DECEMBER 2021

GREEN FUELS FOR MARITIME VESSELS AND THEIR CARBON IMPACTS

WASHINGTON, D.C.
UNITED STATES COAST GUARD

Prepared by: Alison Drapeau, Michaela Kelly, Molly MacAllister
Advised by: Dr. Adrienne Hall-Phillips, Dr. James Hanlan

Submitted to Worcester Polytechnic Institute

TABLE OF CONTENTS

LIST OF FIGURES

AUTHORSHIP

Section Title	Primary Author
Abstract	M. Kelly
Introduction	M. Kelly
Background	M. Kelly
Overview of the Shipping Industry	A. Drapeau
Emissions from the Shipping Industry	M. Kelly
Regulatory Agencies in the Shipping Industry	A. Drapeau
MARPOL Convention	M. MacAllister
MARPOL Annex VI and its Amendments	A. Drapeau
Proposed Alternative Fuels	All
The Well-to-Wake Approach	A. Drapeau
Other Criteria Beyond Emissions	M. MacAllister
Methodology	A. Drapeau
Determining the Total Carbon Impact of Fuels	A. Drapeau

AUTHORSHIP

Section Title	Primary Author
Additional Factors Affecting Fuel Choice	M. MacAllister
Discussion	A. Drapeau
Reducing Carbon Dioxide Emissions	A. Drapeau
Additional Criteria of Assessment	M. MacAllister
Recommendations	M. MacAllister
More Findings	M. Kelly
Limitations	A. Drapeau
Future Research	M. Kelly
Redefining Total Carbon Impact	A. Drapeau
Our Experiences	All
Appendix A	All

ACKNOWLEDGEMENTS

We would like to acknowledge the following individuals for assisting with this project. Without their expertise and guidance, this project would not be possible:

Our advisors from WPI, **Dr. Hall-Phillips** and **Dr. Hanlan**, for their help with navigating the project process.

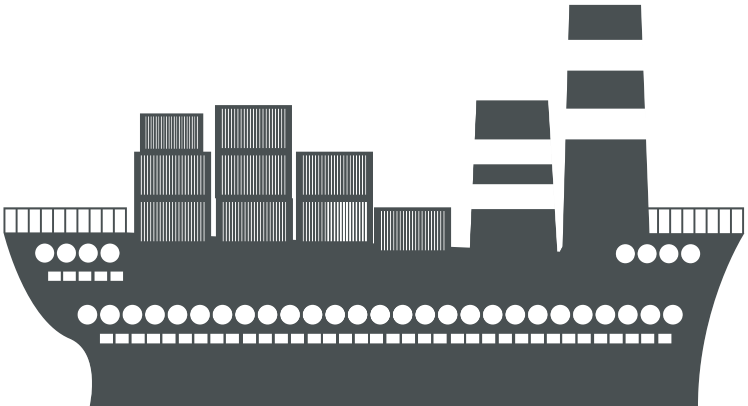
Many USCG personnel whom we met with while working at Headquarters for the duration of the project. **LT Kolb** and **LCDR Velez** for their input in developing this project and for being our primary points of contact at Headquarters. **LT Thomas** for her assistance with developing our methods when calculating total carbon impact. **Mr. Lundy** for his assistance in understanding the goals of future international regulations, especially the future of MARPOL. **RADM Mauger** and **CAPT Cost** for taking the time to meet with us and present us with new ways of problem-solving when working on this project.

Many other USCG personnel who took the time to present the many missions of the USCG to us and provide insight into our sponsoring organization.

Thank you!

ABSTRACT

Climate change is the most pressing scientific problem of the 21st century and major world leaders are seeking solutions. Changes to all industry sectors are needed to reduce global greenhouse gas (GHG) emissions. The shipping industry requires research on how they can best create change. Working with the USCG, we determined that a way for this industry to aid in GHG reductions is using greener alternative fuels to diesel. This project seeks to develop the framework needed to trace the carbon impact of alternative fuels through assessing the performance of the lower carbon content fuels compared to diesel. By evaluating the carbon produced using a well-to-wake approach and a decision matrix analyzing other criteria, it was evident that a switch to biodiesel is the most feasible choice.



INTRODUCTION

Discussion regarding climate change has a strong presence in the current political landscape. New research continues to expand our understanding of how human activity affects our environment and it is evident efforts must be made to limit the amount of air pollutants released from many essential processes. A significant contributor of air pollutants affecting marine environments is the maritime shipping industry. The source of emissions can be traced back to the traditional fuel used to power shipping vessels, which releases harmful emissions into the surrounding environment. These emissions contain a high level of greenhouse gases and remain in the atmosphere, absorbing energy. Thus, commercial shipping can be identified as a major contributor to global warming and, in turn, climate change.

An example of the effect of the shipping industry on the environment can be seen in current events. The COVID-19 pandemic has disrupted all aspects of life, and the shipping industry is taking a substantial hit. As of October 2021, California's ports are in a shipping gridlock due to COVID-19 related supply chain disruptions. Cargo ships are circling off the ports of Los Angeles and Long Beach awaiting their turn to come to port and unload critical goods (Keefe & Manley, 2021). Pre-pandemic, ships were easily able to enter and exit ports without delay, but now dozens of ships are dotting the California coastline. Container ships anticipating entry are compounding the levels of pollutants as they idle (Canon, 2021).

Source: Alison Drapeau

When anchored offshore, vessels use their diesel-fueled engines to power essential components, creating concern for the increase of emissions being released to portside communities. The congregation of vessels in a small region due to pandemic-related complications as the world returns to the "new normal" highlights the problem at hand (Gallucci, 2021). An increase in the size of the shipping industry in future years will lead to an increase in the emissions released if changes are not made. Emissions with a harmful effect on not only the environment but on human health will become more concentrated in certain regions as traffic along popular routes increases and will continue to contaminate our environment.

Several attempts have been made to reduce emissions in shipping by setting and enforcing standards at certain points in the fuel use process. These regulations seek to provide a guide for operating ships in a way that maximizes efficiency and minimizes negative atmospheric impact (Lim, 2016; International Maritime Organization, n.d.). While regulations can limit the number of air pollutants entering the atmosphere from shipping, regulations alone cannot fully eliminate the problem stemming from the use of diesel on shipping vessels.

Current research efforts have identified alternative fuels to diesel for shipping vessels, and feasible options to date include liquefied natural gas, methanol, renewable ammonia, biodiesel, and e-diesel. The goal of such research is to identify a fuel with lower or nonexistent levels of greenhouse gas emissions to mitigate the effects of global warming and climate change. Of particular interest is lowering or eliminating the carbon-based emissions associated with fuels for shipping, including carbon dioxide. While alternatives to diesel have been proposed, the exact carbon impact of the emissions released using these fuels remains unknown.

In addition to emissions from fuel use, consideration must be given to the carbon products generated from the synthesis, processing, and infrastructure needed to switch to these fuels. The need for alternative fuels is also directly connected to President Joseph Biden's new target for the “United States to achieve a 50-52 percent reduction from 2005 levels in economy-wide net greenhouse gas pollution in 2030” (The White House, 2021).

Since its establishment in 1790, the United States Coast Guard (USCG) has served its mission of protecting America's coasts, ports, and seas (USCG, 2021a). The USCG is not only a branch of the nation’s military but also operates under the United States Department of Homeland Security as a federal law enforcement agency. As such, the USCG is uniquely positioned to provide input on initiatives to keep U.S. waterways safe and efficient in collaboration with other agencies. The organization helps develop and enforce regulations to ensure that pollutants do not impact the nation’s waters and ports. The USCG works alongside other regulatory agencies, such as the Environmental Protection Agency (EPA) and the International Maritime Organization (IMO), to enforce environmental regulations and standards affecting marine environments. The most recent reduction target from the Biden Administration adds a critical new mission for the USCG, as the organization must consider its role in the search for and assessment of alternative fuels for shipping.

Source: Alison Drapeau

Our team worked with the hazardous materials division CG-ENG-5 to complete this project. This division is responsible for developing and maintaining regulations to promote the protection of life and environment during the marine transportation of hazardous materials. This division also prepares and presents national positions as a representative for the United States. Many, if not all, of the alternative fuels can be classified as hazardous materials. Whereas CG-ENG-5 is responsible for regulation of these materials in the shipping industry, the division has an interest in increasing the understanding of the environmental impact should there be a switch from traditional fuels to meet reduction targets.

This project involved the identification and assessment of alternative fuels for shipping through a review of current literature and research. Additionally, a comprehensive approach to modeling the net carbon impact of alternative fuels from well-to-wake was employed to account for all emissions of interest associated with a particular option. The identification of these fuel alternatives and their impact will assist the USCG in its role as a maritime environmental protector. It will also serve to inform additional regulations and fuel decisions to reduce greenhouse gas emissions from the shipping industry.

Source: Alison Drapeau

BACKGROUND

This project involves research of potentially drastic changes to an industry directly tied to the global supply chain. Therefore, a top-down approach that first discusses the foundation of the industry is utilized in the background section. There is a problem of harmful carbon-based emissions released from vessels in the shipping industry, and the specific composition and effects of these emissions are discussed. Next, the project research addresses regulatory agencies that are working together to enforce standards for acceptable levels of emissions. Setting standards to limit levels of emissions from shipping is one approach to addressing the problem. A secondary approach of developing alternative fuels seeks to go to the source of the problem and eventually eliminate carbon-based emissions altogether. Through examination of alternative fuels proposed in literature and approaches used to trace carbon impact, a gap in the current research will be identified, and the unique research niche for this project specifically will be presented.

