Bridging the Gap: How Nuclear-Derived Zero-Carbon Fuels Can Help Decarbonize Marine Shipping

Mike Fowler, Clean Air Task Force
Meghan Hammond, Pillsbury Winthrop Shaw Pittman LLP
Jonathan Lewis, Clean Air Task Force
Jeffrey Merrifield, Pillsbury Winthrop Shaw Pittman LLP
Brett Rampal, Clean Air Task Force

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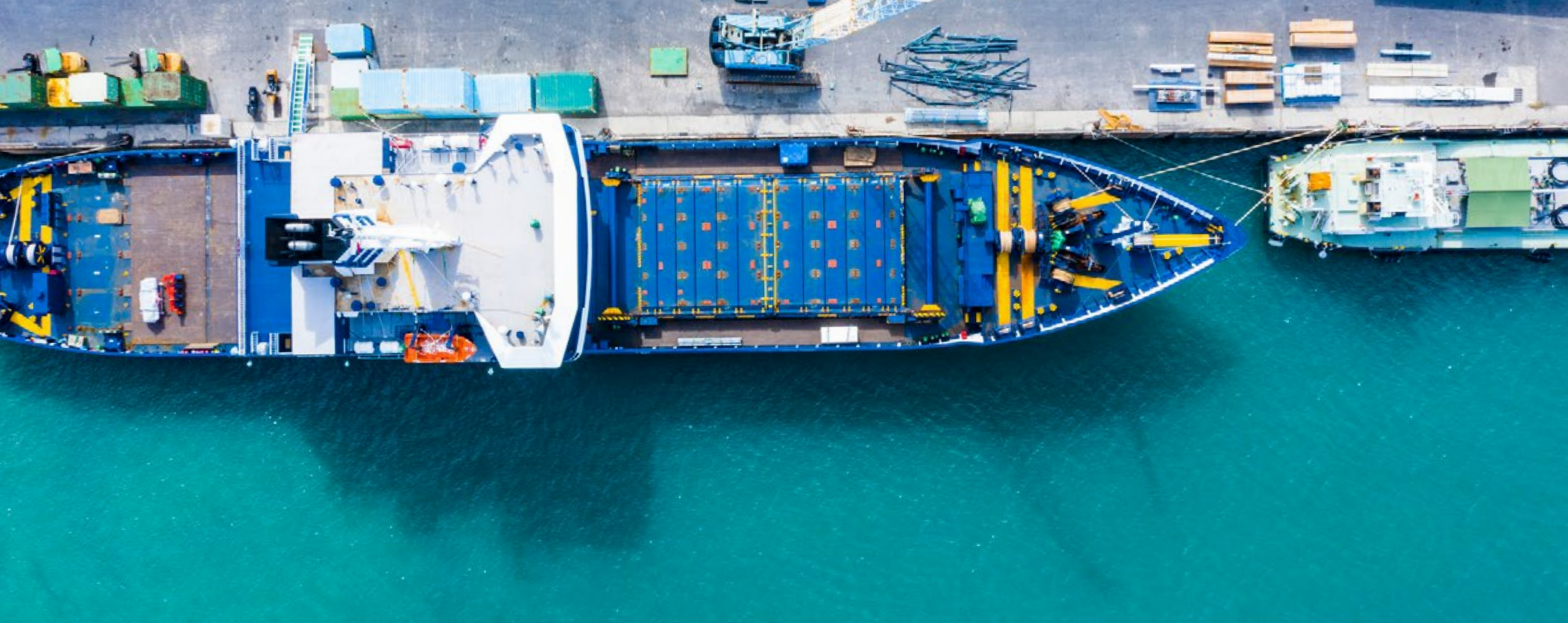

Executive Summary

As the world continues to find ways to decarbonize the electricity sector, our attention needs to turn to hard-to-abate sectors.[1] In 2018, the international shipping industry accounted for 2.6% of the world's carbon dioxide emissions—higher than the international aviation sector. The international shipping community recognizes the need for change and, in lieu of regulations, the International Maritime Organization (IMO) and private actors are driving maritime fleets to modernize and improve fuel efficiency and cost-competitiveness. However, if this sector continues to grow as projected and continues to rely primarily on fossil fuels, sector-wide emissions will triple by 2050.[2] Efficiency gains will help, but such improvements cannot reduce emissions to zero by themselves, let alone offset additional emissions from increased shipping activity.[3] The bottom line is that the maritime sector needs to decarbonize and is under pressure from global organizations and consumers to do so.

Ultimately, eliminating greenhouse gas (GHG) emissions from the global marine shipping sector will require widespread fuel switching, or transitions from conventional fuels to zero-carbon fuels (ZCFs) like hydrogen and/or its more readily useable carrier, ammonia. The ZCF supply chain in the marine sector presents a classic dilemma with users desiring fuel supplies that are practical and affordable, but suppliers unlikely to produce and distribute fuels at scale in advance of market demand. Low-carbon hydrogen produced from renewable electricity, fossil fuels with carbon capture, and nuclear energy can be used to make ZCFs that can play an important role in resolving this dilemma. Additionally, hydrogen-based ZCFs

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[1] Renske Schuitmaker & Pierpaolo Cazzola, *International Maritime Organization Agrees to First Long-Term Plan to Curb Emissions*, INT'L ENERGY AGENCY (Apr. 13, 2018), https://www.iea.org/commentaries/international-maritime-organization-agrees-to-first-long-term-plan-to-curb-emissions.

[2] University Maritime Advisory Services (UMAS), *How Can Shipping Decarbonise?* (2019), https://www.ucl.ac.uk/bartlett/energy/sites/bartlett/files/umas_2019_how_can_shipping_decarbonise_infographic.pdf.

[3] According to a 2017 study by the International Council on Clean Transportation (ICCT), total CO2 emissions from ships increased during 2013 even as many major ship classes became more energy efficient. See Naya Olmer et al., *Greenhouse Gas Emissions from Global Shipping*, 2013–2015, ICCT (Oct. 17, 2017), https://theicct.org/sites/default/files/publications/Global-shipping-GHG-emissions-2013-2015_ICCT-Report_17102017_vF.pdf.

produced from nuclear energy have certain technical and economic advantages, particularly when compared to other zero-carbon options. **Future long-distance shipping reliant on ZCFs would complement hydrogen derived from nuclear energy for reasons such as the existing reliance on a small number of concentrated fueling hubs, the energy density of nuclear technology, the firm and available nature of nuclear energy and the availability of high temperature steam, among numerous others.**

U.S. maritime policy and regulation offers a mechanism to help invest in the sector through incentivizing needed ship-board technologies, fuel switching, and near-term carbon reduction. In addition, the U.S. already has an opportunity to scale up the domestic production of clean hydrogen and ammonia through under-utilized nuclear energy, much of which is accessible by coastal and navigable waterways. **Taken together, U.S. maritime policy and under-utilized nuclear infrastructure could foster development and initial deployment of a nuclear energy derived hydrogen-based ZCF supply chain for maritime shipping. This union would provide immediate environmental benefits, help establish ZCF production infrastructure, and create an enduring global decarbonized industrial leadership position for the country.**

Sufficient investment and exploration of these opportunities could not only lead to the decarbonization of the U.S. domestic fleet, but also create innovation which can be applied across the global shipping industry and solidify U.S. leadership.

The following policy recommendations can help to achieve these goals:

- Increase Research, Development, and Deployment of a Broader Set of Key ZCF Production and End-Use Technologies
- Establish Tax Credits for ZCF Production
- Underwrite Development of Nuclear-Powered ZCF Hubs
- Incentivize New Vessel Construction to Use ZCFs
- Direct the U.S. Maritime Administration (MARAD) to Explore Mechanisms for Supporting U.S. ZCF Supply Chain
- Increase Support of Nuclear Energy Derived Hydrogen-Based ZCF Demonstrations, with Focused Projects on Maritime Fuel Demonstration, through Existing Department of Energy (DOE) Programs
- Incentivize ZCF Use for the Current U.S. Domestic Maritime Fleet
- Develop Incentives to Lower Emissions for Vessels Visiting U.S. Ports
- Build ZCF Vessel Requirements (for New Builds) into Bureau of Ocean Energy Management's (BOEM) Leasing Conditions for Offshore Wind
- Allow Marine ZCFs to Generate Credits in Existing and Prospective Clean Fuel Standards
- Extend Fuel Standards to Inland Vessels
- Promote Technology Inclusivity in Any Policies Supporting the Deployment of Hydrogen-Based ZCFs

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SECTION 1

Introduction

The international shipping industry currently accounts for 2.6% of the world's carbon dioxide emissions—higher than the international aviation sector.[4]

The sector is also responsible for 5% of the world's oil demand, similar to the combined oil demand of the United Kingdom, Germany, and France.[5] Indeed, if the global shipping sector were a country, it would rank sixth on a list of countries with the highest greenhouse gas (GHG) emissions, behind Japan but ahead of Germany, the United Kingdom, and South Korea.[6] As global trade resumes after the COVID-19 pandemic, marine shipping contributions to carbon are expected to grow. As the world continues to find ways to decarbonize the electricity sector, our attention needs to turn to harder-to-abate sectors that could offer opportunity for significant progress.

Unfortunately, the advanced internal combustion systems powering the world's shipping fleet still run on petroleum fuels. These fuels contribute to a variety of harmful pollution impacts, most notably air quality degradation and carbon emissions. **Meeting our climate goals requires significantly lower emissions from vessels relying on fuels as vessels deployed today will remain in service for an average of 30 years into the future.**

The international shipping community recognizes the need for change and maritime fleets are modernizing to provide improved fuel efficiency and cost-competitiveness. 2020 was a watershed year for vessel emissions reductions as the United Nations IMO's new sulfur requirements came into effect. These requirements call for a reduction of sulfur in fuels from 3.5% to 0.5% worldwide, driving shipping owners to adapt operationally and refurbish their fleets to meet these new standards. Despite this progress, it is clear the maritime industry will have to pursue other measures to address carbon emissions.

Ultimately, eliminating GHG emissions from the global marine shipping sector will require widespread fuel-switching, in which most of the fleet transitions from conventional fuels to carbon-free fuels like hydrogen and, most promisingly, ammonia. While several pathways to zero carbon hydrogen are possible, this paper focuses on potential pathways by which nuclear power can contribute to the decarbonization of the shipping sector, principally through use of nuclear-generated electricity technologies that make hydrogen, ammonia, and other ZCFs. The nuclear pathway for marine ZCFs has not yet been a significant part of the marine shipping decarbonization conversation.

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[4] Renske Schuitmaker & Pierpaolo Cazzola, International Maritime Organization Agrees to First Long-Term Plan to Curb Emissions, INT'L ENERGY AGENCY (Apr. 13, 2018), https://www.iea.org/commentaries/international-maritime-organization-agrees-to-first-long-term-plan-to-curb-emissions.

[5] Id.

[6] International Council on Clean Transportation (ICCT) calculated that the shipping sector emitted 932 million CO2-equivalent metric tons of GHG per year 2015, which amounted to 2.6 percent of total global anthropogenic GHG emissions during that period. See Naya Olmer et al., Greenhouse Gas Emissions from Global Shipping, 2013–2015 at 14, ICCT (Oct. 17, 2017), https://theicct.org/sites/default/files/publications/Global-shipping-GHG-emissions-2013-2015_ICCT-Report_17102017_vF.pdf.

SECTION 2

The Challenge of Marine Sector Decarbonization

The shipping industry, like almost every other major sector of the global economy, must achieve significant decarbonization by the middle of the century.[7] In 2018, the IMO announced a commitment to reduce GHG emissions from global shipping by at least 50% below 2008 levels by 2050. A 50% reduction would fall well short of the shipping sector's full obligation in a decarbonizing world, however, amounting to a literal "half measure."

The shipping sector cannot continue to burn fossil fuel and, at the same time, cut its GHG emissions in half, much less achieve full decarbonization. If this sector continues to grow according to long-term projections and continues to power its vessels with fossil fuels, sector-wide emissions will triple by 2050.[8] Efficiency gains, which are typically measured in terms of energy used to move one metric ton of goods one kilometer, will help, but such improvements cannot reduce emissions to zero by themselves, let alone offset additional emissions from increased shipping activity.[9] The IMO's minimum GHG reduction target, combined with future growth projections for the shipping sector and the energy density requirements for powering trans-oceanic travel, indicate that fuel-shifting is necessary.[10]

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[7] Rogelj, J., et al., *Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development*, Intergovernmental Panel on Climate Change (IPCC) (Oct. 8, 2018), https://www.ipcc.ch/sr15/chapter/chapter-2/.

[8] University Maritime Advisory Services (UMAS), *How Can Shipping Decarbonise?* (2019), https://www.ucl.ac.uk/bartlett/energy/sites/bartlett/files/umas_2019_how_can_shipping_decarbonise_infographic.pdf.

[9] According to a 2017 study by ICCT, total CO2 emissions from ships increased during 2013 even as many major ship classes became more energy efficient. See Naya Olmer et al., *Greenhouse Gas Emissions from Global Shipping, 2013–2015*, ICCT (Oct. 17, 2017), https://theicct.org/sites/default/files/publications/Global-shipping-GHG-emissions-2013-2015_ICCT-Report_17102017_vF.pdf.

[10] Lloyd's Register & UMAS, Zero-Emission Vessels: Transition Pathways at 7 (Jan. 2019) (In each of the decarbonization pathways considered, "fossil fuel-based marine fuels (such as Heavy Fuel Oil (HFO), Low Sulphur Heavy Fuel Oil (LSHFO), Marine Diesel Oil (MDO) and Liquefied Natural Gas (LNG)) will completely phase out or will take a small share (~10%) of the total fuel mix in 2050.")

