Decarbonization of the Marine Sector

by

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Abstract

The marine sector is a crucial part to the global economy, it is considered the backbone of global trade and commerce. This industry is responsible for the transportation of products, goods, and people by sea. The marine sector is also composed of navies that patrol the oceans to defend their country. Transportation by water dates to 1787 when John Fitch invented the first steamboat; this technology was later revolutionized by Robert Fulton in 1807 when *The Clermont* was built to transport passengers and cargo between New Orleans, Luisiana, and Natchez Mississippi.

In today's era, 90% of the world trade is carried across the world's oceans by more than 90,000 marine vessels. These cargo vessels as well as most military vessels use fossil fuels as their source of energy for propulsion and onboard needs. Just like automobiles, the marine sector also pollutes the air with carbon dioxide, nitrogen oxides, sulphur oxides, and particular matter. These pollutants contribute to climate change, acid rain, and health issues to humanity and wildlife. To ensure a better sustainable future for our planet and its habitats, the United Nations (UN) has committed to reach net-zero emissions by 2050.

Organizations like MARPOL, who is the main international convention aimed to control pollution from marine vessels, have created regulations since 1983 that monitor the pollution by oil, sewage, garbage and air pollution from ships. Another important organization to marine transportation is the International Maritime Organization (IMO), who in 2020 passed a new emission standard to drop the allowed 3.5% sulphur emissions in marine fuels to 0.5% at a global scale.

Another alternative that can benefit the marine sector to reach net-zero emissions is the transition to renewable energy like hydrogen, ammonia, methanol, wind and solar power. Generating electricity by solar or wind on oceans stations is also gaining traction and could facilitate the swap of batteries or charging ships at these stations while on voyage.

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Acknowledgements

I would like to express my gratitude to the copyright holders of the images used in this report, and for sharing their valuable work in this effort.

Introduction

Since the beginning of industrialization, marine transportation has played a significant role in the development of economies around the globe. Still today, most of the international trade and commerce is carried by marine vessels. While the marine sector is essential to the world's economy, marine shipping plays a major role in contributing to air pollution emissions that can harm our environment and human health.

Recent initiatives and regulations by governments and organizations like IMO have played important roles in reducing the amount of air pollution generated by marine ships. A key factor in reaching the ambitious net-zero emissions goal by 2050 and reducing marine air pollution lies in renewable energy. Renewable energy has become a crucial solution to the demand for climate change and energy security.

The marine sector can benefit from fuels harvested by green means like hydrogen and ammonia, among others. These two fuels are essential to society because they do not generate carbon emissions when producing energy. However, renewable energy currently faces major challenges, like weather conditions, cost and economics, the lack of infrastructure, public acceptance, and government support (Kolkowska, 2024).

During the next 20 years, there is time to develop cargo ships powered by electricity, technologies to swap batteries while the ships are on the ocean, and sites where electricity is generated with wind and solar and used to charge batteries for use in ships. This idea can be done at a reasonable cost because wind and solar are both inexpensive. The electricity generation cost by wind and solar means is about 5 cents/kWh.

The path to a sustainable world lies in changing the energy portfolio. This can be achieved by altering the way energy is currently produced and by reducing or eliminating the emissions of carbon generation factors.

Objectives

The objective of this paper is to share information on the impacts caused by marine transportation, such as air pollution, water pollution, acid rain, and harmful emissions that can impact human health and the environment. Other important topics include a path to a sustainable future by implementing renewable energy resources like hydrogen, ammonia, ethanol, and solar power. These renewable energy sources can replace the fossil fuels currently used by shipping vessels to ensure a more sustainable planet.

Cargo Marine Transportation

The history of transportation dates to 4000 BC, when horses were first domesticated and utilized for transportation (Robinson, 2018). In 1787 the first successful steamboat was invented by John Fitch in the United States. Later Fitch built a larger vessel to carry passengers and freight between Philadelphia and Burlington, but his steam engine design was not very successful in the construction as well as operation costs (Bellis, 2020). However, Fitch was not responsible for revolutionizing the steamboat. In 1807 Robert Fulton created his first steamboat *The Clermont*, which traveled from New York City to Albany (Bellis, 2020). In 1812, Fulton and Livingston designed *The New Orleans*, which was put into service as a passenger and freight service between New Orleans, Louisiana, and Natchez, Mississippi, revolutionizing marine freight transportation (Bellis, 2020).

Today, over 90% of the world trade is carried across the world's oceans by some 90,000 marine vessels (OCEANA, 2021). Figure 1 shows global marine vessel traffic in the year 2015.

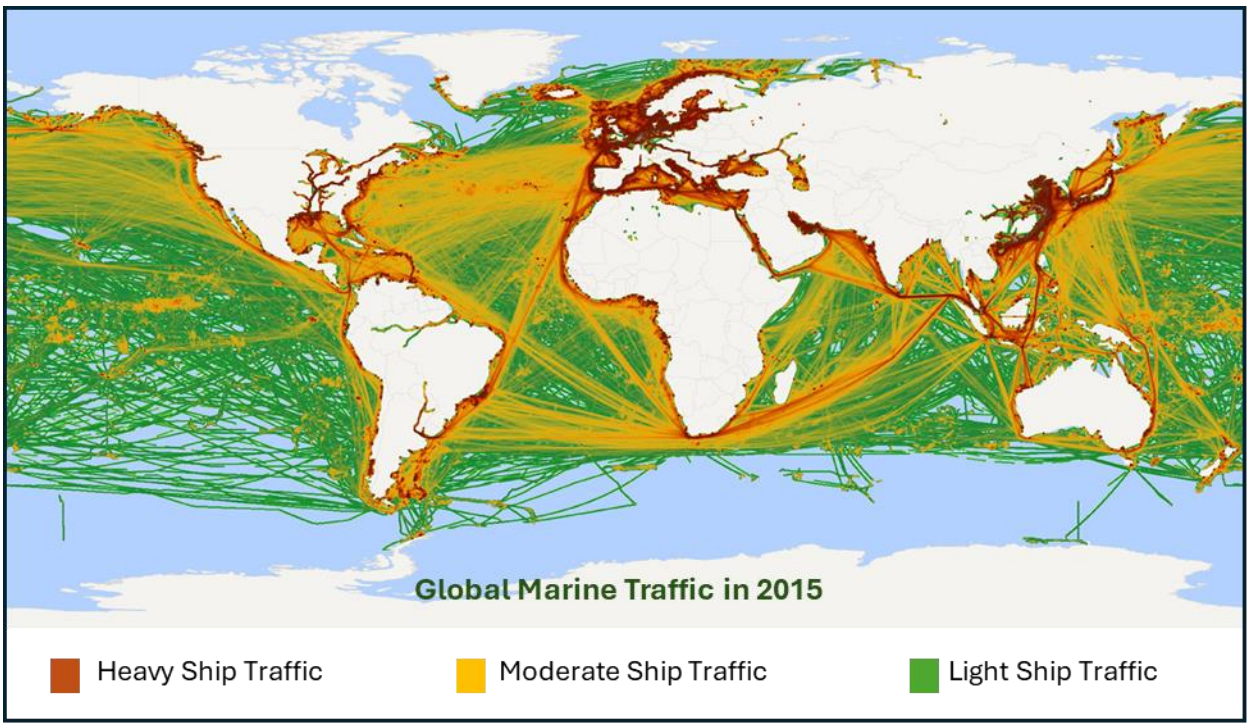

Figure 1: Marine traffic at a global scale in 2015 (Wu et al., 2016)