OVERVIEW OF THE SHIPPING INDUSTRY

Where the topic of this project was directly related to changing the traditional practices that keep a major transportation network up and running, it is important to discuss some basic principles of how this network traditionally operates. To begin from a broad standpoint, shipping is directly tied to the global supply chain and the global transportation of goods. Therefore, the freight transported in the industry is affected by economic trends across international markets. Other factors related to the economic interests of stakeholders in international trade also play a role. Where freight is largely a customer-related factor, the decision to utilize certain ports for shipping that provide strategic locations for the further distribution of goods can be viewed as an investor-related factor (Lam & Hales, 2018). It is thus evident that shipping is an ever-evolving industry whereby virtually everyone across the globe is impacted. Although the scope of this project was primarily the shipping industry in the United States, it is important to consider how the standards used in the United States might affect the industry across the globe.

EMISSIONS RELEASED FROM THE SHIPPING INDUSTRY // OUR PROBLEM

Traditionally, shipping vessels are equipped with diesel engines and require the use of diesel fuel, which is consistent with heavy fuel use in other areas of the commercial transportation sector (Chang et al., 2013). When the ship is running, diesel fuel is injected into the engine, where it ignites quickly before having a chance to mix properly with oxygen present. This process causes high levels of greenhouse gas emissions, especially nitrous oxides and soot containing both sulfur oxides and particulate matter (Chang et al., 2013). The accumulation of these greenhouse gases is exceptionally harmful to the environment.

CARBON DIOXIDE (CO_2)

WHY ITS BAD

This emission is the most prevalent and dangerous greenhouse gas which absorbs solar energy and keeps all that heat close to the Earth's surface. This directly contributes to "extreme weather events, shifting wildlife populations and habitats, rising seas, and a range of other impacts" (Nunez, 2019).

WHY ITS URGENT

According to the Environmental Protection Agency (EPA), carbon dioxide is the most significant greenhouse gas (GHG) released by ships. CO_2 is already an issue, and it has the potential to grow significantly in its atmospheric presence in the near future. “[International shipping] accounts for around 2% of global CO_2 emissions” (Müller-Casseres et al., 2021).Without addressing these emissions immediately, globally, the carbon emissions from shipping could “grow between 50% and 250% by 2050” from its current amount (Serra & Fancello, 2020).

NITROUS OXIDE (N_2O)

WHY ITS BAD

Nitrous oxide emissions have "adverse effects on the ozone layer in the troposphere area of the earth's atmosphere" which directly connects to the greenhouse gas effect and the warming of the earth (Wankhede, 2021). N2O emissions also have negative impacts on human health by degrading air quality and emitting particulate matter linked to respiratory and cardiovascular diseases (Dwortzan, 2021).

WHY ITS URGENT

The damage that N_2O can have on the planet is detrimental. “[Nitrous oxide] molecules stay in the atmosphere for an average of 114 years before being removed by a sink or destroyed through chemical reactions” (EPA, 2021e).

BLACK CARBON (BC) // SOOT

WHY ITS BAD

BC is “very effective at absorbing light and heating its surroundings... when deposited on ice and snow, black carbon and co-emitted particles reduce surface albedo (the ability to reflect sunlight) and heat the surface” (Climate & Clean Air Coalition, a.). BC being deposited directly on the snow and ice greatly accelerates the rapid shrinking of the Arctic.

“At 2.5 micrometres or smaller in diameter, these particles are, many times smaller than a grain of table salt, which allows them to penetrate into the deepest regions of the lungs and facilitate the transport of toxic compounds into the bloodstream” (Climate & Clean Air Coalition, a.). Black carbon particulate emissions have been linked to premature deaths in adults with heart and lung disease, premature deaths in children with respiratory infections, heart attacks, and bronchitis. and asthma (Climate & Clean Air Coalition, a.).

WHY ITS URGENT

Reducing black carbon emissions would aid in reducing health impacts, delaying temperature increases in our climate, and reduce the risk of reaching the irreversible tipping point within our climate system (Center for Climate and Energy Solutions, 2019). Where BC remains within the atmosphere for only days or weeks, cutting its emissions would immediately reduce the rate of warming of our climate.

METHANE (CH_4)

WHY ITS BAD

Methane is a powerful greenhouse gas and hazardous air pollutant. CH4 “has accounted for roughly 30 percent of global warming since pre-industrial times and is proliferating faster than at any other time since record keeping began in the 1980s” (United Nations Environment Programme, 2021).

Methane also has “indirect effects on human health, crop yields, and the quality and productivity of vegetation through its role as an important precursor to the formation of tropospheric ozone” (Climate & Clean Air Coalition, n.d., b.).

WHY ITS URGENT

It has been found that CH4 has contributed to as much as 0.5 °C of warming since pre-industrial times (Nature, 2021).

Although the impacts of methane are substantial, it only takes about a decade for methane to break down. Therefore, the reduction of methane emissions would have critical impacts in the near future.

REGULATORY AGENCIES IN THE SHIPPING INDUSTRY

Regulatory agencies are dedicated to further research regarding the harmful effects of emissions released from fuel use in the shipping industry. Through quantification of emissions released both from individual vessels and from the industry as a whole, these agencies increase understanding of the scope of the problem at hand. In response to this new understanding, regulations are set, often in the form of reduction targets, to limit increases in emissions as the industry grows. Vessel owners must adhere to the guidelines set or face strict penalties (Figure 1). This process of regulation from increased understanding of the effects of emissions creates an ever-evolving landscape that those owning vessels must navigate.

INTERNATIONAL MARITIME ORGANIZATION (IMO)

The IMO is an agency within the United Nations responsible for "developing and adopting measures to improve the safety and security of international shipping and to prevent pollution from ships" (Lim, 2016). Vessel owners are mandated to monitor and submit CO_2 emissions data on a yearly basis to the IMO Data Collection System (DCS), which can then be analyzed for compliance rates of current regulations (American Bureau of Shipping, 2021). The data is used to guide future regulations and reduction targets as well, such as those that appear in the IMO-authored MARPOL Convention.

MARINE ENVIRONMENT PROTECTION COMMITTEE (MEPC)

As a subcommittee of the IMO, the MEPC is responsible for "the control and prevention of ship-source pollution covered by the MARPOL treaty...including air pollutants and greenhouse gas emissions" (International Maritime Organization, 2019a). All member states belonging to the IMO, including the United States, contribute to resolutions of the MEPC determined at regularly held meetings (International Maritime Organization, 2019b). These resolutions respond to amendments of MARPOL and contain further guidelines for determining appropriate reduction targets and mandated vessel self-reporting of carbon impact.

ENVIRONMENTAL PROTECTION AGENCY (EPA)

The EPA is an executive government agency responsible for protecting human life and the environment that partners with the IMO to determine solutions for the shipping industry in its concern of the impact of emissions (EPA, 2021d).

Figure 1 - White-hull USCG Vessel.
The USCG enforces regulations set by the agencies described through inspection of vessels.
(Source: Alison Drapeau)

MARPOL CONVENTION

The primary set of international regulations working to prevent marine pollution from shipping vessels is the International Convention for the Prevention of Pollution from Ships (MARPOL), adopted in 1973 by the IMO (Lim, 2016). This convention includes six technical annexes that have been consistently updated and are the resulting efforts of many international environmental agencies, including the EPA and the USCG (MARPOL, n.d.). These annexes have helped reduce the amount of waste and pollution being released from ships. Therefore, the MARPOL Convention is regarded as “the most important, as well as the most comprehensive, international treaty covering the prevention of both marine and atmospheric pollution by ships” (Lim, 2016).

MARPOL ANNEX VI AND RECENT AMENDMENTS

MARPOL Annex VI addresses the harmful emissions released into the atmosphere from shipping vessels, which fall under the broader classification of air pollutants from shipping. Annex VI also provides regulations of different components of the shipping process in order to minimize the negative impact of these emissions, such as fuel usage. The following is a timeline showing the evolution of air pollution regulations in Annex VI:

2000

2005

2008

Initially, Annex VI is amended to place limits on the sulfur oxide content in marine fuels and on the nitrogen oxide emissions being released through the exhaust gases of ships (EPA, 2021c).

2010

2011

The annex was reevaluated to include regulatory measures for carbon dioxide released from the ships (Chircop et al., 2018). With the inclusion of carbon dioxide in these amendments, MARPOL Annex VI currently outlines the primary set of international regulations for carbon-based emissions from the shipping industry.

2015

2020

2021

Amendments from the 76th MEPC Session introduce a new requirement for vessels over 5,000 gross tonnage to calculate and report their annual carbon intensity indicator (CII) (International Maritime Organization, 2021). The indicator is then used to produce an energy efficiency rating for the vessel, either A, B, C, D, or E, where A is the best rating possible (International Maritime Organization, 2021).

PROPOSED ALTERNATIVE FUELS

The following fuels have been identified as feasible options for adoption in the shipping industry within the timeframe of the 2030 reduction target. The summary table below lists some potential advantages and disadvantages of using each of the fuel types and is followed by further explanation the fuels themselves.