2.1 Current Status of U.S. Domestic Fleet Emissions Reduction

National markets and policies will broadly influence the rate at which industry sectors transition to low- and zero emissions energy systems. The IMO has designated waters off North American coasts as an Emissions Control Area (ECA), which came into effect August 1, 2012.[11] The ECA, which extends 200 nautical miles from the continental U.S., and covers portions of Alaska and Hawaii, requires that vessels within that area burn ultra-low sulfur fuel of 1,000 ppm sulfur (0.1%) or less.[12]

Since the North American ECA was established, U.S.-flag operators have taken steps to transition their fleets to use cleaner burning fuels. However, compliance has primarily consisted of purchasing ultra-low sulfur fuels, installing scrubbers, or transitioning to LNG.[13] The U.S. fleet's seagoing barges have seen less of a fuel transition since the implementation of the ECA limits as they have traditionally burned lower-sulfur fuels and did not require a fleet conversion.[14] Importantly, IMO fuel requirements do not apply to river barges operating on the nation's inland waterway system, which make up the majority of the U.S. domestic fleet. There are, in short, significant opportunities to achieve emissions reductions within the U.S. fleet.

2.2 LNG, Biofuels, and Batteries

As outlined above, in order to achieve just the minimum targets for decarbonization in the shipping sector, all indicators point to fuel-switching. However, the shipping industry is subject to increasing costs and ever-tighter margins.[15] Thus, this transition strongly favors new sources of energy that are:

- Cost-competitive
- Readily producible, storable and moveable at massive scale
- Roughly compatible with existing bunkering, storage, and propulsion technologies
- Sufficiently energy-dense to support a wide range of routes and applications including transoceanic voyages
- Environmentally sustainable
- Familiar in terms of technology and operations to mariners
- Convertible to useful energy through processes that emit zero or near-zero GHG

The remainder of this section briefly examines several alternative fuels for maritime transport against the above criteria, ultimately concluding that hydrogen-based fuels, particularly ammonia, best meet the criteria for fuel switching.

As previously mentioned, liquified natural gas (LNG) has attracted significant attention and investment,[16] in part because it offers some tangible environmental benefits (LNG combustion produces less sulfur dioxide and particulate matter emissions than fuel oil combustion). Yet, the GHG emissions performance of a fully LNG-fueled fleet falls far short of IMO's 2050 GHG emissions reduction target, due to LNG's high carbon content[17] and the emissions (especially methane) from today's LNG supply chain. Recent analyses by the International Council on Clean Transportation and SINTEF Ocean AS have found the net GHG emissions rate from LNG-fueled shipping to be similar to the emissions rate associated with fuel oil and marine gasoil (MGO), using a 20-year global warming potential (GWP).[18]

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[11] The Maritime Executive, *North American Emission Control Area Comes into Effect* (Aug. 1, 2012), https://www.maritime-executive.com/article/north-american-emission-control-area-effective-comes-into-effect.

[12] U.S. Environmental Protection Agency, *Designation of North American Emissions Control Area* (March 2010), https://nepis.epa.gov/Exe/ZyPDF.cgi/P100AU0I.PDF?Dockey=P100AU0I.PDF.

[13] Paul W. Parfomak et al., Congressional Research Service, LNG as a *Maritime Fuel: Prospects and Policy* (Feb. 5, 2019), https://crsreports.congress.gov/product/pdf/R/R45488 (Shippers of dry goods to Alaska, Hawaii, and Puerto Rico have taken delivery or have ordered LNG-fueled and LNG-capable vessels from U.S. shipyards in Philadelphia, PA, and Brownsville, TX. Another company operates five LNG-powered offshore supply vessels built in Gulfport, MS. Other U.S.-flag tanker operators have recently built or have vessels on order with LNG-ready engines, while other operators have chosen to install scrubbers on their existing fleet.)

[14] *Id*. at 6.

[15] See Iain Goodridge, *Three Trends That are Improving Maritime Cost Savings*, THE MARITIME EXECUTIVE (July 6, 2020), https://www.maritime-executive.com/features/three-trends-that-are-improving-maritime-cost-savings-1.

[16] ICCT, *The Climate Implications of Using LNG as a Marine Fuel* at 2-3 (Figs. 1-2) (Jan. 2020), https://theicct.org/sites/default/files/publications/LNG%20as%20marine%20fuel%2C%20working%20paper-02_FINAL_20200416.pdf (hereinafter "ICCT 2020").

[17] LNG is typically comprised of methane (CH_4) and small amounts of ethane (C_2H_6), liquid petroleum gas (C_3H_8), butane (C_4H_{10}), and nitrogen (N_2).

[18] Per ICCT, "Using a 20-year GWP … and factoring in higher upstream emissions for all systems and crankcase emissions for low-pressure

Heavy reliance on biofuels presents a different set of challenges. The net GHG reductions that can be achieved through the use of conventional biofuels made from land-intensive feedstocks like soybeans, rapeseed (canola), and palm oil are modest at best. The net GHG reductions remain low for biofuels because the additional production needed to accommodate demand from the energy sector encourages the conversion of forests and grassland into farmland, a process that transfers enormous volumes of soil carbon into the atmosphere.[19] Biofuels made from waste biomass typically offer better environmental performance because the use of waste material does not encourage the conversion of natural landscapes into farmland. However, aggregating highly dispersed waste feedstocks, like forestry residue can be complicated and expensive. Further, the shipping sector would have to outcompete the aviation industry (which has fewer decarbonization options than the shipping sector) for whatever volume of waste-based biofuel becomes available. At its current size of approximately 3.5 quads per year,[20] the global production of biofuel for transportation markets already poses significant sustainability challenges. These problems could be dangerously exacerbated if biofuel production were increased to meet the projected energy demand from just the global marine freight sector in 2050 (approximately 13 quads per year[21]).[22] Biomass can be converted into a range of fuels and energy carriers that could be utilized by marine vessels—e.g., conventional ethanol, biodiesel, cellulosic biofuels, methanol (see below), hydrogen, electricity—but nearly all forms of bioenergy pose the same questions and raise the same stubborn uncertainties about the amount of biomass available to energy markets, the sustainability of potential supply streams, and the carbon intensity of the production processes and the indirect emissions associated with land use changes.

Methanol also garners attention as a potential marine fuel because it shares several key attributes with LNG. Like LNG, methanol combustion results in lower nitrogen oxide, sulfur oxide, and particulate matter emissions than fuel oil combustion, and it can be used in commercially available dual-fuel marine engines.[23] But another common attribute is that both fuels contain carbon; consequently, methanol-fueled vessels emit significant volumes of carbon dioxide.[24] Although methanol is typically produced from natural gas reforming processes, it can be made through either the gasification or anaerobic digestion of biomass.[25] The use of biomass-derived methanol can be carbon-neutral under specific circumstances involving particular types of biomass, but as discussed above those circumstances are difficult to replicate at climate-relevant scale. There are also efforts in place to produce synthetic methanol using hydrogen and carbon dioxide directly captured from the air (DAC), but because the carbon dioxide concentration in air is quite low, it is unclear whether costs for DAC methanol could be competitive in this sector.

The potential use of batteries on ships is blunted by their practical limitations, both in terms of the routes that these vessels can transit as well as the services these ships can provide. The relatively poor power-to-

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systems, there is no climate benefit from using LNG [in place of residual fuel oil], regardless of the engine technology." ICCT (2020) at 19. SINTEF Ocean AS analysis reached a similar conclusion when it reviewed a 2020 study by Thinkstep, finding that GHG emissions from LNG-fueled low-pressure dual fuel engines exceed those from MGO-fueled engines. Elizabeth Lindstad, *Increased Use of LNG Might Not Reduce Maritime GHG Emissions at All* (June 2019), https://www.transportenvironment.org/sites/te/files/publications/2019_06_Dr_Elizabeth_Lindstad_commentary_LNG_maritime_GHG_emissions.pdf.

[19] Richard Plevin & Daniel Kammen, *Indirect Land Use and Greenhouse Gas Impacts of Biofuels*, in Levin S.A. (ed.), ENCYCLOPEDIA OF BIODIVERSITY (2nd Ed., Vol. 4) (2013), https://escholarship.org/content/qt3fd969cw/qt3fd969cw_noSplash_727bc46d99ee55aa9174d8ad41e3c910.pdf?t=p70uh5; Ecofys et al., *The Land Use Change Impacts of Biofuels Consumed in the EU: Quantification of Area and Greenhouse Gas Impacts* (August 2015), https://ec.europa.eu/energy/sites/ener/files/documents/Final%20Report_GLOBIOM_publication.pdf.

[20] International Energy Agency (IEA), *World Energy Outlook 2019* at Fig. 2-6 (Nov. 2019). One "quad" is one quadrillion British Thermal Units.

[21] U.S. Energy Information Administration, International Energy Outlook 2019: Transportation Sector Freight Sector Energy Consumption by Region and Mode, https://www.eia.gov/outlooks/aeo/data/browser/#/?id=51-IEO2019&cases=Reference (last visited Dec. 7, 2020).

[22] *See* Walter V. Reid, Mariam K. Ali & Christopher B. Field, *The Future of Bioenergy*, 26 GLOBAL CHANGE BIOLOGY 274 (2019), https://doi.org/10.1111/gcb.14883.

[23] The Maritime Executive, *Two Ships Pass Dual-Fuel Methanol Milestone* (July 30, 2019), https://maritime-executive.com/corporate/two-ships-pass-dual-fuel-methanol-milestone.

[24] American Bureau of Shipping, *Sustainability Whitepaper: Methanol as Marine Fuel* 2-3 (February 2021) ("When natural gas is used as feedstock, the GHG emissions from well-to-tank are higher, which implies that well-to-propeller emissions are slightly higher than conventional fuels.") https://absinfo.eagle.org/acton/fs/blocks/showLandingPage/a/16130/p/p-026a/t/page/fm/0

[25] European Technology and Innovation Platform (ETIP) Bioenergy, *Methanol from Biomass Fact Sheet*, https://www.etipbioenergy.eu/index.php?option=com_content&view=article&id=331 (last visited Dec. 7, 2020).

weight ratio of current battery technologies (compared to most liquid and gaseous fuels) effectively limits the range and the payload of battery electric vessels. In a 2020 comparative analysis of multiple fuel options for transoceanic cargo vessel, Lloyd's Register and UMAS, a consultancy affiliated with University College London, determined that "battery technology is simply not competitive and still requires significant development in terms of size, weight and cost of operation before it could be a viable technology as a main propulsion."[26] Energy analyst Vaclav Smil calculates that the battery pack needed to power a large containership from Asia to Europe would weigh approximately 100,000 metric tons and fill roughly 40 percent of the vessel's available cargo space—"an economically ruinous proposition."[27] Consequently, most efforts to commercialize battery-based propulsion systems are focused on near-shore applications.[28] Batteries may play an important role in eliminating emissions of GHG and conventional pollutants from tugs, barges, construction support vessels, and other ships that operate close to shore, but absent significant and transformative changes in battery technologies, the impact that battery-electric systems will have on decarbonizing the long-haul maritime industry in the next several years appears very low.

2.3 Nuclear-Powered Propulsion

In addition to fuel-shifting and alternative fuels, some have proposed vessels which directly use nuclear propulsion to achieve emissions reductions. Since the first nuclear submarine was commissioned in 1954, about 700 nuclear reactors have operated at sea on various vessels. Presently, the U.S. nuclear navy includes 82 nuclear powered warships, four training reactors, and two dedicated labs,[29] with a strong safety record. In addition to the United States, three other countries (Germany, Russia, Japan) have built and operated nuclear-powered vessels for commercial shipping. The U.S. has two nuclear-capable shipyards: Northrop Grumman Newport News in Virginia and General Dynamics' Electric Boat Division in Groton, Connecticut.[30]

Possible tasks for which nuclear powered ships have been proposed include icebreaking. Russia has built nine icebreakers since 1975, including the world's first nuclear-powered surface ship (the NS Lenin) and three recently deployed nuclear-powered icebreakers (the Ural, the Arktika, and the Sibir) that can move through up to 3 meters of polar ice. Others have proposed nuclear powered vessels for long-haul government-operated research vessels because they eliminate the need for refueling, increasing operational endurance, and reducing both GHG emissions and local air pollution. This is especially true for vessels conducting polar region research. Nuclear-powered vessels are not susceptible to the freezing problems that afflict petroleum-based fuels in the Arctic, nor do they emit black carbon particles that "not only absorb heat but also darken snow and ice, reducing regional surface albedo and spurring further glacial melt and sea ice retreat."[31]

However, there are formidable obstacles to direct nuclear propulsion. There are a number of ports around the world that restrict access to nuclear powered military vessels. Additionally, the issue of finding adequate commercially available insurance for commercial nuclear-powered vessels could be a challenge and sovereign liability guarantees might be needed to facilitate the more widespread use of civilian nuclear vessels.[32] Finally, in many parts of the world, there is public opposition to nuclear energy that would make its use in mobile sources such as ships highly challenging.

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[26] Lloyd's Register & UMAS, *Techno-Economic Assessment of Zero-Carbon Fuels* at 34 (Mar. 2020), https://www.lr.org/en/insights/global-marine-trends-2030/techno-economic-assessment-of-zero-carbon-fuels/ (hereinafter LR & UMAS 2020).

[27] Vaclav Smil, *Electric Container Ships Are Stuck on the Horizon: Batteries still can't scale up to power the world's biggest vessels, IEEE SPECTRUM* (February 27, 2019), https://spectrum.ieee.org/transportation/marine/electric-container-ships-are-stuck-on-the-horizon.

[28] *See* BUREAU VERITAS, *Charging Into The Future With Electric Power Systems* (Oct. 7, 2019), https://marine-offshore.bureauveritas.com/magazine/charging-future-electric-power-systems (noting the first wave of battery-powered vessels have been limited to "this limits the potential of purely electric ships to short sea ferries, inland navigation vessels and small boats," including ferries and hybrid battery/diesel vessels to service offshore windfarms).

[29] The United States Government owns two research, development and training laboratories that are used to support the U.S. Navy nuclear propulsion program. One is the Bettis Atomic Power Laboratory, which is located in the Pittsburg suburb of West Mifflin, Pennsylvania and the other is the Knolls Atomic Power Laboratory located in Niskayuna, New York in Saratoga County.

[30] Congressional Research Service, *Navy Nuclear-Powered Surface Ships: Background, Issues, and Options for Congress* (Sept. 29, 2010), https://fas.org/sgp/crs/weapons/RL33946.pdf.

