ballard Power Systems 2021). The concept is for a ship designed to transport up to 2,000 tons of compressed hydrogen at 250 bar. Others are reportedly looking at hydrogen fuel cell-powered cruise ships (Radowitz 2020).

Figure 14. Launching of the hydrogen ferry *Sea Change* for sea trials in 2021. (Photo by All American Marine)

Energy Impacts

Fuel cells can have slightly better thermal efficiency than internal combustion engines—approximately 50 to 60 percent instead of 30 to 55 percent for most diesel engines (Minnehan and Pratt 2017). When used as an auxiliary power source, not the primary mode of propulsion, fuel cells have been found to have the potential for CO_2 emissions reduction ranging between 2 and 20 percent, though the data were sparse (Bouman et al. 2017). If hydrogen produced using sustainable feedstocks and renewable energy is used as fuel, it can potentially result in net-zero well-to-wake emissions.

R&D Needs

Some R&D opportunities relating to hydrogen and fuels cells include:

- R&D is needed to improve fuel cell performance and durability for marine applications. The durability needs to match that of diesel engines currently used aboard most vessels. The long-term durability of fuel cells in marine environments still needs to be demonstrated.

- Additional R&D is needed to decrease the cost of hydrogen and hydrogen infrastructure, such as storage tanks both in ports and aboard vessels. Hydrogen storage system improvements to increase storage density, including improved cryogenic storage with lower evaporative losses and conformable storage tanks, would be beneficial for shipboard use.

VII.5 Natural Gas

Technology Description

Natural gas is a colorless, odorless, nontoxic combustible mixture of hydrocarbon gases, predominantly methane (typically 80 percent or higher). LNG is 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, but not without challenges. Natural gas can also be stored in compressed form, but this is less common in larger volumes. When LNG reaches its final destination, it is turned back into a gas through a regasification process. When combusted, natural gas produces approximately 20 percent less CO_2 emissions than other fossil fuels like HFO, MDO, or MGO, but methane slip, a common phenomenon in which unburned natural gas escapes through an engine's exhaust system, can negate these benefits (International Maritime Organisation 2016). When compared to diesel engines, low pressure natural gas engines can reduce PM by approximately 90 percent, SO_X emissions by 95 percent, and NO_X emissions by more than 75% (Stenersen and Thonstad 2017).

Natural gas is a nonrenewable fossil fuel most commonly obtained from underground wells within rock formations alongside oil reservoirs, though it can be produced synthetically from coal or petroleum. Natural gas can also be produced from biomass or biogas (40 to 90 percent methane), sometimes referred to as renewable natural gas (RNG) or biomethane. 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 (Mintz 2021). Waste feedstocks offer some of the best potential for emissions reduction using RNG on a lifecycle basis and depending on feedstock and production methods, RNG can have low or net zero-carbon emissions.

In 2020, U.S. LNG production was approximately 36,172 billion cubic feet (EIA 2021), but RNG production amounted to approximately 0.059 billion cubic feet (Nemec 2021), which highlights the production challenge if RNG is to be used as a maritime fuel. The methane potential from various waste streams (landfill material, animal manure, wastewater, etc.) in the United States is estimated to be approximately 420 billion cubic feet (NREL 2013), not enough to completely displace traditional LNG produced by nonrenewable sources.

LNG carriers (Figure 15) have been transporting LNG since 1959 and using it as a fuel since the 1960s. When stored, LNG is near its boiling point of -162°C and despite the best insulation available today it will slowly warm up and produce boil-off gas. Given the large surface area of the tanks that this pressure can act against, this gas must be closely monitored to prevent pressure buildup and possible tank rupture. What became common practice on LNG carriers was to use this boil-off gas as fuel for the marine boilers to produce high-pressure steam to drive a turbine for power and propulsion. 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 marine bunker fuels. In 2011, high-pressure injection two-stroke dual fuel (HPDF) engines were introduced, allowing use of either LNG or HFO/MGO (DNV-GL 2019a). Currently, the most popular LNG engine technology is low-pressure injection dual fuel (LPDF), four-stroke, medium-speed engines (Pavlenko et al. 2020). LNG can also be used in conjunction with fuel cells, but this has only been done on a handful of vessels as demonstration projects.

Natural gas is primarily methane, which is a relatively short-lived but a potent GHG, trapping roughly 30 times more heat than the same mass of CO_2. Methane slip is more prevalent in LPDF engines than high-pressure injection engines, but high-pressure engines will emit higher NO_X emissions, which must be controlled for with an exhaust gas treatment method such as selective catalytic reduction (SCR).

Figure 15. LNG carrier at berth transferring cargo. (Photo credit: David Hume)

The LNG ecosystem has matured rapidly in recent years because it is now available globally and in large volumes (DNV-GL 2019b). 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 (International Maritime Organisation 2016). 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 (Nerheim et al. 2021; International Maritime Organisation 2016). Despite this recent growth, and the fact that LNG has been used as a marine fuel since the early 1960s, it still only represents about one to two percent of global fuel consumption for international shipping (DNV-GL 2019b). Some consider LNG to be a transition fuel, in that it could offer marginal improvements in CO_2 emissions reduction over HFO until other lower-carbon alternative fuels are more widely available. Given that LNG's muted GHG benefits, multiple 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 (UK Department for Transport 2019). RNG, if scalable to meet the maritime demand, could alleviate some of these concerns.

Energy Impacts

Natural gas contains less carbon per unit of energy than conventional marine fuels like MDO or HFO, and when combusted it has fewer emissions of CO_2, SO_X, NO_x, PM, and black carbon. Just considering the combustion process, LNG will reduce CO_2 emissions on the order of 5 to 30 percent in comparison to HFO, even after factoring in methane slip in the engine (Bouman et al. 2017; DNV-GL 2019b; Caughlan and Reynolds 2016). However, when assessed on a well-to-wake basis, its impacts may be less beneficial due to other GHGs emitted during production, transport, and combustion. According to the International Council on Clean Transportation (ICCT) when factoring in methane slip and other lifecycle processes, there is no climate benefit from using LNG in the short term, regardless of the engine technology, and in some cases it emits more GHGs on a lifecycle basis than MGO (Pavlenko et al. 2020), see Figure 13.

R&D Needs

Some R&D opportunities relating to natural gas include:

- Given the increase in supply and demand of NG for maritime transport, Additional work should be done to better understand, quantify, and eliminate the methods of methane slip. For example, modeling slip as a function of engine load and to explore the lifecycle consequences of using non-fossil sources of NG, such as biogas (Pavlenko et al. 2020). This modeling should be informed by real-world data because the amount of methane slip from ships is poorly documented (Stenersen and Thonstad 2017). Additionally, research into methods of monitoring and detecting fugitive emissions associated with the transport of natural gas would be beneficial. These actions would allow better quantification of LNG's true lifecycle emissions.
- Significant scale-up of RNG production is required if it is to be used as a maritime transport fuel (Mintz 2021). The resource potential for RNG is limited, especially when using waste feedstocks, and its ability to displace LNG demand in multiple end-use markets is limited. Efforts to quantify the potential of RNG to meet future maritime demand would be valuable. R&D supporting RNG production from landfills, wastewater treatment facilities, and animal manure are encouraged, as is the collection of energy and emissions data about these production pathways for lifecycle emissions modeling.

VII.6 Fuel Treatments

Many fuels in their pure forms are not readily usable for modern fuel handling systems or converters. Fuel treatments serve to fine-tune physicochemical fuel properties for safe storage and service as well as for optimal combustion, energy conversion or emissions mitigation. Fuel treatment generally implies the introduction of precise chemical additives to base fuel compounds or blends. However, in this subsection, we also focus on catalytic fuel reforming, a technology to partially (or fully) decompose fuel (or carrier) molecules to generate energy-dense intermediates for use in the vessel's fuel converter.

Technology Description

Fuel Additives

Fuel additives span a broad range of functionalities and may be organic or inorganic in nature. Typical categories of additives include detergents, ignition enhancers, octane and cetane boosters, lubricants, antioxidant stabilizers, corrosion inhibitors, emulsifiers and deionized water, among others. Some fuel additives may both improve engine performance and reduce GHG emissions, while others serve to extend serviceable lifetimes of vital engine and fuel systems.

For example, NO_x emissions can be reduced by adding small amounts of water to the fuel or combustion process through water fumigation, direct water injection, or water-diesel emulsion. However, by adding water to the combustion process it does increase the amount of fuel required to achieve a desired power output. To overcome this increase in fuel use, some metal-based additives that might include iron, copper, platinum, nickel, calcium, barium, or cerium can be used to improve the overall combustion process (E et al. 2018), thereby reducing NO_x, PM, and fuel consumption.

Reforming

Many of the fuel candidates for decarbonizing maritime transport may be combusted directly in internal combustion (IC) engines or fed directly into fuel cells. An alternative approach is to chemically reform the starting fuel or carrier molecule to generate intermediates that are subsequently used in high-efficiency conversion devices. This alternative strategy affords more flexibility in fuel composition as well as new opportunities for improving energy efficiency. For example, when the chemical reactions employed are endothermic, the reformer may recover waste heat from the fuel converter for other shipboard applications.

Onboard fuel reformers may enable new pathways to improve vessel energy efficiency and emissions footprints via precise thermal integration and recirculation of toxic pollutants through reformer–engine loops. For example, fuels like ammonia or methanol for IC engines may reduce cold-start NOx emissions by serving as the catalyst's reducing agent while the engine warms. Several fuel reforming reactions and catalysts are well-studied, but many technical challenges remain for deploying them at device-relevant scales aboard vessels. Aside from hydrocarbons, numerous fuel candidates have been investigated for fuel reforming applications, including: light alcohols (e.g., methanol, ethanol); light acids (e.g., formic acid, acetic acid); oxygenates (e.g., dimethyl ether) and ammonia. These liquid fuels and H_2 carriers generally have high energy densities and are easier to handle relative to liquified and gaseous H_2.

When performing fuel conversion and reforming on a vessel, some critical considerations include reformer system weight, physical footprint, integrated sensing and controls, fuel tank requirements, duty cycling, and serviceable lifetimes. Overall, different primary fuels, catalysts, propulsion modes, and emissions characteristics will require unique reforming solutions, although many will share common research goals.

Energy Impacts

E et al. (2018) found that through metal-based fuel additives in a water-biodiesel-diesel emulsion blend, they were able to achieve reductions in NO_x upwards of 24 percent and improve the diesel engine thermal efficiency between five and nine percent. In one study examining the benefits of metal-based additives for HFO, researchers found that fuel consumption decreased between 0.4 and 2.2 percent, NO_x emissions decreased between 23 and 32 percent, and PM decreased around 60 percent compared to untreated HFO when tested across multiple engine load settings (Ryu et al. 2016). In a different study, Kannan et al. (2011) found that a metal-based additive added to biodiesel decreased fuel consumption by nearly nine percent, increased thermal efficiency by more than six percent, lowered NOx emissions, and reduced carbon monoxide, total hydrocarbon, and smoke emissions by 52.6 percent, 26.6 percent, and 6.9 percent respectively compared to biodiesel without the additive.

R&D Needs

R&D opportunities for fuel treatments and reforming include:

- Continued analysis and modeling of novel low-cost fuel additives and their effects on fuel properties, combustion, engine thermal efficiency and fuel consumption, and emissions would be beneficial. As new alternative marine fuels, such as some biofuels, are adopted, new additives may be required to help control some certain types of GHG emissions, improve fuel lubricity, or prevent accelerated wear of engine and fuel system components, as examples.