FUELS	ADVANTAGES	DISADVANTAGES
LIQUEFIED NATURAL GAS (LNG)	• Can be used in existing engines with the boil-off gas systems to increase efficiency • Has been used in the shipping industry in recent years on some vessels • Reduces CO2 from combustion by up to 30% compared to other fossil fuels such as diesel • SOx and particulate matter emissions are reduced by 100% • Cheaper than diesel	• Methane slip - a small percentage of unburned methane gas is emitted to the atmosphere • Requires additional structures to be installed on ships (boil-off gas systems)
METHANOL	• "Renewable methanol cuts carbon dioxide emissions by up to 95%" (Methanol Institute, n.d.) • Lower production cost when compared to other alternative fuels • Can safely be stored on ships or in factories because it is much less flammable than gasoline	• Extremely flammable, toxic, and poisonous • Ingestion or inhalation of the fuel can cause severe neurological, gastrointestinal, and ophthalmologic issues • Methanol ignites easily and releases toxic fumes when it is on fire
AMMONIA	• Carbon-free molecule (zero carbon emissions are released when burning it) • An established and reliable infrastructure for ammonia production, storage, and distribution exists already • Able to be used in internal combustion engines with small modifications • Able to be used directly in fuel cells	• The harvesting of hydrogen leaves behind carbon dioxide with the Haber-Bosch method • "Ammonia production consumes about 2% of the world's energy and generates 1% of its CO2" (Service, 2018) • Alternative methods of harvesting hydrogen are less efficient or much slower than the H-B method

FUELS	ADVANTAGES	DISADVANTAGES
BIODIESEL	• Biodegradable and safe to handle • Able to be used in diesel engines • Can be distributed by truck, train, or barge using already existing petroleum diesel fuel tanks and equipment • Produces fewer air pollutants than petroleum-based diesel and aids in GHG emission reductions (FuelEconomy.Gov, n.d.) • Reduces U.S. dependence on foreign oil because it is domestically produced from renewable resources (EPA, 2010 & FuelEconomy.Gov, n.d.) • "Its pure unblended form causes far less damage than petroleum diesel is spilled or released to the environment" (Alternative Fuels Data Center, n.d., a.)	• Currently more expensive • Has lower fuel economy and power compared to petroleum-based diesel (FuelEconomy.Gov, n.d.) • "Acts like a detergent or solvent that can loosen and dissolve sediments in storage tanks" (U.S. Energy Information Administration, 2020 August) • Concern that extensive use of biodiesel would create a tax on the food chain - eventually leading to food shortages (Hasan & Rahman, 2017).
E-DIESEL	• Can be used in existing engines on vessels • Little to no CO_2 emissions when fuel undergoes combustion	• Nitrogen oxides and particulate matter from soot are still produced at high levels when e-diesel is used in traditional engines • Will require significant resources to transition the world to this fuel

LIQUEFIED NATURAL GAS (LNG)

LNG is another fossil fuel that can be used in place of diesel for commercial shipping. For use on cargo vessels, the natural gas is cooled to extremely low temperatures (-160°C) and stored in a specialized tank on the vessel (Balcombe, 2019). A challenge arises in keeping the natural gas in the liquid state within the tanks. To combat this, boil-off gas (BOG) systems must be installed (Gómez, 2014). LNG can be used in several types of engines, where the most feasible engines for shipping used in combination with the BOG systems are 4-cycle gas engines, 4-cycle diesel engines, and 2-cycle diesel engines (Unseki, 2013). LNG has been in use in the shipping industry in recent years on some vessels. Since the first LNG-fueled vessel was commissioned in 2000, there has been an increase in the availability of ships using this fuel. An estimated 117 vessels were in use in 2017 and this number has increased in subsequent years (Balcombe, 2019).

The main disadvantage to using LNG is the phenomenon known as methane-slip. When LNG is used in 4-cycle engines specifically, there is a small percentage of unburned methane gas that is emitted to the atmosphere, approximately 1-2% of the methane that is burned during the combustion process (Unseki, 2013). Where carbon emissions are reduced in one area compared to diesel, they also increase in another area, which brings the overall advantage of using LNG into question.

METHANOL

Methanol is also a renewable fuel option. In production, natural gas is reformed into a synthesis gas, then inserted into a reactor with a catalyst. This process leaves behind methanol, the fuel of interest, and water vapor (DOE, n.d.). One of the most significant advantages of using methanol as an alternative fuel to diesel is that “renewable methanol cuts carbon dioxide emissions by up to 95%” (Methanol Institute, n.d.). Another advantage of using methanol as an alternative fuel to diesel is lower production costs. Compared to other alternative fuel options, methanol’s production is significantly cheaper (DOE, n.d.). In regard to storage, methanol is much less flammable than other fuels such as gasoline, meaning it can safely be stored on ships or in factories (DOE, n.d.). Although there are less harmful carbon-based emissions released by methanol compared to diesel, methanol is extremely flammable, toxic, and poisonous (CDC, 2011). Ingestion or inhalation of the fuel can cause severe neurological, gastrointestinal, and ophthalmologic issues (CDC, 2011). Methanol ignites easily and releases toxic fumes when it is on fire (CDC, 2011). These are a new challenges to consider when proposing methanol as an alternative fuel for the shipping industry and may adversely impact human health, presenting a disadvantage with methanol use for this purpose.

AMMONIA

Ammonia is a renewable fuel option made up of one nitrogen atom bonded to three hydrogen atoms (Service, 2018). It is an attractive alternative to diesel fuel because it is a carbon-free molecule (Al-Aboosi et al., 2021). As such, an advantage of burning ammonia for use on ships compared to hydrocarbon-based fuels such as diesel is that zero carbon emissions are released. Another advantage of using ammonia as an alternative fuel is “there is already an established and reliable infrastructure for ammonia production, storage, and distribution” (Al-Aboosi et al., 2021). An established infrastructure allows an easier transition from diesel fuel to ammonia. Another factor increasing the ease of adoption of ammonia is its high-octane rating, which allows the fuel to “be used in internal combustion engines with small modifications and directly in fuel cells” (Al-Aboosi et al., 2021).

Although ammonia itself is a carbon-free molecule, its production process is not carbon-free. The most widely used process of making ammonia is called the Haber-Bosch method (Service, 2018). This process involves forcibly splitting two bonded nitrogen atoms with the aid of an iron catalyst and combining them with hydrogen (Service, 2018). The harvesting of hydrogen leaves behind carbon dioxide while “generating the pressure needed to meld hydrogen and nitrogen in the reactors consumes more fossil fuels” (Service, 2018). The unfortunate truth of ammonia production with the Haber-Bosch method is it “consumes about 2% of the world's energy and generates 1% of its CO2” (Service, 2018). The Haber-Bosch method is not the only way of producing ammonia, though. Other methods are being developed to find a cleaner production process, but currently, these methods are less efficient or much slower than the Haber-Bosch method (Service, 2018).

BIODIESEL

Biodiesel, also referred to as B100, is a renewable fuel manufactured with agricultural resources such as vegetable oils and animal fats (EPA, 2010). Biodiesel is biodegradable and safe to handle, and is able to be used in diesel engines. This fuel is produced with a process called transesterification which "converts fats and oils into biodiesel and glycerin (a coproduct)" (Alternative Fuels Data Center, n.d., b.). Biodiesel can be distributed by trucks, trains, and barges using already existing petroleum diesel fuel tanks and equipment (U.S. Energy Information Administration , 2020 June) This 'greener' fuel produces fewer air pollutants than diesel and aids in GHG emission reductions (FuelEconomy.Gov, n.d.). Biodiesel also "reduces emissions of carbon monoxides, particulate matter (PM), and sulfates, as well as hydrocarbons and air toxics emissions" (EPA, 2010). From an international economic standpoint, biodiesel will help reduce U.S. dependence on foreign oil because this alternative fuel is domestically produced from renewable resources (EPA, 2010 & FuelEconomy.Gov, n.d.). This agriculural production also reduces the fuel's overall carbon impact, as it is "offset by the carbon dioxide absorbed from growing soybeans or other feedstocks used to produce the fuel" (Alternative Fuels Data Center, n.d., a.).

The main disadvantages to biodiesel is its cost and the fact that "biodiesel acts like a detergent or solvent that can loosen and dissolve sediments in storage tanks, which can affect the performance of end-use equipment" (U.S. Energy Information Administration, 2020 August). Additionally, because the fuel source is derived from agricultural resources, there is a concern that if biodiesel was used extensively, there would be a tax on the food chain eventually leading to food shortages (Hasan &Rahman, 2017).

E-DIESEL

E-diesel belongs to a category of synthetic fuels known as electrofuels or e-fuels. E-fuels are produced from CO2, water, and an input of renewable electricity using a series of chemical reactions in the Fischer-Tropsch process (Brynolf, 2018). The final product is a blend of hydrocarbons that can be used in internal combustion engines in place of petroleum-based hydrocarbon fuels (Brynolf, 2018).

Several companies working on e-diesel production have experimented with synthesizing Fischer-Tropsch diesel with renewable sources of electricity. Sources that have been considered in e-diesel production for the shipping industry include wind power, solar power, and nuclear power, each with varying but reduced carbon impacts relative to nonrenewable electricity production (Kranenburg et al., 2020). While e-diesel is being produced and used on a limited scale in the transportation sector with some automobiles in Europe, it is worth noting e-diesel production in the United States and in other areas of the transportation sector remain in the early development stages (Kranenburg et al., 2020). Incorporating renewable energy for electricity needed in efficient e-diesel production is a massive infrastructural undertaking on a global scale that will take significant resources and likely have a net carbon impact. Analysis of Fischer-Tropsch diesel produced with non-renewable electricity sources is discussed in this project with the acknowledgement that e-diesel may have a lesser total carbon impact with this infrastructure in place.