This mode of transportation uses fossil fuels as its source of energy, producing carbon dioxide emissions that contribute to global climate change and acidification in a very significant way (OCEANA, 2021). The types of air pollution emitted from marine shipping are the following: carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur oxides (SO_2), and particulate matter (PM_x) (Clear Seas, 2020). Carbon dioxide contributes to climate change by trapping the sun's heat. These climate changes include extreme temperatures, shifting rainfall patterns, and melting of the arctic glaciers (Clear Seas, 2020). Nitrogen oxides cause major health issues such as lung inflammation and can cause lung failures in the long run. Nitrogen oxides do cause acidification of soil and water which is known as acid rain and is known to decrease crop and vegetation productivity due to ground-level ozone. Sulfur oxides have similar effects as nitrogen oxides, they cause lung inflammation when inhaled, to worsen the situation, it can lead to heart and lung failures in the long run if they enter the bloodstream. Sulfur oxides also cause acid rain (Clear Seas, 2020).

These large vessels consume great amounts of fuel with estimated emissions from 15 mega-ships matching those from all the cars in the world (Heckstall, 2018). This is mainly because of the type of fuel these giant vessels consume; 95% of the world's shipping fleet runs on much lower quality diesel fuel (Cullinane and Berqvist, 2014). This type of fuel is referred to as "bunker fuel". It is much cheaper as it is pretty much considered a waste product of the standard oil refining process. It is a cross combination between a liquid and solid that is too thick for road vehicles; some consider this fuel as the "bottom of the barrel" (Cullinane and Berqvist, 2014). Due to its low quality, even the most modern marine engines produce higher emissions than the regulated on-road diesel engines (Cullinane and Berqvist, 2014). Table 1 demonstrates the different GHG emissions by categories emitted by the marine sector.

Table 1: GHG emissions emitted by marine transportation in the year 2021 (Narjiss, 2023) [1], (SINAY, 2023)[2], (Comer Bryan 2023)[3], (Energy Efficiency & Renewable Energy 2024)[4], (Ian 2024)[5], (Congressional Budget Office 2022)[6], (EPA IV 2024)[7]

Emissions Emitted by the Shipping Industry in 2022		
	Million Metric Tons per Year	*Total Global Contribution*
Carbon Dioxides (CO2) released	940.0 [1]	3.00% [2]
Nitrogen Oxides (NOx) released	23.0 [3]	15.00% [1]
Sulfur Oxides (SO2) released	3.70 [4]	9.00% [5]
Total GHG Released by the Transportation Sector (Includes Shipping Vessels)	6343.0 [6]	28.00% [7]

Passenger Cruise Ships

Another form of commercial marine transportation is the cruise ship. Travel by cruise ships has become a very popular form of vacation for passengers who are seeking to explore the world by ocean since the 19th century. These cruises sail to some of the world's most desirable vacation destinations and offer an incredible number of amenities such as casinos, theaters, spas, and discos, among others. Cruise ships date to 1900, the *Prinzeesin Victoria Luise* was the first German passenger ship launched during that year (Austin, 2021). The *Prinzeesin Victoria Luise* had 120 cabins with a capacity for 192 first class passengers along with 161 crewmembers. After six years of service, she was accidentally grounded off the shore of Jamaica (Austin, 2021). Today, cruises make up a considerable part of the global travel industry. The total number of cruise ships in the world was estimated to be 454 by the end of 2023 (Thakkar, 2023). These giant cruises operate in various regions across the globe, from the Mediterranean Sea to the Pacific Ocean. In recent years, the global cruise industry grew to over 27 million U.S. dollars. However, travel restrictions brought by the coronavirus (COVID-19) pandemic damaged this sector hard in 2020 (Statistaca Research Department, 2021). According to Statista, the number of cruise passengers previously increased from 17.8 million in 2009 to about 30 million a decade later. However, in 2020, these numbers decreased to just under 6 million passengers.

While cruise ships are known for limbo, shrimp cocktails, and luxury accommodations, little is known about how these floating cities are affecting the environment. Cruise ships require more fuel than a typical marine freight ship because of the energy demand of the onboard hotels and leisure facilities provided onboard as well as propelling the ships through the water (Transport & Environment, 2024). An analysis by sustainable transport group Transport & Environment revealed that Carnival Corporation, the world's largest luxury cruise operator, emitted nearly 10 times more sulfur oxide (SO_x) around European coasts than did all 260 million European cars in 2017. Royal Caribbean Cruises is the second largest cruise operator, yet this fleet emitted four times more pollution to the environment than the European car fleet (Transport & Environment, 2024). A study made in Europe found that the most polluted ports in this continent are Barcelona, Palma De Mallorca, Venice, Southampton, and Civitavecchia (McNulty, 2019). According to this study, Spain, Italy, and Greece are the countries most exposed to pollution from the emission of sulphur dioxide (McNulty, 2019). These countries have become target to air pollution because they are major important cruise destinations, but also because they have less strict fuel standards

which allows cruise ships to burn the most sulphurous fuel along their coastlines (Transport & Environment, 2024). Another problem that adds to this equation is that in these European ports marine fossil fuel is not taxed, while electricity is, making it favorable to generate the electricity needed for their restaurants and on-ship entertainment by burning fuel while docked in these ports (McNulty, 2019). Figure 2 shows the alarming amounts of SO_x pollution generated by cruise ships compared to car emissions in these European ports.