[31] Laura Stricker, Clean Air Task Force, *Buying Time: Controlling Black Carbon and Methane Emissions in the Arctic* (August 31, 2015), https://www.catf.us/wp-content/uploads/2015/08/CATF_WhitePaper_BuyingTime.pdf.

For these reasons, this report focuses on nuclear energy use for intermediate fuel production rather than direct propulsion.

2.4 Hydrogen and Ammonia as Marine Fuel

Hydrogen-based fuels—especially ammonia, which is made by combining hydrogen with nitrogen—offer a robust pathway to marine sector decarbonization. Hydrogen and ammonia can be produced through processes that emit little or no GHG (either by using electricity from zero-carbon generation technologies to extract hydrogen atoms from water molecules, or by installing carbon capture and storage systems at facilities that reform natural gas - mainly methane - into streams of hydrogen and carbon dioxide). Because hydrogen and ammonia contain no carbon atoms, the process of converting them into energy in an engine or a fuel cell produces no carbon dioxide.

The use of hydrogen as fuel in vessels, usually ferries and tugs, is currently being developed for commercial use in Europe, North America, and Asia.[33] Liquified hydrogen has a relatively low volumetric energy density, but still higher than compressed hydrogen gas and batteries, and it may be an acceptable fuel for certain short distance marine routes (Table 1).[35] Hydrogen can be produced through electrolysis (splitting water molecules with electricity), or by reforming hydrocarbon feedstocks.

Table 1: Comparison of Various Marine Fuel Options[34]

Fuel[a]	Energy Density, LHV[b], MJ kg-1	Volumetric energy density, GJ m-3	Storage pressure, bar	Storage temperature, °C	CO_2 emissions x 10^3, kg per trip[c]
MGO	42.7	36.6	1	rt[d]	277
HFO	40.4	38.3	1	rt[d]	286
LNG	50	23.4	1.0	-162	220
Methanol	19.9	15.8	1	20	254
Compressed hydrogen	120.0	7.5	700	20	0
Liquid hydrogen	120.0	8.5	1	-253	0
Liquid ammonia	18.6	12.7	1 or 10	-34 or 20	0

Notes on Table 1: a) MGO: marine gas oil; HFO: heavy fuel oil; LNG: liquified natural gas; b) LHV: lower heating value; c) CO_2 based on a single trip from Piraeus to Rotterdam (5893km) of a container ship with a size 1000 TEU (additional details available in original publication); d) rt: room temperature.

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[32] The authors did consider the potential use of ammonia to convert non-nuclear ships of the U.S. Navy to this carbon free source. We are not recommending such a change at this time for several practical reasons including the number of personnel on the ship who could be exposed to ammonia releases in the event the ship came under hostile fire during a conflict as well as the understandable concern of the Navy about the increase in fuel consumption that would make their warfighting job even more difficult during a conflict situation. We believe the Navy should continue to evaluate options for deploying nuclear reactors on additional vessels within their fleet (outside of the submarine and carrier fleets that are already powered with this carbon free source) and should consider other carbon free and low carbon options to reduce overall Navy carbon emissions.

[33] *See* The Motorship, *Norway Plans Hydrogen Network for Ships* (Jan. 9, 2020), https://www.motorship.com/news101/alternative-fuels/norway-plans-hydrogen-network-for-ships; Sandia National Laboratories, SF-BREEZE (April 1, 2020), https://energy.sandia.gov/programs/sustainable-transportation/hydrogen/market-transformation/maritime-fuel-cells/sf-breeze/; Martyn Wingrove, *Japan Takes Leap into Hydrogen Fuel*, Riviera (Oct 19, 2019), https://www.rivieramm.com/news-content-hub/news-content-hub/japan-takes-a-leap-into-hydrogen-fuel-56658.

[34] T.Ayvali et al., *The Position of Ammonia in Decarbonising Maritime Industry: An Overview and Perspectives: Part I*, Johnson Matthey Technol. Rev., 2021, 65, (2), 275, doi:10.1595/205651321×16043240667033. See also Karin van Kranenberg et al., *E-Fuels: Towards a More Sustainable Future for Truck Transport, Shipping and Aviation* at Tbl. 1 (July 2020), https://emis.vito.be/sites/emis/files/articles/91/2020/vankranenburg-2020-efuels.pdf for batteries.

The latter is by far the dominant commercial process today, but currently results in significant emissions of greenhouse gas.[36] Commercial electrolysis is practiced at a smaller scale historically and is electricity-intensive. Additionally, the deep cryogenic conditions needed to liquify hydrogen (-253°C / -423°F) make the fuel challenging to produce and store, particularly on space-limited cargo ships.

Ammonia also entails an energy-intensive production process, but it has physical properties (*e.g.*, storability) similar to liquid petroleum gas and a volumetric energy density roughly 50% higher than that of liquified hydrogen even before considering insulation and other tank requirements. Ammonia is produced by reacting gaseous hydrogen and gaseous nitrogen over a catalyst at elevated pressure and temperature. Nitrogen can be extracted from ambient air, although the process—which is accomplished through cryogenic separation or other means—requires electricity. Once hydrogen and nitrogen gases are available, the manufacture of ammonia is a straightforward process, and has been practiced at an industrial scale for decades using established commercial technology. Currently, most of the ammonia produced world-wide is used to fertilize crops. Given the trends and technology development underway, that status is likely to change as ammonia exhibits many of the positive attributes that are needed for a next-generation shipping fuel.

Ammonia is carbon-free and can be both produced and combusted without emitting carbon dioxide. It can be burned in new or modified two- and four-stroke engines that are substantially similar to the engines that power the majority of ocean-going ships, and it can be stored as a liquid at modest refrigeration (-33°C) in the same types of tanks used to hold liquid petroleum gas or under modest pressure. Ammonia production has been carried out at large scale for over a century, and is massively scalable because it is made from abundant natural resources. Ammonia's superior energy density makes it possible for ammonia-fueled ships to travel farther and carry larger cargoes than ships powered by batteries or hydrogen.

2.5 Ammonia Transition

Marine vessels, especially the transoceanic container ships, bulk carriers, and oil tankers that collectively account for 55% of the marine sector's GHG emissions,[37] are particularly well positioned for a shift to ammonia-fueled internal combustion engines and combustion turbines (and possibly solid oxide fuel cells). Ocean-going ships can more easily accommodate heavier engines and larger fuel tanks, and ships are already fueled by professionals who can be trained to manage ammonia safely. Ammonia can also be integrated gradually into the shipping sector's fuel mix, which allows stakeholders to manage the cost of their transition to cleaner fuel. The supply chain for ammonia bunker fuel can build on an existing industrial base that produces approximately 180 million metric tons of ammonia annually.[38]

However, nearly all of the ammonia produced today is done so using highly carbon-intensive processes. Almost 3 metric tons of CO_2 can be emitted for every metric ton of ammonia produced.[39] Thus, traditionally produced ammonia is not a viable end-point for the maritime fuel transition to ZCFs.

Ammonia can be produced with low- or zero-lifecycle GHG emissions, however, using several production pathways. As mentioned above, one approach is to capture and permanently sequester the GHG that is produced (and typically released) in the course of methane reforming. Another is to use electricity

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[35] The electrification of the propulsion system—in which a direct drive motor is used instead of a traditional propeller shaft—could play a complementary role in reducing emissions from commercial vessels, particularly if the direct drive is paired with fuel cell or battery storage technologies. The newly commissioned guided missile destroyer U.S.S. Zumwalt (DDG-1000) uses a General Electric high-voltage propulsion drive train consisting of multiphase converters and advanced induction motors, making it the Navy's first fully electric powered ship (the Zumwalt uses gas turbines to generate the electricity). In addition to providing propulsion, heating and cooling and other ship power needs, the all-electric drive system is also more energy efficient than traditionally powered ships.

[36] As discussed below, carbon capture and storage systems can be used to significantly reduce the amount of carbon dioxide emitted from existing and new-build gas reforming facilities.

[37] Dan Rutherford et al., ICCT, *Potential CO2 Reductions Under the Energy Efficiency Existing Ship Index* at 5 (Nov. 2020), https://theicct.org/sites/default/files/publications/Marine-EEXI-nov2020.pdf.

[38] Trevor Brown, *Updating the ,literature: Ammonia consumes 43% of Global Hydrogen*, Ammonia Energy Ass'n (Jan. 3, 2020), https://www.ammoniaenergy.org/articles/updating-the-literature-ammonia-consumes-43-of-global-hydrogen/ (noting that US Geological Survey indicates that 180 million metric tons of ammonia were produced globally in 2018).

[39] Trevor Brown, *Ammonia Production Causes 1% of Total Global GHG Emissions, Ammonia Industry* (Apr. 26, 2016), https://ammoniaindustry.com/ammonia-production-causes-1-percent-of-total-global-ghg-emissions/.

generated from wind, solar, or other zero-carbon energy sources to power the electrolysis of water. This paper will further explore the production of ammonia through zero-emission pathways powered by nuclear resources. As more ammonia made from low- and zero-carbon production processes becomes available, it can be blended at increasingly higher levels with conventionally produced ammonia to progressively reduce the overall carbon intensity of the ammonia used to fuel ship engines and the overall carbon footprint of the maritime industry.

Indeed, numerous recent studies have identified wide-scale fuel-switching to ammonia as one of the most promising tools for decarbonizing the marine shipping sector.[40] Lloyd's Register and UMAS found that "ammonia produced from hydrogen, where the hydrogen is produced from NG [natural gas] with CCS, can be considered to be comparable to biofuels in the short-term and becomes the lowest cost zero-carbon option out to the 2050s. Furthermore, over time, the production and supply of ammonia can transition from NG to hydrogen produced from renewable energy, providing a more resilient long-term transition pathway."[41]

The shipping industry has already taken notice. In 2018, AP Møller Maersk AS, the world's largest container ship and supply vessel company, announced it would reduce CO2 emissions from operations to zero (on a net-basis) by 2050.[42] In 2019, the company identified ammonia as one of the fuel options it would investigate,[43] and in 2020 it became a founding company in the new Center for Zero Carbon Shipping in Denmark.[44] Finally, MAN Energy Services, whose engines "cover an estimated 50% of the power needed for all-world trade,"[45] is both designing new ammonia-compatible dual-fuel engines[46] and developing the capacity to retrofit its existing engines to accommodate ammonia fuel.[47]

That being said, like most fuels, ammonia presents risks that must be carefully managed. Ammonia is a toxic substance, and when it leaks into the atmosphere under some circumstances it can facilitate the formation of health-damaging fine-particulate matter.[48] Ammonia combustion can also produce nitrogen oxide (NOx) pollution, which aggravates respiratory illnesses and contributes to ozone formation.[49] These risks can be mitigated through the use of safety protocols that have allowed for the safe use of ammonia in industrial settings for more than 100 years as well as modern combustion practices and technologies.

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[40] See, e.g., LR-UMAS (2020); Alfa Laval, Hafnia, Haldor Topsoe, Vesta, Siemens Gamesa, *Ammonfuel--An Industrial View of Ammonia as a Marine Fuel* (Aug. 2020), https://hafniabw.com/wp-content/uploads/2020/08/Ammonfuel-Report-an-industrial-view-of-ammonia-as-a-marine-fuel.pdf; Shell, *Decarbonising Shipping: All Hands on Deck* (July 2020), https://www.shell.com/promos/energy-and-innovation/decarbonising-shipping-all-hands-on-deck/_jcr_content.stream/1594141914406/b4878c899602611f78d36655ebff06307e49d0f8/decarbonising-shipping-report.pdf; MAN Energy Solutions, *Engineering the Future Two-Stroke Green-Ammonia Engine* (2019), https://www.man-es.com/docs/default-source/marine/tools/engineering-the-future-two-stroke-green-ammonia-engine.pdf?sfvrsn=2b4d9d8a_10 (hereinafter "MAN-ES (2019)"); Kyunghwa Kim, et al., *A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments*, 8 J. MAR. SCI. ENG. 183 (2020), https://www.mdpi.com/2077-1312/8/3/183/htm.

[41] LR-UMAS (2020) at 4.

[42] Kate Wheeling, *At COP24, the Shipping Giant Maersk is Leading the Way to Zero Emissions*, Pacific Standard (Dec. 7, 2018), https://psmag.com/environment/at-cop24-the-shipping-giant-maersk-is-leading-the-way-to-zero-emissions.

[43] Michael Angell, *Maersk Outlines Fuel Choices for Shipping's Carbon-Free Future*, Freightwaves (Oct. 24, 2019), https://www.freightwaves.com/news/maersk-outlines-fuel-choices-for-shippings-carbon-free-future.

[44] Press Release, *New Research Center Will Lead the Way for Decarbonizing Shipping*, A.P. Møller - Mærsk (June 25, 2020), https://www.maersk.com/news/articles/2020/06/25/new-research-center-will-lead-the-way-for-decarbonizing-shipping (announcing Maersk's 400 million DKK donation and the founding company partners of ABS, A.P. Møller - Mærsk, Cargill, MAN Energy Solutions, Mitsubishi Heavy Industries, NYK Line and Siemens Energy).

[45] MAN Energy Solutions, Marine Engines & Systems, https://marine.man-es.com/ (last visited Dec. 7, 2020).

[46] MAN-ES (2020).

[47] MAN Energy Solutions (2019), Future Proof Your Investment: Solutions For Retrofitting To Alternative Fuels–Now Adding Ammonia (NH3) (presentation on file with authors).

[48] *See* Clean Air Plans; 20016 Fine Particulate Matter Nonattainment Area Requirements; San Joaquin Valley, California, 85 FED. REG. 17382 (proposed Mar. 27, 2020), https://www.federalregister.gov/documents/2020/03/27/2020-05914/clean-air-plans-2006-fine-particulate-matter-nonattainment-area-requirements-san-joaquin-valley

[49] Conveniently, selective catalytic reduction (SCR), the pollution control technology commonly relied on by power plants and ships to reduce NOx emissions, uses ammonia as a reagent.