BASELINE FUELS

The baseline diesel fuels that we will be utilizing for comparison to the performances of the alternative fuels are Marine Diesel Oil (MDO) and Heavy Fuel Oil (HFO). MDO is a distillate fuel that is created through a process of refining that "involves heating the crude oil with or without the use of a catalyst" (Ship Insight). The process to produce HFO leaves "behind a sludge-like residue made from the end of the oil refining process" (Degnarain,2020). Both fuels emit carbon dioxide, sulfur, nitrogen oxides, and black carbon and directly contribute the warming of the planet.

THE WELL-TO-WAKE APPROACH

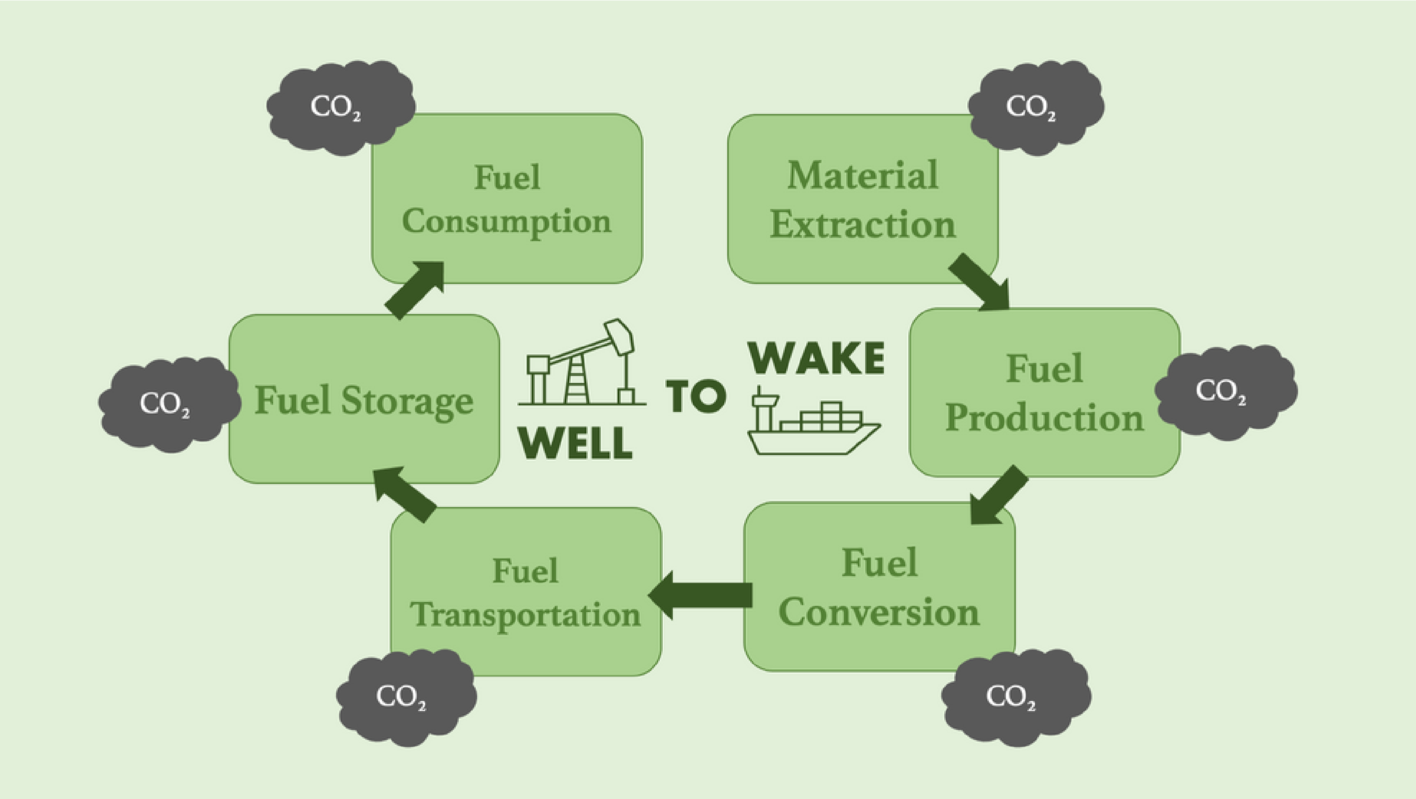


Figure 2 - Well-to-Wake Overview.
Carbon emissions at each step in the fuel lifecycle are considered to determine the total carbon impact of a given fuel. The "tank" stage occurs between fuel storage and fuel consumption.

There are several steps in the “lifecycle” of a fuel that contribute to its carbon impact beyond fuel consumption. Consideration of alternative fuels for shipping from "well" to "wake" is a strategy to determine the total carbon impact of the fuel more accurately (Figure 2). "Well" refers to the extraction of the material needed to produce the fuel. "Wake" refers to the wake of a shipping vessel, which is the wave created as the vessel moves through the water. As a vessel in motion is using the energy from the fuel, this marks the end point of measuring the carbon impact of the fuel.

An additional term, "tank," refers to the point of fueling up a shipping vessel, where the fuel enters a tank for storage before use. Alternative fuels are often assessed on their tank-to-wake carbon impact, where only the emissions from consumption of the fuel are considered. However, results obtained from this approach only tell part of the story.

OTHER CRITERIA BEYOND EMISSIONS

The carbon impact of alternative fuels is not the only factor that plays a role in analyzing their utilization. Factors such as toxicity and flammability are also important when determining if the fuel is safe for use in the shipping industry. In addition, factors such as existing infrastructure and ease of adaptability contribute to how likely the shipping industry will want to turn away from MDO and HFO. The five criteria that have been identified as the most critical factors contributing to the decision to use specific alternative fuels are shown below.

CRITERION	DEFINITION
EXISTING INFRASTRUCTURE	The number of facilities already in place to support the production, transportation, and acquisition of the fuel.
EASE OF ADOPTION	The number of changes that would be required to use the fuel on current shipping vessels.
HEALTH HAZARD	The adverse effects the fuel has on human life through physical touch, inhalation, and ingestion.
ENERGY RETURN ON INVESTMENT (EROI)	The amount of energy used to extract/produce the fuel compared to how much energy the fuel provides (Carbon Brief, 2013).
FLAMMABILITY	The ease at which the fuel catches on fire.

METHODOLOGY

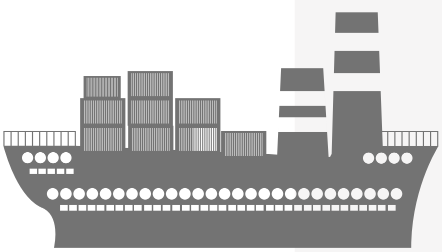
The purpose of this project was to provide recommendations for various alternative fuel options for the maritime shipping industry. This required a process of gathering and analyzing specific information to produce our model for determining the most viable alternative. The creation of this model involved gathering data in several key areas: identification of optimal alternative fuel candidates, stages in the lifecycle of the fuel for carbon emissions analysis, and additional factors affecting fuel acquisition decisions.

There are two main sets of methods used to obtain data to support the recommendations made. First, the total carbon impact of the fuels, or the mass of carbon dioxide emitted from well-to-wake when they are used in the shipping industry, was calculated and used to assess the options considered. Although carbon impact is important, there are several other criteria to consider when recommending a switch to an alternative fuel. The second main set of methods accounts for this, where the fuels are assessed on carbon impact and other criteria simultaneously using a decision matrix.

DETERMINING THE TOTAL CARBON IMPACT OF FUELS

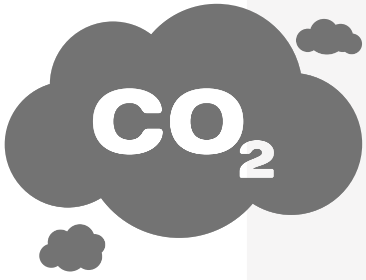
When developing methods to quantify the total carbon impact of each fuel considered, the team looked to past studies and efforts to do so. This initial process was guided by the research question: How do current procedures used to trace carbon impact consider the entire life of the fuel, and in what areas do current procedures fall short of this consideration? The following steps were then used to trace the total carbon impact (mass of carbon dioxide emitted) from well-to-wake for each fuel, where Microsoft Excel was used to keep track of and perform all calculations:

1 Define Average Vessels



- Following discussion with USCG personnel, the team decided to define average vessels for four main categories of particular interest: bulk carriers, container ships, general cargo ships, and oil tankers.
  - For each vessel type, average capacity (average deadweight tonnage) and average distance traveled in one year are extracted from available data in the Fourth IMO Greenhouse Gas Report (International Maritime Organization, 2021).

2 Calculate carbon emissions for traditional fuel, tank-to-wake



- Using the CII calculation defined in recent amendments to MARPOL Annex VI, data from step 1, and additional data from the Fourth IMO Greenhouse Gas Report, the mass of carbon dioxide emitted from the four average vessels in one year tank-to-wake, assuming traditional fuel use (HFO, MDO), was calculated.

3 Calculate carbon emissions for alternative fuels, tank-to-wake

- With values for the mass of carbon emissions from the average vessels using traditional fuel obtained, a series of calculation steps using conversion factors from various sources was used to determine the mass of carbon dioxide emitted in one year should each of the average vessels instead use the alternative fuels considered (Figure 3).