- Analysis and identification of commercially relevant formulations, with emphasis on understanding reaction kinetics, transport limitations, and catalyst cyclability and stability. Multiscale modeling tools, spanning the molecular and reactor scales, should be developed to understand and predict the physics and chemistry of fuel reforming networks. Catalytic reforming presents opportunities for novel design concepts (e.g., 3D-printed reactors or microreactors) for both mobile and stationary reforming applications. Technoeconomic and life cycle analyses that consider various trade-offs such as space, weight and energy, are crucial to assess and down-select viable reforming scenarios and operational strategies.

VIII. Energy Sources and Carriers – Clean Energy

Renewable or clean energy can be used onboard vessels to provide supplemental propulsion or offset fuel consumption. These renewable energy technologies can be used for other non-vessel applications as well; for example, solar, wind, or wave energy could be incorporated as a distributed energy resource into a port microgrid (see the port section for more information). This section reviews wind, solar, wave and current, as well as nuclear technologies being used for maritime decarbonization onboard vessels.

VIII.1 Wind Energy

Technology Description

This section considers recent technologies used for supplemental wind propulsion on commercial vessels, generally referring to kites and rotor sails because they have received the most attention with respect to helping reduce fuel consumption of and emissions from larger commercial ships (Comer et al. 2019). More modern takes on traditional cloth and rigid sails on fixed masts are also under investigation by some companies but are not considered here.

Kites and rotor sails convert the kinetic energy of wind into forward thrust, which is applied to the vessel, thereby reducing or completely offsetting the energy, and thus fuel, required to propel the ship. Towing kites are deployed off the bow of a ship and are flown high above the deck to harness the power of the higher-altitude winds. They are typically parafoil-shaped and are 1,000 square meters or more in size. Kites have several advantages over more conventional forms of wind propulsion, including the fact that they can be actively controlled to increase apparent wind speed and increase pulling force, they fly at higher altitudes with higher wind speeds, and involve no masts taking up deck space (Naaijen and Koster 2007). Streamlined deployment and stowage of kite systems is critical to preventing interference with ship operations.

Rotor sails are spinning vertical columns that provide supplemental propulsion. They are typically 18 to 30 meters tall, 1 to 3 meters in diameter, and are installed on the deck of a ship. As wind comes across the deck of the ship, the spinning rotors generate forward thrust by using the Magnus effect, a phenomenon wherein a spinning body generates a forward thrust when exposed to a perpendicular fluid flow. The resultant forward thrust thus replaces or supplements the propulsive power of the main engines. Rotor sails can be quite large relative to ship size and care must be taken to not affect vessel stability. Rotor sails work best when the wind direction is roughly perpendicular to the direction of vessel travel.

Figure 16. Rotor sails deployed on the *M/V Maersk Pelican.* (Photo ©Norsepower)

Energy Impacts

The energy impacts of supplemental wind propulsion will of course depend on vessel size, voyage length, and wind speed and direction. Generally, these technologies are believed to offer reductions in fuel consumption and emissions on the order of 1 to 20 percent (Comer et al. 2019; L. Liang 2021; Airseas 2018) although some research on modeling kite performance suggests fuel savings potentials of up to 50 percent (Naaijen and Koster 2007). The actual impacts will depend on vessel route, wind speed, and direction among other factors.

R&D Needs

Some R&D opportunities relating to supplemental wind propulsion include:

- Rotor sails and kites need to collect more operational data across vessel types and voyage profiles to better understand their impact on fuel economy for different vessel types. For instance, it has been noted that supplemental wind propulsion systems may actually increase fuel consumption for some vessel types (O'Rourke 2006).
- Some wind systems, like rotor sails, take up large amounts of deck space and extend the height of the vessel. The height of these rotor sails can be adverse for vessels that pass underneath bridges or other height-limiting infrastructure. Moreover, the stability of vessels is likely to be affected by increasing the weight above the center of gravity, and a spinning rotor may induce gyroscopic effects, further affecting stability. Methods to reduce the size and weight would be beneficial to reduce the costs and stress on the vessel.

- Kite systems would benefit from operational improvements to assist vessels with the ability to launch and recover kites with minimal human interaction or disruption to the ship's normal operations while under way. Methods of automation for control, launch, and stowage of kites would be advantageous to reduce the operational burden and costs for the vessel crew.
- Modeling efforts to predict optimum rotor sail size or kite sail area relative to vessel types, routes, and seasonal wind patterns would be beneficial to help vessel owners/operators better understand the performance of these systems and their payback periods.

VIII.2 Solar Energy

Technology Description

Solar photovoltaics (PV) at their most basic level convert sunlight into electrical energy. Individual solar cells are connected in series and parallel combinations to form modules and arrays to deliver desired levels of power. One of the major advantages of PV is its modularity, enabling the fabrication of systems ranging from a few watts to megawatts (Ginley and Cahen 2011). PV systems are used in the marine environment for a variety of remote electrical energy applications, like powering long-endurance uncrewed surface vehicles or ocean weather buoys. There is even a burgeoning interest in using underused surface area on lakes, rivers, reservoirs, oceans, and other bodies of water to deploy floating solar PV systems. Solar PV systems are almost always used in conjunction with energy storage such as rechargeable batteries. PV is not commonly found on commercial vessels, because of limited deck space, extreme weather, and impact hazards that might shatter the PV panels.

Solar PV devices could be mounted directly onto the deck or superstructure of some vessels, helping offset the energy consumption of the vessel. Solar PV could also be integrated into the tops or sides of sun-exposed shipping containers, particularly refrigerated containers that require energy inputs to power the refrigeration system that keeps the containers' perishable contents cool.

Energy Impacts

There are few examples of solar PV being used on commercial vessels. In one study that investigated the feasibility of solar panels on a Roll-On/Roll-Off vessel as a source of auxiliary power, the researchers determined that the vessel had 2,593.5 m^2 of available surface area for solar PV, which would produce 334,063 kWh/year of power. This would allow for an offset of 7.8 percent in energy production and avoid more than 47 tons per year of low sulfur fuel oil and 26 tons per year of diesel oil (Karatuğ and Durmuşoğlu 2020).

R&D Needs

Some R&D opportunities relating to shipboard solar include:

- Commercial maritime applications for solar PV, such as on containers or on the deck of a ship, will subject the panels to falling debris (wrenches, cargo stowage equipment, etc.), strong winds, and salt spray. Making PV panels tougher and more resilient to impact loads would help with adoption in the industry.

- Containers revolutionized cargo transport due to their standard shape, allowing for more efficient cargo-handling. Given that these containers all have near identical shapes and designs, they present an opportunity for easy integration of solar PV systems. Research into the most optimal way to integrate solar PV into containers for minimal cost, maximum benefit, and minimal disruption of normal operations is needed. Containers are designed for stacking, so research could look into both the hardware and logistical aspects of stacking PV-equipped containers. Refrigerated containers need energy to keep their perishable contents cool during transport. This energy can come from an external electrical connection or from an integral diesel genset. Research that investigates the potential for integrating solar PV with refrigerated containers would be also useful to help minimize energy consumption onboard vessels or while the refrigerated containers are awaiting transport in port.

VIII.3 Marine Energy

Technology Description

Wave energy converters are devices that convert the kinetic and potential energy of ocean waves into useful mechanical or electrical energy. Onboard vessels, wave energy can be used for energy harvesting, propulsion, or stabilization (Bøckmann and Steen 2016; Belibassakis and Filippas 2015). An example of wave-powered propulsion can be found on several smaller surface craft, such as the unmanned surface vehicles Wave Glider (built by Liquid Robotics) or the Autonaut, which both use oscillating hydrofoils to generate a forward propulsive thrust. This method of propulsion using wavefoils can be scaled for larger applications such as commercial vessels. Wave energy can also be used to induce a gyroscopic motion that can be used for ship stability (gyrostabilizers) (Perez and Steinmann 2009) or for producing power (Townsend and Shenoi 2012; Bracco et al. 2011) by harvesting energy from the wave-induced rotational motions of a marine vessel. In these systems an input torque (rolling of a ship) causes a variation in the spin axis of a flywheel acting at an angle of 90 degrees to the input spin, which produces a torque that can be used to drive a generator.

Figure 17. Wavefoils deployed in dock on *M/S Teistin*. (©Wavefoil)

Current energy technologies use the kinetic energy from flowing water to harvest energy. These systems most often take the shape of turbines that use lift or drag from the flowing fluid over the turbine blades to create rotation, which then drives a shaft connected to an electrical generator and produces electricity. There are two ways that a current turbine may be fitted to a vessel. One method is to use a modified vessel propeller, the other is to have a stand-alone turbine attached to the hull. These systems are common in the sailing and yachting industry and are often referred to as hydro-chargers or hydro-generators. With a modified propeller, the propeller blades have a variable pitch that can be angled at different directions relative to the water current direction so that it can be used for propulsion or energy harvesting. In the second method a small current turbine is deployed in the water as needed to recharge vessel batteries and is then stowed when not needed. The power output of these turbines varies with size and speed, but is typically in the range of 50–500 watts, though larger systems on the order of kilowatts are possible (Yutuc 2013).

Energy Impacts

A retractable WaveFoil system deployed on a passenger ferry is claimed to reduce fuel use by 5–15 percent (Wavefoil 2021), which agrees with scaled modeling in which researchers found that wavefoils attached to a commercial tanker vessel could reduce ship resistance by 9–17 percent and also lead to reductions in heaving and pitching (Bøckmann and Steen 2016). In one modeling study of a hydroelectric generator integrated onto a large tanker vessel, the researchers determined fuel savings on the order of 3.5 percent were possible (Yutuc 2013).

R&D Needs

Some R&D opportunities relating to marine energy for shipboard use include:

- Using wave energy as a propulsive mechanism on recreational and commercial vessels is not widespread. Research into how applicable this technology is for different vessel types and hull configurations would be valuable. Research into the optimization of the hydrofoil shape would lead to better fuel efficiencies.
- Using wave energy for gyrostabilizers or power production onboard has been studied for over a hundred years, but these systems have historically not seen widespread use because of their relatively large size that affects vessel loading and the inability of the control systems to maintain performance over varied sea states (Perez and Steinmann 2009).
- Advances in materials, mechanical design, electrical drives, and advanced computer control systems for gyrostabilizers and power take-off units for ships is needed. Making these systems suitable for commercial vessel operations is critical, perhaps through modularity such as a containerized system that could be easily loaded onto and unloaded from vessels. Investigating the applicability of these systems for different vessel types and sea conditions using modeling and simulation would be beneficial.
- Researching other methods of wave energy harvesting onboard vessels would be beneficial. For example, ship rolling caused by ocean waves can also be used as a potential source of energy harvesting and anti-roll tanks fitted with power take-offs may be an area worthy of future investigation (Alujević et al. 2019).
- Hydro-chargers are commercially available from companies such as Swi-Tec, Watt & Sea, Eclectic Energy, Oceanvolt, and others (Fortescue 2017). At the time of this writing, a consumer can buy one online for less than $4000 USD. While these systems may already be commercially ready, research needs to be conducted to investigate the opportunity to scale current generators for larger vessels or make them more efficient at lower speeds. Particularly as mid-size passenger ferries shift toward hybrid or all-electric configurations, there may be opportunities to incorporate hydro-chargers into the power system. Moreover, there may be opportunities to research the potential of these systems for use on vessels while they are in port or at mooring in particularly strong currents instead of when under way.
- Studying the effect of the location of the wavefoils on calm-water resistance, for instance by means of computational fluid dynamics, would be interesting to pursue as future work (Bøckmann and Steen 2016).