SECTION 3

ZCF Production and the Role for Nuclear Energy

The practicality and economics of the ZCF supply chain is the most critical issue in achieving maritime fuel-switching. How those fuels are produced is critical to ensuring a low- or zero-carbon lifecycle. While steam methane reforming is the more common practice for the global production of hydrogen and ammonia, declining costs and a focus on reducing emissions has renewed interest in electrolysis technologies. Electrolysis utilizes electricity and an electrolyte medium made from ceramic, polymers, or a liquid alkaline solution to split water into its hydrogen and oxygen constituents.[50] The basic tenets of electrolysis were pioneered more than two hundred years ago, and the technology was widely used for commercial hydrogen production by the early 1900s.[51] The 1920s and 1930s saw a significant global expansion in electrolysis capacity, but less costly steam methane reforming systems eventually captured the bulk of the hydrogen supply market.[52] However, electrolysis is poised to regain its ground—if a zero-carbon source is used to generate the power needed for electrolysis, it can reduce the lifecycle carbon emissions associated with the production and eventual use of hydrogen and ammonia to near zero.

Nuclear energy offers numerous aspects that make it well suited for pairing with electrolysis and potentially provides nuclear technology the opportunity for entry into new markets, such as maritime shipping. Pairing electrolysis with low-emissions electricity sources and specifically nuclear electrolysis are both well proven with decades of experience in European hydroelectric hydrogen plants and naval submarines for oxygen

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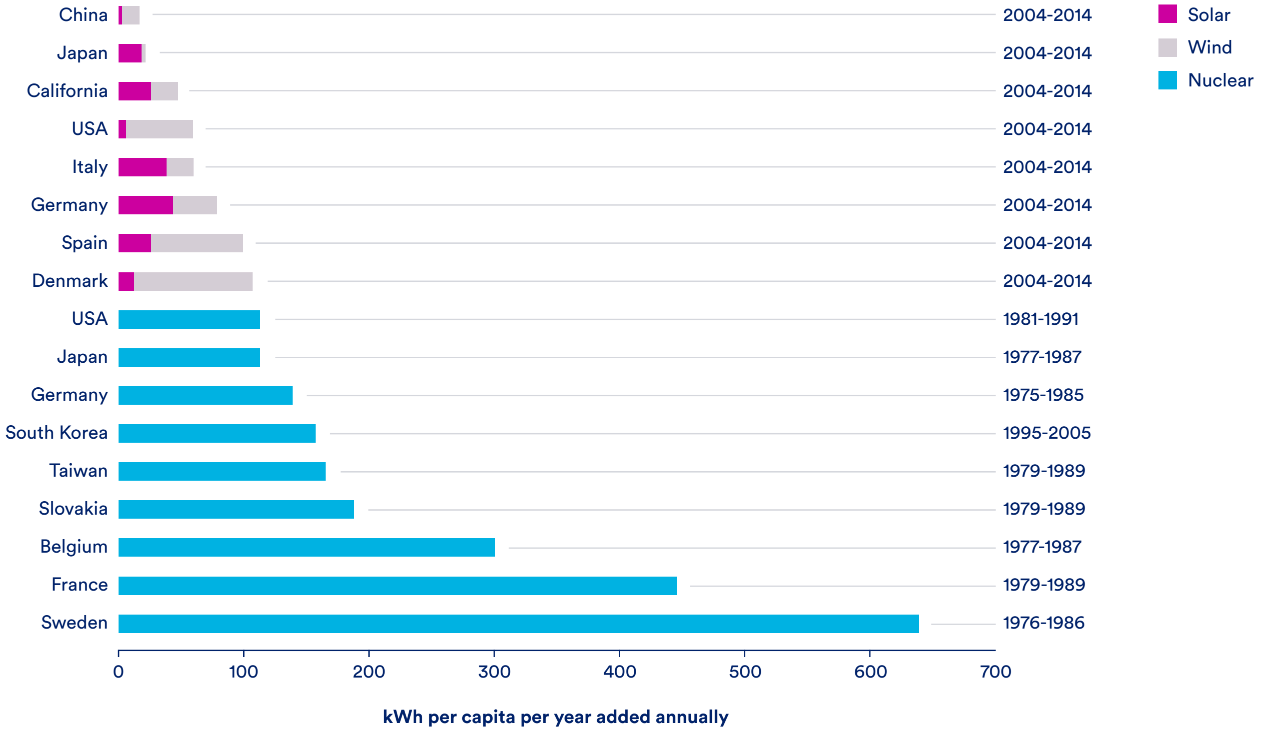
[50] DOE EERE, Hydrogen Production: Electrolysis, https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis.

[51] Greig Chisholm and Leroy Cronin, Hydrogen from Water Electrolysis, in *Storing Energy* at 318 (2016), http://www.chem.gla.ac.uk/cronin/media/papers/Chisholm-Chapter_16_2016.pdf.

[52] B. Kroposki et al, Electrolysis: Information and Opportunity for Electric Power Utilities at 6 (National Renewable Energy Laboratory, 2016), https://www.nrel.gov/docs/fy06osti/40605.pdf.

Figure 1: Average Annual Increase of Carbon-free Electricity per Capita During Decade of Peak Growth[53]



production, respectively. Several nations are currently examining the potential role for existing and future nuclear power plants in hydrogen production and can lay the groundwork for nuclear technology to help achieve worldwide emissions goals.

3.1 The Compatibility of Nuclear Energy and Electrolysis

Hydrogen Consumption at Nuclear Power Plants – Nuclear power plants utilize hydrogen to varying degrees in their daily operations. The largest use of hydrogen in nuclear power plants is for the control of hydrogen water chemistry (HWC) to mitigate stress corrosion cracking in boiling water reactors (BWRs) which comprise about one-third of the current U.S. reactor fleet. Additionally, numerous BWRs and pressurized water reactors in the U.S. utilize hydrogen to cool their generators, as do a large number of fossil generating units, but the consumption per unit is smaller than for HWC. Each BWR in the U.S. consumes around three metric tons of hydrogen each day for HWC and the entire U.S. reactor fleet consumes less than 200 kg of hydrogen each day for generator cooling purposes.[54] As already established users of hydrogen, existing nuclear power plants offer a unique opportunity to explore hydrogen production for on-site demand and demand in other sectors, including shipping. Additionally, the proximity of many existing nuclear power plants to established waterways increases their utility for marine ZCF production.

Historically Fast-Scaling – Nuclear energy is historically proven to be able to quickly scale to potential energy needs, such as those required for a transition from carbon emitting fuels to hydrogen-based fuels provided through electrolysis. Figure 1 shows numerous historical examples of the fastest global additions of carbon-free electricity, of which the largest additions are from nuclear energy.

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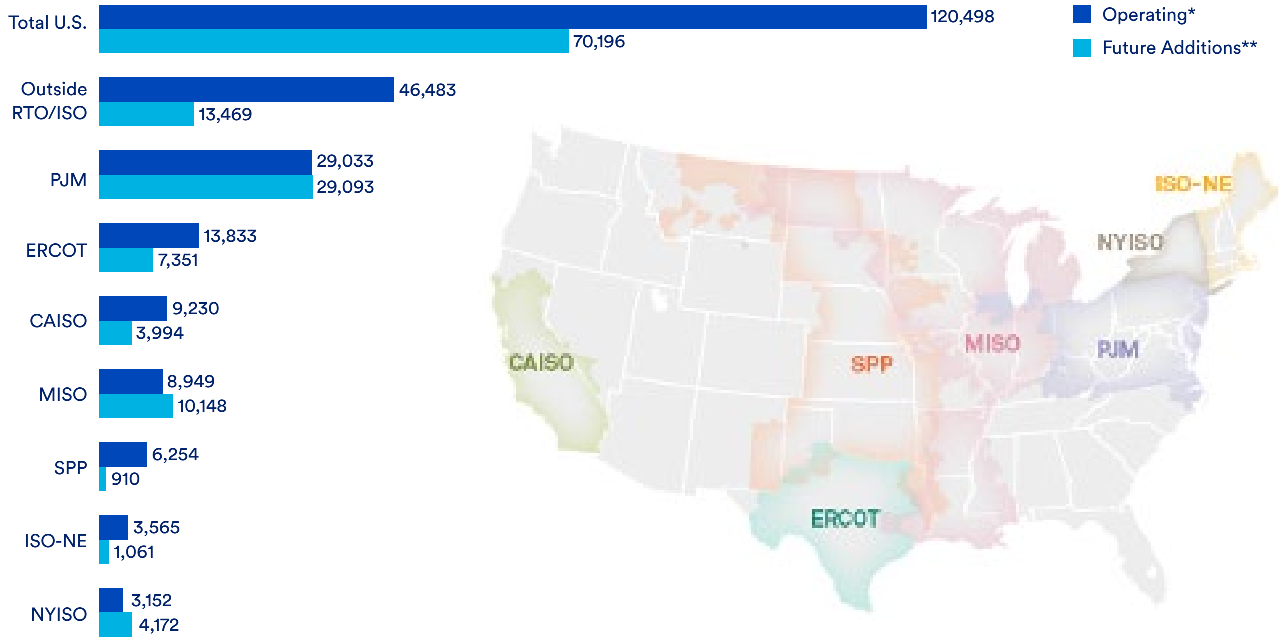
[53] Junji Cao et al., *China-U.S. Cooperation to Advance Nuclear Power*, 353:6299 SCIENCE MAG. 547, 548 (2016), https://science.sciencemag.org/content/353/6299/547.

[54] General Electric Global Research Center, *Feasibility Study of Hydrogen Production from Existing Nuclear Power Plants using Alkaline Electrolysis*, December 2008, https://www.osti.gov/biblio/945378.

Figure 2: Gas Plant Additions Since 2008 in the U.S. and by Region (MW)[55]



Source: S&P Global Market Intelligence

Data compiled August 1, 2019. Outside RTO/ISO covers all or part of states not participating in regional power markets.

* Reflects the current capacity for operating plants that came on between Jan 1, 2008 to Aug 1, 2019. Excludes gas plants that started operations but retired or became out of service in the period.

**Reflects the planned capacity for projects scheduled to operate in 2019 to 2027.

There are a variety of small modular advanced nuclear reactors (sized in the tens or hundreds of MWe) that are under development which are intended to be factory built and/or modularly deployed. By utilizing simplified designs as well as adopting the engineering, fabrication, and construction techniques utilized by the natural gas units that have been widely deployed in the U.S. over the last 20 years (as shown in Figure 2), they could reduce the cost and speed of construction when compared with previously deployed nuclear units. Additionally, some challenged western deployments of nuclear technology, such as the abandoned V.C. Summer project in South Carolina, teach important lessons for future nuclear deployments about effective project management, financing, engineering, and construction approaches that can improve the cost and timeline.[56] This strategy could allow advanced nuclear energy to be widely deployed for energy production or electrolysis.[57]

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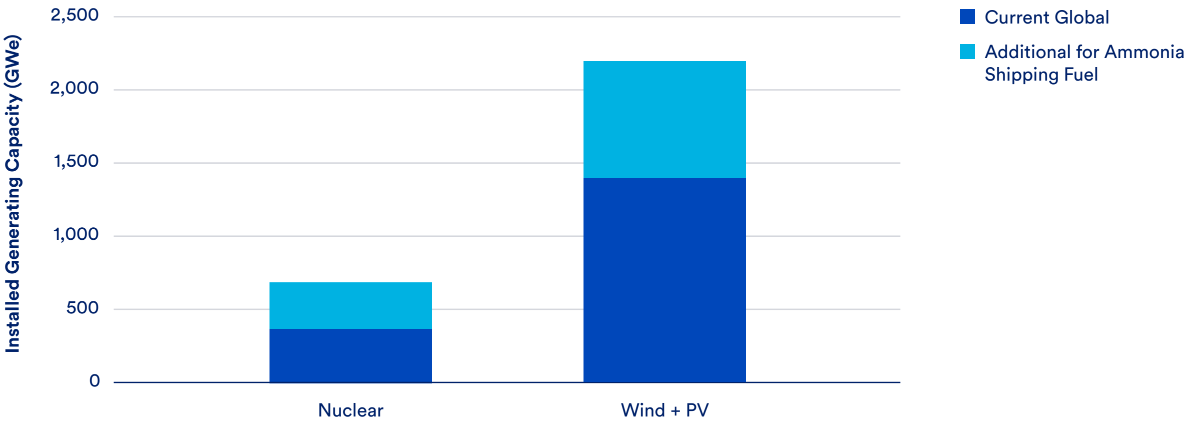
[55] *Id.*

[56] *See, e.g.*, Energy Technologies Institute, *The ETI Nuclear Cost Drivers Project: Summary Report* (Apr. 20, 2018), https://d2umxnkyjne36n.cloudfront.net/documents/D7.3-ETI-Nuclear-Cost-Drivers-Summary-Report_April-20.pdf?mtime=20180426151016; Philip Eash-Gates et al., *Sources of Cost Overrun in Nuclear Power Plant Construction Call for a New Approach to Engineering Design*, 4 JOULE 11, 2348 (2018), https://www.sciencedirect.com/science/article/abs/pii/S254243512030458X?dgcid=author; Massachusetts Institute of Technology, *The Future of Nuclear Energy in a Carbon-Constrained World* (2018), http://energy.mit.edu/research/future-nuclear-energy-carbon-constrained-world/.

[57] Stephanie Tsao & Richard Martin, *Overpowered: Why a US Gas-Building Spree Continues Despite Electricity Glut*, S&P GLOBAL (Dec. 2, 2019), https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/overpowered-why-a-us-gas-building-spree-continues-despite-electricity-glut-54188928.