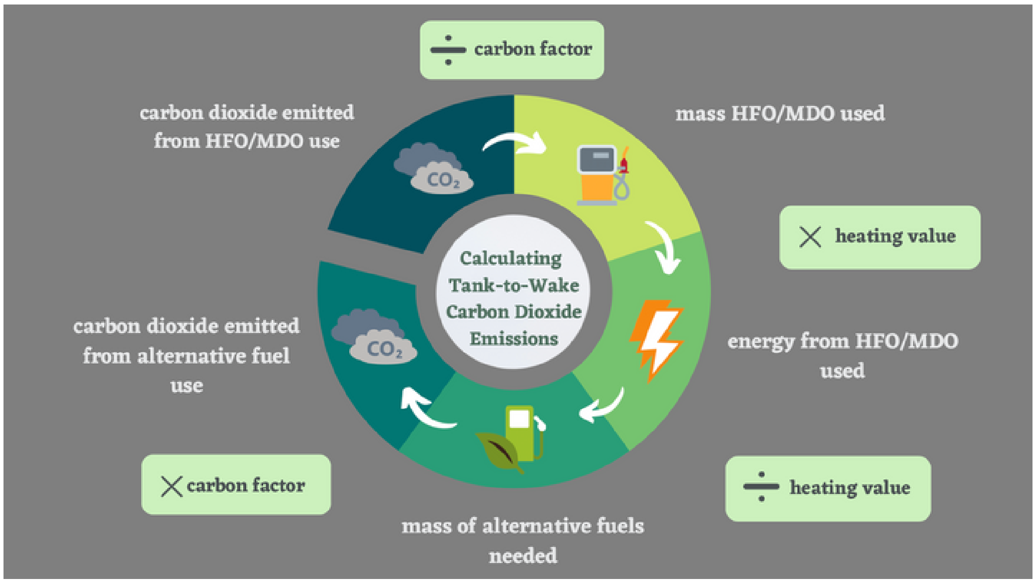


Figure 3 - Tank-to-Wake Carbon Emissions Calculation Steps.

An overview of the calculation steps to ultimately obtain the theoretical mass of carbon dioxide emitted from the average vessels, should they switch to each of the alternative fuels and maintain the same capacity and distance travelled.

4 Calculate carbon emissions for all fuels, well-to-tank

- To determine the amount of carbon dioxide produced during the well-to-tank processes, the team utilized the GREET database (Argonne National Laboratory, 2021). GREET models the well-to-tank processes for several different fuel types, including those considered in this project, and provides data on the emissions released during these processes. The team adjusted the parameters in the GREET database to obtain a conversion factor to convert the previously determined amounts of each fuel needed to power the average vessels to the mass of carbon dioxide emitted from well-to-tank.

5 Add well-to-tank + tank-to-wake

- To determine well-to-wake carbon impact for each of the average vessels and each of the fuels considered, well-to-tank carbon dioxide emissions from step 4 were added to tank-to-wake carbon dioxide emissions from steps 2 and 3.

ADDITIONAL FACTORS AFFECTING FUEL CHOICE

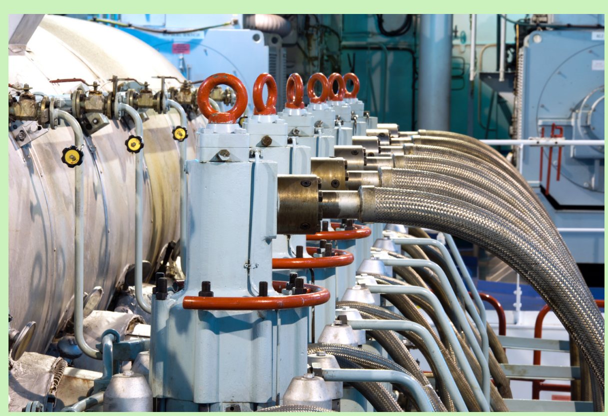
After considering the carbon impact of each alternative fuel, the team turned to other factors that affect the decision of which fuel is the best option. With help from ENG-5, the following factors are what the team decided were the most important to consider: existing infrastructure, ease of adoption, health hazard, Energy Return on Investment (EROI), and flammability. To determine if certain fuels perform better than diesel in these criteria, the team gathered information from literature and had open discussions with US Coast Guard members. The research question the team used to guide this information gathering was: How can the factors be quantified to allow them to be compared to one another and to diesel?

EXISTING INFRASTRUCTURE

This factor was quantified by counting the number of existing ports in the U.S. that had the fuel available. It was assumed that every U.S. port would have HFO and MDO. It was also assumed that each port with HFO and MDO would also support biodiesel and e-diesel.

EASE OF ADOPTION

This factor was quantified by stating whether or not each fuel could be efficiently used in an internal combustion engine.



HEALTH HAZARD

This factor was quantified by using the National Fire Protection Association (NFPA)'s scale. This scale ranks health hazard from 0-4, with 0 being least hazardous and 4 being most hazardous.

EROI

This factor was quantified by dividing the energy from the use of the fuel by the energy needed to extract and produce the fuel.

FLAMMABILITY

This factor was quantified by using the National Fire Protection Association (NFPA)'s scale. This scale ranks flammability from 0-4, with 0 being least flammable and 4 being most flammable.

DISCUSSION

After developing and following methods for data collection, there emerged certain points to focus on in analysis of the data and presentation of the findings to meet the objectives of the project. First, it is necessary to analyze the values obtained for total carbon impact for each of the average vessels theoretically using each of the fuel types. These values should be presented graphically for easy comparison of total carbon impact and to determine the areas of most significant reduction across both vessel type and fuel type. Once these areas are identified, a decision to recommend a switch to an alternative fuel from the list of those considered or to seek additional solutions to solve the problem at hand can be made.

Second, the "scoring" of the alternative fuels on additional criteria should be presented in an organized way to easily display the best and worst ranked fuels when factors beyond total carbon impact are considered. Presenting this data using the decision matrix accomplishes this and also allows for recommending a switch to an alternative fuel, should a favorable choice be presented. Lastly, discussion of an interview with an expert working as an alternative fuels researcher provides additional insight into smart choices for fueling the shipping industry and allows for a comparison with the findings of this project.

REDUCING CARBON DIOXIDE EMISSIONS

Carbon dioxide is at the forefront of the discussion of reducing greenhouse gas emissions around the globe and traditional definitions of carbon impact are mainly focused on carbon dioxide. Therefore, a comparison of annual well-to-wake carbon dioxide emissions across the fuel options considered for each of the average vessels considered is pertinent. A summary of the mass of well-to-wake carbon dioxide emitted by each vessel type over a one-year period is included below (Figure 4).

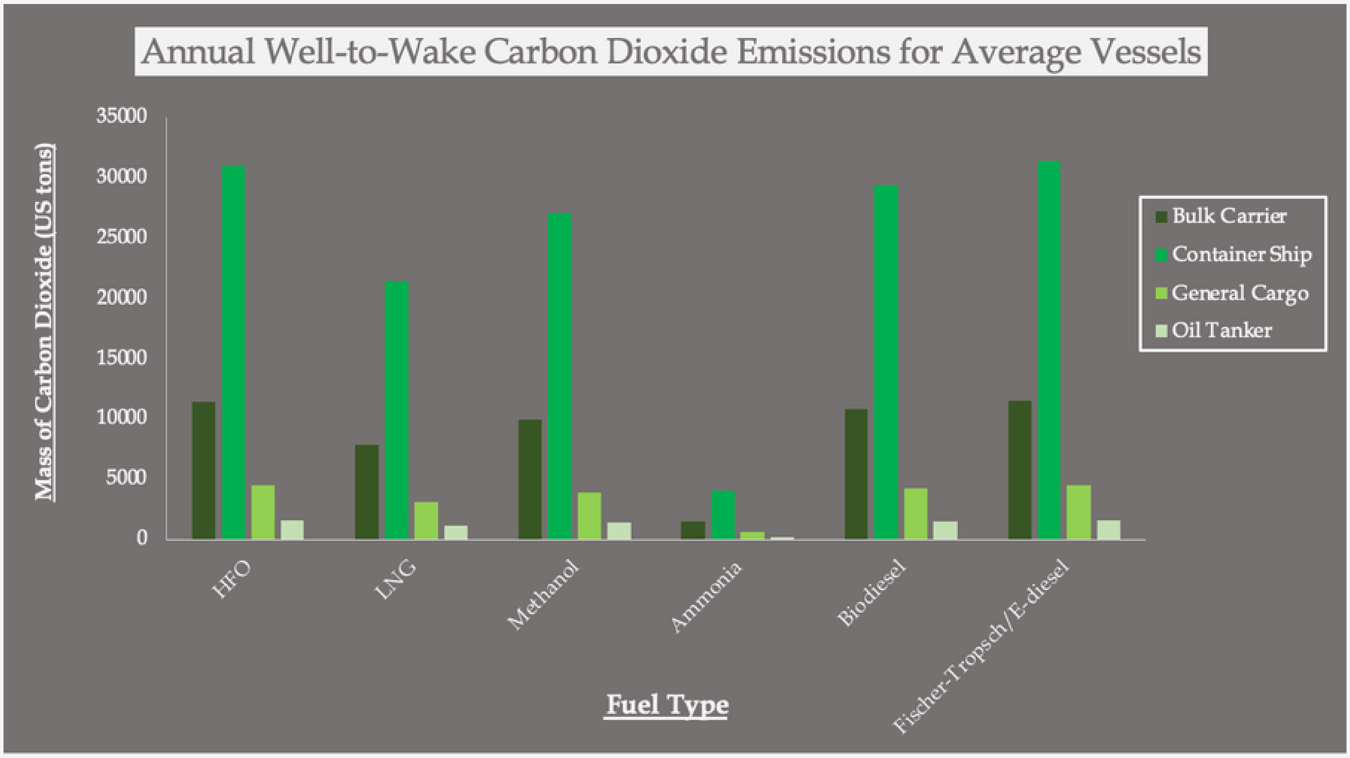


Figure 4 - Well-to-Wake Carbon Dioxide Emissions.
The mass of carbon dioxide for each vessel type considered using each type of fuel considered is displayed.