VIII.4 Nuclear Energy

Technology Description

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 5 to 10 years (Hoque et al. 2018) 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 been operated at sea on a variety of vessels, though mostly military (Hirdaris et al. 2014; Gravina et al. 2012).

A nuclear reactor is a device used to initiate and control a sustained nuclear chain reaction and it can be classified by the coolant it uses, its technology generation, the type of reaction, fuel used, or other variables. Most current marine nuclear reactors operate using a fission reaction with uranium as a fuel. During a self-sustaining chain reaction, the heat produced can be used to superheat water and produce steam, which in turn can be used in a common Rankine cycle with a steam turbine to provide propulsion or electricity. Most marine reactors in use today are classified as pressurized water reactors (PWRs), a variant of light water reactors (LWRs) that use water as a coolant to control the heat produced by the reaction. Other types of advanced reactors can use liquid metals, gas, or salts for coolant instead of water. Small modular reactors (SMRs) are advanced designs that may utilize any coolant type (water, liquid metal, gas, molten salt) (Hoque et al. 2018) and are generally recognized to have relatively small physical footprints, generation capacities ranging from tens to hundreds of megawatts, reduced capital investments, the ability to be sited in locations not possible for larger nuclear plants, and the ability to incorporate incremental power additions (DOE Office of Nuclear Energy 2021). Microreactors are even smaller than SMRs, have the potential to be transportable and factory fabricated, and provide both civilian and defense sectors with a clean, reliable, and resilient energy supply to provide electricity and process heat for multiple applications including off-grid communities, industrial processes, remote and forward military bases, and disaster relief missions (DOE Office of Nuclear Energy 2021). For reference, a commercial ocean-going vessel would likely require approximately 10 to 80 megawatts of power from a main propulsion engine.

Traditional nuclear reactors and their associated auxiliary systems tend to be relatively large and expensive and consequently take up large amounts of valuable space on a ship. For some vessel types, like military vessels or icebreakers, this trade-off between space and refueling time is worth it. But for a typical ocean-going vessel that is in port relatively frequently, the economic justification for a nuclear system is challenging. Modern SMRs and microreactors will be smaller and less expensive than their traditional counterparts, which may make them more appealing to the commercial maritime sector, either for ships or ports. For example, it is claimed that some small modular reactors are small enough to fit into a standard shipping container (Gravina et al. 2012)

Energy Impacts

Nuclear reactors have zero GHG emissions during operation and could effectively reduce the emissions from vessels by close to 100 percent. There are some emissions associated with the mining and processing of fuel for nuclear reactors, but the total lifecycle emissions from a small modular reactor are estimated to be on par with renewables such as wind and solar.

R&D Needs

Some R&D opportunities relating to nuclear energy for shipboard use include:

- Incorporating small modular reactors into commercial vessels will require new design regulations and standards to ensure protection of people and the environment.

Established practices and safety for incorporating nuclear reactors into commercial vessel design are nascent (Hirdaris et al. 2014), so new studies and designs that modify small modular reactors for maritime propulsion would be beneficial. For example, nuclear-powered ships entering territorial waters may face several challenges or restrictions. Novel modular ship designs that allow a ship to separate the nuclear propulsion module and the cargo-carrying module may address these concerns (Gravina et al. 2012). Improving the security aspects of small modular reactors when used on commercial vessels will also be important.

- Scrapping costs for a nuclear-powered vessel, particularly for the decommissioning of the reactor, will be high, and efforts to reduce these end-of-life costs and recyclability would improve the total cost of ownership economics.

IX. Energy Sources and Carriers – Hybrid and All-Electric

IX.1 Hybrid and All-Electric

Most non-fossil fuel engine propulsion systems being considered by the maritime industry are based on an electrified (instead of mechanical) powertrain. Electric-based powertrains may be a way to help future-proof vessels as new technologies become available over a ship's 30 year or more operating life (Bryn 2020). Integrating marine engines with hybrid technology could also offset fuel consumption and reduce emissions. This section provides an overview of hybrid and full-electric vessels as well as the battery technology that enables them.

Technology Description

Batteries and Energy Storage

Energy storage is critical to many other energy technologies and ERMs for vessels, particularly fuel cells and solar PV (Caughlan and Reynolds 2016). There are three broad categories of energy storage for maritime applications: electrochemical batteries, super capacitors, and flywheels (Hansen and Wendt 2015). Batteries are by far the most common in use in the maritime industry today and are the focus of this section.

There are many different types of rechargeable electrochemical batteries that use different types of metals and electrolytes, but there are four chemistries that have the most commercial relevance: lead acid, nickel cadmium, nickel metal hydride, and lithium ion (Li-ion). When selecting a battery chemistry, several important characteristics must be considered, including the power density (peak power per weight or volume), energy density (energy stored per weight or volume), thermal stability, flammability, toxicity, service or cycle life (number of charge-discharge cycles a battery can endure), charge rates, and cost. Li-ion batteries are the most common battery chemistry currently used for transport applications because of their relatively high energy density, power density, and cycle life (Berdichevsky and Yushin 2020; DNV-GL 2019b; Caughlan and Reynolds 2016).

Batteries can be integrated into a ship's electrical system in several different ways. They can be used to provide peak shaving, load leveling, frequency control, and improved power quality, and they can enable switching off all engines to reduce noise or emissions while providing propulsion when used in conjunction with electric motors (Kalikatzarakis et al. 2018). Batteries can be used in partnership with traditional combustion engines (hybridization) or the vessel can rely entirely on batteries (full-electric). Some maritime vessels are accustomed to handling containerized or modular cargo, which makes them potentially well-suited to swappable battery packs that are encased in a shipping container. A number of projects and companies are investigating this arrangement and its associated business models, such as the Current Direct project in Europe, funded by the European Commission's Horizon 2020 fund, that is demonstrating a waste transport barge with a swappable battery system (Current Direct 2021).

Hybrid and Full-Electric Vessels

Hybridization generally refers to integrating electric motors and internal combustion engines for the purposes of providing electrical power or propulsion. There are different ways to characterize hybrid vessels—plug-in hybrid and battery hybrid, for example. Regardless of the arrangement, a hybrid vessel uses both electrical and mechanical power or propulsion to varying degrees. A plug-in hybrid ship can be arranged in a serial or parallel arrangement. In a parallel arrangement, the vessel can propel itself either in conventional mode using the engines or in full-electric mode using the batteries and electric motors. In a serial arrangement, electric motors provide the propulsion and they are powered by generator engines and/or batteries. In a battery hybrid arrangement, batteries are used to complement the engine to smooth out and steady the engine's load, thereby improving engine efficiency.

In either the serial or parallel arrangement, the batteries can be charged using shore power (ideally provided by low- or zero-emissions renewable energy) or using onboard engines. These different arrangements are suitable for different vessel purposes. For example, a small passenger ferry that operates on short routes and can recharge frequently would likely operate in a serial arrangement, and predominantly use shore power to charge the batteries when in port. Conversely, a tugboat has intermittent periods of high-power demands when actively handling larger vessels but is often idle with low-power needs. In this situation a parallel arrangement may be more appropriate.

A full-electric ship resembles a hybrid vessel with a serial arrangement: the power system for propulsion and auxiliaries is based entirely on electric motors and batteries but is charged from an energy source external to the vessel instead of from onboard engines. The first full-electric vessels to operate in the U.S. are the *Maid of the Mist* tour boats operating at Niagara Falls; they are charged by locally generated and zero-emission hydropower.

Full-electric propulsion is most feasible for commercial short-sea operations (MAN Energy Solutions 2019) in which vessels have relatively modest energy requirements, travel relatively short distances with regular schedules, and frequent port visits that could be used for recharging. Ideal ship types for battery hybridization typically have large variations in power demands, high redundancy requirements, and/or low utilization of the engine for long periods of time.

Plug-in hybrid and full-electric vessels require shoreside infrastructure for recharging batteries, such as new fast-charging systems, transformers, switch gear, new electrical distribution throughout the port, and potential modifications to piers and docks to accommodate vessel charging. Hybridization that incorporates shore charging from the regional electrical grid, or plug-in hybrids, can lead to greater emissions reductions than if the vessel relied on onboard engines for battery charging. In fact, the Washington State Ferry fleet will not be able to meet their emissions reduction goals of 45 percent reduction by 2030 and 70 percent by 2040 without shore charging (WSDOT 2020).

Energy Impacts

On a full-electric ship, the power system for propulsion and auxiliaries is based entirely on batteries charged from the onshore electric grid while at berth. If the electricity provided by the regional grid comes from a renewable or clean energy source, a full-electric ship or plug-in hybrid ship operating exclusively in full-electric mode may be considered to emit no CO_2, NOx, PM, and SO_X (DNV-GL 2019b) during its operating life, thus reducing emissions by nearly 100 percent (Caughlan and Reynolds 2016). Plug-in hybridization of ships could reduce fuel consumption on the order of 10 to 40 percent depending on the ship (DNV-GL 2016). As an example, the hybridization of the Washington State Ferry *Jumbo Mark II* vessels will lead to a 27 percent reduction in fleet-wide emissions once shore charging is available (WSDOT 2020).

R&D Needs

Some R&D opportunities relating to hybrid and all-electric vessels include:

- Battery production-scaling and cost reductions are mainly driven by major industries such as automotive, consumer electronics, and industrial power, not the maritime industry. These markets are pushing toward maximum energy density at minimum cost. Improvements in specific energy, energy density, and specific power will affect the lifetime and safety of the battery, which are critical for maritime applications. The main cost drivers for lithium-ion batteries in maritime vessels compared to those for consumer electronics and electric vehicles are related to requirements related to safety, performance, and service life. The theoretical limits of a battery's performance depend on the engineering and integration of the key components: the anode, cathode, electrolyte, and separator. Research on these various components will lead to further reductions of battery costs (Berdichevsky and Yushin 2020; DNV-GL 2016).
- The optimization of all-electric ships operating in coastal routes creates new challenges in ship design optimization and route optimization (see separate related chapters). Fast passenger vessels tend to have more slender hull forms and reduced volume, yet also have high-power demands when in transit, which makes them a difficult, but attractive option for electrification. Potential research areas include new designs that focus on ship weight, draft, hull form optimization, battery selection, charging and route optimization, and recharging technology (Papanikolaou 2020; WSDOT 2020).
- Shore charging systems for marine vessels are far more complex than those for ground vehicles. Research on autonomous fast-charging systems that can easily be retrofitted to existing port infrastructure to serve a variety of vessels. Additionally, researching how these systems can best integrate with the electrical grid will aid in long-term planning for terminal operators as well as electrical utilities.
- Not all ports offer the same electricity infrastructure, which can restrict how and where electrified ships operate. There is currently a lack of a globally standardized connections for both the physical connector and the power quality for ship-to-shore charging. While this challenge is more pertinent to larger vessels that engage in international trade, thus more applicable to shore power, it can be an issue even between regions of the same country. While this will likely be addressed in time, it adds cost and restricts technology adoption. Government support through suggestion

of common standards for connections and power would be beneficial (UMAS et al. 2019).

X. Energy Efficiency

Reducing emissions from the maritime industry depends on both reducing energy use and ensuring that the energy is provided by low- or zero-emission fuels. Energy efficiency is concerned with getting the most out of energy inputs (i.e., fuel) by reducing losses. The conversion of chemical energy in a fuel to mechanical energy for propulsion involves numerous energy losses along the way, which present opportunities for improvement (see Figure 18). 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 will come into force in January 2023.

