Powering the Shipping Industry of the Future

Introduction

International shipping facilitates the movement of millions of tons of raw materials, intermediate goods, and other commodities worldwide.[1] In fact, upwards of 90 percent of the world trade currently relies on cargo and container ships. While enabling global commerce, the shipping industry also accounts for two to four percent of annual emissions worldwide, whether calculating by carbon dioxide alone or including other emissions.

Assuming current technology and practices, and projecting the growing trend in demand, the shipping industry is expected to contribute as much as 17 percent of global emissions by 2050.[2] Accordingly, industry stakeholders and regulators have expressed desires to achieve emissions reductions primarily through alternative fuel options, with checkpoints in 2030 and 2050.

Large container ships have long burned bunker fuel, a byproduct of the oil refining process. This is convenient and efficient, due to the energy potential of this easily stored and transported fuel. However, bunker fuel emits both CO_2 and other emissions and has steadily been subjected to more stringent emissions regulations by the U.S. Environmental Protection Agency, with allowable sulfur content gradually being reduced.[3]

With governments focused on mitigating climate impacts and the private sector focused on efficiency, alternative fuels have begun receiving significant research and investment. This brief provides an overview of potential fuels to power the shipping industry of the future. Each fuel option has benefits and drawbacks, and the viability of each depends on both market investment and government regulation.

Fossil Fuels

Bunker Fuel

The term "bunker fuel" denotes any fuel oil that is utilized by large commercial marine vessels. Specific to container ships, bunker fuel can be either standard white diesel that is used to power large land vehicles, or marine gas oil, which is considered a low-sulfur fuel oil.[4] Bunker fuel in ships has traditionally contained sulfur, which is a natural component of crude oil. However, burning fuel with sulfur can cause significant respiratory problems in populations that live near ports and areas of high ship traffic.[5]

Because bunker fuel is made from the "dregs" of the oil refining process,[6] the amount of sulfur in bunker fuel has been consistently targeted, leading to a global sulfur cap of 3.5 percent.[7] In January 2020, the global upper limit for the sulfur content in shipping fuel was reduced further to 0.50 percent as part of a decades-long plan to curb sulfur emissions from ships.[8]

This reduction in sulfur content will help lower sulfur oxide (SOx) emissions worldwide and lead to an annual reduction of 8.5 million metric tons of SOx per year.[9] Some shipowners have outfitted their container ships with sulfur scrubbing exhaust systems, which remove the sulfur oxide emissions as the bunker fuel is burned.

Almost 16 percent of the global shipping fleet has sulfur scrubbing technology, however, the volatility of oil prices has impacted their economic viability.[10] This price instability has also made other fuels more enticing alternatives to power container ships. As it stands, bunker fuels represent status quo in the industry. This means the benefits and drawbacks of alternative fuel are measured against the storage and transportability, costs, emissions, and other features of bunker fuel.

Liquified Natural Gas (LNG)

Liquified natural gas (LNG) is natural gas that has been liquified by cooling to -260 degrees Fahrenheit, primarily for transportation and storage.[11] LNG terminals and tankers allow for the transportation of natural gas to areas of the world that are in accessible to pipelines. Recently dual-fuel engines on container ships have allowed LNG to be used as a primary fuel for ships, and the U.S. has experienced a large increase in LNG exports since 2015, meaning ships could potentially burn part of their LNG payload along the way.[12] This existing import and export infrastructure has made LNG a very appealing alternative fuel for the tanker ships that transport LNG as well as other large ships, which can either burn LNG alone or burn it alongside other fossil fuels.

LNG has a lower environmental impact than other fossil fuels due to sulfur being removed before the liquefaction process. Because of this, very little SOx and particulate matter are emitted when LNG is burned.[13] LNG is also easy to diffuse leading to a reduced risk of explosions.[14] Carbon dioxide emissions from LNG are nearly 25 percent lower than standard fossil fuels, and with LNG being offered at competitive prices, it is seen by the shipping industry as both an alternative to bunker fuel and a potential bridge fuel to future power sources.[15]

The disadvantages of using LNG as shipping fuel are mainly due to space concerns and the costs of maintaining storage temperature. LNG would take up 150 percent of the space that fuel oil requires on a container ship.[16] This would require substantial increases to fuel storage facilities, which could decrease the amount of space for cargo on a ship. LNG must also be kept at -260 degrees Fahrenheit while stored, which requires specialized containers, equipment, and additional energy to maintain that temperature.[17] There is also a danger of boil-offs inside the storage tanks if the storage area is affected by heat, which causes LNG to evaporate and increases the pressure and temperature on a vessel's storage containers.[18] Boil-off gas must either be reliquefied on board, burned as fuel, or burned in a gasification unit to relieve the pressure on storage tanks.[19]

