The Future of Internal Combustion Engines in the Ocean Freight Industry

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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STS Research Paper

Introduction

The Environment & The Ocean Freight Industry

The purpose of this paper is to analyze the current state of Internal Combustion Engines (ICEs) in the ocean freight industry, considering environmental and sustainability pressures, including the rise of alternate fuels, electrification, and climate regulation. Over a century of infrastructure development, efficiency and power increases, and decreasing costs has led to a society defined by using ICEs for everything from transportation to lawn care tools to shipping and more. However, emission of harmful pollutants is a byproduct of ICEs, which has caused decades of debate. Beginning in the 1960s and becoming widespread in the 1990s, scientists and climate activists have been warning of adverse effects of these emissions gases on public health and the environment (Skelton, 2023). Following criticism, scientists and engineers have developed and continue to develop technologies such as emission control devices, alternate fuels, and electric motors.

Electric vehicles, mainly personal cars, have become a common sight on roads across the world. Electric vehicles flood the vehicle market, government debate, and the news cycle. Largely absent from this discussion is the issue of the global supply chain. Many goods we take for granted in our daily life have taken a long trip to be in our hands, many times even from across seas. This global supply chain is largely dependent on the function of the ocean freight industry, as we saw in March 2021 with the Ever Given's five billion dollar disruption of the supply chain when it got stuck in the Suez Canal and captivated a global audience (Gross, 2025). Ocean freight is a large user of ICEs, with its emissions causing 3% of global CO_2 emissions annually. If unchanged, ocean shipping could represent 10% of global greenhouse gas emissions by 2050 (*Ships,* n.d.). This situation begs the question: How do alternative fuels and their electric equivalents impact the future of the internal combustion engine in ocean freight applications?

Actor Network Theory as an Analytical Framework

To examine this topic, I will be utilizing the STS framework known as Actor Network Theory (ANT). Actor Network Theory is an approach to social theory which posits that everything, human and nonhuman, is an actor in changing networks of relationships. Since everything is in the network, there are no external social factors to be considered outside of these relationships. One main, yet contentious, foundation of ANT is that actors can be nonhuman. This implies that nonhuman factors such as technology, the environment, art, or more, can interact with humans to drive actions, participating in the network. Another important concept in ANT is the idea of Translation. Translation is the idea that different actors can come together and align their interests and influences to work towards a common goal (this can be called a forum). Other important concepts in ANT are the evolution of networks/relationships and how different actors can carry more power/influence than others.

Actor Network Theory In Context

I am using Actor Network Theory to address my research question because of the variety of actors, the forums they create, and external relationships involved in the ocean freight industry. One forum aimed at more sustainable solutions may include climate activists, environmental engineers, alternate technologies, governmental agencies, regulations, and the environment. Another forum, which could be pro internal combustion engine, may include the oil suppliers, the current fleet of ships, and more. Both forums contain a mix of human and non-human actors, which is a main characteristic and benefit of ANT. However, there are more actors and relationships external to these main groups/forums. Using ANT, it is easy to internalize these would-be-externalities such as pollution and electric infrastructure at ports that have large impacts–positive or negative–on the high influence actors. Finally, the power difference between actors, a key tenet in ANT, is an important piece of my analysis. Actors such as governmental bodies and shipping companies may have more power over other actors such as activists and consumers. Even non-human actors such as alternate technologies play a large role (have lots of power) in whether or not a shift away from ICEs is even possible. Analyzing the power imbalances in important relationships is a key tool in understanding the current state of this industry and predicting where it may go in the foreseeable future.

Historical Background

The focal point of modern environmentalism is the present and future harm brought by greenhouse gas emissions. The greenhouse effect is crucial to the function of our planet; it is a layer of gases in the atmosphere that helps to regulate the habitable conditions that life on earth relies on. Key greenhouse gases are carbon dioxide, water vapor, and methanol (Mann, 2025). They allow short wavelengths of light from the sun to enter the atmosphere, while blocking longer wavelengths of light from leaving the atmosphere. This traps energy from the sun, heating our planet amongst other things. However, higher levels of greenhouse gases enhance the effect leading to global warming, climate change, health risks, and more. Currently, this is a man-made effect as a result of carbon dioxide emissions from burning fossil fuels (Menon, 2024). Fossil fuels are a nonrenewable resource made from millions of years of organic material being compressed, leading to coal, oil, and natural gas.