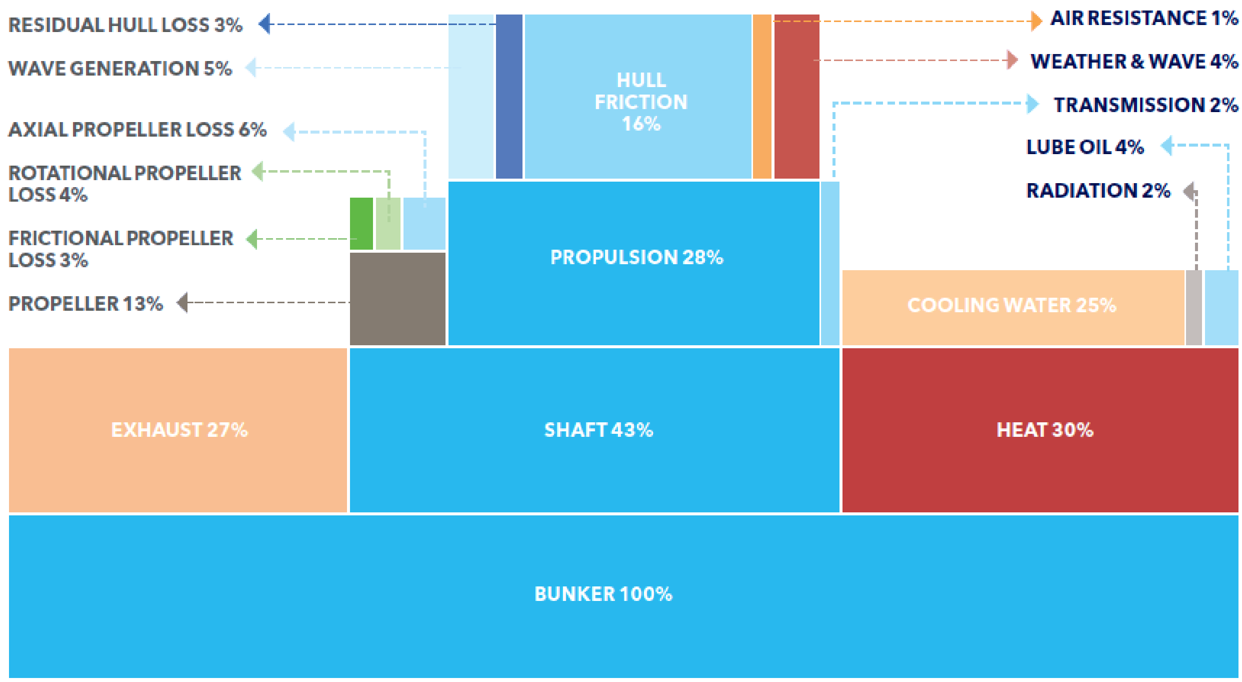

Figure 18. Use of propulsion energy onboard a small, well-maintained cargo ship in a rough sea (DNV-GL 2018).

X.1 Waste Heat Recovery

Technology Description

Waste heat recovery (WHR) systems attempt to recover heat energy that is rejected during the operation of a steam plant or diesel engine. For example, roughly 50 percent of fuel energy introduced into a diesel engine is rejected as heat, mostly through cooling water or exhaust gas (Caughlan and Reynolds 2016; see Figure 18). On a vessel, heat can be used for multiple purposes, such as to power an exhaust generator that provides additional electrical generation capacity; evaporate seawater to produce potable freshwater; or heat up fuel oil to reduce its viscosity. If waste heat is used for power generation, it allows the vessel to produce more power without using more fuel. There are several different methods of varying degrees of maturity and suitability for commercial vessels. Two common methods are using an exhaust gas turbine generator, which uses exhaust gases to drive a turbine, or using a steam turbine generator, which uses exhaust gas to produce steam to drive a steam turbine (Faber et al. 2020). These systems operate under similar operating principles of converting thermal energy to mechanical energy. Their effectiveness depends largely on the amount of waste heat available, in terms of both flow rate and temperature. Note that some of these systems may affect the overall emissions of the vessel if not properly integrated; for example, lowering the exhaust temperature too far may lead to the formation of caustic sulfuric acid in the exhaust system, which would reduce the efficacy of after-treatment catalysts.

Energy Impacts

WHR on vessels is widely employed and has been shown to lead to efficiency improvements of anywhere from 3 to 15 percent (Caughlan and Reynolds 2016; Baldi and Gabrielii 2015) and lead to CO_2 emissions reductions ranging from 1 to 20 percent (Bouman et al. 2017). The IMO Fourth Greenhouse Gas Study modeled the CO_2 abatement potential of these technologies to be between 1 and 3 percent over the next 30 years (Faber et al. 2020).

R&D Needs

Some R&D opportunities relating to waste heat recovery on vessels include:

- Steam-based WHR systems for both four- and two-stroke diesel engines are commercially available by major original equipment manufacturers (OEMs) (Baldi and Gabrielii 2015). Other forms of WHR, such as super critical CO_2 and Organic Rankine cycles, are less common and would benefit from technoeconomic analysis to further cost reductions and efficiency improvements. The integration of WHR systems with nascent alternative fuels that are considered potential replacements for traditional fossil fuels (biofuels, methanol, ammonia, hydrogen) will need to be investigated to understand their impact on overall system efficiency and emissions.

X.2 Shipboard Power Management

Technology Description

Ships need energy for a variety of applications (see Figure 2). Shipboard power management systems are broadly used to control the energy produced and consumed by the vessel through automation. Such systems can be designed to optimize on a number of variables such as emissions, costs, system downtime, etc. and are used to control shipboard equipment like engines, motors, valves, or other equipment that can affect vessel energy consumption. Such automated management systems can lead to switching off certain pump motors, adjusting diesel engine loads to run more efficiently, synchronizing generators, or any number of actions depending on the control strategy. Power management systems on vessels are commonly employed to assist in the automatic synchronizing and load balancing of the ship's multiple service diesel generator engines to meet fluctuating electrical power demands from cargo equipment and other vessel machinery. They can be managed to monitor equipment performance, set event alarms, calculate energy or fuel usage trends, recommend maintenance, or even troubleshoot system issues.

Energy Impacts

The energy and emission impacts from using power management systems on ships vary, but generally have demonstrated fuel savings of between 5 and 17 percent (Kalikatzarakis et al. 2018), though other research has found the savings to be closer to 3 percent or less (Bouman et al. 2017).

R&D Needs

Some R&D opportunities relating to shipboard power management include:

- The control algorithms and strategies used for balancing load across energy producers—either fuel cells, diesel generator engines, or batteries—is an area of ongoing research and will intensify as more hybrid and all-electric ships come online. R&D on advanced control strategies for existing engine designs, as well as new control strategies for full-electric and hybrid vessels without affecting vessel operations or safety would be beneficial.

X.3 Engine Design

Technology Description

Diesel engines are one of the most prevalent technologies in the maritime industry. Through the combustion of fuel, they are also one of the largest sources of emissions. Myriad engine designs are used for vessel primary propulsion, electrical power generation, emergency backup power, and other functions. Direct-drive, slow-speed (400 RPM and less) and medium-speed (400 RPM to 1400 RPM) diesel engines are the most common form of propulsion for large commercial vessels (Caughlan and Reynolds 2016; ABS 2014). Smaller vessels such as tugboats, ferries, and fishing boats are more likely to be equipped with high-speed engines (1400 RPM or more) with speed-reduction gears when used for propulsion. Recreational boats are more likely to use smaller gasoline engines or high-speed diesel engines, depending on their size and application. Low-speed engines are commonly two-stroke crosshead engines with 4 to 12 cylinders that use turbochargers and aftercoolers that can reach power ratings of 85 megawatts or more. Medium and high-speed engines are usually four-stroke engines with 10 to 24 cylinders and are also usually turbocharged (Harrington 1992). These engines are immense in size and weight and are one of the largest expenditures in vessel construction, so careful analysis must be performed when selecting an engine to ensure it is appropriately matched to vessel propulsion needs. Diesel engines are most efficient at 80 percent to 90 percent of their rated capacity (or maximum continuous rating), and efficiency decreases at lower engine loads.

These engines have traditionally been designed to operate on fossil fuels such as MDO, MGO, and residual fuel oil using the diesel cycle (DNV-GL 2019b). These engines are compression-ignition engines wherein the liquid fuel is introduced as an atomized spray and is ignited using the heat of the compressed air in the cylinder. Recently there has been increased interest in dual fuel engine designs that have the ability to use liquid and gaseous fuels—diesel oil and natural gas being examples—which allows the engine to operate on the Otto cycle (i.e., spark ignition) when in gas mode and the diesel cycle (i.e., compression ignition) when using liquid fuels. When using a gas as fuel in a dual fuel engine, the engine cannot simply rely on the heat of the compressed air to start ignition of the fuel; instead it must use an ignition source (spark plug or liquid fuel) to initiate ignition. The fuel flexibility of the dual fuel engine design comes at a small cost to efficiency—the average energy efficiency of dual fuel engines varies from 45 to 50 percent (Nerheim et al. 2021). Major marine engine manufacturers such as MAN, Wärtsilä, and Caterpillar have multiple engine offerings that use dual fuel technology. While natural gas is the most common alternative fuel used in dual fuel engines, other alternative fuels being investigated include methanol and ammonia.

Numerous standards and regulations guide engine design, operation, and safety, which goes beyond the scope of this report, but two of particular note for U.S. vessels stem from the EPA and IMO, and are commonly referred to as Tier Standards. These engine regulations are structured around engine categories that are based on rated power and engine displacement. As an example, Category 3 diesel engines range in size from 2,500 to 70,000 kilowatts which would encompass most large marine engines used in ocean-going commercial vessels. The EPA has four tiers, which increase in their stringency over time, and are largely meant to limit NO_X emissions. Tier 4 engines are the current standard for new engines, though there have been amendments to the rule due to the unavailability of Tier 4-compliant engines for some vessel types such as high-speed commercial vessels (EPA 2020). Another regulation that has influenced engine design is an IMO regulation that prohibits fuels with flash points less 60°C (such as methanol), though recent amendments and interim guidelines to this regulation are under way or in-place, respectively.

Energy Impacts

Diesel engines do have theoretical limits on their efficiency, but marine diesel engines are considered among the most efficient of internal combustion engines due to diesel's high energy density and greater power resulting from the high compression ratio. Modern diesel engines can achieve thermal efficiencies between 50 and 60 percent (Caughlan and Reynolds 2016; ABS 2014). Still, this means that there are substantial losses in the engine systems even in the most efficient of engines, and marginal improvements in system efficiency are possible. Engine emissions are affected by numerous factors, the most important being the fuel and its characteristics; certain fuels will inherently have fewer emissions. Even with fossil fuels, intelligent engine design can have substantial impacts on emissions reduction. For example, IMO and EPA engine tier standards have gradually led to drastic reductions (90 percent or more) of NO_X and PM emissions since the early 2000s, for example. Dual fuel engines have been shown to lead to GHG reductions of up to 24 percent, even with methane slip, when compared to traditional engines using just MDO (DNV-GL 2019b).

R&D Needs

Some R&D opportunities relating to marine engine design include:

- Efficient engine design is an area of continuous study that features numerous opportunities to improve performance and system efficiency. Areas of suggested R&D of most benefit to the maritime industry would focus on engine designs that accommodate alternative fuels such as methanol, ammonia, and biofuels. Given the long operating lives of commercial ships and the required design modifications for existing engines to use these fuels, specific research could look into optimal injection patterns, pressures, and temperatures; combustion chamber and piston head geometry; suitable lubricating oils that do not adversely react with the fuels in the engine cylinders (Kass et al. 2018); pilot fuel ratios for optimal combustion and minimal emissions; and improvement of the engine materials and components that may interact with certain fuels or experience accelerated corrosion.