Energy Density – Natural resources and land are precious commodities and the inherent energy density of nuclear technologies limits key resource consumption. Nuclear energy utilizes less land[58] and resources than any other large-scale energy source—a key attribute in building up a large-scale, low-carbon hydrogen and ammonia supply. Making hydrogen and ammonia from renewable energy-powered electrolysis offers clear carbon-reduction benefits, but also substantial scaling challenges. Huge amounts of wind and solar generating capacity would be needed to make enough ammonia to satisfy demand from the shipping sector. Containerships and bulk carriers consumed 118 million metric tons of heavy fuel oil-equivalent fuel in 2018.[59] If those same ships ran on ammonia instead of conventional fuel oil, they would have consumed 223 million metric tons of ammonia.[60] Producing that much ammonia from electricity would require 2.3 million GWh/year[61] — a substantial increase over the total amount of electricity generated from wind and solar globally in 2018 (1.8 million GWh).[62] Figure 3 shows the additional installed capacity needed to produce 2.3 million GWh per year using nuclear energy at 93.4% capacity factor and a blend of wind and solar power at 31.9% capacity factor, compared to the current global installed capacity of each pathway.[63] Roughly a quarter million square kilometers

Figure 3: Comparison of Clean Electricity Needed for Marine Fuels Production



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[58] Written testimony of Armond Cohen, U.S. House of Representatives Committee on Energy and Commerce, Subcommittee on Energy, Hearing on Building a 100 Percent Clean Economy: Advanced Nuclear Technology's Role in a Decarbonized Future (Mar. 3, 2020), https://www.catf.us/wp-content/uploads/2020/03/Armond-Cohen-Testimony-March-3-2020.pdf; *see also* Strata, *The Footprint of Energy: Land Use of U.S. Electricity Production* (June 2017), https://www.strata.org/pdf/2017/footprints-full.pdf; Anne M. Trainor et al., *Energy Sprawl is the Largest Driver of Land Use Change in the United States*, 11 PLOS ONE 9 (2016), https://journals.plos.org/plosone/article/file?id=10.1371/journal.pone.0162269&type=printable.

[59] IMO, *Fourth IMO GHG Study 2020—Executive Summary* (2020), at page 7, Fig. 5, https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20Executive-Summary.pdf)

[60] Conversion assumes that 1.89 metric tons of ammonia fuel replace 1 metric ton of HFO fuel in marine containership reciprocating engines systems. See Kim et al, A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments, Journal of Marine Science and Engineering (2020), https://www.mdpi.com/2077-1312/8/3/183

[61] Conversion assumes 10.25 MWh of electricity is required to produce one metric ton of ammonia, including electrolysis for hydrogen production, air separation for nitrogen production, and Haber-Bosch synthesis. Range of conversion factors accounts for varying assumptions in different studies about the electrolysis technologies used and the estimated performance of those technologies. See LR-UMAS (2020), https://www.lr.org/en/insights/global-marine-trends-2030/techno-economic-assessment-of-zero-carbon-fuels/; Alfa Laval, Hafnia, Haldor Topsoe, Vesta, Siemens Gamesa, *Ammonfuel–An Industrial View of Ammonia as a Marine Fuel* (Aug. 2020), https://hafniabw.com/wp-content/uploads/2020/08/Ammonfuel-Report-an-industrial-view-of-ammonia-as-a-marine-fuel.pdf.

[62] According to data from the International Renewable Energy Agency (IRENA), in 2018 the world generated 1,262,914 GWh from wind and 562,033 GWh from solar. In 2020 global installed capacity of wind and solar was 1440 GW, but generation figures for 2019 and 2020 are not yet available. IRENA, *Renewable Energy Statistics 2020* (July 2020), https://www.irena.org/publications/2020/Jul/Renewable-energy-statistics-2020.

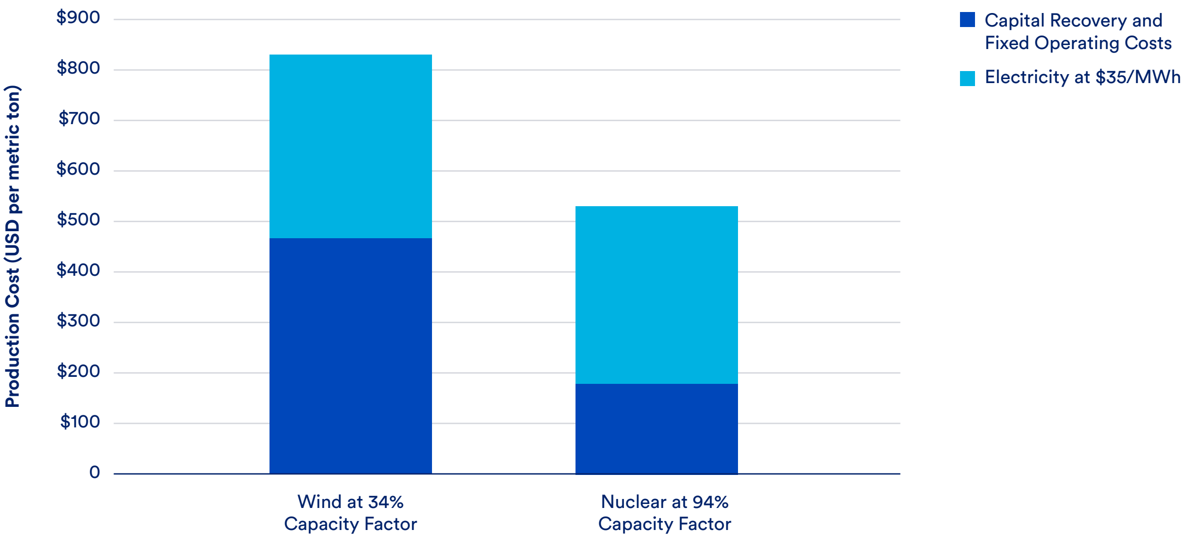
[63] Typical capacity factors for nuclear, wind, and solar generators based on US DOE EIA data for 2019; see Electric Power Monthly Table 6.07.B. Blend of wind and solar is based on energy-weighted US average for 2019. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=table_6_07_b.

of land could be required for the wind and solar option, including both direct equipment footprint and spacing, similar to the total area of Illinois and Indiana combined.[64] Any transition away from current reliance on fossil fuels will have resource impacts; however, the energy dense nature of nuclear energy offers an important complement for renewable and clean energy expansion to reduce overall resource usage for hydrogen-based ZCFs.

Electricity Availability – For numerous reasons, such as on-site fuel capacity and maintenance requirements, electricity from nuclear power plants is available on an almost continuous basis. Electrolysis technologies are most economic when paired with reliable and available electricity.[65] Hydrogen and ammonia produced through electrolysis would typically be lowest cost from an electricity source with the highest capacity factor (a measure of how often a generator is producing electricity). Figure 4 shows the impact of capacity factor on production costs for ammonia based on electrolytic hydrogen assuming the hydrogen and ammonia production facility only operates when the clean electricity supply is available, for typical capacity factors of 34% and 94% respectively for wind and nuclear generators in the US as described below. Indicative capital and operating costs developed by the Ammonfuel industry group and an electricity cost of $35/MWh have been assumed for illustration.[66]

Table 2 shows average US capacity factors for various energy sources, some of which could operate at higher capacity factors but are typically as high as possible for existing clean energy technologies.

Figure 4: Illustrative Clean Ammonia Production Costs vs. Capacity Factor



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[64] Estimated by CATF assuming 127 km2 per TWh/yr for wind and 15 km2 per TWh/yr for PV per Anne M. Trainor et al., *Energy Sprawl is the Largest Driver of Land Use Change in the United States*, 11 PLOS ONE 9 (2016), https://journals.plos.org/plosone/article/file?id=10.1371/journal.pone.0162269&type=printable.

[65] Andrew Lee, *EDF Plan Vast Hydrogen Production at UK Plants*, RECHARGE (Feb. 26, 2020), https://www.rechargenews.com/transition/edf-plans-vast-hydrogen-production-at-uk-nuclear-plants/2-1-763048.

[66] Ammonfuel estimates $190 per metric ton of ammonia production for capital and fixed operating costs for combined electrolysis and ammonia synthesis at large scale today, assuming an 85% capacity factor, not including electricity costs. That cost has been adjust for capacity factor here, assuming for the sake of illustration that all costs except electricity scale with capacity factor. $35/MWh is illustrative of typical levelized cost of electricity estimates for recent wind and potential future nuclear in the US, per Lawrence Berkeley National Laboratory, Wind Energy Technology Data Update: 2020 Edition and Clean Air Task Force Advanced Nuclear Energy: Need, Characteristics, Projected Costs, and Opportunities. See Alfa Laval, Hafnia, Haldor Topsoe, Vesta, Siemens Gamesa, *Ammonfuel--An Industrial View of Ammonia as a Marine Fuel* (Aug. 2020), https://hafniabw.com/wp-content/uploads/2020/08/Ammonfuel-Report-an-industrial-view-of-ammonia-as-a-marine-fuel.pdf, https://emp.lbl.gov/sites/default/files/2020_wind_energy_technology_data_update.pdf, at https://www.catf.us/wp-content/uploads/2018/04/Advanced_Nuclear_Energy.pdf.

Table 2: Average US Capacity Factors for Various Energy Sources, 2019[67]

Energy Source	Capacity Factor
Thermal Solar	21.2%
Photovoltaic Solar	24.3%
Wind	34.4%
Hydroelectric	41.2%
Coal	47.5%
Combined Cycle Natural Gas	57.3%
Wood Biomass	59.0%
Geothermal	69.6%
Nuclear	93.4%

High Temperature Steam – Typical electrolysis projects, such as those relying on proton exchange membrane technology, have utilized electricity and water at low temperature; however, the economics and efficiencies can be improved by utilizing high temperature steam electrolysis (HTSE).[68] Nuclear power plants, both existing and future designs, generate significant excess heat which could be for process or industrial applications. While HTSE has not been practiced at a nuclear power plant yet, it is being widely studied and nuclear heat cogeneration has been performed using over 40 existing reactors in Russia and Europe since the 1970s.[69]

Bringing Fuel Production to The Bunkering Site – Existing and future nuclear energy technology lends well to deployment of small reactors on barges for mobility and proximity to potential end users. Russia completed the world's first commercial floating nuclear power plant,[70] *Akademik Lomonosov* (shown in Figure 5), which began commercial operations in May 2020[71] and China is also building a floating commercial nuclear power plant originally scheduled to be completed in 2021.[72] Leveraging construction capabilities and experience at shipyards to deploy barge based nuclear energy could allow electrolysis units to replace existing transfer point infrastructure in or near ports and their end users. Fuels are currently produced near natural resources and then refined and transported to fueling locations across an extensive supply chain. Singapore, for example, accounts for 20% of global bunkering sales,

Figure 5: Akademik Lomonosov

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[67] EIA, Electric Power Monthly, 6.07.A & 6.07.B, data for 2019, accessed 13 July 2021, https://www.eia.gov/electricity/monthly/

[68] Konor Frick et al., Idaho Nat'l Laboratory, Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the MidWest (Sept. 2019), https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_18785.pdf.

[69] IAEA, *Opportunities for Cogeneration with Nuclear Energy* (2017), https://www-pub.iaea.org/MTCD/Publications/PDF/P1749_web.pdf.

[70] The first floating nuclear power plant was the barge MH-1A Sturgis, which included a pressurized water reactor installed in a converted WWII Liberty Ship. Operated by the U.S. Army, the 10 MWe reactor powered a portion of the Panama Canal from 1968-1975. Chris Gardner, *STURGIS Nuclear Decommissioning Completed by U.S. Army Corps of Engineers Team* (Sept. 14, 2018), https://www.nab.usace.army.mil/Media/News-Stories/Article/1632590/sturgis-nuclear-decommissioning-completed-by-us-army-corps-of-engineers-team/#:~:text=The%20STURGIS%2C%20a%20former%20World,use%20in%20the%20Panama%20Canal.

[71] Nuclear Engineering Int'l, *Akademik Lomonosov Begins Commercial Operation* (May 25, 2020), https://www.neimagazine.com/news/newsakademik-lomonosov-begins-commercial-operation-7938482.

[72] *See, e.g.*, SMR Nuclear, *SMR Global Status Report* (Apr. 2020), http://www.smrnuclear.com.au/wp-content/uploads/2020/04/SMR-GLOBAL-STATUS-REPORT-APRIL-2020_v4KP.pdf; Brian Wang, *Status of New Nuclear Power Plant Construction*, NEXTBIG FUTURE (Sept. 3, 2019), https://www.nextbigfuture.com/2019/09/status-of-new-nuclear-power-plant-construction.html.

but imports its raw crude oil from the Middle East and Southeast Asia.[73] Shipborne nuclear hydrogen and ammonia production systems, composed of increased or fully manufactured (rather than stick-built) content, could both dramatically improve zero-carbon fuels production costs and change the fuels supply and delivery paradigm by producing zero-carbon fuel directly at ports for bunkering and other infrastructure tie-ins.

3.2 State Sponsored Nuclear Hydrogen Electrolysis Projects

As nations look to decarbonize electricity production and other sectors within their borders, existing nuclear power plants are offering opportunities to provide new decarbonization capabilities through hydrogen electrolysis and the production of hydrogen-based ZCFs. In the United States, pilot projects across multiple nuclear power plants, owned or operated by several different utilities, will be demonstrating nuclear-fueled electrolysis in the coming years. The Department of Energy (DOE) H2@Scale program is funding a $7.2M joint effort (50/50 public/private cost share) between Exelon, Nel Hydrogen, and three national labs to install a 1 MW proton exchange membrane (PEM) electrolyzer at an existing Exelon nuclear power plant for dynamic participation in an organized electricity market and to satisfy existing hydrogen demands.[74] Energy Harbor, Arizona Public Service, Xcel Energy, and the Idaho National Lab are partnering with the DOE to pursue hydrogen production at Davis-Besse, Palo Verde, and an Xcel nuclear power plant in Minnesota (potentially, Prairie Island), respectively.[75] These projects at U.S. nuclear power plant sites will potentially examine high temperature reversible steam electrolysis for energy storage, hydrogen injection into gas turbines (at Palo Verde), and hydrogen supply for existing markets such as transportation.[76] $9.1M in funding through the Light Water Reactor Sustainability (LWRS) program in the DOE office of Nuclear Energy has been utilized for studies supporting these additional demonstrations. The DOE also recently announced over $26 million in funding awards for two new nuclear hydrogen demonstration projects: $13.7 million for a fully-functional hydrogen plant capable of testing diverse electrolysis technologies with Xcel energy in Minnesota and $12.5 million for a 250 kW solid oxide electrolysis demonstration project ready to integrate into a nuclear environment.[77] In Europe, the UK government and French utility, EDF, partnered together in the Hydrogen to Heysham consortium study on the feasibility of demonstrating a combined 1MW alkaline and 1MW PEM electrolyzer to generate 800 kg of hydrogen every day at the Heysham nuclear plant.[78] While this demonstration program failed to proceed to the next stage, EDF has confirmed that the project remains one of their corporate priorities.[79]

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[73] Shell bunkering unit tops Singapore's list of 2020 marine fuel suppliers, Reuters, 14 January 2021, https://www.reuters.com/article/singapore-bunker/shell-bunkering-unit-tops-singapores-list-of-2020-marine-fuel-suppliers-idUSL1N2JP0MV, and US DOE EIA at https://www.eia.gov/international/analysis/country/SGP

[74] Sonal Patel, *Exelon is Exploring Nuclear Power Plant Hydrogen Production*, POWER MAG. (Aug. 29, 2019), https://www.powermag.com/exelon-is-exploring-nuclear-power-plant-hydrogen-production/.