Although it is hard to pinpoint when environmentalism and climate concerns first began, the modern movement can be traced back to the 1960s and maybe as early as the 1950s. The early movement mostly questioned land destruction and poor air quality as effects of industrialization, fossil fuel burning, and pesticide use. Notable U.S. government action at the time includes the establishment of the Environmental Protection Agency (EPA) in 1970, the Clean Air Act, and the Clean Water Act. It wasn't until the 1990s and early 2000s that greater concern for global warming and climate change grew.

The shipping industry has long ties with fossil fuel burning, beginning with coal powered ships in the 1800s and shifting to oil powered internal combustion engines in the 1900s. Despite their negative effects on the environment, fossil fuels revolutionized how the world economy functions. Sea transportation with fossil fuel power is faster, more reliable, and safer than their sail powered counterparts. This enabled more international trade, developing small economies and acting as a foundation for the global economy. Currently, 80% of the world trade volume is carried by sea (United Nations Conference on Trade and Development, 2023, p. 55).

It may seem as though the shipping industry–specifically ocean freight–is absent from the global discussion on climate change and global warming. Indeed, it seems the media and politicians tend to focus on more visible issues such as electricity generation and transportation. Although unnoticed by the public, there is a conversation about the ocean freight industry's notable effect on the environment. As of 2023, the industry represented 3% of global greenhouse gas emissions. This may not seem like much, but this is a 20% increase over the previous decade. If unchecked, this is expected to reach 130% of its 2008 level by 2050. Making matters worse, the 2023 fleet of sailing ships was composed of 98.8% fossil fuel ships (United Nations Conference on Trade and Development, 2023, pp. 55-57). This concern doesn't even include other environmental issues not associated with fossil fuel usage, such as the finite nature of oil, potential for disastrous oil spills on ecosystems, and acid rain which can harm crops. So, how can the ocean freight industry reduce its carbon footprint?

There are multiple methods to consider for the decarbonization of the ocean freight industry. Potential methods include efficiency techniques, carbon capture and sequestration, alternative fuels, hybridization, and electrification. Efficiency techniques categorize methods for ship captains and crews to increase the efficiency of their fossil fuel burning ships. These methods include: route planning to more efficiently follow currents and weather patterns; slow steaming to run at more efficient speeds; and hull and propeller cleaning. Not only do these methods reduce emissions, but they also reduce fuel costs for the ship owners.

These solutions, however, do not solve the problem of greenhouse gas emissions. Alternate fuels such as hydrogen, methanol, biofuels, liquified natural gas (LNG), and systems that use electric power such as hybrid or fully electric, represent a cleaner and more sustainable future for the shipping industry. Unfortunately, these technologies are different stages of early development. Their costs and capabilities are still being discovered, so present risk is large.

As of 2023, the average age for a ship in the ocean freight industry fleet was 22.2 years, meaning that much of the fleet is from a time that was less concerned with efficiency and environmentalism. That being said, 21% of the ships on order are cleaner with LNG, methanol, and hybrid technologies (United Nations Conference on Trade and Development, 2023, p. 29, p. 69).

Part of the pressure pushing the industry towards efficiency and sustainability can be credited to regulatory agencies. The International Maritime Organization (IMO) created by the

United Nations creates mandatory guidelines for ships to follow to increase safety, decrease pollution, and prioritize efficiency. The IMO created a publication in the 1970s called the International Convention for the Prevention of Pollution from Ships (MARPOL), triggered by multiple oil spill incidents. Thus, most of MARPOL 'annexes' are aimed at preventing oil discharge, as well as sewage and garbage discharge, from ships engaged in international trade. Annex VI, however, does set standards for ship emissions, specifically sulfur oxide content, nitrous oxide, carbon dioxide, and particulate matter. It also includes Energy Efficiency Design Index (EEDI) requirements for new ships and Ship Energy Efficiency Management Plan (SEEMP) requirements for all ships (Menon, 2024).