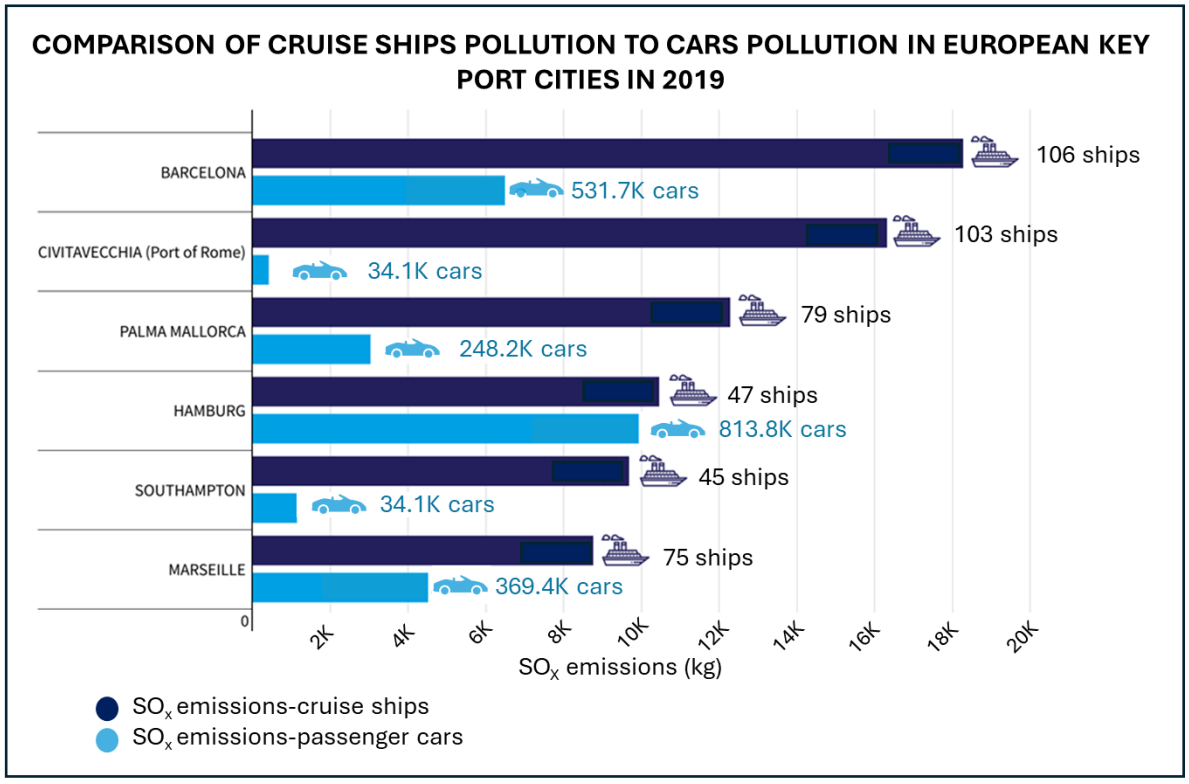

Figure 2: Pollution generated by cruise ships compared to cars in European ports (T & E, 2023)

Besides polluting the air, cruise ships are accountable for other types of pollution. Like other big vessels, cruise ships use great amounts of ballast water to stabilize the ship while traveling. As these vessels travel for long stretches, the ballast water is often filled from one region and discharged in a completely different region when required by the ship load (Marine Environment, 2020). Transporting and discharging this ballast water pollutes local species and marine life since the ballast water contains microbes in addition to vegetation and other sea animals (Marine Environment, 2020). Another type of pollution created by cruise ships is noise pollution. Unlike other ships, cruise ships contribute heavily to marine noise pollution as these vessels create large amounts of noise from the entertainment on board as well as the noise pollution created from the propellers and machinery. These noises disturb marine animals like killer whales and dolphins, harming their very sensitive hearing and often leading to their unwanted death (Marine Environment, 2020). The most alarming is waste pollution generated by cruise ships. All cruise ships generate gray water from sinks, showers, laundries, and galleys (Beachapedia, 2020). Other pollutants include sewage from toilets, oily bilge water, hazardous wastes from dry cleaning, wastes from plastic, and paper food waste (Beachapedia, 2020).

According to the Bureau of Transportation Statistics (Beachapedia, 2020), in the year 2019, a 3,000-passenger cruise ship (considered an average size, some carry 5,000 or more passengers) generates the following amounts of waste on a typical one-week voyage:

- 1 million gallons of "gray water"
- 210,000 gallons of sewage
- 25,000 gallons of oily bilge water
- Over 100 gallons of hazardous or toxic waste
- 50 tons of garbage and solid waste (in 2017 this was changed to 16 tons)
- Diesel exhaust emissions and ultrafine particles similar to levels in highly polluted urban areas

Although these modern cruise vessels have the capability of treating wastewater and solid waste onboard, there have been several violations where cruise companies have been fined for illegally discharging contaminated waste into the ocean. In December 2016, Carnival Corp. Princess Lines was convicted of illegally dumping oil-contaminated water in the ocean off the coast of England, the court fined Princess Cruise Lines a penalty of $40 million (Beachapedia, 2020). Carnival Corp. pleaded guilty to six violations in 2019 and was fined a $20 million penalty. All of these violations were in reference to illegal discharges of wastewater, plastics, and other harmful materials (Beachapedia, 2020).

Marine Transportation in the Arctic

The Arctic region covers eight different countries, Norway, Finland, Russia, Iceland, Sweden, United States, Canada, and Greenland. These eight arctic “states” came together in 1996 to establish the Arctic Council (Arctic Council Secretariat, 2023). This organization promotes cooperation, coordination, and involvement with the Arctic indigenous communities to address issues that involve the sustainability and protection of the Arctic environment. Aside from what many people believe, the Arctic consists of more than just snow-covered terrain. It is composed of coastal wetlands, sea ice, glaciers, wide rivers, mountains, and an Arctic Ocean body, which covers about 5.4 million square miles (World Wildlife Fund, 2023).

Polar ice serves a crucial role in our planet’s climate and polar ecosystems. The presence of sea ice covered in snow reflects the sun’s energy, thus reducing the absorption of solar radiation and seasonal warming (Arctic Report Card, 2022). Sea ice also serves as a platform for marine and mammal life. It also provides connection paths for indigenous communities of the north to influence their commercial transportation (Arctic Report Card, 2022).

The Arctic faces many threats including fisheries management, oil and gas development, mining, and shipping traffic. However, the single greatest threat to the Arctic is global warming. As global warming increases, the coverage of polar ice in the Arctic decreases. According to a 2022 study by Finnish and Norwegian scientists, the Arctic ice has been warming four times faster than the rest of the world over the last forty years (Bradley, 2023). This phenomenon is capturing the attention of the shipping industry about opening new commercial routes and potentially reducing the transit time between Europe, the U.S., and Asia. Studies show that future Arctic routes could be between 30 and 50% shorter than those traditionally used like the Panama and Suez Canal routes (Bradley, 2023). Figure 3 shows the ice reduction during the summer months of 2022. These routes may be available sooner than expected according to scientists. It is projected that by the year 2035, major parts of the Arctic will be ice free during the summer months. Gaining access to these routes will not only benefit the commercial shipping industry but may also attract the attention of cruise ships as well as commercial industries that can potentially gain access to intact resources that this region treasures.