KEY FINDINGS

- **The container ship** is consistently responsible for the **most carbon dioxide production** across all fuel types.
- **The oil tanker** is consistently responsible for the **least carbon dioxide production** across all fuel types.
- Switching to **Fischer-Tropsch diesel** from the baseline of HFO would result in **slightly greater carbon dioxide emission production**. This is likely not accurate for e-diesel, where carbon dioxide emissions could be reduced from well-to-wake.
- The **most dramatic carbon dioxide reduction** is seen with **ammonia**, which shows an approximately **87% reduction in well-to-wake carbon dioxide emissions** from the traditional HFO fuel.

There is also merit to examining both the well-to-tank carbon emissions and the tank-to-wake carbon emissions across the fuel types. Doing so reveals the specific stages where each fuel contributes the most carbon dioxide emissions. With this knowledge, resources can be distributed to efforts to develop additional technology that reduces emissions in either the production or the use of certain fuels, potentially increasing the amount of greener alternative options. A summary of the annual well-to-tank carbon dioxide emissions for average vessels and the annual tank-to-wake emissions are shown below (Figure 5, Figure 6).

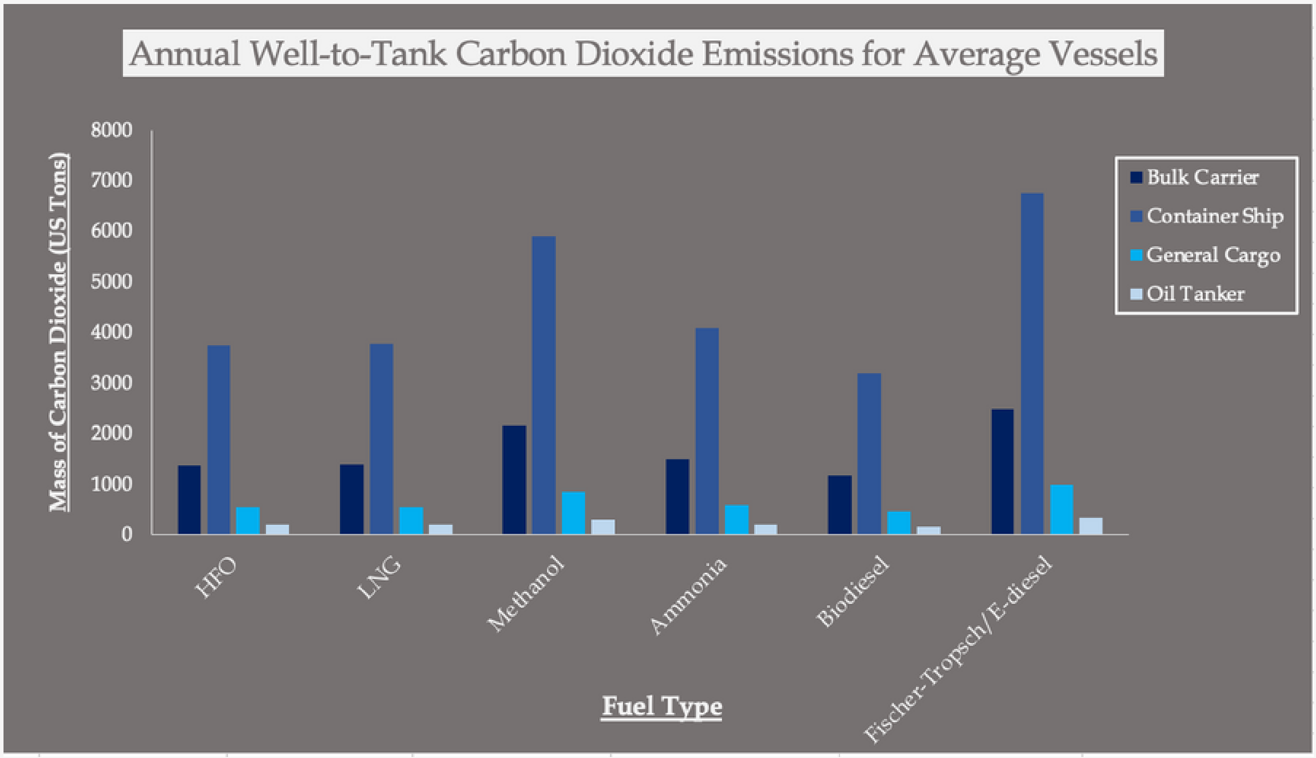


Figure 5 - Well-to-Tank Carbon Dioxide Emissions.
The mass of carbon dioxide for each vessel type considered using each type of fuel considered is displayed.

KEY FINDINGS

- **All of the alternative fuel types, except for biodiesel**, have a **greater amount of well-to-tank CO2 emissions** compared to the baseline HFO.
- A **switch to biodiesel** would also only result in a **marginal reduction in well-to-tank emissions**, approximately 15%.

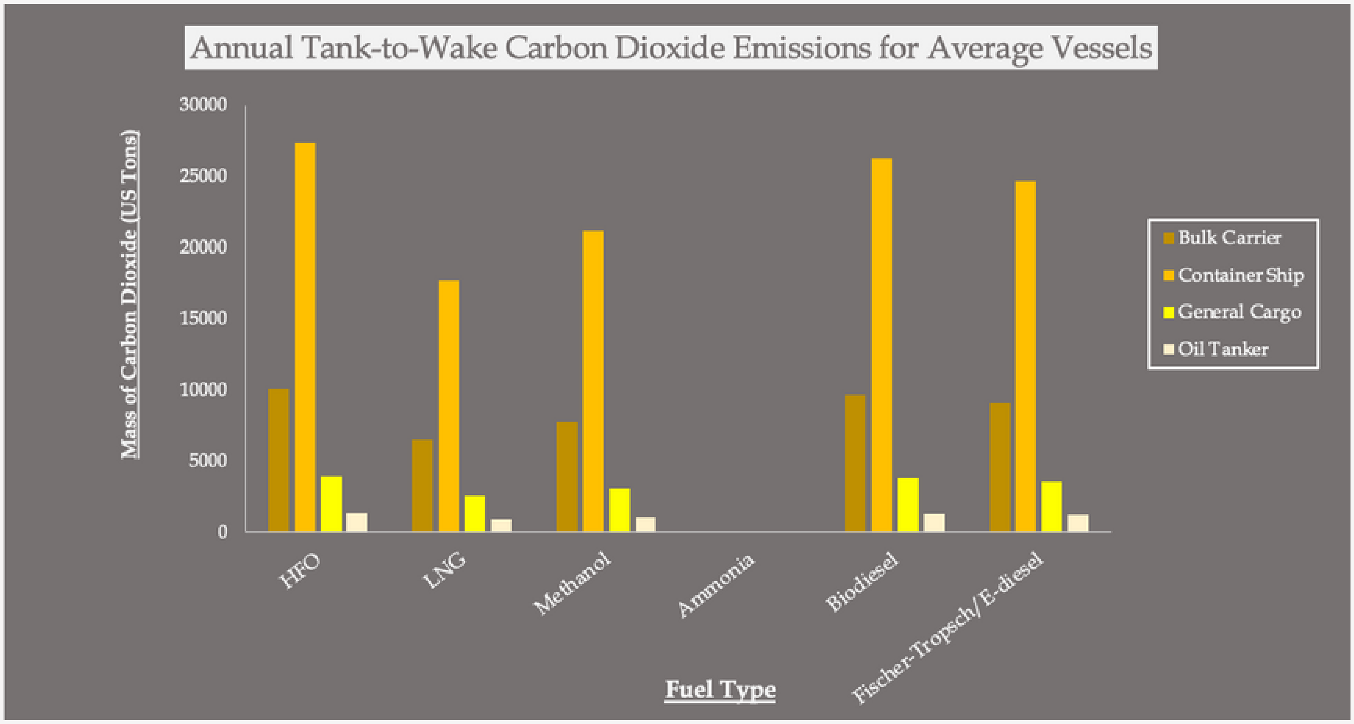


Figure 6 - Tank-to-Wake Carbon Dioxide Emissions.
The mass of carbon dioxide for each vessel type considered using each type of fuel considered is displayed.

KEY FINDINGS

- **All fuel options** considered have a **reduced amount of carbon dioxide emissions** from tank-to-wake.
- The most dramatic reduction occurs with ammonia, where **ammonia use on ships** emits **no carbon dioxide** (a 100% reduction).

ADDITIONAL CRITERIA OF ASSESSMENT

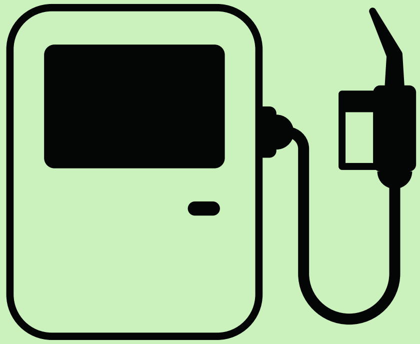
Once the annual well-to-wake carbon dioxide emissions for each fuel option were calculated, the other factors that contribute to fuel selection were considered. A decision matrix displaying the alternative fuels and the scores these fuels received under the additional criteria they were assessed on is included below (Figure 7).