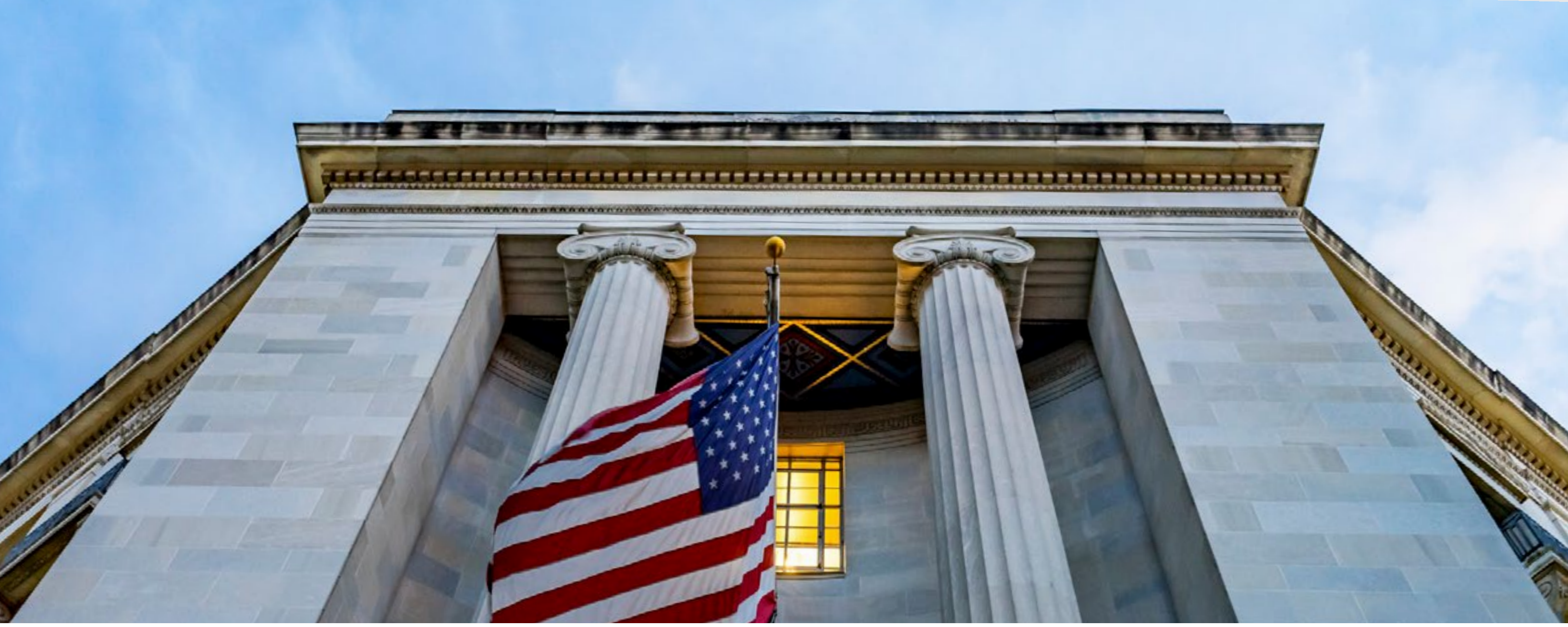
[75] ClearPath, August 2020, *Integrated Energy Systems: Getting More from our Nuclear Workhorses*, https://clearpath.org/tech-101/integrated-energy-systems-getting-more-from-our-nuclear-workhorses/

[76] Sonal Patel, *Three More Nuclear Plant Owners Will Demonstrate Hydrogen Production*, POWER MAG. (Sept. 11, 2019), https://www.powermag.com/three-more-nuclear-plant-owners-will-demonstrate-hydrogen-production/.

[77] Press Release, *U.S. Department of Energy Announces $26.9 million for Advanced Nuclear Technology*, Dep't of Energy (Oct. 8, 2020), https://www.energy.gov/ne/articles/us-department-energy-announces-269-million-advanced-nuclear-technology.

[78] *See* EDF Energy, *Hydrogen Supply Program: H2H Feasibility Report* (Oct. 11, 2019), https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/866374/Phase_1_-_EDF_-_Hydrogen_to_Heysham.pdf.

[79] Andrew Lee, *EDF Plan Vast Hydrogen Production at UK Plants*, RECHARGE (Feb. 26, 2020), https://www.rechargenews.com/transition/edf-plans-vast-hydrogen-production-at-uk-nuclear-plants/2-1-763048.



SECTION 4

The Jones Act: Leveraging an Old Law to Accelerate Marine Fuel Decarbonization

One of the biggest obstacles faced in decarbonizing the maritime sector is incentivizing cost-stressed private providers to fuel-switch. The issue is urgent; vessels being constructed now will be on the water for at least 20-30 years.[80] This section will provide a background on potential ways to incentivize that fuel switch and construction by taking advantage of the Jones Act[81] —a U.S. cabotage law that requires vessels transiting between two points in the U.S. to be U.S. flagged, among other requirements—making it a useful tool for meeting climate- and environment-related policy goals.

In brief, the Jones Act provides that a non-U.S. flag vessel "may not provide any part of the transportation of merchandise by water, or by land and water, between points in the United States to which the coastwise laws apply."[82] The Act has been historically applied to coastwise[83] trade within three miles of U.S. shoreline,

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[80] Stephen Harris & Markus Baker, *Shipping's Voyage to Zero Carbon is Uncertain*, GREENBIZ (Nov. 7 2019), https://www.greenbiz.com/article/shippings-voyage-zero-carbon-uncertain.

[81] Merchant Marine Act of 1920, Pub. L. 66-261, 41 Stat. 999 (1920). Enacted in 1920, it has been subsequently amended and recodified as the Jones Act.

[82] The "United States," is defined to mean "the States of the United States, the District of Columbia, Guam, Puerto Rico, the Virgin Islands, American Samoa, the Northern Mariana Islands, and any other territory or possession of the United States." However, the Jones Act does not apply to American Samoa, the Northern Mariana Islands, or the Virgin Islands in certain circumstances. *Id.*

[83] Though obscure to modern ears, the term "coastwise" was well understood at the time of the Jones Act's enactment to require commerce among U.S. ports along the coast. Black's Law Dict. (10th ed. 2014); *see also Webster's New International Dictionary of the English Language* 425 (1910) (defining "coastwise" as "[a]long the coast; carried on by water between places on a coast; as, coastwise business."); BENJAMIN W. POPE, 1 LEGAL DEFINITIONS 231 (1919) (defining "coasting trade" as "[d]omestic trade between port and port in the United States….").

as well as to certain (but not all) energy development-related activities taking place on the Outer Continental Shelf (OCS) on the basis that the Outer Continental Shelf Lands Act (OCSLA) extended the Jones Act to the OCS. In order for a vessel to be U.S. flagged, and thus Jones Act compliant, it must be built in the United States, manned with U.S. citizen crews, and have at least seventy-five percent U.S. citizen ownership.[84]

While essentially a protectionist law, the Jones Act could also be used as a tool for the U.S. to reduce maritime carbon emissions and establish U.S. leadership in decarbonizing the maritime sector. The most direct way to employ the Jones Act in this effort would be to amend the Act so that it effectively requires vessels that transit between U.S. ports to use zero carbon fuels. However, amending the Jones Act itself could be a lengthy and politically fraught process. Rather, this paper identifies several U.S. market and regulatory requirements created by the Act that policymakers can adjust to advance the development and deployment of zero-carbon marine fuels in the U.S. fleet.

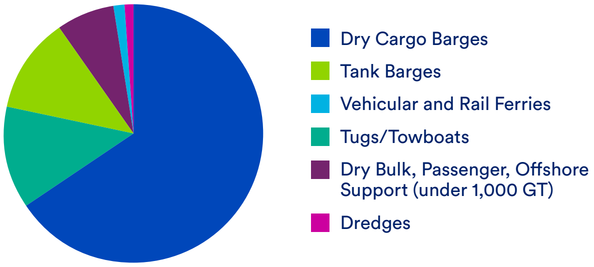
Specific strategies (described in detail below) include: modifying the terms of leases issued by the U.S. Department of Interior to offshore wind farm developers, to require the use of zero-emissions construction and support vessels; targeting relevant U.S. Department of Transportation research, demonstration, and development programs more pointedly at zero carbon fuel-powered vessels; expanding the scope and amount of a stipend that the U.S. Department of Defense pays to U.S.-crewed and -flagged commercial vessels, to defray the incremental cost of transitioning to zero-carbon fuels; and adjusting a Department of Transportation loan guarantee program so that it explicitly advantages the construction of zero-emission vessels.

The Act is a subject of debate in the U.S. due to the likelihood that increased costs to meet U.S. flag requirements will lead to higher domestic shipping costs, particularly for Puerto Rico, Alaska, and Hawaii. The age and dwindling size of the Jones Act fleet has caused some defense officials, who traditionally cite the Jones Act positively in relation to shipbuilding and workforce capabilities, to call for reassessment of the fleet and to, “rethink policies of the past in order to face an increasingly competitive future.”[85] The Act, through its requirements for U.S. flagged vessels, has a history of being used to achieve certain domestic policy goals for the U.S., such as ensuring military sealift capabilities and providing transport for food aid through the United States Agency for International Development (USAID).

The Jones Act fleet covers oceangoing and offshore supply vessels, but also river barges, tugboats, and various passenger vessels as well. According to a January 2019 study by the Transportation Institute, the Jones Act fleet consists of approximately 41,000 vessels and associated equipment.[86] About 77% of those vessels are dry cargo and tank barges, and primarily carry the nation’s dry and liquid bulk commodities (e.g., corn, soybeans, coal, and ammonia) along inland waterways like the Mississippi River, Ohio River, and Illinois Waterway. Figure 6 shows the breakdown of the private U.S. domestic shipping fleet and their roles.

The oceangoing fleet mainly serves routes where land-based transport is not an option (Alaska, Hawaii, Puerto Rico) and consists of approximately 100 vessels, the largest category being tankers.[87] Additionally, sea cargo, predominantly oil, is carried by about 150

Figure 6: U.S. Flag Privately-Owned Domestic Fleet, 2015



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[84] 46 U.S.C. § 12112; 46 C.F.R. § 67.19. The Jones Act essentially bars foreign built and operated vessels from engaging in U.S. domestic commerce and was put into place to secure the nation’s shipbuilding and maritime workforce capabilities.

[85] Written testimony of General Darren McDew, U.S. Transportation Command, House Armed Services Committee, Subcommittees on Readiness and Seapower and Projection Forces, Hearing on National Defense Authorization Act for FY2019 at 45 (Mar. 8, 2018).

[86] Transportation Institute, *The Jones Act: Critical to Economic and National Security* (Jan. 2019), https://transportationinstitute.org/jones-act/#1571078940843-e3f6cee5-809f.

[87] Congressional Research Service, Shipping Under the Jones Act: Legislative and Regulatory Background (Nov. 21, 2019), https://crsreports.congress.gov/product/pdf/R/R45725.

specially-designed seagoing barges called Articulated Tug Barges (ATBs), which are paired with and propelled by tugboats. The U.S. Ready Reserve Fleet (RRF) is a fleet of Government-owned vessels used to transport Department of Defense cargoes during major contingencies—it currently consists of about 46 vessels with an average age of 45 years.[88] Another significant portion of the Jones Act fleet are those vessels serving the Great Lakes, primarily as support to the steel industry in Michigan, Indiana, and Ohio.

The oceangoing fleet is also shrinking. In 1950, the U.S. had approximately 434 oceangoing vessels, down to approximately 99 today. This is worrisome from an emissions standpoint, as water transport of cargo contributes fewer emissions than truck or rail. However, domestic shipping has lost market share to these higher-emission options.[89]

As stated above, the requirement that vessels transiting between two points in the U.S. meet the requirements of the Jones Act, makes it a useful tool for achieving policy goals—which can include incentivizing a transition to ZCFs. Indeed, the primary purpose of the Act itself is to maintain an easily deployable fleet for the national defense, in turn providing support for the domestic shipbuilding industry who can be called on when U.S. national security is threatened. Therefore, it seems reasonable to leverage these tools for climate security.[90]

The most straightforward way to accomplish this is to amend the Act itself to require that vessels use ZCFs in order to be Jones Act compliant.[91] However, this would be a drastic change to politically fraught legislation. Instead, as discussed below, several agencies and programs supporting or working in concert with the Jones Act fleet can more easily support this transition.