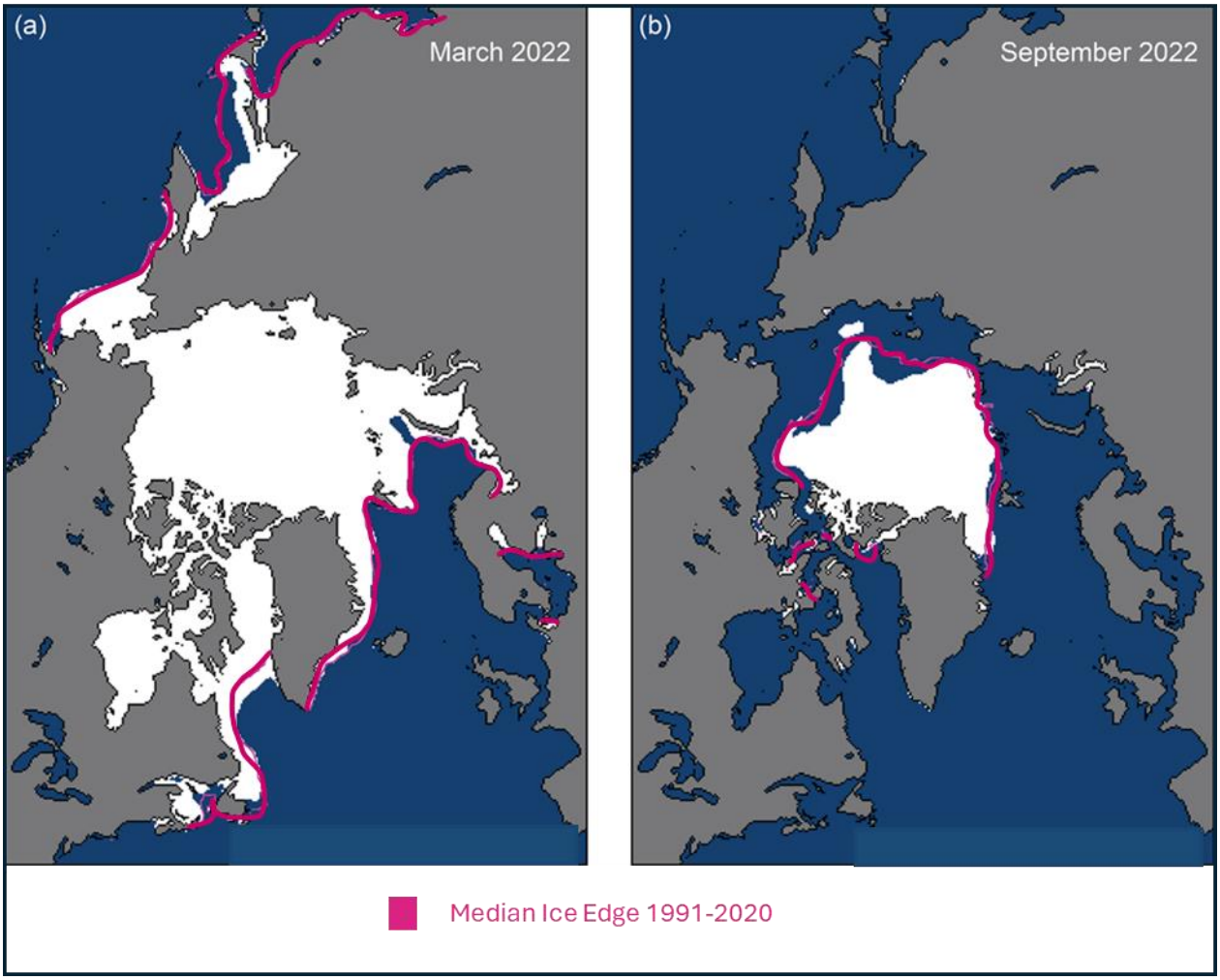

Figure 3: Arctic ice depletion during summer months (NOAA, 2022)

While the results of ice melting in the Arctic are mainly negative, a study from Brown University in Rhode Island says otherwise. According to Brown University studies, the opening of these new Arctic routes will create an eco-friendly shipping route, thus reducing the carbon footprint of emissions caused by ships. Also, geopolitical disputes have already arisen regarding what country within the Arctic states can control the territories in the Northwest Passage and Northern Sea Route.

In conclusion, the Arctic and Antarctic are known to be the "world's refrigerator", helping reflect heat back into space. This phenomenon helps balance other areas of the planet that absorb heat. If the ice continues to deplete, the sea levels could rise, increasing coastal erosions that warm the air and ocean temperatures creating frequent and intense coastal storms like hurricanes. This phenomenon could cause more intense heatwaves, as well as extreme winters on our planet, affecting our food crops, and wildlife (Poynting and Stallard, 2024).

Military Marine Transportation

The navy fleet from each country also plays an important role in air pollution. In today's modern navies, the typical support fleet that revolves around aircraft carriers includes corvettes, destroyers, and frigates (Military Factory, 2021). To get an idea of the navies fleet size of the world in 2021, four major countries

with the biggest navy fleets are mentioned here. The Chinese Navy, known as the People's Liberation Army Navy (PLAN), is the largest in the world with a fleet of 777, Russia is second with a fleet of 603, third is North Korea with a fleet of 492, and the United States with a fleet of 490 falls in fourth place (GFP, 2021). These fleets are composed of aircraft carriers, corvettes, frigates, coastal types, amphibious assault/support vessels, and auxiliaries (GFP, 2021). Most of the navy's fleets run on diesel engines and release the same pollutants into the atmosphere as the marine commercial freight ships.

The most modern aircraft carriers are typically powered by nuclear reactors; these carriers can run for decades before refueling is needed (Patent Yogi, 2021). Although these giant aircraft carriers run on nuclear power, they still need jet fuel supply for the fighter jets onboard (Patent Yogi, 2021). For example, an American Nimitz class carrier can carry about 50 fighter jets, and it has the capability of storing 3 million gallons of jet fuel. This amount of fuel can refuel the 50 jet fighters onboard 20 times each (Patent Yogi, 2021). Not only do aircraft carriers use nuclear power as their energy source, but most submarines are also nuclear powered. Nuclear powered submarines can run for about 20 years without refueling. However, submarines also need electric power to operate the equipment aboard (EPA I, 2021). To supply this power, submarines are equipped with diesel engines and/or nuclear reactors (Brain and Freudenrich, 2000).

Despite the positive impact of nuclear technology on military marine vessels, the ratio of nuclear power to petrol engine vessels remains low worldwide. In 2003, there were 160 registered nuclear-powered ships worldwide (World Nuclear Association, 2003). This number is just a fraction when compared to thousands of petrol-driven vessels in today's navies. On the bright side, Navy governments such as NATO countries regulate their marine vessels to stay in compliance with environmental laws. For example, the United States Navy complies with federal, state, and local environmental laws and regulations, as well as conservation and pollution prevention.

Air Quality and Acid Rain

Acid Rain

Acid rain is a form of precipitation composed of high levels of nitric and sulfuric acids. Acidic precipitation is caused by natural means, such as volcanoes, decaying vegetation, and man-made activities (USGS, 2020). Most acid rain is produced due to human activities like coal-burning power plants, factories, and automobiles (Nunez, 2019). When fossil fuels are burned, sulfur dioxide (SO_2) and nitrogen oxides (NO_x) are released into the atmosphere. These air pollutants react with oxygen, water, and other substances to form airborne sulfuric and nitric acid (Nunez, 2019). Figure 4 illustrates the acid rain pathway introduced into our environment.

