EXECUTIVE SUMMARY

GREEN FUELS FOR VESSELS AND THEIR CARBON IMPACTS

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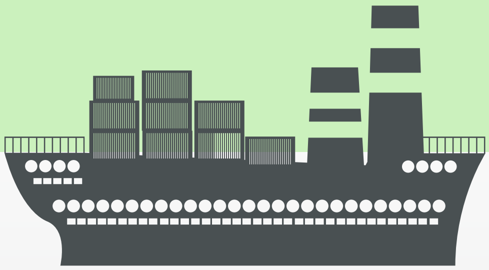
Purpose of the Project

Climate change is one of the most pressing scientific concerns of the modern day where many world leaders are seeking solutions. While changes to many industries are required to reduce greenhouse gas production, one industry where more research is needed to strategize changes to reduce emissions is the shipping industry. Particularly of interest is reducing the carbon impact of shipping, where amendments to MARPOL Annex VI, the primary set of international regulations for air pollution from shipping vessels, have recently presented new ways to calculate the carbon intensity of individual vessels using traditional diesel fuel. Performing these calculations using vessel data available from recent years reveals staggering amounts of carbon-based emissions with traditional fuel use.

One proposed way of reducing these emissions is switching to an alternative fuel with a different carbon content from the traditional fuel. Before such a change can occur, it is necessary to develop a framework to analyze the potential carbon impacts of various fuel options. Information gathered will ensure a responsible choice is made and will determine if this will indeed reduce carbon-based emissions from shipping. This project seeks to develop this framework to trace the carbon impact of alternative fuels should a switch occur in the shipping industry and also assess the feasibility of a switch.



Goals and Objectives

1. Present a definition of total carbon impact for the shipping industry that encompasses all areas where emissions are produced.
2. Calculate the annual emissions from both traditional and proposed alternative fuel choices intended for use on average vessels in the shipping industry to assess total carbon impact.
3. Assess the fuel options on additional criteria to determine the feasibility of a switch in the timeframe of the Biden administration’s 2030 reduction target.
4. Provide recommendations for reducing the carbon impact of the shipping industry based on findings from completing the aforementioned goals.

Methods of Data Collection

In order to address the first goal of defining total carbon impact in a way that encompasses all areas where emissions are produced, the well-to-wake approach was used. With this method, all carbon dioxide emissions produced from the material extraction stage to produce the fuel (well) to the consumption of the fuel (wake) are considered. To calculate well-to-wake emissions, a separate calculation of well-to-tank and tank-to-wake emissions, (tank being the stage of storing the fuel on a vessel before use) was necessary based on the data sources utilized. Tank-to-wake emissions for each of the fuel types on each of the average vessels analyzed were calculated using several equations and data from various sources, heavily relying on the Fourth Greenhouse Gas Report published by the International Maritime Organization. Well-to-tank emissions were calculated using the GREET database developed by the Argonne National Laboratory. Well-to-tank emissions from a given fuel used on a given vessel were added to the corresponding tank-to-wake emissions to determine well-to-wake emissions and total carbon impact.

To determine the feasibility of switching to an alternative fuel beyond total carbon impact, each alternative fuel option was assessed on performance compared to the baseline traditional fuel used in the shipping industry. All additional criteria considered were defined numerically and values were obtained for each fuel option. The performance of the fuel for a certain criterion could then be determined definitively as better, equal to, or worse than the baseline and relative scores could be assigned accordingly. These scores were then presented in a decision matrix and addition of the individual criterion scores for a fuel to produce a rank score determined the most feasible alternative fuel for the shipping industry to switch to. To either support or refute these findings, an interview was conducted with an alternative fuels expert who conducts research in the field.

Findings

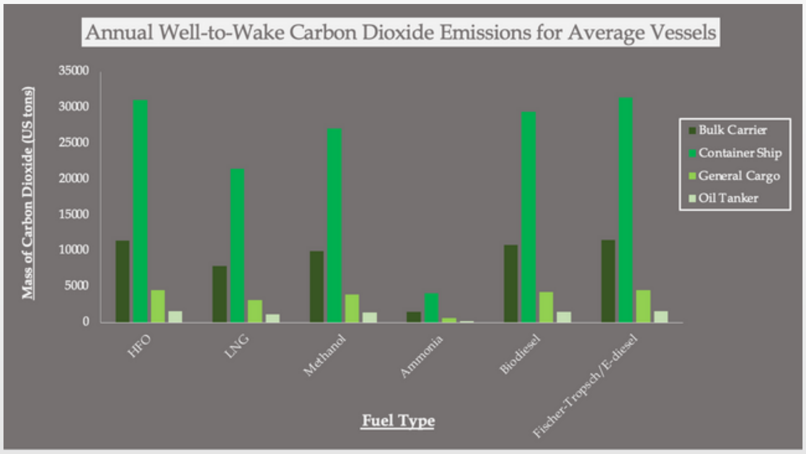


Figure 1 - Well-to-Wake Carbon Dioxide Emissions.
The mass of carbon dioxide for each vessel type considered using each type of fuel considered is displayed.

- **The container ship** is consistently responsible for the **most carbon dioxide production** across all fuel types (Figure 1).
- **The oil tanker is** consistently responsible for the **least carbon dioxide production** across all fuel types (Figure 1).
- 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.

Findings (Continued)

Where there were separate calculations performed for well-to-tank carbon dioxide emissions and tank-to-wake carbon dioxide emissions, there were also conclusions to note about both of these respective stages:

- **All of the alternative fuel types, except for biodiesel**, have a **greater amount of well-to-tank CO_2 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%.
- **All fuel options** considered have a r**educed 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).

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	-1	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**	**+1**	**-2**

Figure 2 - Decision Matrix with Rank Scores.
The scores across each criterion row represent better (+1), equal (0), or worse (-1) performance than the baseline. Rank scores are sums of each column of the matrix (each fuel type). A higher score represents a more feasible option for a switch.

- Although **ammonia** appears to be the best choice when only considering total carbon impact, it has the **lowest rank score** (tied with methanol) when assessed among other criteria (Figure 2).
- **Biodiesel** received the **highest rank score** and performs better than the baseline when assessed on all of the listed criteria, making it the **most feasible choice to switch to** (Figure 2).
- Biodiesel is the only fuel option to receive a positive rank score, indicating a switch to any of the other alternative fuels would not likely be without **significant negative effects** (Figure 2) .

Summary of Recommendations

Based on total carbon impact alone, a switch to ammonia from traditional fuel would reduce carbon dioxide emissions most significantly.

Based on multiple criteria across various areas, a switch to biodiesel from traditional fuel presents the most feasible and responsible choice while still reducing total carbon impact.

Certain vessels, such as the container ship, contribute more carbon dioxide emissions, and efforts focused on these vessels would likely have the most significant impact.

There exists a need to reduce well-to-tank emissions for all alternative fuel options considered (besides biodiesel) to have these fuels perform equal to or better than the baseline traditional fuel, which may be a target of further research.