Criteria	Baseline Fuel (HFO)	LNG	Methanol	Ammonia	Biodiesel	E-diesel
Existing Infrastructure	0	-1	-1	-1	0	0
Ease of Adoption	0	-1	0	-1	0	0
Health Hazard	0	-1	-1	-1	0	0
Energy Return on Investment (EROI)	0	+1	-1	-1	+1	-1
Flammability	0	-1	-1	0	0	0
Total Carbon Impact	0	+1	+1	+1	+1	-1
Rank Score	**0**	**-2**	**-3**	**-3**	**+2**	**-2**

Figure 7 - Additional Criteria Decision Matrix.
Decision matrix displaying the scores for each alternative fuel option for each additional criterion.

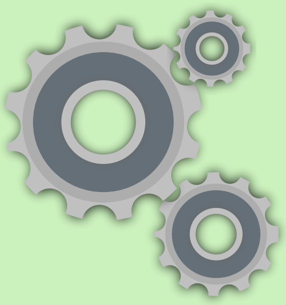
In this decision matrix, the emissions criteria that each fuel was evaluated on are listed in the far-left column. The alternative fuels were ranked with either a +1 score in each criterion if the fuel performed better than the baseline, a -1 score in the criterion if the fuel performed worse than the baseline, and a 0 score if the fuel had equivalent performance to the baseline. Scores were then added down each column. The highest scoring alternative fuel is the best performing alternative fuel. As the decision matrix shows, this fuel is biodiesel.

EXISTING INFRASTRUCTURE



- The existing infrastructure for biodiesel and e-diesel is the same as the baseline; therefore, these fuels each scored 0.
    - The assumption that the infrastructure in place for MDO & HFO can also support biodiesel and e-diesel was made (Sinha, 2021).
- The existing infrastructure for LNG, methanol, and ammonia is less developed than the baseline (Det Norske Veritas, 2021); therefore, these fuels each scored -1.

EASE OF ADOPTION



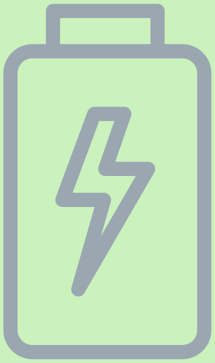
- Methanol, biodiesel, and e-diesel can each be used in the average internal combustion engines found on ships with no alterations needed due to their similar composition to the baseline fuel (Demirbas, 2010); therefore, these fuels each scored 0.
- LNG is difficult to keep in a liquid state. A boil-off gas (BOG) system must be installed to combat this (Gómez, 2014); therefore, this fuel scored -1.
- Ammonia is inefficient when used in an internal combustion engine due to its "high ignition temperature and low flame velocity" (Dincer & Erdemir, 2020). Alterations must be made to the internal combustion engine in order for the fuel to perform most efficiently; therefore, this fuel also scored -1.

HEALTH HAZARD

- The baseline fuels, HFO and MDO, both have a health hazard rating of 1 (Global Companies LLC, 2016).
- Biodiesel and e-diesel also have a health hazard rating of 1 (Global Companies LLC, 2016) (Chevron, 2015); therefore, these fuels each scored 0.

- LNG and methanol have a health hazard rating of 2, meaning it is more hazardous than the baseline (PGW, 2015) (Global Safety Management, 2015); therefore, these fuels each scored -1.
- Ammonia has a health hazard rating of 3, making it the most hazardous fuel analyzed (Airgas, 2019); therefore, this fuel also scored -1.

EROI



- The EROI values calculated range from 0.43 to 1.57, where ammonia has the least EROI and biodiesel has the most EROI.
- The baseline fuel (HFO) has an EROI value of 0.89.
- LNG had a greater energy return on investment than the baseline, 0.92; therefore, LNG scored +1 along with biodiesel.
- Methanol and e-diesel (Fischer-Tropsch diesel used) had a smaller energy return on investment than the baseline, 0.73 and 0.64, respectively; therefore, these fuels each scored -1 along with ammonia.

FLAMMABILITY

- The baseline fuels, HFO and MDO, both have a flammability rating of 2 (Global Companies LLC, 2016).
- Biodiesel and e-diesel also have a flammability rating of 2 (Global Companies LLC, 2016) (Chevron, 2015); therefore, these fuels each scored 0.
- LNG has a flammability rating of 4, making it the most flammable fuel being analyzed (PGW, 2015); therefore, this fuel scored -1.
- Methanol has a flammability rating of 3, meaning it is more flammable than the baseline (Global Safety Management, 2015); therefore, this fuel also scored -1.
- Ammonia has a flammability rating of 1, making it the least flammable fuel analyzed (Airgas, 2019); therefore, this fuel scored +1.

RECOMMENDATIONS

> "Ammonia has the largest reduction in CO_2 emissions from the baseline fuel."

> "The alternative fuel option that had a reduction in carbon dioxide emissions and scored the highest in the decision matrix is biodiesel."

> "Efforts to reduce CO_2 emissions on specific ships should focus on container ships."

> "There is a need to reduce well-to-tank emissions for all alternative fuel options considered."

The results for the well-to-wake analysis revealed that ammonia has the largest reduction in CO_2 emissions from the baseline fuel, HFO. Although this reduction in CO_2 is significant, it is also important to consider alternative factors. In the decision matrix, ammonia was one of the lowest scoring alternative fuel options. This is due to the fact that ammonia does not have an established infrastructure in the U.S., it cannot efficiently be used in an internal combustion engine, it is highly toxic, and it has a lower energy return on investment.

The alternative fuel option that had a reduction in carbon dioxide emissions and scored the highest in the decision matrix is biodiesel. This alternative fuel option already has an established infrastructure in the U.S., it has the same health hazard and flammability rating as the baseline fuel, and it has a better energy return on investment than the baseline fuel. Therefore, biodiesel is a promising alternative fuel option that has the most likelihood of being adopted within the next decade.

Out of the four average ships examined, the container ship consistently produced the most CO_2 emissions. This is due to its large deadweight tonnage and the vast number of nautical miles it travels each year. In order to make the most significant impact to reduce CO_2 emissions on specific ships, efforts should focus on container ships.

Although all of the alternative fuels had a reduction in CO_2 emissions compared to the baseline in the tank-to-wake portion of their lifecycles, all fuels but biodiesel had a greater amount of well-to-tank CO_2 emissions. This reveals that there is a need to reduce well-to-tank emissions for all alternative fuel options considered to have these fuels perform equal to or better than the baseline fuel.

MORE FINDINGS

To confirm or refute our findings, we conducted a semi-structured interview with a biofuel expert. It was important to obtain a first-hand account of the research being conducted in the alternative fuel industry to understand the feasibility of switching to our recommended fuel. Our interview aided to confirm our findings and justify our recommendation to the switching of biofuels. Below are direct quotes from the interview and the terms perspectives and responses to them. The used interview questions can be found in Appendix A.

“Starting with say food waste or similar waste type streams - the next proposal we write would be for scaling that up to like a ton per day scale. And if that goes well that would take us like three or so years, we get data and then typically in chemical engineering you go like a hundred-fold every time. And so that would take it from one ton and the next step up would be something like a hundred tons per day. Which is roughly what we think the scale needs to be to be as economical as possible. Again it’s going to be really hard to beat petroleum based on value but if you look at the whole impact you start to valorize the environmental damage that your avoiding. You can get there... By about 2025 you’re at 100 tons per day scale is feasible, that’s a reasonable time frame... and you just scale it up from there”.

The expert that we interviewed agrees with our findings that making a switch to biodiesel/ biofuels is feasible to meet the 2030 GHG deadline set by President Biden. The biofuels expert also states that it is difficult to make that comparison of values to petroleum, but looking at the big picture - the environmental damage that you're avoiding is very valuable.

“You can push on that in changing it from 25% efficient to 30% efficient, and that matters. But it’s not gonna be game changing, right? So, if you really want to be game changing and push towards net zero that’s got to be well to tank”

“Almost certainly any alternative fuel that you come up with will be more expensive. So, the tank to wake, what that can do is reduce the amount of fuel you need so you can manage costs that way”

The biofuels expert answer corresponds with our findings. All of the alternative fuels ranked worse in the well- to- tank stage compared to the baselines. It's clear that focusing on reduction in this area would make a 'game changing' impact. More attention needs to be directed towards the production stages of alternative fuels and identifying where we can lower the carbon being emitted through those processes.

“We think that if we have something like a biofuel - that its closed loop - so we don’t worry too much about the CO2 because we’re going to grow more food and that closes the loop that way. But what we do worry about though is the other emissions. So if you made some fuel that looked really good but it emitted 3x as much soot or something like that, then that would make you wonder”

This brings attention to the need of considering additional emissions when utilizing the well-to-wake process in analyzing the total carbon impact of an alternative fuel. While a fuel may not emit as much carbon as traditional diesel fuel, it may be emitting lots of other negative emissions, making it a less optimal and responsible choice.

“We start the new fuel, but actually it leaks, all of the fuel lines leak because the fuel isn’t compatible with their fuel lines. So that’s no good. You need to look at that kind of compatibility with the fuel delivery system. The tank that holds it, the piping that gets it from the fuel tank to the engine, and then of course there’s engine compatibility”

Expanding criteria when evaluating the feasibility of an alternative fuel is extremely important when ensuring that the fuel is actually capable of being utilized with ease. Considering all aspects when evaluating the ease of adoption of a fuel is something that could be continued in the future work of this project.