4.1 Zero-Carbon Vessels for the Offshore Wind Sector

The burgeoning offshore wind sector in the U.S. will increase the need for U.S. mariners and vessels. As seen in the North Sea, (Figure 7) multiple different kinds of vessels are needed to construct and maintain an offshore wind farm.[92] These specialized service vessels do not currently exist, and will have to be purpose-built in U.S. shipyards in order to be Jones Act compliant. Indeed, an offshore wind company only announced construction of the first of these vessels in 2020.[93] Building this new vessel fleet offers a unique opportunity to ensure that those newly constructed vessels are low- or zero-carbon. One way to require this is through the Bureau of Ocean

Figure 7: The Offshore Wind Farm Arkona, 35 km NE of the island of Ruegen, Germany

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[88] Statement of Mark H. Buzby, Administrator Maritime Administration U.S. Department of Transportation, Before the Committee On Armed Services (Mar. 11, 2020), https://www.transportation.gov/testimony/sealift-and-mobility-requirements-support-national-defense-strategy.

[89] Congressional Research Service, Shipping Under the Jones Act: Legislative and Regulatory Background at 14-15 (Nov. 21, 2019), https://crsreports.congress.gov/product/pdf/R/R45725.

[90] The ability to deploy dual-fuel capable ships with the ability to switch between ZCFs and traditional bunker fuel, would allow for greater reduction in greenhouse gases than other options but would retain the operational flexibility for the military to fuel these ships in areas where ammonia may not be readily available.

[91] In order to transport merchandise under the Jones Act (46 U.S.C. § 55102), in addition to being owned by U.S. citizens, a vessel must receive a coastwise endorsement under 46 U.S.C. § 12112 which requires it be built in the U.S. This section could be amended to also require vessels are low-emission or use ZCFs.

[92] *Assessment of Vessel Requirements for the U.S. Offshore Wind Sector*, Dep't of Energy (Sept. 24, 2013), https://www.energy.gov/sites/prod/files/2013/12/f5/assessment_vessel_requirements_US_offshore_wind_report.pdf.

[93] Edison Chouest, Ørsted, and Eversource recently announced construction of the first Jones Act compliant Special Operations Vessel to support offshore windfarms. *See* Press Release, Edison Chouest Offshore Affiliate Executes Long-Term Charter Agreement With Ørsted And

Energy Management's (BOEM) bidding process for[94] offshore wind leases. Through its bidding process, BOEM could require, as a condition of the lease, that support and service vessels built in the last five years operate with low- or zero-carbon energies. In this way, all bidders on the lease will be subject to the same requirement for ZCF supply vessels in order to win the bid. When constructed, not only will these vessels become a part of the U.S. fleet for 20 years or more, their construction will supply U.S. shipyards with the technical know-how to build low or ZCFs vessels for other applications.

4.2 Maritime Environmental and Technical Assistance (META) Program

An established pathway to pursue research into use of alternative fuels in the U.S. flag fleet is the MARAD Maritime Environmental and Technical Assistance (META) Program. The program promotes the research, demonstration, and development of emerging technologies, practices, and processes that improve maritime industrial environmental sustainability. An important component of MARAD's META Program is to test, evaluate, and demonstrate the viability and applicability of alternative technologies which can reduce port and vessel emissions.

The META program has conducted a number of feasibility studies and demonstration projects into the viability of LNG as a marine fuel—*e.g.*, a Great Lakes Natural Gas Feasibility Study, a comprehensive LNG Bunkering Study, and two LNG marine fuel demonstration projects.[95] This work, in part, has spurred the nascent transition to LNG fuels.

Additionally, META has already conducted studies for the use of hydrogen fuel cells, including the San Francisco Bay Renewable Energy Electric Zero Emission (SF-BREEZE) ferry feasibility study, in conjunction with Sandia Labs.[96] The study concluded that the SF-BREEZE project was feasible, and the American Bureau of Shipping has issued a conditional approval for the ferry's design.[97]

Figure 8: Iron Ore Barge at the Two Harbors Terminal, Two Harbors, MN

4.3 Maritime Security Program

The Maritime Security Program (MSP) was enacted in 1996 to ensure the Department of Defense has access to a fleet of U.S. crewed, and U.S. flagged militarily useful vessels in a time of need and to "maintain a United States presence in international commercial shipping."[98] To help U.S. operators overcome the cost differentials between U.S. and foreign crews, the program provides an annual stipend of $5 million per vessel, which

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Eversource For Provision of The First U.S. Jones Act Compliant Windfarm Service Operation Vessel (Oct. 1, 2020), https://www.prnewswire.com/news-releases/edison-chouest-offshore-affiliate-executes-long-term-charter-agreement-with-orsted-and-eversource-for-provision-of-the-first-us-jones-act-compliant-windfarm-service-operation-vessel-301143725.html.

[94] Note that while BOEM could implement the same requirement for offshore oil and gas operations, those service vessels are already built and in operation, unlike the offshore wind farm service vessels which still need to be constructed.

[95] META Program, LNG https://maritime.dot.gov/innovation/meta/maritime-environmental-and-technical-assistance-meta-program (last visited April 29, 2020).

[96] Sandia Report, *Feasibility of the SF-BREEZE: a Zero-Emission, Hydrogen Fuel Cell, High-Speed Passenger Ferry* (Sept. 2016), https://maritime.dot.gov/sites/marad.dot.gov/files/docs/innovation/meta/9841/sf-breeze-ferry-feasibility-study-report-sandia-national-laboratory-2.pdf.

[97] Matthew Tremblay, F*easibility of Hydrogen-Powered High Speed Ferry Proven*, THE MARITIME EXECUTIVE (July 6, 2017), https://www.maritime-executive.com/features/feasibility-of-hydrogen-powered-high-speed-ferry-proven.

[98] 46 U.S.C. § 53102 (Establishment of Maritime Security Fleet).

increases to $5.3 million per vessel from 2022-2025, and eventually to $6.8 million by 2032.[99] While the stipends are authorized annually by Congress, the program itself is authorized to be in place through 2035 and is currently limited to 60 ships.[100] Congress could put additional stipends into place for vessels that fuel-switch to ZCFs and potentially increase the number of ships eligible for a stipend.

4.4 Title XI Federal Ship Financing Program

Many newly built domestic ships receive a federal loan guarantee under the Maritime Administration's "Title XI" program, through which the U.S. government guarantees repayment of 87.5% of the debt assumed during new ship construction.[101] MARAD regulations permit the consideration of "other relevant criteria" which have often been used to promote public policy goals when making approval evaluations for loans.[102] In 2015, the program was modified to include the use of "environmental initiatives that are likely to increase efficiency and lead to future cost savings" and it explicitly encouraged applicants "to emphasize any public benefits or costs of GHG or criteria pollutant emissions caused or reduced by vessel(s) to be constructed or reconstructed."[103]

The rule as proposed, in 2014, had been more explicit than the final rule, specifically naming "alternative energy technologies" to power ships as part of the relevant criteria in evaluating a loan application.[104] MARAD defined alternative energy technologies as "energy derived from non-traditional sources (including, but not limited to, liquefied or compressed natural gas, bio-fuels, solar, and wind)."[105] Thus, while MARAD may be more likely to approve loan applications for ships with ZCF designs, the requirement is not currently explicit, but it could be made to explicitly require low-carbon or ZCF energy sources.

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[99] 46 U.S.C. § 53106.

[100] 46 U.S.C. § 53103(d).

[101] 46 C.F.R. § 298.21(a).

[102] 46 C.F.R. § 298.14(b)(6).

[103] Final Action Regarding "Other Relevant Criteria" for Consideration When Evaluating the Economic Soundness of Title XI Maritime Loan Guarantee Program Applications, 80 Fed. Reg. 22421 (Apr. 22, 2015).

[104] Proposed Policy: "Other Relevant Criteria" for Consideration When Evaluating the Economic Soundness of Applications Under the Title XI Maritime Guaranteed Loan Program, 79 FED. REG. 10075 (Feb. 24, 2014); *See also* REUTERS, *New Fuel Rules Push Shipowners to Go Green with LNG* (Aug. 15, 2018), https://www.reuters.com/article/us-shipping-fuel-lng-analysis/new-fuel-rules-push-shipowners-to-go-green-with-lng-idUSKBN1L01I8.

[105] *Id.*

SECTION 5

Potential Case Study for Nuclear-Based Hydrogen/ Ammonia Supply Chain

One of the most daunting tasks facing the ZCF transition in the marine sector are fuel supply chain issues.[106] Case studies to find potential solutions to the supply chain issues could be funded through MARAD's META program, the DOE H2@Scale program, or similar programs to explore the feasibility of ZCF supply chains for the maritime sector.

Any consideration of such infrastructure should include hydrogen and ammonia production from nuclear. In particular, nuclear plants which are facing early closure could be repurposed as hydrogen or ammonia production facilities. As the Department of Energy recently stated, "[t]en nuclear reactors could produce about 2 million tonnes annually or one-fifth of the current hydrogen used in the United States."[107] Nuclear power plants, particularly economically vulnerable plants in the upper Midwest, are sited nearby existing pipeline infrastructure, as demonstrated in Figure 9 on the next page.

In a report from the Columbia University's School of International and Public Affairs (SIPA), several U.S. ports were identified as potential first-movers in developing a ZCF supply chain in the Americas. Houston was identified as a prime candidate for hydrogen supply and "the prime candidate to be the first large-scale blue hydrogen producer in the network."[108] Texas is currently the largest hydrogen-producing state in the nation, and Houston's

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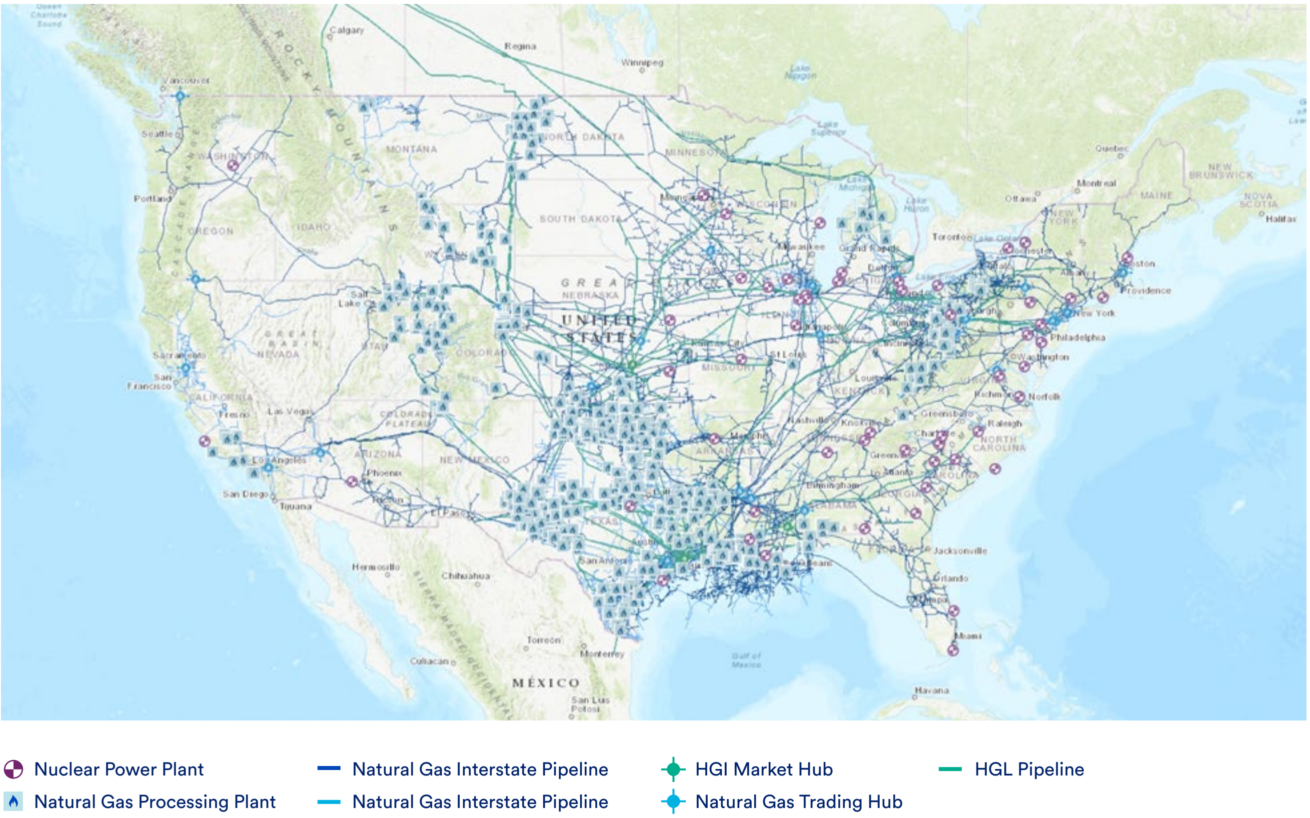
[106] Jonathan Lewis, *Building a Globally Networked Supply of Zero-Carbon Shipping Fuel*, CLEAN AIR TASK FORCE (July 8, 2020), https://www.catf.us/2020/07/building-a-globally-networked-supply-of-zero-carbon-shipping-fuel/.

[107] *Could Hydrogen Help Save Nuclear?*, Dep't of Energy (June 24, 2020), https://www.energy.gov/ne/articles/could-hydrogen-help-save-nuclear

[108] Columbia University's School of International and Public Affairs (SIPA), *Zero Carbon Fuels for Marine Shipping*, Clean Air Task Force (May 2020), https://www.catf.us/wp-content/uploads/2020/06/2020_SIPA_Zero-Carbon-Shipping.pdf.

Figure 9: U.S. Existing Gas and Nuclear Capacity

Source: U.S. Energy Information Administration



access to both the Gulf and the Mississippi river make it an ideal hub for both domestic and international shipping.

Additionally, Texas is home to two nuclear plants, including the South Texas Project in Bay City, approximately 90-miles from the Port of Houston. As described above, existing nuclear power plants can be ideal for hydrogen production since they produce high quality steam at lower cost and emissions than natural gas boilers, with the potential to create hydrogen as a commodity.[109]

However, because Houston is accessible from the Mississippi River, it opens up the possibility of nuclear-produced hydrogen along the entire river which can be transported to a hub either through available barge or pipeline. In particular, River Bend Station in St. Francisville, Louisiana could also be an ideal plant for a case study. Not only is River Bend near the Mississippi, it is also adjacent to a chemical plant. Thus, a study could explore the practicalities of nuclear-produced hydrogen for both export and industrial processes. Figure 10 shows the existing gas infrastructure adjacent to nuclear power plants in Texas and Louisiana with the South Texas Project and River Bend identified.