- There is also considerable ongoing research into dual fuel engine designs, but methane slip remains a well-documented issue with negative climate impacts for low-pressure injection engines (Pavlenko et al. 2020; DNV-GL 2019b). Research into techniques and technologies that mitigate methane slip in dual fuel engines is recommended.
- Hybrid vessels are becoming increasingly attractive as a method for reducing emissions. Additional research supporting hybrid vessel designs is recommended to address issues such as power quality, high capital costs, and low-load inefficiencies (Caughlan and Reynolds 2016).

X.4 Auxiliary Machinery Efficiency

Technology Description

This emissions reduction measure is a broad category that includes design modifications and efficiency upgrades to a variety of shipboard machinery that uses or produces energy. In isolation, most of these pieces of machinery are not large consumers of power, but in aggregate they can become more sizable. Efficiency improvements could be as simple as switching cargo hold lighting from compact fluorescent to LED lighting to reduce electrical energy used for lighting, or more sophisticated changes such as complex geometry for cooling surfaces in heat exchangers used for keeping fluids within desired operating temperature ranges. Variable frequency drives (VFDs) for electrical motors on pumps and fans are machinery modifications that can lead to substantial energy savings because pumps are so omnipresent on vessels. When a pump or fan motor is equipped with a VFD, it allows the equipment to operate more efficiently at partial loads by reducing the required power; for instance, reducing a pump's speed by 10 percent will save almost 30 percent in power consumption (Räsänen and Schreiber 2012). Given the large number of pumps on vessels for ballast water, cooling water, fuel oil transfer, firefighting, etc., VFDs can lead to substantial energy reductions. Other auxiliary equipment that may benefit from efficiency improvements include the HVAC system, freshwater generation, air compression, and lubricating oil purification.

Energy Impacts

The energy and emissions impacts for energy efficiency modifications to auxiliary machinery vary tremendously. In pump and fan applications, onboard vessels using VFDs can cut the energy consumption for these applications by as much as 60 percent (Räsänen and Schreiber 2012).

R&D Needs

Some R&D opportunities relating to auxiliary machinery efficiency include:

- The breadth of R&D for this topic is immense. Suggested research areas of benefit to the maritime sector include conducting energy use studies on ships to assess efficiency opportunities; developing compact and ultra-efficient heat exchanger designs for various cooling systems; improving centrifugal pump designs; or improving the performance of VFDs for integration with ship pumps and fans.

XI. Exhaust Treatment

The combustion of traditional fossil fuels in marine diesel engines produce the following elements and compounds in the exhaust gas: unreacted air which is mostly N_2 (nitrogen) and O_2 (oxygen); H_2O (water vapor); CO_2 (carbon dioxide); CO (carbon monoxide); NO_X (nitrogen oxides); SO_X (sulfur oxides; unburned hydrocarbons (HCs); and/or PM (particulate matter). Some of these emissions contribute to the global greenhouse effect and climate change, smog, respiratory illnesses, acid rain, and other harmful effects (Sofiev et al. 2018; Vidal 2009). As a whole, the maritime industry contributes an astonishing 2.5 to 3 percent of global GHG emissions, including approximately 940 million metric tons per year of CO_2, alongside 15 percent of NO_X and up to 9 percent of SO_X emissions worldwide (Faber et al. 2020). To further contextualize these values, a single container ship emits as much CO_2 as 75,000 light-duty passenger cars, and as much NO_X and PM as 2,500,000 cars. Exhaust gas emissions from maritime transportation are of increasing environmental concern, and existing emissions treatment strategies will require renewed R&D attention to address new challenges introduced by the advent of novel fuel and propulsion technologies.

This section reviews three different measures of particular interest for mitigating maritime emissions through post-combustion exhaust treatment: NO_X control measures, PM control, and onboard carbon capture and sequestration.

Exhaust Treatment and Carbon Capture

Technology Description

NO_X and SO_X Control Measures

NO_X control measures can be split into a handful of categories grouped around basic principles, such as reducing peak temperature in the engine cylinders; reducing time duration at peak temperatures; or chemical reductions of NO_X. By reducing temperatures, this technique avoids the ideal ratio of chemicals that result in higher concentrations of NO_X (EPA 1999). Lower temperatures are achieved by creating an excess of fuel, air, flue gas, or steam in the combustion chamber. Chemical reductions of NO_X is a different form of NO_X control that uses a chemical to separate oxygen from nitrogen. Selective catalytic reduction (SCR) reactors are commonly used for chemical reduction; they employ reduction catalysts to convert NO_X gases into benign N_2 using ammonia (NH_3) as a reductant. SCR is a widely employed after-treatment system on most commercial vessels that use IC engines, especially in those that traverse emission control areas. Indeed, modern SCR systems can reduce approximately 95 percent of NO_X emissions from vessel exhaust (Z. L. Yang et al. 2012). Future NO_X control solutions for the maritime sector may require significant modifications depending on the fuel and propulsion mechanisms employed in next-generation vessels; for example, NH_3 may lead to higher NO_X emissions.

Exhaust gas cleaning systems, often referred to as scrubbers, are generally employed to curtail SO_X emissions. They operate by exposing the exhaust gas directly to water to remove water-soluble pollutants like SO_2, SO_3, and NO_2. The wash water is treated to remove any accumulated sludge or adjust pH and then either discharged overboard (open loop) or recirculated (closed loop). There are three types of scrubbers: wet, dry, and hybrid scrubbers. Wet scrubbers use seawater or freshwater as wash water; dry scrubbers incorporate a dry medium such as calcium carbonate (EPA 2011); and hybrid scrubbers use a combination of the two. Wet scrubbers have seen widespread adoption since the IMO global fuel sulfur limit came into effect in January 2020, and they make up nearly 90 percent of the installations aboard vessels (Osipova et al. 2021). This regulation limits the amount of sulfur allowed in fuels used and carried by ships, except for those vessels equipped with appropriate scrubber systems. This widespread use of wet scrubbers has raised concerns about high concentrations of acidic effluent and other pollutants being discharged into the ocean through the wash water (Osipova et al. 2021). There are also potential issues with establishing the supply chain at ports for consumable materials needed for the scrubber (i.e., caustic soda) and disposal of effluent from non-open loop scrubbers.

Particulate Matter Control

PM refers to solid particles (i.e., ash and elemental carbon) and liquid droplets (i.e., organic carbon and other aerosols), and PM pollution resulting from combustion processes poses significant risks for human health and the environment. Although international maritime transportation is only responsible for a few percent of global total PM emissions, approximately 70 percent of trade routes are concentrated within 250 miles of coastlines. PM emitted by marine diesel engines may encompass a variety of organic and inorganic components, such as soot (carbonaceous solid particles), incompletely combusted hydrocarbon fuel and/or lubricating oils, ash, metals, and metal nitrates, sulfates, and carbonates. This complex assortment of substances often includes solid particles or aerosols ranging from single nanometers (10^{-9} m) to tens of microns (10^{-5} m) in size; as expected, the fuel quality, combustion strategy, and engine maintenance quality play significant roles in the composition and distribution of the PM emitted.

Diverse technological solutions are required for effective mitigation and are usually accomplished through four primary approaches: substitution of cleaner combustion fuels; reduced fuel consumption via improved energy efficiency and/or vessel design; optimized engine performance; and implementation of emissions control systems. Regarding the fourth approach, wet exhaust scrubbers (WESs), diesel particle filters and electrostatic precipitators (EPs) are three technologies of varying maturity used to curtail PM from marine diesel engines.

Onboard Carbon Capture and Storage

Carbon capture and storage (CCS) systems are capable of isolating, storing, and/or re-using CO_2 emissions to prevent their release to the atmosphere. They have been used for decades in other industries but are relatively new to the maritime industry aboard vessels. CCS is currently undergoing commercial deployment in heavy industries with concentrated point source emissions (e.g., manufacturing, oil refineries, coal-fired power plants, etc.) to mitigate immediate-term climate change impacts; however, several modern CCS concepts are still unproven at scale and may not be economically competitive. Large capital and spatial demands as well as high energy intensity are characteristic drawbacks of most CCS processes to date.

Three general methods are used for carbon capture: pre-combustion capture, oxy-fuel capture, or post-combustion capture (Zhou and Wang 2014). Post-combustion is believed to be the most pertinent method for ship-based carbon capture (Feenstra et al. 2019). In the typical post-combustion process, exhaust gas is exposed to a CO_2 capture solvent or solid adsorbent within an enclosed absorption column. Through a series of chemical processes, the CO_2 is chemically reacted with or physically dissolved in solvents or adsorbents, heated and separated, and exits as a gas for storage while the CO_2-depleted gas is released to the atmosphere. Liquefied CO_2 takes up approximately one-five-hundredth of the volume of gaseous CO_2, so for cost-effective and practical storage onboard a ship, the CO_2 must be converted to a liquid by mechanical compression (Seo et al. 2015; Feenstra et al. 2019). The liquefication process is energy-intensive however, and depends largely on the temperature and pressure required for producing the liquid CO_2. The stored liquid CO_2 can be sequestered (e.g., in large tanks, deep sea, or underground caverns), or used for fuel synthesis or fuel reforming (see the methanol section). Creative concepts in onboard circularity may allow for integrated fuel synthesis, reforming, and CCS if carbon and energy balances permit.

Energy Impacts

The emissions impacts from these various measures can be significant. For example, commercial caustic WES units have been demonstrated to remove up to 60 percent of micron-scale PM from marine diesel engine exhausts. CCS systems are capable of capturing up to 90 percent of CO_2 emitted from fossil fuels (Feenstra et al. 2019). The NO_X emissions reduction of most control methods ranges from 50 percent to upwards of 90 percent for SCR (Z. L. Yang et al. 2012). According to the EPA, wet scrubbers are capable of removing upwards of 95 percent of SO_X emissions from exhaust gas, though the ICCT has noted in a recent study that the effluent from these scrubber systems is contributing to high concentrations of wash water effluent loaded with pollutants discharged into sensitive marine environments (Osipova et al. 2021; EPA 2011).

R&D Needs

Some R&D opportunities relating to exhaust treatment and carbon capture include:

- R&D needs for NO_X and SO_X control measures vary depending on the fuel type, sorbent media, and other characteristics. Investigations into optimal NO_X control measures for alternative fuels, such as NH_3, that are just starting to be considered would be beneficial. SCRs are mature technologies, but their durability and efficacy specifically at low loads is an important area of research. Moreover, there is recent industry interest in investigating water injection and fuel emulsification as practical NO_X control measures, so additional research into this method for various engine types and fuels would be beneficial. Researching the local and global environmental impacts of wash water discharge of open loop scrubber systems is needed, as is pH management of the released effluent. Finally, unique thermal recuperation and/or gas–liquid mixing concepts may also improve SCR operability ranges and material lifetimes and are deserving of future investigation.
- Low-carbon fuels such as renewable methane, methanol (MeOH), ethanol (EtOH), dimethyl ether (DME) and others will require different combustion strategies and

emissions control solutions than those used with MDO, possibly including novel catalyst and adsorbent formulations. Combustion of nitrogen-dense fuels like renewable NH_3 may result in NO_x concentrations that exceed tolerances of today's SCR catalysts by several orders of magnitude. Particular attention should be paid to effluent nitrous oxide (N_2O) concentrations, as this particular pollutant possesses a global warming potential nearly 300 times larger than CO_2. Regardless of fuel or combustion strategy, rational catalyst and reactor design lie at the heart of maritime NO_X control measures and are predicted to play a central role in R&D platforms.