Actor Network Theory Analysis

Identifying Actors

In completing an analysis with Actor Network Theory (ANT), it is first necessary to lay out the relevant actors, which will create the foundation for mapping relationships, analyzing the translation (forums), analyzing power dynamics, and drawing conclusions. Actors can be identified as either human or nonhuman. It is difficult and lengthy to list all possible actors, so key ones will be identified. Human actors include: the shipping companies who control operations, invest in new technologies, and adopt technological systems; regulators including individual governments, supranational groups, and their agencies such as the IMO; scientists and engineers who create ship technology; captains and crew that operate the ships; activists and their organizations which support environmentally conscious policy; investors both into new technologies and the shipping companies; and finally the business owners and consumers that rely on shipping for delivery of goods. Nonhuman actors include: the ships themselves and their propulsion systems; alternate and conventional fuel systems (oil, LNG, methanol, etc.); electric systems including batteries, generation methods, and motors; port infrastructure to support different types of ships and propulsion systems; and finally the environment with its climate change affliction.

Mapping Network

Next, using these actors, we can map out present relationships between them as a network. One relationship is centered around regulatory influence. Regulatory bodies mentioned above, along with climate activists, require and urge shipping companies to act certain ways for the sake of the environment. They use environmental data to set these standards, often impacting the ships, personnel working on them, and the adoption of new technologies. This reveals another relationship, centered around new technologies. Shipping companies work with engineers and scientists to create systems that adhere to these policies and also to increase their profitability. These technologies may utilize alternative fuels or retrofitting older ships. Another key relationship is the maintenance of these ships, both new and old. Local governments work with ports, engineers, and ship crews to maintain ships. New infrastructure is needed to supply alternate fuels or electricity, which also involves the government and suppliers of these energy sources.

Forums & Translation

Actor Network Theory uses a tenet called translation to describe and analyze how different actors come together as forums to work towards common goals. Here we can identify three main forums: the environmental forum, the fossil fuel proponent forum, and the price-focused forum. The environmental forum includes predictable actors: regulatory agencies, environmental activists, alternate fuel systems, electric systems, and the environment. This forum comes together with the common goal of reducing carbon emissions and generally decarbonizing the ocean freight industry. Importantly, this goal is primarily motivated by environmental concerns over all else. The fossil fuel proponent forum is a result of the legacy, carbon dependent industry. This mainly includes oil producers, ship manufacturers, the existing ship and port infrastructure, and the fuel itself. This forum is not concerned with the environment, but instead on upholding the successful, century old oil dependent industry.

Finally, there is the price-focused forum. This forum is defined by its motivation to be economically efficient. It is not particularly concerned with the means, sustainability vs. oil, but with which will be more price effective. This forum includes the ship manufacturers, their investors, consumers, efficiency methods/technologies, and the goods being shipped. Historically, and even maybe still, this forum is aligned with the fossil fuel proponent forum. However, as the environment worsens and new technologies are discovered/developed, relationships shift and they can be easier distinguished. Perhaps now this forum is more central, and how its relationships shift will define the future of the industry.

Power Dynamics

In determining the future direction of the industry, then, it is imperative to understand the power dynamics at play. In the environmentalist forum, the government and regulatory agencies have high power to influence where the industry goes, although they must do so in an economically conscious way. The fossil fuel forum’s highest power is the existing ship fleet and infrastructure. To completely change this represents a high monetary and time cost. The price focused forum has utmost responsibility to uphold the global economy, accounting for 80% of global trade. It pits the other two forums against each other, forcing them to strike the right balance between social responsibility and economic viability. As for the fossil fuel forum, they support what can be referred to as a "black box," meaning they are above examination for this context. Fossil fuel systems have already been widely adopted and have proven their success, meaning they are not held to questioning. It is up to the environmentalist forum to prove its economic viability in order to justify regulations. In other words, they have the burden of proof to demonstrate success to the price focused forum. Success, as the environmental forum is concerned, is defined by economic and technological viability, along with environmental health.