In general, transitioning the marine shipping sector (and other fuel-intensive sectors of the economy) to ZCFs will require a coordinated systems approach involving federal support for fuel production, infrastructure build-out, and end-use technology adoption. Accordingly, the development of these interconnected components would benefit from policies that focus on catalyzing ZCFs regional hubs.

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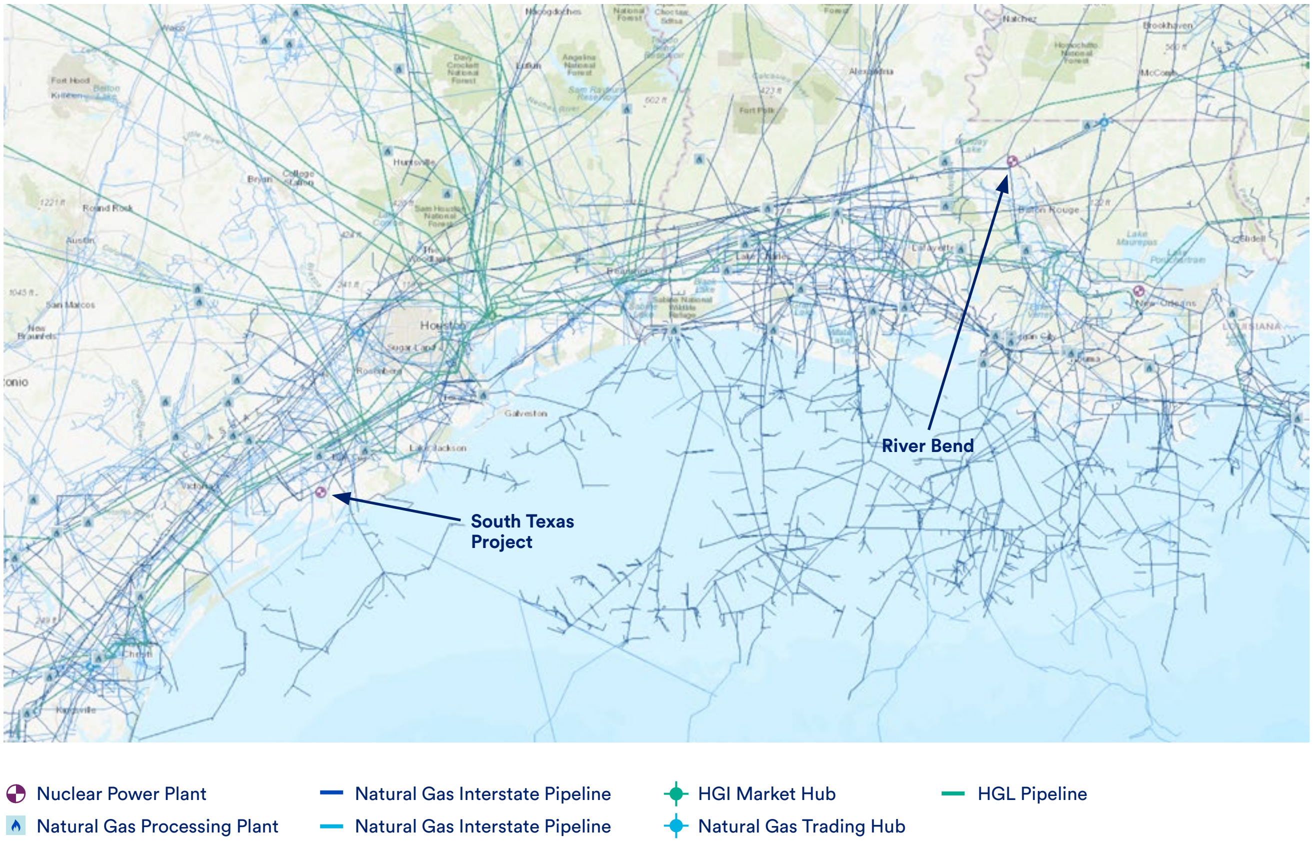
[109] *Could Hydrogen Help Save Nuclear?*, Dep't of Energy (June 24, 2020), https://www.energy.gov/ne/articles/could-hydrogen-help-save-nuclear.

Figure 10: Texas Gulf Coast Existing Gas and Nuclear Capacity

Source: U.S. Energy Information Administration



A hypothetical hub in the Houston region might include a 600 MW electrolyzer[110] powered by nuclear generation that produces approximately 100,000 metric tons of hydrogen per year; an ammonia synthesis loop; and a short pipeline that connects the ammonia production site to portside storage, loading, and fueling terminals on the Houston Shipping Channel. The decarbonized ammonia could be delivered to vessels with ammonia-compatible propulsion systems and shipped to agricultural-sector consumers interested in improving the climate impact of their products by investing in fertilizer with a significantly reduced lifecycle carbon intensity. The federal government could, through low interest development loans and cost-share grants, substantially defray the cost of building and operating a hub. Current proposals in Congress would allocate $2 billion each for clean hydrogen demonstration hubs.

In conjunction with the Jones Act, such a hub could have material beneficial impacts on existing industries in the area, for example, shipbuilding and similar activities. Over time this development might even offer a transition pathway for existing extractive industries and job markets.

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[110] This is roughly 4 times larger than the world's largest single electrolysis plant so far; however, larger scales are possible through the installation of multiple modules. See Stephen Szymanski, Nel Hydrogen, *Renewable Hydrogen from Electrolysis: How Do We Get To a Relevant Scale?*, H2@Scale Consortium Kick-Off (Aug. 1, 2018), https://www.energy.gov/sites/prod/files/2018/08/f54/fcto-h2-scale-kickoff-2018-13-szymanski.pdf.

SECTION 6

Policy Recommendations

The following areas and topics represent useful opportunities for decarbonization through increased use of nuclear-derived energy in the maritime sector, including hydrogen and ammonia fuels made with nuclear power.

6.1 Policies to Promote ZCFs for Maritime Applications, Including Nuclear-Based Production and Distribution

Increase research, development, and demonstration of maritime-relevant ZCF production and end-use technologies — As discussed in Section 4.2, the META program within MARAD offers an established pathway into potential maritime-relevant ZCF research and has previously examined hydrogen fuel cell opportunities for maritime applications. Congress should direct DOE and MARAD (through its META Program) to sponsor RD&D on key technologies that could be used for maritime applications as well as other applications including ammonia solid oxide fuel cells, ammonia reciprocating engines, large-scale ammonia cracking, high-temperature nuclear electrolysis, thermochemical water splitting, the logistics of nuclear-generated hydrogen or ammonia into the U.S. bunkering system, and advanced methane reforming. Not only could these projects build on the existing data built by META, but funding for demonstration projects would be an attractive incentive for newbuild Jones Act-compliant vessels.

Establish tax credits for ZCF production — All ZCFs, including nuclear energy derived hydrogen-based ZCFs, are likely to cost more than incumbent high-carbon fuels at least for some time, so Congress should enact production tax credit-type policies to mitigate the difference between market rates and production costs for such fuels.

Underwrite development of nuclear energy-derived hydrogen-based ZCF hubs — Congress should make eligible low-interest development loans through the DOE's loan program office and cost-share grants to cover the construction costs of key components of ZCF hubs that tie together nuclear-powered hydrogen and ammonia production, pipelines and other connective infrastructure, and end-use technologies. Shipping companies, ports, and fuel producers can work in concert to make ammonia available to a significant portion of transoceanic vessels by developing ammonia bunkering capacity at a relatively small number of leading ports situated along major shipping routes.[111]

Incentivize new vessel construction to use ZCFs — Strengthen the requirements to qualify for the Maritime Administration's "Title XI" loan guarantee program, which insures 87.5% of the funding for new ship construction (discussed further in Section 4.4). The program currently encourages applicants "to emphasize any public benefits or costs of greenhouse gas or criteria pollutant emissions caused or reduced by vessel(s) to be constructed or reconstructed" but this incentive should be made to more explicitly require low-carbon or ZCF energy sources for loan guarantees. Any new vessel under construction will be on the water for 20+ years necessitating incentives now to affect the future fleet; however, MARAD should be directed to work with U.S. stakeholders to develop a workable technological transition timeline for the implementation of any requirements.

Direct the MARAD to explore mechanisms for supporting U.S. ZCF supply chain — Few vessels are designed to handle the transport of hydrogen over inland waterways.[112] MARAD could conduct a study to evaluate the sufficiency of the existing U.S.-owned fleet of hydrogen or ammonia transport barges or other transport vessels to bolster the U.S. ZCF supply chain.

Increase support of nuclear energy derived hydrogen-based ZCF demonstrations, with focused projects on maritime fuel demonstration, through existing DOE programs — As discussed in Section 3.2, DOE is supporting four hydrogen demonstrations at operating nuclear power plants using existing DOE programs. Additional funding should be applied through these or other DOE programs to support further demonstration of nuclear ZCF demonstrations. Projects with consideration of direct maritime fuel applications and/or located at plants in close proximity to existing shipping or gas infrastructure, such as Riverbend Nuclear Station in St. Francisville, Louisiana or the South Texas Project nuclear generating station in Bay City, Texas should be given priority.

6.2 Policies to Promote ZCF Vessel Deployment

Incentivize ZCF use for the current U.S. domestic maritime fleet — As discussed in Section 4.3, increase the stipend per vessel under the maritime security program (discussed in Section 4.3) by an annual amount which is sufficient to offset the net present value cost of fuel transition, to incentivize shipowners to begin changes now. Consider expanding sustainability stipends beyond the 60 vessels in the Maritime Security Program to have a broader impact on the entire U.S. domestic fleet and phasing in requirements for low or ZCF usage/compatibility for program eligibility.

Develop emission requirements for vessels visiting U.S. ports — The U.S. could explore an approach to incentivize low or ZCFs in U.S. waters and ports. After the Exxon Valdez oil spill in 1989, Congress passed the Oil Pollution Act of 1990 (OPA 90) which required that tanker vessels of 5,000 gross tons or more must be double-hulled to sail in U.S. waters. This requirement had far-reaching effects and changed the standard design in the tanker industry. An approach to incentivize low or ZCFs in U.S. waters could follow a similar structure, and would drive private investment and innovation in the sector.

Build ZCF vessel requirements (for newbuilds) into BOEM leasing conditions for offshore wind — As discussed in Section 4.1, as a lease condition for BOEM's future offshore wind leases, it could require that new, specialized service vessels supplying offshore wind farms use low-carbon fuel or ZCFs. This would incentivize the new fleet of offshore wind service vessels—which will need to be built in the U.S. to be Jones Act compliant—to use low- or zero-carbon fuels, as well as new construction, particularly for offshore wind farm service and support vessels that have yet to be constructed.

Allow marine ZCFs to generate credits in existing and prospective clean fuel standards — The vast majority of GHG emissions associated with international shipping and aviation occur outside U.S. jurisdictions, which poses a problem for any prospective clean fuel standard

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[111] Jonathan Lewis, *Building a Globally Networked Supply of Zero-Carbon Shipping Fuel*, CLEAN AIR TASK FORCE (July 8, 2020), https://www.catf.us/2020/07/building-a-globally-networked-supply-of-zero-carbon-shipping-fuel/.

[112] U.S. DRIVE, *Hydrogen Delivery Technical Team Road Map* at 30, Dep't of Energy (June 2013), https://www.energy.gov/sites/prod/files/2014/02/f8/hdtt_roadmap_june2013.pdf. [114] Cal. Code Regs. Tit. 17, §§ 95480-90 (2020).

designed to reduce GHG. But while it is difficult for U.S.-based policymakers to penalize or otherwise regulate the use of high-carbon fuels used in international travel within a state or federal clean fuel standard, there are steps that can be taken within such programs to promote the use of low-carbon fuels. For example, the California Low Carbon Fuel Standard (LCFS) has a provision that allows producers of low-carbon aviation fuels to generate LCFS credits, even though the aviation sector is not subject to the LCFS emissions reduction requirement.[113] The purpose of the provision is to stimulate the adoption of low-carbon fuels within a sector that is otherwise beyond the reach of the LCFS. A similar provision could be used for marine shipping, both within the California LCFS and any prospective federal clean fuel standard.

Extend fuel standards to inland vessels — Strengthen fuel standards for barges plying the nation's inland waterway system. Such vessels are currently exempt from the IMO fuel standards, as discussed in Section 2.1. This could provide a further opportunity to utilize hydrogen-based ZCFs or other low carbon fuels for these applications, while potentially creating demand for hydrogen produced by inland nuclear plants.

6.3 Promote Technology Inclusivity in any Policies Supporting the Deployment of Hydrogen-Based ZCFs

As nations and maritime fleet operators consider transitions to hydrogen-based ZCFs, the arbitrary exclusion of clean energy technologies from any promotional policies can only serve to be detrimental. Creating an even and inclusive playing field, including nuclear energy technologies as a potential source of hydrogen-based ZCFs, is paramount to ensuring a practical and economic transition.

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[113] Cal. Code Regs. Tit. 17, §§ 95480-90 (2020).

SECTION 7

Conclusion

Global marine shipping will be one of the most challenging sectors to drive to zero-carbon emissions, but low- and zero-carbon fuels are the most likely solution.

These fuels can be derived from renewable energy, natural gas with carbon capture, and nuclear energy. Since each pathway has its advantages and challenges, in order to maximize the chance of success in addressing climate change, all of these pathways should be developed as options. This report explored the nuclear energy option because it has the particular advantage of high efficiency, low land-use, and a historic track record of rapid scale-up when policy and private sector incentives are aligned. There are many steps the United States can take in the short term to make this option a reality, such as using existing underutilized nuclear capacity. By aligning public and private incentives, and implementing policies that can drive innovation and deployment, the United States will be in a better position to tackle the emissions from this challenging sector, and provide global technology and market leadership.