- R&D needs for maritime NO_X control measures straddle a broad range. Similar to HD on-road vehicles, trends in ultra-lean IC engine operation help to reduce thermal losses and improve engine efficiency, but modern NO_X reduction catalysts cannot operate at cold-start (<150°C) temperatures, particularly in the presence of excess oxygen (air). NO_X adsorbent traps provide one solution to the cold-start problem, but material formulations frequently rely on platinum group metals (PGMs) as the active site phase. Thus, progress in HD on-road SCR catalysis and NO_X adsorption could enable direct, immediate-term technological advancements in the maritime sector.
- R&D needs for maritime PM control vary with the fuel, air/fuel ratios, fuel injection methods, exhaust temperatures, and other factors. Hence, such plant-level considerations are emphasized when defining PM R&D needs. In this vein, several opportunities exist to incorporate renewable electricity inputs into PM control strategies: beyond EPs, early technology readiness level (TRL) technologies such as microwave plasma reduction and direct nonthermal plasma reduction are promising for NO_X and PM abatement, possibly even as intensified onboard operations. (Notably, original equipment manufacturers (OEMs) such as Ford have conducted extensive R&D on plasma topics and while none of these R&D efforts achieved commercial readiness for on road applications, new opportunities may exist in the maritime sector.) For all technologies explored, digital process controls, sensing, and automation will remain crucial enabling features of all future maritime emissions solutions.
- R&D needs for onboard CCS span multiple time and length scales. At the molecular scale, the design of new solid and liquid sorbents should emphasize enhanced CO_2 capture rates and minimal hysteresis effects upon desorption. At the microscale, investigations into sorbent formulations may identify optimal surface-area-to-volume ratios for the spatially efficient design of materials. At the device scale, there are significant R&D needs for space-saving designs to minimize impacts on cargo-carrying capacity. Of particular emphasis should be the order-of-magnitude matching of rates associated with various onboard processes: combustion exhaust generation, CO_2 uptake, CO_2 desorption, sorbent regeneration, co-product emissions management and carbon-based fuel synthesis and/or reforming, among others. Research supporting the development of energy efficient liquefaction systems for CO_2 would also be beneficial (Seo et al. 2015).
- CO_2 isolated from maritime CCS may be used for onboard or offboard (electro)synthesis of low- or net-zero-carbon fuels, or electrofuels. Emerging chemical

and electrochemical pathways to sustainable fuel molecules that utilize CO_2 as a reactant are under active investigation by universities and national laboratories, and downscaled, modular reactors that can utilize CO_2 recovered from ship-based CCS may enable localized access points for onboard or onshore fuel synthesis. Relatedly, proposed marine fuels such as methanol (MeOH) are expected to require onboard fuel reforming operations to generate hydrogen with CO_2 as a byproduct, the latter of which must be separated and stored via CCS. Creative concepts in onboard circularity may allow for integrated fuel synthesis, reforming, and CCS if carbon and energy balances permit. Finally, downstream of fuel operations, oxy-combustion involves burning a fuel in an oxygen-enriched atmosphere using recirculated CO_2 as a carrier gas, while this method has advantages, at present it is economically, energetically, and spatially prohibitive for most marine vessels.

XII. Port Infrastructure

Port infrastructure enables all the activities and operations that occur in ports, including cargo operations, vessel logistics and husbandry, cargo storage and the intermodal transport of cargo among others. These port activities, and the infrastructure and assets that enable them, can lead to concentrated emissions that affect the surrounding region, particularly port communities. Moreover, port infrastructure is particularly sensitive to the impacts of climate change in the form of sea-level rise and increased storm intensity. For these reasons, many ports are already planning for and investing in ERMs, such as the Ports of Long Beach and Los Angeles, Port of Seattle, and Ports of Oakland as examples (San Pedro Bay Ports 2017). In this section, methods of emissions reduction for port infrastructure are discussed, including cargo-handling equipment, microgrids, and smart grids.

Cargo-handling Equipment

Technology Description

In bustling waterfront facilities where vessels load and offload their cargoes, various kinds of equipment are used to efficiently move freight vertically and horizontally in and around ports (see Figure 19). They also allow for integration with other transportation modes such as rail or long-distance trucks. While the types and amount of equipment vary between terminals and ports, typical cargo-handling equipment (CHE) in container terminals is sometimes referred to in broad terms as yard equipment and may include mobile gantry cranes, quay cranes, stacking cranes, straddle carriers, reach stackers, container handlers, specialized forklifts, and utility tractor rigs (also known as yard trucks or yard tractors). Cranes, such as rubber-tire gantry (RTG) cranes and container cranes, and trucks are typically the largest sources of port emissions; in some cases they account for more than half of port emissions (Hang Yu et al. 2017; Wilmsmeier and Spengler 2016; Budiyanto et al. 2021).

Ship-to-shore mobile cranes move cargo from the ship to the pier; these cranes are either in a fixed position or move along a track parallel to the pier face. Mobile cranes and equipment, such as RTG cranes or container handlers are often smaller in size and do the work of moving the containers around the terminal. Mobile cranes in use today commonly use diesel generator engines, but increasingly many large U.S. ports have converted over to hybrid or fully electric systems (San Pedro Bay Ports Technology Advancement Program 2021). Indeed, some industry publications note that electrifying RTGs offers the most immediate way of reducing fuel consumption and emissions in ports (Hirvonen et al. 2017). Some mobile and ship-to-shore crane systems use a form of regenerative braking, or energy recuperation (harvesting the potential energy while lowering containers to help reduce energy needs on the next container lift (UMAS et al. 2019), flywheels, or other forms of short-term energy storage to improve efficiency (Fahdi et al. 2019). For example, in 2012 the Port of Savannah deployed 27 electrified RTG cranes with energy recuperation, which allows them to self-power for 18 minutes of each hour, which resulted in an annual savings of $10 million for the port, or about 7.3 gigawatt-hours in electricity costs per year (Gilmore 2017).

Figure 19. Automated electric cranes unload shipping containers onto autonomous guided, electric vehicles at the Long Beach Container Terminal facility in Long Beach, California. (Photo by Dennis Schroeder, NREL)

Yard tractors are another large source of emissions at most ports. Different kinds of trucks are required to move containers: one set that moves containers short distances at the terminal, known as hostlers, and another set of trucks that transports containers on-road to other modes of transport, known as drayage trucks. The hostlers and trucks that remain at the terminal are typically Class 8 trucks that are more robust and heavy-duty. Although terminals vary in their needs, depending on the types of ships and cargo, the largest container ports will have a significant number of these vehicles to support their operations in moving loaded containers. For example, 90 percent of all yard trucks in the Port of Oakland were models that supported heavy marine terminal applications (AECOM 2019).

To reduce the GHG emissions of yard tractors, ports and terminals have explored a variety of diesel fuel alternatives such as biofuels and LNG, hydrogen fuel cells, as well as converting to battery hybrid or all-electric in some cases. Yard tractors are considered heavy-duty vehicles and electrification of these vehicles is not always straightforward, but as of 2020 the San Pedro Bay Ports plan to employ a total of 37 battery-electric or fuel cell drayage trucks, and the Port of Tacoma has plans to employ 6 battery-electric trucks later in 2021 (San Pedro Bay Ports Technology Advancement Program 2021; The Northwest Seaport Alliance 2020).

Energy Impacts

Emissions impacts from hybrid and all-electric cargo-handling equipment vary. Switching to electrified cranes can demonstrate between an 80 percent and a 90 percent reduction in energy costs and a 67 percent reduction in GHG emissions (Y.-C. Yang and Chang 2013; Y.-C.

Yang and Lin 2013) relative to diesel-powered RTGs. One study found that RTGs that leverage energy recuperation reduced GHG emissions at two terminals in the Port of Tokyo by 40 percent (Fahdi et al. 2019). Yard tractors and trucks can achieve varying levels of emissions reductions depending on their load profiles and the technologies used.

One industry report notes that the most efficient hybrid straddle carriers on the market can consume up to 40 percent less fuel and emit 50 tons less CO_2 per year compared to traditional diesel-powered models (Hirvonen et al. 2017).

R&D Needs

Some R&D opportunities relating to CHE include:

- Container terminals vary in size and location, which can affect the range that an electric or hybridized vehicle will need to travel. Some analysis has been undertaken at large U.S. ports to understand torque and range needs for electric drayage trucks, but further study across a larger number of ports would help overcome barriers to adoption of such electric-powered vehicles. For example, some terminal operators have noted that the decreased range of electrified yard equipment often means that they need two vehicles to accomplish the same amount of work as one traditional vehicle. Moreover, continued improvements in the energy density, safety, cost, and performance of batteries in heavy-duty marine yard equipment would be beneficial (Amar et al. 2017).

Microgrids and Smart Grids

Utilities around the Nation have been deploying smart grid technologies, in various forms, for the past 30 years. These new technologies have increased reliability, resilience, efficiency, and reduced emissions wherever they have been deployed (DOE 2018). These same technologies have the potential to support future port operations, including decarbonization through electrification.

Technology Description

Ports and terminals have numerous electrical loads such as offices, lighting, and increasingly cargo-handling equipment and vessels, such as ship-to-shore cranes, on-pier container refrigeration, and shore power for ships when they are in port (Port of Seattle 2021; Fang et al. 2020). The electrification of these vehicles and vessels can take the form of directly charged electric batteries and/or the production of hydrogen for hydrogen fuel cell vehicles. As ports look toward direct electrification of equipment, powering vessels, and the production of e-fuels, constraints on local electrical infrastructure can become a critical challenge. For example, modeling suggests that under aggressive electrification scenarios, electricity energy demand at all ports in the United Kingdom (UK) will increase from 20 gigawatt-hours in 2016 to more than 4 terawatt-hours in 2050 (UMAS et al. 2019). Smart grids and microgrids offer a potential solution.

The U.S. Department of Energy (DOE) defines a microgrid as “a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode" (Ton and Smith 2012). Microgrids are deployed in numerous settings, from industrial facilities to rural villages, to provide resiliency and energy security. Microgrid power capacity ranges from a couple megawatts upwards of 30 megawatts.

While there are range of definitions for what constitutes a "smart grid," the concept is most closely associated with the integration of modern communications and control systems to increase operational flexibility (DOE 2021). For "normal operations" this can include, but is not limited to, advanced sensing and controls, the integration of renewable generation resources, and the electrification of end-use loads. For "abnormal operations," technologies such as microgrids allow for independent local operations if there is a loss of the bulk power system (Schneider et al. 2016; Lasseter 2002; Li et al. 2017; Schneider et al. 2020).

For a port, one or more microgrids could be deployed to support electrification efforts and to act as a resiliency resource if there is a loss of the bulk power system. Microgrids can integrate a range of technologies, including but not limited to, solar PV, wind, battery energy storage, diesel and/or national gas engines, electric vehicles, fuel cells, controllable end-use loads, and advanced controls. While there are a wide range of microgrid types and designs, their basic function is to coordinate local resources to maintain a stable frequency and voltage for critical end-use loads.

During normal operations microgrids could help increase system flexibility and coordinate any local generating resources (Lasseter 2002). During abnormal events, such as a loss of the bulk power system, the microgrids could operate locally to support critical port operations (Li et al. 2017). And if properly designed, networks of microgrids could locally support the offloading of ships during extreme events, providing a critical supply route for necessary materials during a disaster.