Discussion

Through the Actor Network Theory analysis, it is discovered through a web of relationships, differing priorities, and power dynamics that the future nature of the ocean freight industry is dependent on the ability of the regulating authorities and engineers to present a viable, sustainable solution. For the solution to be viable and sustainable, it must meet an agreeable set of criteria. I set out criteria as follows: the solution must seek to decrease carbon emissions; the solution must seek to decrease other forms of pollution; the solution must have a realistic timeline; the solution must not drastically increase the cost of international shipping, which ultimately gets passed onto the consumer. Currently, the IMO has a goal of net neutral emissions by 2050 (Menon, 2024). A natural first step is to gauge the current and expected development of fossil fuel alternatives in the ocean freight industry.

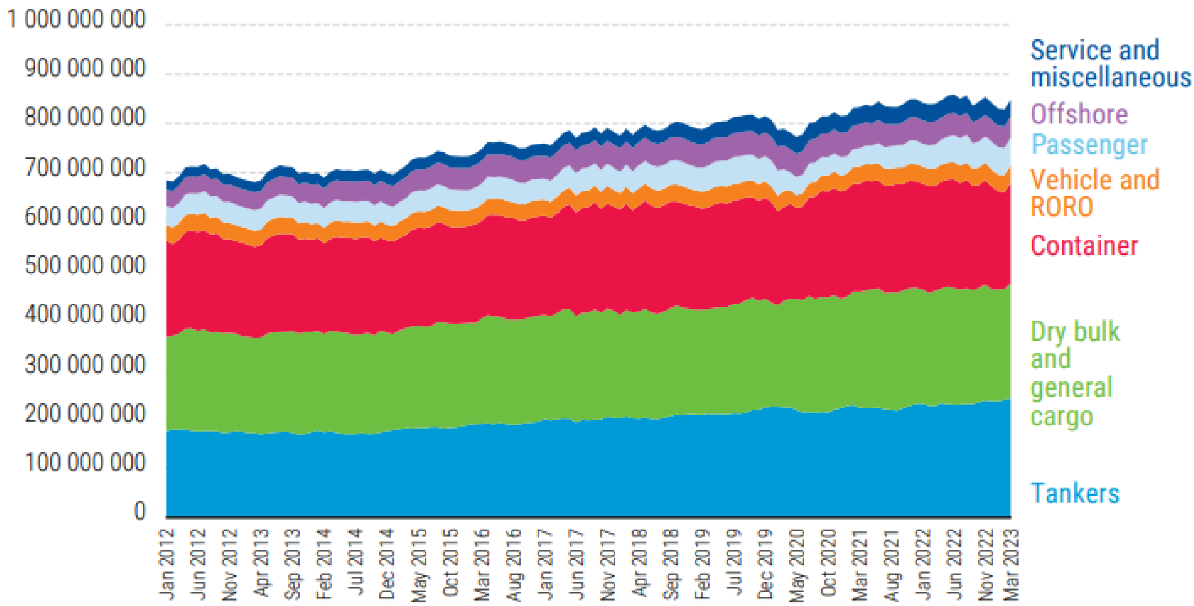
State of Efficiency & Alternative Technologies

Reviewing recent research will be an effective way to understand the current state of development and future outlook. In his 2024 book *Energy Efficiency in Shipping for Environmental Sustainability*, Menon explains the benefits of the widespread fossil fuel engines (primarily heavy fuel oil, then marine diesel oil) as cost effective, long range, energy density, and long lifetime. The explained deficiencies are emissions, legally required maintenance, noise, and vibrations. While acknowledging that these engines will be in use for the foreseeable future, probably past the 2050 carbon free deadline, he proposes implementing systems to improve emissions and efficiency on current ships such as exhaust gas recirculation, selective catalytic reduction, organic rankine cycle for waste heat recovery, and turbo compound systems. He also proposes engine power limitation and shaft power limitation, to ensure the engine isnt running faster than needed, staying in an optimal range. Many of these strategies are also used in the automotive industry to increase efficiency. For new fossil fuel ships, he recommends improved combustion efficiency, advanced engine control systems, carbon capture and storage, deactivating cylinders under low loads, and slow steaming (the method of going at slower speeds to increase efficiency, including just-in-time arrival). These sorts of systems ought to be used in the short term transition away from fossil fuels, as they are generally cost effective by increasing fuel efficiency while not creating a risky paradigm shift. These directives are a good start, but fundamentally can never reach a zero carbon future.