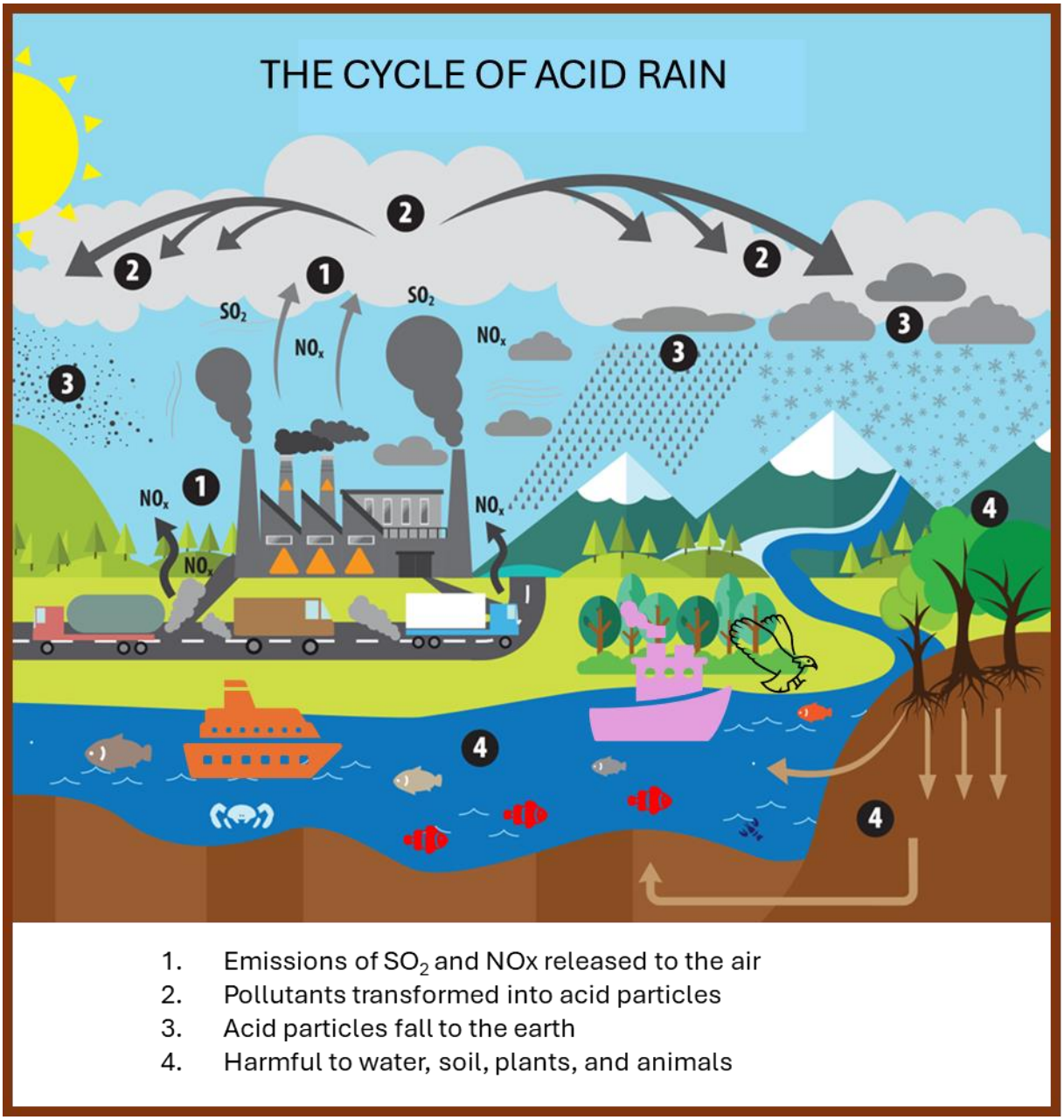

Figure 4: Formation of acid rain (EPA II, 2024)

Acid rain not only occurs as rain, but it can also occur in the form of snow, fog, and microscopic particles that settle on the earth's surface (Nunez, 2019). The ground environment can generally adapt to small amounts of acid rain because the soil is slightly basic, due to naturally occurring limestone, which contains a pH higher than 7 (USGS, 2020). Because bases neutralize acids, these limestone soils tend to balance out some of the acid rain (USGS, 2020). However, in areas where limestone does not occur naturally, such as the Rocky Mountains and part of the northwestern and southeastern United States, the presence of acid rain can harm the environment. Acid rain can have a pH of about 5.0 to 5.5, and it can even be in the 4 range in areas of high industry presence, major car traffic areas, and ports with heavy marine vessel activities (USGS, 2020).

Acid rain plays a crucial factor in harming the natural environment and wildlife. Some fish and animals such as frogs, have a hard time adapting to and reproducing in an acidic environment (USGS, 2020). Acid rain has many ecological effects, especially on lakes, streams, wetlands, and other aquatic environments (Nunez, 2019). These water streams can become more acidic with the presence of acid rain resulting in more aluminum desorption from the soil, which is later carried into lakes and streams. This combination makes water toxic to fish and other aquatic animals. Acid rain and fog also damage forests, especially those at higher elevations. The effects of acid rain, combined with other environmental stressors, leave trees and plants less healthy, and more vulnerable to cold temperatures, insects, and disease (Nunez, 2019).

Not only is acid rain affecting wildlife and forests, but also recent studies discovered that acid rain may have been the cause of a massive landslide that occurred in China in 2009. (Morton, 2018). A new study suggests that China's acid rain may have been the main contributor in weakening the limestone causing a deadly landslide that killed 74 people in southwest China (Carr, 2018).

Regulations on Marine Transportation

The International Maritime Organization (IMO) is the United Nations specialized agency with responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships. The EPA also participates in the U.S. delegation to the IMO. In addition, the Marine Environment Protection Committee (MEPC) is a group of member states within IMO that works on maritime safety, security, and the prevention of marine pollution (EPA III, 2024). MARPOL is the main international convention aimed at the prevention of pollution from ships caused by operational or accidental causes, and it was adopted by the International Maritime Organization (IMO) in 1973. As of January 2018, 156 flag states form part of MARPOL, each ship should follow the regulation of the flag state nation's maritime law in the open sea at all times (Chopra, 2019). In other words, the ship's flag displays the nationality of the ship, under whose laws the ship must comply in international waters (Chopra, 2019).

MARPOL currently includes six technical Annexes that reflect special areas with strict controls on operational discharges. Table 2 shows these regulations and the date these were implemented.

Table 2: MARPOL Annex Regulations (IMO I, 2019)

Annex	Title	Entry in Force
Annex I	Prevention of pollution by oil & oily water	2 October 1983
Annex II	Control of pollution by noxious liquid substances in bulk	2 October 1983
Annex III	Prevention of pollution by harmful substances carried by sea in packaged form	1 July 1992
Annex IV	Pollution by sewage from ships	27 September 2003
Annex V	Pollution of garbage from ships	31 December 1988
Annex VI	Prevention of air pollution from ships	19 May 2005

A recent study from IMO showed that the shipping industry was responsible for emitting 2.89% of emissions at a global scale in 2018, this could increase to 18% if no action is taken by 2050 (Guo et al., 2023). In 2020, the IMO implemented new emissions standards in a regulation called IMO 2020. In this regulation, the global sulphur limit dropped from an allowed 3.5% sulphur in marine fuels to 0.5% (IMO, 2020). This new emission standard is forecasted to lead to a 77% drop in overall sulphur oxide emissions from ships, a reduction equivalent to 8.5 million metric tonnes after 2020 of SO_x (IMO, 2020). As mentioned previously, sulphur oxides are linked to asthma, pulmonary, cardiovascular, and respiratory

diseases. Reducing these harmful emissions will help improve the health of populations, especially those that live in the most trafficked ports and coasts.