Ships that can electrically connect with shore infrastructure can be an electrical load, but also a form of distributed energy storage or a distributed energy resource. A ship might even be considered a microgrid if it can connect to and isolate from the main electrical grid. During emergencies, electric and electric hybrid vessels could potentially serve valuable roles in providing power to a port's microgrid, improving the resiliency to natural disasters or other major outage events that might strike the port.

Generation Sources

The electrical infrastructure of the last century can be characterized by remote large central generating stations (coal, natural gas, nuclear, hydro, etc.) connected to load centers (population centers) by high-voltage transmission lines (69,000 volts to 765,000 volts) (Wood and Wollenberg 1996). While the nation's electrical infrastructure will continue to rely on central generating stations and a strong transmission system, the penetration of renewable generation sources is rapidly increasing. Some of these renewable resources are being deployed as large central stations, but there is also a large amount of smaller distributed generation. The most recognizable form of this type of distributed generation is solar PV. The increasing deployment of generation resources near, and at, ports provides a range of opportunities to support their operations during normal and abnormal conditions.

System Control

One of largest challenges for power system operations is that electricity must be produced as it is consumed because there is a very limited amount of energy storge. For this reason, control systems are necessary to maintain a reliable source of electricity. Historically, the nation's electrical infrastructure has been overbuilt to support peak electrical load. By one estimate, 10 percent of all generation assets and 25 percent of all distribution assets are deployed to cover just 5 percent of the hours in a year (D. Rastler 2010). Advanced control systems allow for greater asset utilization, which minimizes over-building the system and increases reliability and resiliency. For ports, advance power system controls can allow them to support improved operations and continue operations if/when there is a loss of the bulk power system.

Utilities that currently supply ports as electrical customers understand that these are large industrial loads. The challenge is that the electrification of ports has the potential to increase the electrical demand by several orders of magnitude, which is well in excess of what existing local electrical infrastructures can support. While the expansion of service through the construction of additional power lines is an option, this is not always feasible. Ports are often in areas with limited access to rights-of-way and/or in areas where there may not be physical space for constructing new overhead or underground lines. It may not be possible for existing substations and transmission lines to supply the additional load. Additionally, simply building more lines may not be the most cost-effective, or operationally flexible, way to supply these future loads.

Energy Impacts

The energy and emissions impact of adopting microgrids or smart grids at ports varies tremendously and is affected by numerous factors such as generation assets, capacity, etc. For ports such as the Port of Seattle, which is served by Seattle City Light (SCL), electrifying the port loads results in reduced emissions because of the generation mix of SCL (84 percent hydroelectric, 6 percent unspecified, 5 percent nuclear, 4 percent wind, and 1 percent biogas (Seattle City Light 2021)). Even for utilities with a generation mix that is high in fossil fuels, local pollution will be reduced, as well as overall pollution due to the higher operational efficiencies of large generating stations.

The impacts of electrification at a port could lead to substantial new electrical loads such as electrofuel production (ammonia or hydrogen), recharging of large vessels or heavy-duty ground transport, or vessel cold-ironing as examples. For example, an analysis of UK ports forecasts that by 2050 under a business-as-usual scenario, energy consumption from ports is likely to increase by a factor of 15 relative to 2016 consumption (UMAS et al. 2019) These potential future load increases should be considered when developing microgrids in seaports. For both smaller ports such as Kodiak Alaska and larger ports such as Long Beach, CA, supplying enough electrical power for complete electrification may not be possible with the legacy infrastructure. This is especially true if the electrification includes the fleets that are supported by the ports.

R&D Needs

Some R&D opportunities relating to microgrids and smart grids include:

Research is needed on how to most effectively supply the large amounts of electricity that will be needed for future port operations, with a specific focus on the deployment of smart grid technologies and microgrids while bearing in mind the long-term planning needs of ports, terminal operators, and electric utilities (Gerdes 2020). These technologies will allow a more effective utilization of existing assets, reduce unnecessary over-building of infrastructure, and provide options for resilient operations when there is a loss of the bulk power system due to extreme events. Specific areas of research include the following:

- Critical to planning any microgrid in a port is the need to understand the current and future electrical energy demands. Collecting the data (duty cycle, peak power, charging rates, etc.) about existing electrical energy consumers (e.g., hybrid cargo-handling equipment) as well as future loads (e.g., all-electric harbor craft) and will be essential for modeling and designing resilient port microgrids.
- Develop and evaluate the different architectures and generation resource mixes for port electrification, while ensuring that ship and port operations are properly considered. For example, it will be important to determine how to incorporate flexible charging of electric cargo-handling equipment so as not to affect cargo operations or longshoreman labor schedules.
- Determine how microgrids, and networks for microgrids, can be co-located with other port assets and integrated with the regional electrical grid or utility. This is necessary to ensure optimal use of high-value port space and the mixed-ownership operational environment of port. Working with electrical utilities will necessitate alignment between utility and port/terminal planning cycles, which are not always on the same time scale.
- Determine how microgrids, and networks for microgrids, can support critical port operations during extreme events, including, but not limited to, how they can serve as regional resources for importing supplies, act as points of refuge, and act as energy sources for critical social loads such as hospitals. This research should include how full-electric and hybrid vessels could be used as assets to the grid in the form of flexible storage.
- Better quantify the need for resilience and reliability of U.S. port infrastructure, conduct research to quantify the cost of outages based on various threat vectors (extreme weather events or malicious attacks for example). This could be performed at a national scale initially, and applied to specific ports to support their decision-making efforts.

XII.1 Bunkering Infrastructure

Technology Description

Ship refueling, often referred to as bunkering, is the process of supplying fuel to ships for marine boilers, engines, and other fuel consumers. Traditional fossil fuels such as MDO, MGO, HFO, and increasingly LNG have substantial refueling infrastructure globally. Alternative fuels like methanol, ammonia, hydrogen, and advanced biofuels will need to scale up storage and fuel transfer infrastructure across major shipping routes to meet future demand. For electrification and hybridization, recharging infrastructure is discussed in Section IX.1, Energy Sources and Carriers – Hybrid and All-Electric.

Storage facilities such as fuel tanks receive fuel from production facilities and are used for the long-term storage of fuel. Fuel transfer systems are the networks of piping systems, pumps, and other equipment that are used to move the fuel from storage tanks to fixed distribution points throughout the port complex. Sometimes vessels and cargo-handling equipment can refuel directly from fixed distribution points, but many vessel berths may be too far away and must instead rely on a mobile refueling option. Bunker barges and trucks perform the "last-mile delivery" of the fuel by transporting the fuel from fixed distribution points throughout the port complex to vessels or other end-users. The general view across the maritime industry is to leverage existing infrastructure where possible to hopefully reduce costs and optimize the use of limited space. For this reason, alternative fuels are often assessed for their ability to leverage existing fuel infrastructure.

Ammonia, hydrogen, and LNG when used as fuels are all commonly stored in either pressurized or refrigerated tanks, which differ substantially from what is used for traditional fuel oils. Methanol and biofuels may be able to take advantage of similar fossil fuel infrastructure with minor modifications. Some alternative fuels under consideration have long been carried by vessels as cargo, such as ammonia, LNG, and methanol, and the storage facilities for these fuels already exist in some ports to varying levels of capacity. For example, methanol is available at all major shipping hubs (DNV-GL 2019a), but hydrogen is not yet widely available. Note that most alternative fuels have lower energy densities than traditional fossil fuels, so additional storage infrastructure will likely be required when switching to these fuels to provide the same amount of energy.

When transferring these fuels from storage to vessels, bunker trucks or vessels will need to be specially tailored to the fuel they will carry. The mode of transport will depend on the fuel and how it is most effectively transferred for a given quantity. For example ammonia is typically stored in pressurized containers as a gas for relatively small volumes, but liquefied and stored in refrigerated containers for larger volumes (DNV-GL 2021). Methanol is a liquid at ambient conditions, so bunkering for methanol is relatively similar to that for conventional fuel oil (ABS 2021; Andersson and Salazar 2015) and would only require minor modifications; the same is true for some biofuels. LNG and hydrogen require specialized transfer facilities with proper piping, sealing, and gas detection and potentially liquefaction facilities, which is considerably more complex than traditional fuel oils (see Figure 20). LNG has seen the most adoption as an alternative marine fuel in recent years. LNG bunkering infrastructure is currently limited (DNV-

GL 2020) but growing—several new bunkering vessels and barges are being built (DNV-GL 2019a). For context, the world's first purpose-built LNG bunker vessel went into operation in 2017. As of this writing, there are very few bunker vessels purpose-built for hydrogen, ammonia, or methanol or any that could be easily retrofitted to accommodate these fuels.

Figure 16. Non-mobile LNG bunkering infrastructure at port. (Photo by David Hume)

R&D Needs

Some R&D opportunities relating to bunkering infrastructure include:

- With regard to refueling at seaports with alternative fuels, research is needed to support the safe storage and transfer of alternative fuels under consideration. The volumes of fuel needed at port complexes can be substantial and proper storage and supply chains will need to be developed. Planning these investments will need accurate modeling of demand forecasting. For example, according to one study, the potential hydrogen demand at U.S. ports by 2030 ranges from 25,000 kilograms per day for smaller ports to 250,000 kilograms per day for the largest ports in Long Beach and Los Angeles (Steele and Myers 2019). Additional research efforts could support the design, construction, and safe operation of purpose-built bunker vessels and trucks for alternative fuels such as hydrogen, methanol, and ammonia.
- See Section IX.1, Energy Sources and Carriers – Hybrid and All-Electric for electric charging infrastructure R&D.

XIII. Port Operations

Cold-Ironing

Technology Description

When vessels are at anchorage or in port they still need power for a variety of electrical loads for ancillary systems such as heating and cooling of the living areas, cooling fans, cargo pumps, sewage pumps, or refrigerated containers, as examples. Electrical power is often produced using auxiliary IC engines, which run on fossil fuels which leads to localized emissions in and around the port; for example, an estimated 55 percent of the total emissions in a port are from ships (Budiyanto et al. 2021). Instead of using auxiliary power systems, an alternative approach is to connect the ship directly to shore power from the port's electricity supply, a practice known as cold-ironing.

Cold-ironing is broadly applicable across nearly all vessel types and sizes, but the EPA categorizes systems into two main categories: high capacity and low capacity. High-capacity systems are generally greater than 6.6 kilovolts and are intended for larger vessels such as containerships and cruise ships. Low-capacity systems are rated for less than 480 volts and service smaller vessels like harbor craft, tugboats, and fishing boats (EPA 2017). U.S. high-capacity systems generally have power capacities ranging from 8 megawatts to 40 megawatts, while low-capacity systems range from 100 kilowatts to 400 kilowatts. The time that a vessel spends in port connected to shore power depends on numerous factors, but typically the average time in port for vessels at some of the largest U.S. ports ranges from 10 to 90 hours. These systems can be fixed and use the port's microgrid or regional electrical grid, or they can be mobile on a truck or barge and use a self-contained power system fuel such as a hydrogen fuel cell.

According to the EPA's Shore Power Technology Assessment at U.S. Ports, as of 2017 there were 16 U.S. ports with shore power installations, the majority being on the West Coast (EPA 2017). In 2007, the California Air Resources Board (CARB) approved the "Airborne Toxic Control Measure for Auxiliary Diesel Engines Operated on Ocean-Going Vessels At-Berth in a California Port" Regulation, also known as the At-Berth Regulation, which aims to reduce at-berth emissions from engines using shore power or other engine emission control technologies (California Code of Regulations 2021). Other regions across the world are considering similar regulations, which may lead to more widespread use of cold-ironing as an emissions-reduction measure.