In his book, Menon (2024) also goes into alternative fuels. He explains the benefits and downsides of LNG, biofuels, methanol, ammonia, and hydrogen. Liquefied natural gas poses great potential for reducing emissions from conventional fuels, but it is still a fossil fuel and releases carbon emissions. Biofuels are a carbon neutral solution, but there is concern that its production would take away from food production as it is made from biomass. Ammonia and methanol both come in many forms, with green ammonia and green methanol being the only truly carbon neutral types (different manufacturing methods). They have issues such as their price, energy density, and adoption costs. Hydrogen, similarly, is only carbon neutral when it is green hydrogen. Green hydrogen is proposed as being the future of marine fuels, as cost and safety concerns can be dealt with. Implementation has begun in smaller craft, and larger vessels are in building stages.

Figure 1

Carbon dioxide emissions by main vessel types, tons, January 2012–March 2023



Source: UNCTAD (2023) based on data provided by Marine Benchmark, June 2023.

In “Challenges and Solutions of Ship Power System Electrification,” an article published in *Energies*, researchers engage in a quantitative analysis of real electric ships. They analyze five typical ships, with a range of sizes and use cases. From their study, they concluded that lithium-ion battery technology was the most promising electricity storage method due to its energy density, safety, and lifespan (Bei et al., 2024). They compare different charging/energy replenishment methods, based on turnaround time and implementation costs. To analyze the economic viability of these ships, the authors compare the electric ships to their closest diesel counterparts in a life cycle cost analysis. In the end, they find that electric ships tend to have much higher upfront costs, when considering the vessel, batteries, and charging infrastructure compared to their diesel counterparts. However, the operating costs of electric boats were lower than that of diesel boats. Using a conservative twenty year lifespan for the vessels, the authors conclude that the small to mid sized electric ships are actually more effective in the long term than the diesel boats (Bei et al., 2024). This implies that a transition to an electric fleet for smaller vessels such as transport ships and dry bulk cargo ships for inland, lake, and near-shore scenarios is economically feasible now. This small to mid ranged vessel size accounts for a majority of shipping GHG emissions, representing a large opportunity for reducing fossil fuel emissions (demonstrated in Figure 1). Menon has high hopes for electric ships, though does not do a deep quantitative analysis. He writes about the potential development of various wind technologies, solar energy, and tidal electricity generation.

Recommendation

Decarbonizing the shipping industry will require time and sacrifice. The IMO has laid out its emissions goals, with a hefty goal of neutral annual carbon emissions by 2050. Given the life expectancy of 20-30 years per ship in the current ocean freight fleet, it is unlikely that all ships in the water will be carbon neutral by 2050. That being said, there is real possibility for economically effective, yet also environmentally conscious solutions to the present problem. Owners of small to medium sized ships–which account for a majority of GHG emissions (Figure 1)–should act quickly to replace their fossil fuel fleets with electric alternatives. This will be a large initial investment, but research has shown that these ships will be more cost effective in the long term than the current fleet. Additionally, acting now will help these owners align their businesses with current and future regulations. As for larger vessel owners, the best immediate course of action is to practice efficient methods and even retrofit their fleets with efficiency devices. Efficient travel will not help the IMO reach its goal, but it is a step in the right direction and will even save ship owners money on extra fuel. They should direct future ship orders towards alternative fuel systems, primarily LNG and biofuels. Finally, owners ought to invest in green hydrogen and hydrogen propulsion systems. Green hydrogen is produced from electrolysis on water, the most abundant resource on the planet. With the proper investment, research, and development, hydrogen is expected to be the future energy source of the shipping industry and beyond.