Chemicals

Hydrogen

Hydrogen has been used in multiple industrial processes and its demand has been steadily increasing since the late 1970s. It is a light, easily storable, energy-dense gas that produces no CO_2 when combusted, but does generate nitrogen oxides.[20] Additionally, hydrogen can be utilized as a fuel in gas or liquid form and used in fuel cells rather than combustion. Hydrogen also contains roughly three times as much energy potential as fossil fuels once it is compressed into liquid form.[21]

While naturally occurring, most hydrogen is bonded to other elements, so to produce hydrogen itself traditionally requires using fossil fuels in processes of reforming or gasification of natural gas or coal.[22] A version of "carbon-free" hydrogen, known as *green hydrogen,* can be produced through a process known as electrolysis. The process works by using electricity to split water into hydrogen and oxygen and depending on the source of the electricity.[23]

On top of its energy density and versatility, more *green hydrogen* can be produced as long as there is water and electricity. This cuts down on transportation costs, as hydrogen does not need to be moved to areas of high energy need and can be produced locally.[24]

A recent study explained that hydrogen could have powered nearly all container ships crossing the Pacific Ocean in 2015, but several barriers remain that inhibit its adoption.[25] The barriers to hydrogen fuel are mainly economic and capacity-oriented.

Completely green hydrogen currently is four times more expensive than hydrogen produced using fossil fuels.[26] Moreover, the investment in extracting hydrogen, compressing enough of it to be a reliably energy-dense liquid or gas, and storing it has continued to hamstring its use for shipping, potentially meaning ships would need extra ports of call to refuel.[27] The capacity costs of utilizing hydrogen mainly come from using hydrogen fuel cells; it would take a considerable number of fuel cells to power a container ship, which is more space not being used to move goods.[28]

Hydrogen requires 7.6 times the storage volume of bunker fuel needed to produce an equal amount of energy and must be stored in high-pressure tanks or special cryogenic dewars.[29] While this spacing issue has limited hydrogen's viability, that could be changing as the economics of retrofitting container ships to maintain space for cargo is becoming cheaper.[30] A breakthrough remains needed for hydrogen to become fully viable, the question remains as to whether it will come from the energy industry or the shipping sector.

Methanol

Methanol or wood alcohol is commonly used in chemical processes throughout the U.S. Methanol is produced mostly through reforming natural gas with steam, then converting and distilling the gas mixture.[31] While it does take more energy to produce methanol from natural gas, its simplicity means that it can be transported and stored at atmospheric temperature and pressure.[32] Current storage, transportation, and bunkering systems in ships may already be compatible with methanol, adding to its appeal. Methanol has been used as an effective alternative fuel and additive for automobiles as recently as the 1990s, and the technology is widely available for its manufacturing.[33]

The benefits of methanol are mainly due to its economic viability. Methanol is cheap to produce relative to other alternative fuels and can be produced from natural gas and biomass.[34] In fact, methanol can be produced by any carbon source, and municipal waste, forest biomass, and black liquor from pulp mills have all been used to produce methanol.[35] Methanol's lower risk of flammability than standard gasoline also makes it a safer fuel to monitor and utilize for ships.[36]

The drawbacks of methanol include a lower energy density than bunker fuel and hazards posed by methanol's corrosive properties.[37] Higher injection flow rates due to the lower energy density would be needed for ships and altering ship engines could impact cargo space available and be costly. Adequate safety features for crew members on ships would need to be implemented, as well as support infrastructure onshore to facilitate safe refueling.[38]

Ammonia

Ammonia is a compound of both nitrogen and hydrogen that is used as a building block for most household cleaning items, pharmaceutical products, and fertilizers. As an energy source for container ships, it is a relatively new alternative fuel. The process of manufacturing ammonia is normally very carbon-intensive.[39] The annual global production of ammonia exceeds 150 million metric tons, currently representing 1.8 percent of global CO_2 emissions, with demand projected to increase.[40] Innovations like electrolysis may soon slash the carbon intensity of its production; and utilizing ammonia through combustion or fuel cells produces no CO_2, but some nitrogen oxides.

Ammonia has several factors that make it an appealing alternative fuel. Ammonia has been used as a fuel source previously during past diesel shortages, and the Haber-Bosch process of manufacturing ammonia has been well established for over 100 years.[41] Fuel cells also have been used as an effective way to store and use ammonia's energy. Ammonia also has 10 times the energy density of a lithium-ion battery and remains liquid at room temperature and moderate pressures, making storage easy.[42,43] Ammonia liquid contains 50 percent more energy than the same volume of liquid hydrogen.[44]

The widespread use of ammonia in other industries means that problems of ignition of ammonia can be solved using waste heat from the combustion process.[45] Much like hydrogen, ammonia has several barriers to widespread implementation ranging from the manufacturing process to concerns about different types of emissions and overall safety.