The IMO 2020 regulation also enhanced the use of marine exhaust gas cleaning systems (EGCS) on shipping vessels, also known as scrubbers. Before the shipping industry adopted these EGCS's, the entire exhaust went directly into the atmosphere, causing harm to our environment. By appropriately using these scrubbers, the shipping sector can eliminate up to 98% of the SOx emissions while getting rid of particulate matter and other harmful substances produced from marine engine combustion. Currently, there are three types of scrubbers, open-loop, closed-loop, and hybrid. The functionality of these units works by neutralizing the acidic nature of the gases and removing particulate matter of the exhaust gas streams that pass through the scrubber, these units are packed with an alkaline scrubber material, and seawater or freshwater is mixed to assist in the process (Sethi, 2021). An onboard treatment plant is later used to remove the "wash" water once the scrubbing process is complete. Finally, the scrubber sludge is sent to a holding facility tank where it is later safely disposed of and processed on shore.

Transition to Renewable Energy and Reducing Green House Emissions

Hydrogen

The new regulation implemented by IMO to limit the sulphur content of ship fuel to 0.5 percent worldwide, and the recently adopted resolutions to reduce greenhouse gas (GHG) emissions to net-zero by 2050 are changing the future of marine fuels on a great scale. As the climate emergency grows, so does the urgency to transition to low and zero-greenhouse gas emission energy sources across all sectors of the economy including the marine transportation industry. New technology for net-zero GHG is evolving fast, and there is a vast majority of projects across the globe performing research, development, and intense testing on these new fuels for use in maritime applications and other transportation sectors.

Future maritime fuels require the following attributes: they need to be an efficient energy carrier; they contain a high-energy content, safe to use and store; they need to be produced at scale and to be cost competitive; and they have minimal environmental impacts (Tennent, 2022). The most promising green alternative fuels in the maritime industry are hydrogen, ammonia, methanol, and electrified engines. Figure 5 shows how these alternative fuels are made.

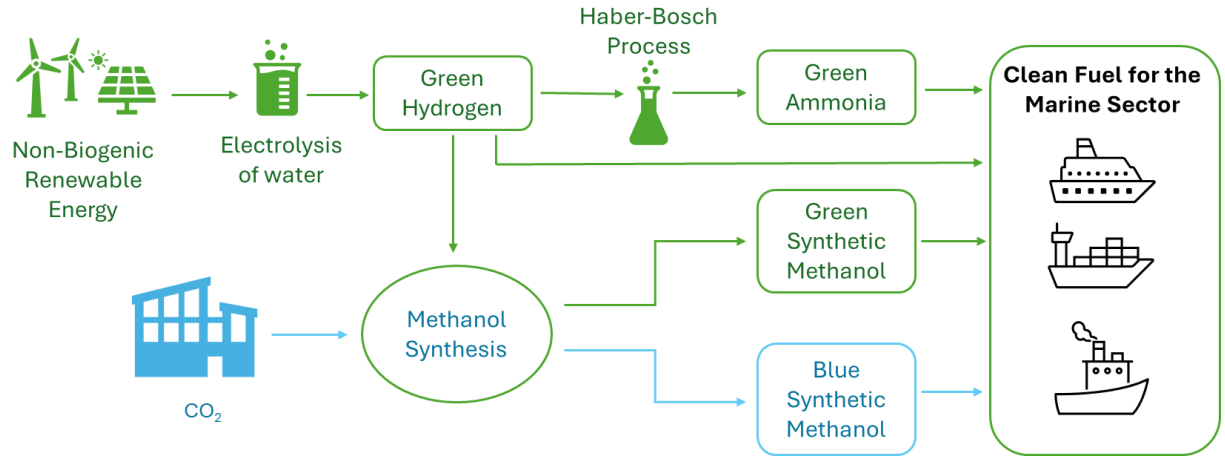

Figure 5: Process of alternative marine fuels (Tennent, 2022)

Hydrogen can be produced as a clean alternative to methane and can be identified as a natural gas. To produce hydrogen, the molecule must be separated from other sources where it occurs. In fact, the

production of hydrogen can come from many different sources, with the most common ways to produce this fuel being steam methane reforming and electrolysis (Guizar Barajas and Erickson, 2024).

Electrolysis uses water as feedstock. In this process, the water molecule is split into its basic components, hydrogen, and oxygen, by means of electricity. The most favorable ways of producing hydrogen are Polymer Electrolyte Membrane (PEM) Electrolyzers, Alkaline Electrolyzers, and Solid Oxide Electrolyzers (Godula-Jopek and Stolten, 2015). In a PEM electrolyzer, the water goes into the system and reacts at the anode to split the molecule into hydrogen ions and oxygen. At this point, while electrons are flowing through an external circuit, the positive hydrogen ions pass through the membrane into the cathode side. Once in the cathode side, hydrogen gas is formed with the assistance of an external circuit. Reactions 1-3 show the PEM process (Godula-Jopek and Stolten, 2015).

Anode: $H_2O(l) \rightarrow \frac{1}{2}O_2(g) + 2H^+ + 2e^-$ (1)

Cathode: $2H^+ + 2e^- \rightarrow H_2(g)$ (2)

Full Reaction: $H_2O(l) \rightarrow H_2(g) + \frac{1}{2}O_2(g)$ (3)

Hydrogen has an outstanding combustion efficiency (Godula-Jopek and Stolten, 2015) that has made this gas a fuel choice for the future.

Ammonia

Another technology in the spectrum of marine fuel solutions is ammonia (NH_3). This fuel can enter the market very soon while offering a zero-carbon alternative to traditional marine fuels. Currently, the broadest way of producing ammonia is through the Haber-Bosch process, which was developed by German chemists, Fritz Haber and Carl Bosch, in the early 20th century (Pattabathula and Richardson, 2016). Today, most ammonia is produced from natural gas (72%) and coal (22%) (IRENA, 2022), but new technology is on the horizon to produce ammonia from carbon-free resources (Pattabathula and Richardson, 2016). The Haber-Bosch process reaction is shown in Equation 4.

$N_2 + 3H_2 \rightarrow 2NH_3$ (4)

Despite helping in the agriculture sector, ammonia could also play a key role in a carbon-free fuel system because it has the convenience of storing and transporting clean hydrogen. A big benefit to this futuristic fuel alternative is that ammonia is a widely produced chemical in the world. Thus, the logistical infrastructure needed for green ammonia is already in place in terms of storage and transportation. For example, marine vessels that already transport it can even benefit from using ammonia to power their ships.