Conclusion

The internal combustion engine is a marvel of engineering and has enabled daily life as we know it. It is responsible for transportation, shipping, and electricity generation in certain cases. It revolutionized a millennium of travel and commerce, creating in a century a global economy characterized by international and transoceanic trade. As we now know, however, internal combustion engines rely on limited fossil fuels which have a plethora of harmful effects on the environment including potential oil spills, acid rain, poor air quality leading to health issues, global warming, and climate change. The ocean freight industry, which accounts for 80% of global trade and roughly 3% of global greenhouse gas emissions, is facing pressure from climate activists and regulating bodies to reduce its carbon footprint (United Nations Conference on Trade and Development, 2023, p. 55).

There are numerous ways to decarbonize the ocean freight industry. Except for efficient shipping techniques, each solution relies on initial investments from governments and the shipping companies. However, to say that these solutions aren’t cost effective would be provably false. To decrease the carbon footprint of the shipping industry, owners need to take deliberate and smart action. Firstly, small to medium sized vessels ought to be replaced with electric ships and their accompanying infrastructure. These vessels account for a majority of GHG emissions and have been shown to be environmentally and economically efficient. Medium to large sized vessels ought to practice efficient techniques and adopt technologies that will increase travel efficiency. Not only does increased efficiency mean reduced emissions on the environment, but also lowered fuel costs for owners and operators. New ships ordered should take advantage of the low carbon and carbon neutral technologies such as liquified natural gas and biofuels, respectively. Finally, to create an emission free fleet of vessels, ship owners need to invest research and development money into electric technology–such as wind, solar, and tidal power–and hydrogen (particularly green hydrogen) to power the next generation of the global economy.

Bibliography

Actor-network theory. (2025, March 2). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Actor%E2%80%93network_theory&oldid=1278468970

Bei, Z., Wang, J., Li, Y., Wang, H., Li, M., Qian, F., & Xu, W. (2024). Challenges and Solutions of Ship Power System Electrification. *Energies*, *17*(13), 3311-3335. https://search.lib.virginia.edu/sources/articles/items/a9h_178411954

Environmentalism. (2025, March 12). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Environmentalism&oldid=1280165325

Gross, J. (2025, March 12). A Giant Container Ship Got Stuck in the Suez Canal. *The New York Times*. https://www.nytimes.com/2025/03/12/business/ever-given-suez-canal.html?smid=url-share

Lucà Trombetta, G., Leonardi, S. G., Aloisio, D., Andaloro, L., & Sergi, F. (2024). Lithium-Ion Batteries on Board: A Review on Their Integration for Enabling the Energy Transition in Shipping Industry. *Energies*, *17*(5), 1019-1055.

Mann, M.E. (2025, February 26). greenhouse gas. Encyclopedia Britannica. https://www.britannica.com/science/greenhouse-gas

Menon, A. (2024). Diesel Engines and Energy Efficiency. *Energy Efficiency in Shipping for Environmental Sustainability*. Routledge. https://doi.org/10.1201/9781032702568

Muniesa, F. (2015). Actor-Network Theory. In *Behavioral Sciences* (Second Edition, pp. 80-84). Retrieved from Science Direct database. https://doi.org/10.1016/B978-0-08-097086-8.85001-1

Raźniewska, M., & Wronka, A. (2024). Transport Fleet Electrification Development Conditions—Perspective of Transport, Shipping, and Logistics Industry in Poland. *Energies*, *17*(17), 4288-4307.

Ships. Transport & Environment. (n.d.). https://www.transportenvironment.org/topics/ships

Skelton, R., & Miller, V. (2023, August 22). *The Environmental Justice Movement*. National Resources Defense Council. https://www.nrdc.org/stories/environmental-justice-movement

United Nations Conference on Trade and Development. (2023) *Review of Maritime Transport 2023*. https://unctad.org/system/files/official-document/rmt2023_en.pdf

United Nations Conference on Trade and Development. (2024) *Review of Maritime Transport 2024*. https://unctad.org/system/files/official-document/rmt2024_en.pdf