Most ammonia today is produced from natural gas, so in order for ammonia to be less carbon intensive, its manufacturing process must be decarbonized.[46] Using carbon capture technology to capture natural gas emissions from the ammonia manufacturing process is one way to limit ammonia manufacturing emissions.[47] A new technology called a solid oxide electrolysis cell (SOEC) streamlines the development of *green* ammonia.[48]

SOECs allow nitrogen to be withdrawn from the air, hydrogen to be separated out from water using electrolysis, and to have the Haber-Bosch process powered by clean energy to produce green ammonia.[49] Due to SOEC being a relatively new technology, green ammonia is expected to be commercially available by 2023.[50] In addition to manufacturing concerns, ammonia gas is extremely corrosive, and existing ships would need to be adapted to handle its corrosive properties.[51] Finally, perhaps the largest barrier to ammonia adoption is it requires special handling. Ammonia is extremely toxic and exposure to concentrations greater than 5,000 parts per million (ppm) can be fatal.[52]

Nuclear

Fission

Because other alternative fuels possess safety risks and need additional innovation and technology to become carbon neutral, nuclear power may be a favorable alternative fuel for ships. The U.S. Navy currently utilizes nuclear powers for 10 Nimitz-class aircraft carriers, 86 submarines, and other ships and bases.[53,54]

In fact, the *USS Dwight D. Eisenhower* has run carbon-free for 20 years on a single “chunk” of uranium, while the *USS John F. Kennedy* and its 3.2-million gallon tank gets roughly 13 inches to the gallon due to the fuel oil energy being used for onboard logistics in addition to propulsion.[55]

Because aircraft carriers are massive in size and travel long distances, nuclear energy has attracted considerable investment from figures like Bill Gates, who want to see a safer, more efficient, and easily mass-produced nuclear reactor for container ships.

The upside to nuclear power is its longevity and zero carbon emissions. For shipping, nuclear power produces large amounts of electricity, allowing for onboard refrigeration, radar, and other systems to get their power directly from the reactor.[56] For areas of the ocean that are harder to operate, like in the Arctic where sea ice needs to be broken, or journeys that will provide little opportunity to refuel, nuclear power has the capacity to provide ships with large amounts of energy.[57] New types of reactors also address rightly held safety concerns.

In conventional light-water reactors, water absorbs heat from the nuclear fission process, which creates the steam used to turn turbines. However, a steam buildup can cause a pressurized explosion. A Gates-founded company, TerraPower has developed the Natrium Reactor, which uses liquid sodium as an alternative to water because it has a higher boiling point and absorption capacity.[58] This means that high pressure never builds up inside the reactor. Additionally, the reactor does not rely on outside power to secure the reactor in the event of an emergency but uses the produced heat already within the system to power safety features.[59]

Many negatives of nuclear power center on the extremely high construction costs due to safety regulations and energy storage technology currently still being developed. In the U.S., the actual costs of building a nuclear power plant end up almost three times higher than proposed costs.[60] Innovative reactors like the Natrium Reactor address these costs by shrinking the reactor size and the reactor operating at a lower pressure, negating the need for additional pressure-retaining facilities.[61]

The additional decommissioning process for a nuclear plant and the question of what to do with nuclear waste also pose barriers to using nuclear power in shipping. The U.S. Navy has a laborious process for decommissioning its nuclear craft, which involves disposing of the reactor and adjacent parts of the submarine that have been rendered radioactive in secure locations.[62] Finally, the lack of a central disposal facility for nuclear waste in the U.S. means that nuclear waste is stored on-site where it is produced.[63] Modifying existing shipyards to be able to handle reactor waste from decommissioned container ships is the most important factor in making nuclear power viable for shipping.

Additional national security concerns may arise if adversarial actors or even pirates commandeer ships with nuclear reactors or irresponsible parties simply fail to properly manage waste. Private or state ownership of shipping fleets may impact the prudence of utilizing nuclear power for commercial ships.

Conclusion

The international maritime industry's crucial role in transporting goods worldwide on its nearly 60,000-ship fleet underpins multiple key industries.[64] That makes economically and environmentally efficient operation essential to key sectors of economies worldwide. Currently bunker fuel is the primary fuel source for cargo vessels, but climate goals and public health advocates have advocated a departure from the sulfur burning and CO_2 emissions of this status quo. Several alternative fuels have the potential to help the shipping industry meet the goal of achieving 40 percent reduction in emissions by 2030.[65]

Among these are alternative fossil fuels like liquified natural gas, other elemental compounds, such as hydrogen, methanol, and ammonia, and nuclear power through fission.

Each alternative fuel has a different set of benefits and drawbacks. In some instances, alternative fuel viability or fuel combinations depend on what area of the world has the available technology and investment. Continued innovation in the field of alternative fuels is still needed in the power sector and shipping industry. That investment may mean that the necessary breakthroughs are just on the horizon.

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Author

Roy Mathews
Public Policy Associate, Alliance for Innovation and Infrastructure

For more information or inquiries on this report, please contact the Aii Media Coordinator at comms@aii.org

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