Studies from companies like RTI International completed a study on several shipping companies. These companies believe that ammonia will play a key role in the future with model predictions estimating the use of 200-700 metric tons per year globally by 2050, with up to 39% of this low-carbon ammonia production being used in the shipping industry (RTI, 2023).

Despite ammonia combustion being a carbon-free fuel, research shows that it can still have negative effects on the environment. The combustion of ammonia can potentially produce nitrogen oxides (NO_x and N_2O), which are well known greenhouse gases that form particulate matter in the air (RTI, 2023). On the bright side, technology to treat NO_x pollution like catalytic converters and scrubbers is already in place and can be used to mitigate these emissions while helping decarbonize the shipping industry.

Methanol

Methanol is another important alternative to marine fuel. Methanol is a safe, proven cost-competitive marine fuel that can be used for the commercial shipping industry (Methanex, 2024). This green fuel could help the shipping industry meet the increasingly strict air emissions regulations if it becomes available at over 125 of the world's largest ports.

When compared to other alternative fuels, methanol has its own unique and important qualities, it is a liquid fuel under ambient conditions. This makes methanol easy to transport, store, and bunker using similar safety procedures and logistics that are already in place for diesel. These characteristics are important in terms of economics, the cost of converting diesel engines to methanol dual-fuel vessels and infrastructure to store and supply methanol, making this fuel's cost significantly lower than other alternative fuels (Methanex, 2024).

Currently, the main source of methanol production comes from natural gas in steam reforming, followed by synthesis gas conversion. There are multiple production methods for methanol: Brown methanol, produced from coal, a non-renewable source; Grey methanol produced from natural gas, also a non-renewable/fossil fuel; and Blue methanol produced from a process that uses carbon capture and storage (Methanex, 2024). Other types include E-methanol, which is produced using green hydrogen. Lastly, Bio-methanol is produced from renewable natural gas which is sourced from landfills, sewage plants, and animal manure (Methanex, 2024).

The advantages of methanol make this fuel a leading alternative for today and the future while offering the shipping industry a promising road to decarbonization. Maersk, a giant in the shipping industry has invested in 36 containerships to be powered by methanol to be delivered by 2027.

Solar Energy and Batteries

Transportation of goods and services, including travel, contributes to approximately one quarter of greenhouse gas emissions worldwide (IEEE, 2024). Electrifying the transportation sector such as automobiles, airplanes, trains, and ships is a promising step in reaching the ambitious net-zero greenhouse gas emissions goal by 2050. The automobile industry is making great progress in electrifying the personal transportation sector. In the past five years, the Electric Vehicle (EV) market increased with promising numbers. According to Edmunds sales data, in February 2024, the EV market was 6.5%, compared to 83.1% for fossil fuel powered vehicles (Montoya, 2024). In the U.S. alone, the sales in the EV car industry rose from 0.3 Million in 2019, to 1.6 Million in 2023 (Straughan and Mitchner, 2024). The drawback of EV's is that the source of electricity to charge their batteries is mainly from fossil generated fuels.

Just like electric vehicles, the shipping industry can benefit from adopting the battery technology source to power their propellers and generators on board. Currently, the electrification of ships has started to become more dominant, especially on small cargo ships and ferries. For example, cities like Amsterdam, Stockholm, Seattle, and Hong Kong are seeking to migrate their ferries to all-electric or hybrid vessels (IEEE, 2024). In Tokyo, a 60-meter-long tanker, *The Akari* (powered by lithium-ion batteries) is already in service. The vessel uses its batteries for propulsion and onboard electricity needs (Gallucci, 2021). This tanker has the capacity of 3.5 a megawatt-hour (MWh) energy system, which is the equivalent of 40 Tesla Model S battery packs (Gallucci, 2021), giving this vessel enough power to navigate for many hours before plugging into a shoreside charging station. Another example is Maersk, the largest shipping company by volume, is already transitioning to battery hybridization on a containership while operating in the regions of East Asia and West Africa (Kersey et al., 2022).

The evolving battery powered ship vessels share the same disadvantage as electric vehicles. Their plugged power supply primarily comes from fossil fuels. For a vessel to be considered “green powered”, its energy needs to come from green sources like solar or wind power. To assist in this challenge, many countries are pursuing the idea of using solar energy as a reliable source in marine energy applications (Paulson and Chacko, 2019). The use of photovoltaics (PV) is ideal for generating green power for shipping vessels to charge the onboard batteries. However, ships require a large surface area for PV panel installation, making it a challenge to accommodate cargo. The full electrification of ships is currently an option for short voyages and small vessels like ferries (Kistner et al., 2024), batteries are still not efficient, and their weight is not optimal for long voyages (PNNL, 2024).

Solar energy is a clean source of energy, and it has been adapted as a great resource to our daily needs. The idea of producing energy in the ocean has been increasing since the construction of the first floating photovoltaic power plant (Huang et al., 2023). One way to transform global shipping is to transition to electric batteries. These batteries can be charged from solar panel stations on the ocean. The ocean has plenty of space for solar panels and windmills to produce electricity, and the cost to generate this electricity is reasonable at a range of 2.5 to 5 cents/kWh (Ghosh, 2023). It is possible to generate electricity at many locations on the ocean to provide battery swapping for electric cargo ships at different locations. These batteries can be charged by either solar or wind (Huang et al., 2023). One idea may be to have small boats that take charged batteries to the large cargo ships and swap them. Another alternative may be for the small boat to have an onboard system of already charged batteries to connect to the large ship and charge its batteries while on route. In general, an electric ship would be more efficient because electric motors are known to be more efficient when compared to a ship powered by fuel.

To get an idea of the magnitude of energy used by a ship, we are taking an 8000 TEU containership as an example to run some calculations. An 8000 TEU containership traveling at a common speed of 24 knots uses about 225 tons/day of bunker fuel (Jean-Paul, 2024). Using this fuel consumption, speed of the ship, the energy content of the fuel (41 MJ/kg), and efficiency of a combustion engine (35%) versus an electric motor (85%), we can calculate that an 8000 TEU containership needs 1,055,000 kWh of electricity to operate in a single day. In other words, this containership consumes 988 kWh of energy per kilometer traveling at 24 knots, or 15,900 kWh every ten miles at the same speed.

Public Policy and Economics

Green energy is a promising solution to our environmental crisis. The different candidate fuels that could drive the shipping industry to meet the IMO goals are promising, yet such technology still is evolving and needs the assistance of government policies and development in infrastructure. For a market to afford green hydrogen, it would need to be produced at about $0.5 USD/kg. Studies reveal that the production cost of green hydrogen will not even reach less than $3 USD/kg by 2050 (Wan and Butterworth, 2024).