LIMITATIONS

There are limitations to the findings presented in this project and conclusions drawn are only valid within a certain frame of analysis. To begin, this project defined average vessels for four categories of vessels that operate within the shipping industry. This is not an exhaustive list and there are other categories that were not considered in this analysis. Our findings do not accurately represent these additional vessels and conclusions about these vessels cannot be drawn from the work presented here. Additionally, values calculated for total carbon impact of the average vessels in this project were for a single vessel in each category. Conclusions about the total carbon impact of this category across the international fleet cannot necessarily be drawn from the findings presented here.

The framework of analysis developed in this project is tailored towards fuels deemed feasible for adoption within the next decade. These fuels are all liquid fuels with similar well-to-wake processes. There are other alternative fuel options under development with vastly different well-to-wake processes. For example, both hydrogen and nuclear power present attractive options for greenhouse gas emissions reduction in commercial shipping. However, these options could not be accurately assessed using a liquid fuel framework because many points of concern not seen with liquid fuels would not be addressed.

// FUTURE RESEARCH //

In this project, we assessed the viability of transitioning to an alternative fuel to achieve reaching greenhouse gas emissions goal reductions set by President Biden. Through our research and calculations we found that biodiesel is the most feasible fuel to be transitioned to. But further investigation will aid in having a more precise answer. Many different adaptations, iterations, and perspectives on our work are left for future interpretations and projects. Future research concerns new proposals of the methods to complete calculations of the carbon impacts and a more in-depth assessment of the additional criteria.

1

DIFFERENT PROPOSED METHODS ON CALCULATING THE CARBON IMPACT OF THE FUELS // REDEFINING TOTAL CARBON IMPACT

Aim for the use of even more precise numbers and methods, rather than making general assumptions. Aim to include other emissions and utilize CO_2e and consider Prime Movers. Expand sources beyond GREET.

2

EXPANDING THE LIST OF PROPOSED ALTERNATIVE FUELS

Addition of Hydrogen & Nuclear Energy
These energy sources were not considered in our project because they were not within the scope of the 2030 reduction target, but are important fuels to examine.

3

EXPANDING TYPES OF CRITERIA TO BE EVALUATED

Possibly consider the criteria that our team had to omit due to time constraints. These include: cost, stakeholders, policy, storage, prime movers, etc. With more criteria comes a more precise conclusion.

4

CARBON CAPTURE SEQUESTRATION

"Putting a CO_2 carbon capture device on a ship - that would be tank to wake - so now you can burn any fuel that you want to but their capturing the CO_2 and then presumably when you get back to land, you'd drop it back off and unload your CO_2"
- Biomass Fuel Expert

REDEFINING TOTAL CARBON IMPACT- FUTURE RESEARCH (CONTINUED)

When considering future research for this project, one of the more pressing matters presented is the need to reevaluate the definition for total carbon impact to include other emissions besides carbon dioxide. While the focus of many recent reduction targets and regulation efforts is carbon dioxide, other emissions from fuel use in the shipping industry also contribute significantly to global warming. A particular fuel may have low carbon dioxide emissions when used on maritime vessels, but may have relatively high levels of black carbon, methane, or nitrous oxide emissions. Before the industry switches to an alternative fuel, it is important to evaluate the impact of these other emissions to ensure the solution to the problem isn't in fact creating additional problems for later years.

The GREET database is a good resource for analyzing the well-to-tank emissions of fuels and does provide data for the black carbon, methane, and nitrous oxide emitted from the production of fuels. However, the GREET database is not a good resource for tank-to-wake emissions beyond carbon dioxide. $CO2$ emissions are based on the carbon content of the fuel and are independent of other ship components. However, black carbon, methane, and nitrous oxide emissions require consideration of other ship components, such as vessel engines and prime mover systems. GREET is limited in the vehicles that can be modeled for tank-to-wake emissions analysis and does not include maritime vessel engines as of 2021. Thus, more complicated equations with more variables than the carbon intensity indicator equation are needed to perform the necessary calculations.

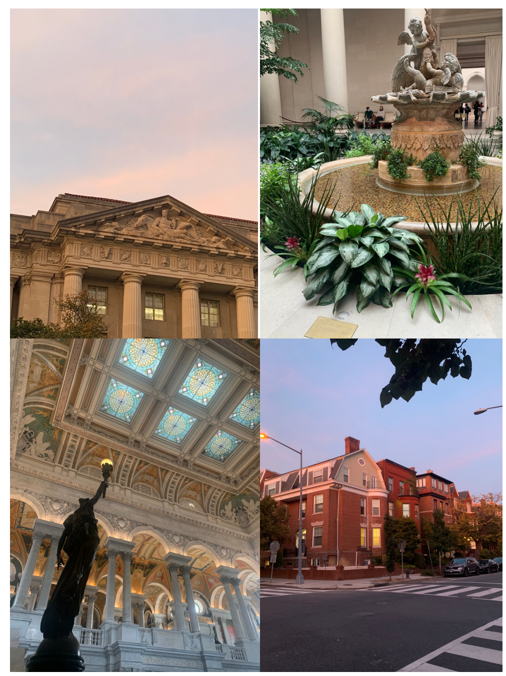
A source that includes these calculations for black carbon is the *Black Carbon Emissions and Fuel Use in Global Shipping 2015* report published by the International Council on Clean Transportation and many serve as a starting point for this future analysis (Comer et al., 2017). Black carbon, methane, and nitrous oxide can be converted to carbon dioxide equivalents ($CO2e$) and added to carbon dioxide emissions to create a new value for total carbon impact that more accurately assesses the potential harm of using a particular fuel.

OUR EXPERIENCES

Alison - Traveling to Washington, DC to complete IQP has been a worthwhile and unique experience that I am grateful for. I genuinely enjoyed the opportunity to work on this project where I was able to learn about topics I hadn't studied before, discover new interests, and work in an environment that fostered both innovation and collaboration at the United States Coast Guard Headquarters. I also appreciate the opportunity to live in our nation's capital in close proximity to so many iconic and historic sites. Exploring the city led me to many great places I can't wait to go back to, including the International Spy Museum, the Basilica of the National Shrine of the Immaculate Conception, and countless bakeries and restaurants with such a wide variety of new foods to try.

Source: Alison Drapeau

Michaela - Throughout my time in Washington, I've grown as a person and learned a lot about myself throughout this IQP experience. I've adjusted to living in a place that I've never been to before, learned to take the metro, and adapted to the culture of living in a city. I loved going to the Smithsonian Museums, exploring Georgetown and Old Town Alexandria, going to a comedy show, seeing a Washington Capitals game, and finding small bookstores and coffee shops. I am so appreciative of our Coast Guard sponsors who guided us through our project, took us on trips to see the USCG air detachment, and organized meetings with other members of the Coast Guard to explore different career paths. I loved being in D.C. and can't wait to visit again one day.



Source: Michaela Kelly

Molly - Living in Washington D.C. and working at the USCG Headquarters has been an amazing and unique experience. I really enjoyed going to all the museums and memorials and learning more about our country's history. Being able to work closely with members of the military was also a valuable experience, especially as a midshipman in the Navy ROTC program preparing to commission as an officer in 2023. I am particularly grateful for the opportunity to go to the Pentagon and speak with several submarine officers. I know my experiences during this IQP project will prepare me for the rest of my time at WPI, along with my time in the U.S. Navy.

Source: Molly MacAllister

Recording Request (to be asked before recording starts):

Good afternoon, [ ]. Before we begin, do you mind if this interview is recorded, so our team can refer back to it to verify our notes?

Interview Introduction (to be read out loud at beginning of recording):

Hello, [ ]. We are Alison Drapeau, Michaela Kelly, and Molly MacAllister. We are students from Worcester Polytechnic Institute completing a project with the United States Coast Guard on fuel options in the shipping industry. To do this, we have been gathering information on possible fuel alternatives to diesel. If you are willing, we would like to ask you a few questions about your experience within the fuel industry. Your answers will be kept completely confidential and anonymous. And if you prefer not to answer a question, we will skip it. If you would like to end the interview at any time, notify a team member and anything recorded will be erased.

This interview will be recorded only for the purpose of being able to refer to it if any information is missed in notetaking. After being reviewed, the team will delete the recording. Where this interview is being conducted over Zoom, the video recording will be deleted after use. Zoom is also capable of saving a separate audio file after recording; the team is capable upon request to just review the audio file rather than the video file. Can you verify again for the recording that you consent to being recorded?

Interview Questions:

1.How did you first get interested in alternative fuels research and why did you choose to focus on biofuels?

2.We are considering the well-to-wake carbon impact of the alternative fuels in our project. There seems to be a division in research, regulation efforts, etc. in focusing efforts to reduce emissions either from well-to-tank or from tank-to-wake. Although both are important, does one of these options stand out to you as more feasible given the 2030 reduction target date? Where can we reduce emissions the most in the near future?
a.Where the articles you provided to us were recently published and the catalysts discussed are now beginning to increase the yield of biocrude oil when used in CHTL processes, is 2030 (Biden administration) a realistic target date to scale up production and increase availability of biocrude oil to produce diesel? How about the 2050 reduction target date from the IMO?

3.What does the process of identifying alternative fuels for research look like? For example, how does one relate the problem of cleaning the Great Pacific Garbage Patch (GPGP) and need for alternative fuels for maritime use (how is this idea formulated)?

4.Besides carbon and environmental impact, what other criteria are important to consider when evaluating a new alternative fuel option?
a.We're trying to put together a weight system for our additional criteria. Are any of our criteria more immediately important over others, in your professional opinion?

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