Energy Impacts

Ports can either take electricity directly from their local distribution network or generate their own electricity. The magnitude of any potentially emissions reductions from cold-ironing depends on the generation assets used to provide the electricity for these service areas (EPA 2017). The emissions reduction benefits of shore power have been assessed by numerous organizations and researchers. For example, the CARB estimated that their At Berth Regulation, which is designed to reduce air emissions from diesel auxiliary engines on container ships, passenger ships, and refrigerated cargo ships while at berth, would achieve a net reduction of 122,000–242,000 metric tons of CO_2 emissions, or about a 38 to 55 percent reduction, in 2020 for California ports. Using shore power can also help vessels and ports reduce other emissions. In one study from 2013 assessing the impacts for the Port of Charleston, SC, shore power was found to reduce CO by 92 percent, NO_X by 98 percent, PM by up to 66 percent, SO_2 by up to 73 percent, and CO_2 by 26 percent; these reductions were forecasted to increase in magnitude as the local power company reduces its use of coal for electricity generation (J. J. Corbett and Comer 2013).

R&D Needs

Some R&D opportunities relating to cold-ironing include:

- Shore power has been used by the U.S. Navy for many years, but in the commercial realm it has only seen more widespread adoption within the last decade (Fang et al. 2020), and is still not widespread globally. Further studies into best locations for shore power systems, studies of emissions impacts at the ports, and ideal capacity ratings for the ports for installations based on predicted future loads and vessels served by the port are suggested. This research effort overlaps significantly with port microgrid planning and grid integration to ensure that cold-ironing of larger vessels does not disrupt regular gird operations. The EPA Ports Initiative has conducted significant research on shore power capabilities at U.S. ports (EPA 2017), but each port will need to conduct their own detailed studies to understand current and future electrical loads from cold-ironing and other energy consumers.
- Recent advances have been made in developing shore power systems that use alternative fuels and technologies resulting in very low emissions. For instance, SNL has been working industry partners to develop a prototype hydrogen fuel cell shore power system rated for 120 kilowatt. Further research investigating the design, operation, and economics of fuel cell generators and other similar systems would be beneficial to encourage broader use at ports for cold-ironing (van Biert et al. 2016).
- Given the limited port stays of many commercial vessels, streamlined connections and transfer operations to/from shore power are essential for vessel operators to prevent disruption of cargo transfers. Research into power delivery systems, cabling, siting, retrofitting of vessel, and other elements that relate to the physical connection to shore power would be beneficial. Supporting global standards and compatibility on shore power connections would help accelerate industry adoption (Zis 2019).

Port Automation and Capacity Optimization

Technology Description

Automation and capacity optimization often go hand-in-hand for port operations. Automation, or using computer algorithms, can be used to guide or control port operations and equipment in the most efficient ways. Capacity optimization refers to the most optimal use of port space to handle cargo throughput. Port automation and capacity optimization can lead to emissions reductions through numerous ways, but generally through more optimal use of equipment and space, thereby reducing overall emissions intensity for the unit of cargo moved.

Automation could include better scheduling of ground transport fleet and other mobile cargo-handling equipment; automated mooring systems for vessels; ideal route or path planning within the port, potentially using autonomous vehicles; or mitigating idle times of trucks through improved scheduling or gate management (Shiri and Huynh 2016), as examples. Automation generally goes hand-in-hand with electrification, which leads to further reductions in energy consumption and emissions. Container terminals have been thought of as being the most suitable for automated cargo-handling (Chu et al. 2018) because of the more standardized nature of the cargo and regular schedules. The first automated container terminal (ACT) was developed in the early 1990s and today there are around 50 globally (Wang et al. 2019), or roughly 3 percent of the 1600 container terminals in the world. Automation requires reliable and frequent data about spatial and temporal location of equipment and cargo, which requires sensors and streamlined data management systems. Because there may be multiple parties involved between shippers, cargo owners, port owners, terminal operators, and trucking companies, managing these data can be a challenge.

The layout of ACTs must consider numerous factors such as the cargo-handling equipment, equipment cycle times, recharging points, charge times for hybrid and all-electric equipment, idle times, storage space, vessel size, etc. (Wang et al. 2019; Budiyanto et al. 2021). If cargo-handling resources are sited close to where they are needed to reduce traveling distance and congestion, vessels can potentially have their cargo transferred in less time, thereby leading to reduced port emissions attributed to shorter vessels at berth and reduced travel time by cargo-handling equipment.

Energy Impacts

The benefits of automation depend on the specific measure implemented. Because trucks have been shown to be one of the largest contributors to GHGs, considerable GHG reduction can be achieved by minimizing the idling time through gate management (Hang Yu et al. 2017; EPA 2021b). Review of energy and cost savings with automation, modeling costs for standard truck purchase, operation, and maintenance, compared to the same for intelligent automated vehicles over a 15-year period, indicated a nearly 35 percent cost savings if intelligent automated vehicles are used, mostly due to saved energy costs (Kavakeb et al. 2015). Or as another example, a terminal in the Port of New York and New Jersey installed one of the first advanced truck appointment systems in the United States, which resulted in CO_2 reductions of approximately 23,149 tons and a fuel cost savings of $5.3 million in 2017 (EPA 2021b). Note that the emissions benefits from automation are often hard to separate from the emissions benefits of cargo-handling equipment that often go hand-in-hand.

R&D Needs

Some R&D opportunities relating to port automation and capacity optimization include:

- Research into novel algorithms for overall management of cargo from ship to shore for individual terminals will increase efficiency and reduce energy consumption at ports from both the cargo-handling equipment and the vessels calling on the Container

Terminal (Budiyanto et al. 2021; Wang et al. 2019). Little literature investigates the intersection of terminal layout strategies and their impacts on emissions, so further research in this area of study, particularly for ACTs, would be beneficial.

- Automation relies on robust data that are updated frequently. Streamlining the collection, ingestion, and processing of these data into complicated algorithms is often a large challenge for ports seeking to adopt automated processes due to data silos and a lack of data standards (Chu et al. 2018). Research in standard data protocols (format, processing, etc.) would help in the deployment of automated technologies at ports.
- Automation can lead to worker displacement and job loss in some situations. Understanding these social and economic impacts is a critical area of study to ensure that such maritime ERMs lead to positive outcomes for the local community (Guerin 2018).

XIV. Systems Integration

This report has identified a variety of ERMs and considered each in isolation for the sake of clarity. However, there is substantial opportunity in integrating some of these technologies and fuels to achieve even greater emissions reductions. There are limitless ways this could be accomplished; two are presented here as hypothetical examples:

- A seaport microgrid could be powered by renewable energy resources such as solar, wind, and wave. The energy would be used to power typical port activities such as recharging hybrid cargo-handling equipment and lighting up terminals with efficient lighting systems. The microgrid could also be sized to provide power for electrolysis, producing hydrogen that is used in the production of electrofuels like e-methanol or e-ammonia and eventually in fuel cells or other direct clean-hydrogen uses. The electrolyzer would also need freshwater, which would come from a reverse osmosis desalination plant at the port that receives pressurized seawater from pumps driven mechanically by wave energy or electrically from the microgrid.
- A fleet of plug-in hybrid tugboats could be used in a mid-size port to assist the docking of larger vessels that call on the port's terminals. They could recharge periodically when in port, being fed by the regional electrical grid that is powered by renewable energy. Thanks to voyage optimization of the larger vessels and a robust data transfer system, schedules are known well in advance by all stakeholders, which allows for smart charging of the vessels during periods of low demand on the electrical grid. When the tugboats are at berth and inactive they could be used for flexible grid storage, using their large battery storage systems for voltage and frequency regulation. After a major outage event such as an earthquake, the tugboats could be used to power the port's microgrid to help the port provide logistical support to emergency responders.

Systems integration requires a holistic perspective that looks for opportunities for linking technologies together to improve overall energy efficiency or achieving greater emissions reduction. Many of these technologies will need to be integrated into existing infrastructure or modified to accommodate existing regulations, which will require a systems perspective.

Systems thinking is particularly important for electrical grid resilience and disaster recovery, for example. After major natural disasters, such as earthquakes, hurricanes, or tsunamis, restoring logistical services is one of the first priorities to ensure that emergency responders and supplies can reach the people that need them. While the port is most concerned with its day-to-day operations serving shipping companies and terminal operators, in emergencies it can serve a critical function in support of the local community. Several major ports in California, including San Diego, Long Beach, and Los Angeles understand this, and in recent years have invested significant capital in construction of port microgrids to help them ensure energy security and demand flexibility. For example, the Port of Long Beach is even using a mobile battery system that will be installed on a flatbed truck to serve critical loads that the microgrid might not be able to reach (Gerdes 2020). This mobile storage concept could be easily applied to electric ships as well, which are essentially mobile floating battery banks. Ships can and do serve vital roles in disaster recovery. Traditionally, that role has been to transport people and supplies. For example, New York City relied on its ferry operators to carry out response efforts for the September 11, 2001 terror attacks, the Northeast Blackout in 2003, and Superstorm Sandy in 2012 (Guzenfeld 2017). As cold-ironing becomes more prevalent, and all-electric and hybrid vessels become increasingly more common, these ships can serve dual roles as transport and power providers.

XV. Conclusion

This report is a response to legislative language set forth in section 3001(a) of the Consolidated Appropriations Act, 2021 (Pub. L. 116-260, Div. Z, Title II, codified at 42 U.S.C. § 17214(b)) requesting from the U.S. Department of Energy's Water Power Technologies Office a study of non-power sector applications for advanced marine energy technologies with respect to the R&D needs for the maritime transportation sector and its associated maritime energy infrastructure. While there are many R&D opportunities within the maritime industry, this report focuses on those related to reducing the energy consumption and GHG emissions of maritime activities due to Administration priorities and a clear and urgent need expressed by the private sector.

The maritime industry is responsible for nearly three percent of global GHG emissions, or approximately one gigaton every year. Under business-as-usual scenarios these GHG emissions are set to increase throughout the next decades by 30 percent or more, however the industry needs to rapidly reduce its GHG emissions to put it on a pathway to meet U.S. and international goals and targets set for 2050. This may seem far away, but the commercial vessels and port equipment being built this decade will be in operation for the next 25 to 30 years or more, therefore these assets need to be contributing to emissions reductions today.

There are numerous ERMs that can be grouped into decarbonization pathways such as electrification, low-carbon fuels, energy efficiency, operations optimization, and exhaust treatment. Some ERMs offer modest reductions in emissions or fuel consumption while others could lead to zero-emissions. Given the numerous options available, it is important to consider the fuel or technology's impact on a full lifecycle basis.

The commercial readiness and technological maturity of these ERMs varies, but each would benefit from additional R&D activities to increase performance or efficiency or decrease costs. The maritime industry is inherently global and complex; while these ERMs are presented in isolation within this report, it is critical that a systems perspective be used and ERMS be integrated together when possible to achieve even greater reductions. Moreover, the R&D identified is not the sole responsibility of any single office or organization, it will require collaboration and coordination across multiple government offices, universities, cluster organizations, nonprofits, and other industry stakeholders.

The maritime industry is undergoing a once-in-a-century energy transition to meet ambitious goals for GHG emissions reduction. To reach these targets the rate of deployment and adoption of low-carbon fuels and technologies must accelerate. The R&D identified in this report for alternative fuels, energy efficiency, electrification, and other decarbonization pathways can help industry achieve these goals and successfully navigate the energy transition.

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