Despite the high projected costs of green energy production, governments around the globe are passing policy incentives that could help pave the way for a global sustainable energy transition (Plug, 2023). Not only will these policies help the environment, but they also have the potential to generate 30 million jobs by 2050 (Plug, 2023). In the United States, the Biden administration recently announced $7 billion USD in subsidies to create seven Regional Clean Hydrogen Hubs (Lesser, 2024). In addition, U.S. companies will be eligible to receive a production tax credit of up to $3 USD/kg for green hydrogen produced. Furthermore, the U.S Department of Energy envisions the production of 10 million metric tons (MMT) of green hydrogen annually by 2030, 20 MMT by 2040, and 50 MMT by 2050 (Plug, 2023).

Green ammonia also comes with a very high production cost, up to four times more expensive when compared to traditional ammonia. The current price to produce green ammonia is $1.04 USD/kg (Warden, 2023). This price is considering that the production of ammonia occurs on a site that accounts for an established infrastructure of renewable resources like wind and solar (Future Bridge, 2022). The production cost of green ammonia is expected to drop more than 50% by the year 2050, once the technology matures (Future Bridge, 2022). Shipping companies will also suffer the cost of retrofitting their engines to account for ammonia conversion. It is estimated that a 14,000 TEU containership cost of engine conversion will be around $4.6 million USD, and a 210,000 DWT cargo carrier will cost $3.1 million USD (Warden, 2023).

According to the Methanol Institute, the production of e-methanol from green hydrogen is significantly more expensive than bio-methanol produced from biogas. Currently, the production costs for e-methanol range from $1.12-2.38 USD/kg (Ship & Bunker News, 2023). The cost to produce e-methanol has the potential to decrease to $0.26-0.63 USD/kg once renewable technology is more available. This could take 2 to 3 decades (Ship & Bunker News, 2023). Table 3 gives an overview of the different fuels and their costs to produce.

Table 3: Costs of different fuels for marine transportation (Ship & Bunker, 2024)[1], (Navarrete and Zhou, 2024)[2], (Warden, 2023)[3], (Ship & Bunker News, 2023)[4], (Leonardo, 2024)[5]

Shipping Fuels Costs	
	Per Metric Ton ($USD)
Heavy Fuel Oil (July 2024)	$694.50 [1]
Green Hydrogen 2024	$4,000-$6,000 [2]
Green Ammonia 2023	$1,040 [3]
Green Methanol 2023	$1,120-$2,380 [4]
Solar Energy 2024	$0.075/kWh [5]

Despite these high costs, large companies like SunGas Renewables, Carbon Sink, and WasteFuel are planning on working together towards a targeted production of 4.4 million mt/year of green methanol; this will be produced at sites in the United States to take advantage of the Inflation Reduction Act that offers major subsidies to low-carbon transition projects (S&P Global, 2023). The vice-president of SunGas also announced in late 2023 that the company is targeting to build six plants, each with a capacity to produce around 400,000 mt/year of methanol from forestry and wood products residues (S&P Global, 2023).

In conclusion, there are many uncertainties in having a close estimation for the production cost of green energy, this is because green energy is under development, there is little reliable experience in the field and the technology is yet not fully developed. Due to these reasons, the production costs remain high; these production costs, however, may go down as technology matures.

Challenges and Solutions

The development of renewable energy has dramatically increased in the last decade. It has emerged as a vital solution to the global climate crisis and energy security.

Despite the positive outcome this new technology has to offer, the renewable energy industry faces many challenges, like political government policies, the lack of infrastructure, storage, and high costs. The

transition to renewable energy requires extensive infrastructure development, costs that are competitive with fossil fuels, public acceptance, and policy strategies, among others (Kolkowska, 2024).

One of the biggest challenges that the shipping industry may encounter when using solar power to charge their batteries is the surface area needed to install solar panels. Today, a single solar panel has the capacity of producing 400 watts, which in turn is 1.5 kWh/day (Leonardo, 2024). The average size of a solar panel is 1.64 m^2. To power Tokyo's 3.5 MWh lithium batteries tanker *The Akari*, for example, 2,334 panels would be needed, covering a surface area of 3,827 m^2. *The Akari* is only 60 meters in length. Therefore, the need to plug and charge onshore is currently the only viable option for this vessel.

Nevertheless, the average price in the U.S for solar panels is very competitive at $0.75/W, plus a 30% federal tax credit (Leonardo, 2024). The cost of installing a system on a cargo ship would be budget friendly. Extensive research and technology will be needed to design specific solar panels that could fit in a cargo shipping vessel to provide the power needed for its batteries. To date, the most viable option would be to carry batteries on board to power the ship. Going back to our 8000 ETU containership example, we can use further calculations to determine the cost while considering the weight of batteries to power this ship. Taking into account the power load of 5kg/kWh required to electrify this containership, and considering the weight of 165,000 tons of the ship, we can calculate that 3.2% of the weight would be required for batteries. When comparing the weight of the fuel (225 tons) in this bunker to the 5,275 tons of batteries needed to be electrified, the difference in mass seems alarming, however, the weight of the fuel tank is not considered in this comparison, making the battery use a viable option.

The production of green energy also has its unique challenges. Green hydrogen production typically occurs by electrolysis, steam reforming, and fermentation with an efficiency of 60-80% by calorific value (Guizar Barajas and Erickson, 2024). The mass production of green hydrogen in the electrolysis sector could benefit from higher energy efficiency, the increase of onsite compressors, and increasing the lifetime of electrolyzers (Guizar Barajas and Erickson, 2024). The electrolysis sector currently presents two major challenges, cost and efficiency. Because electrolysis requires electricity to split the water molecule, it can cost over 50% more to produce green hydrogen than hydrogen produced through fossil fuel means.

One of the challenges that green ammonia production might face is competing with fertilizer for food production. According to the United Nations (UN), the world's population will increase to more than 9 billion in the next 35 years (Guizar Barajas and Erickson, 2024). This growth in population will potentially bring serious socio-economic challenges when producing green ammonia.

Just like green hydrogen, green ammonia is expensive to produce and short in supply. On the production side, ammonia would need the development of infrastructure to increase its presence. From the market perspective, the cost of green ammonia will depend on competition from other sectors (Guizar Barajas and Erickson, 2024).

Currently, the Biden administration is pushing to reduce the cost of producing green hydrogen, this initiative is aiming at reducing the production of green hydrogen to $1 USD per kilogram in the next decade (John, 2023).

Conclusions and Recommendations:

As policies from organizations like IMO get more demanding in favor of our environment, the need for clean energy production needs to increase to help reduce greenhouse gas emissions and find better

alternatives in the green fuel energy sector. This demand presents challenges in the growth and development of new technologies to produce marine fuel for our future ships.

Renewable energy is revolutionizing our planet. The cost of these new green technologies might be high now; but, in the future, there are hopes that this alternative energy cost will fall. On the other hand, technology is evolving, making new advancements that can benefit the marine sector and help improve the quality of our oceans and air.

Governments play a vital role in renewable energy and its future. Governments must establish consistent policies that provide clear paths and incentives that promote investment to secure a future of sustainability. Research and development also play a crucial role in paving the way for renewable energy. The collaboration between research institutions, governments, and industry leaders can support this cause by reducing costs, improving efficiency, exploring new technologies, and developing next-generation energy storage technologies (Kolkowska, 2024).

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