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A study on the necessity of integrated evaluation of alternative marine fuels

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ABSTRACT

On 13 April 2018, the International Maritime Organization (IMO) published an initial strategy on reduction of greenhouse gas (GHG) emissions from ships. The ambitious vision of this strategy is to reduce the total annual GHG emissions from international shipping by at least 50% by 2050 compared to 2008. One of the solutions to achieve this vision is to operate vessels on alternative marine fuels that generate less or no GHG emissions, like liquefied natural gas (LNG), hydrogen, ammonia, methanol, ethanol, biofuel, synthetic fuel, electricity (produced by battery), and so on.

The challenge is that each alternative fuel has its own characteristic on various aspects. For instance, some alternative fuels may generate no GHG emission but can have higher risk than conventional marine fuel. Other alternative fuels may generate no GHG emission with relatively low risk, but the capital and/or operational expenditure can be significantly higher than other fuels.

The main objective of this paper is to explore the properties of selected alternative marine fuels and to emphasize the necessity of integrated evaluation of them. It is concluded that the alternative marine fuels need to be comprehensively evaluated with respect to environmental impact, risk to human, and business value.

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Alternative fuel; integrated evaluation; environmental impact; risk to human; business value

Introduction

The International Maritime Organization (IMO) has addressed greenhouse gas (GHG) emission from international shipping for decades (MEPC 2018). Assembly resolution A.963(23) adopted on 5 December 2003 requested the Maritime Environment Protection Committee (MEPC) to prepare consolidated statements to limit or reduce GHG emissions from international shipping (Resolution A 2003). In response to this request, MEPC adopted MEPC.203(62) that introduced mandatory requirements for energy efficiency of ships (MEPC 2011) in 2011, MEPC.229(65) that urged IMO to promote the transfer of energy-efficient technologies (MEPC 2013) in 2013, and MEPC.278(70) that required to collect record and report fuel oil consumption data (MEPC 2016) in 2016. As the continuation of these efforts, IMO published *Initial IMO strategy on reduction of GHG emission from ships (Initial Strategy)* in 2018 (MEPC 2018). The ambitious vision of this strategy is

to peak GHG emissions from international shipping as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008 whilst pursuing efforts towards phasing them out as called for in the Vision as a point on a pathway of CO₂ emissions reduction consistent with the Paris Agreement temperature goals

To achieve this vision, the Initial Strategy suggested short-, mid- and long-term measures with possible timelines, and they are summarized in Table 1.

These GHG emission reduction measures can be classified into two large categories: (1) to improve technical/operational energy efficiencies via innovative technologies and (2) to operate vessels on alternative low- and zero-carbon fuels. These two categories correspond with the following definition of green ships by Lee and Nam (Lee and Nam 2017).

A green ship, or eco ship, means a ship that has reduced GHG emissions through the development of technologies related to fuel savings and alternative fuels.

Bouman et al. (2017) conducted a thorough study on 19 technologies related to fuel savings (hull shape optimization, voyage optimization, resistance reduction devices, propulsion efficiency devices, and so on) and two alternative fuels (LNG and biofuels). The CO₂ emission potentials of the 19 fuel-saving technologies approximately range from 1% to 35%, while biofuels have about 80% of CO₂ emission reduction potential. A recent study of DNV-GL (DNV-GL 2019) shows that it is possible to achieve carbon-free ship operation (tank to propeller) through a couple of alternative marine fuels. Operating vessels on alternative marine fuels is therefore one of the most potent measures to reduce GHG emission that encompasses the whole timelines from short-term to long-term timeline. Promising alternative marine fuels are liquefied natural gas (LNG), hydrogen, ammonia, methanol, ethanol, biofuel, synthetic fuel, electricity produced by battery, and so on.

Table 1. A summary of short-, mid- and long-term measures to meet the Initial Strategy.

Timeline	Short-term	Mid-term	Long-term
	From 2018 to 2023	From 2023 to 2030	Beyond 2030
Measures	<ul style="list-style-type: none"> ● Improve energy efficiency framework ● Develop technical and operational energy efficiency measures ● Encourage national policies, incentives, and port activities ● <i>Initiate research on alternative fuels and innovative technologies</i> ● Undertake additional GHG emission studies 	<ul style="list-style-type: none"> ● <i>Implement programme for the effective uptake of alternative fuel</i> ● Operational energy efficiency measures ● Innovative emission reduction mechanism ● Enhance technical cooperation ● Develop feedback mechanism to learn and share lessons learned 	<ul style="list-style-type: none"> ● <i>Pursue the development and provision of alternative fuels</i> ● Encourage and facilitate the general adoption of other possible innovative emission reduction mechanisms

The challenge is that each alternative fuel has its own characteristic on various aspects. For instance, some alternative fuels may generate no GHG emission but can have a higher risk than conventional marine fuel. Other alternative fuels may generate no GHG emission with relatively low risk, but the capital expenditure (CapEx) and/or operational expenditure (OpEx) can be significantly higher than other fuels. The other alternative fuels may generate a certain amount of GHG emission, but the risk and expenditures can be lower than other alternative fuels. To build and operate sustainable vessels, we need to understand various properties of alternative fuels and evaluate overall aspects of each alternative fuel.

The main purpose of this paper is to explore the advantages and disadvantages of selected alternative marine fuels and to emphasize the necessity of integrated evaluation of them. For this purpose, the remaining part of this paper is organized as follows: properties of four alternative marine fuels are explored in “Alternative marine fuels” section, and “Necessity of integrated evaluation for alternative fuels” section discusses various aspects that need to be considered for alternative fuels and emphasizes the necessity of an integrated evaluation of alternative fuels. Conclusion and future works are introduced in “Concluding remarks and future works” section.

Alternative marine fuels

In this section, advantages and disadvantages of five selected alternative marine fuels (LNG, hydrogen, ammonia, biofuel, and electricity) produced by battery

are explored. In the strict sense, electricity is not a fuel, but it is included in this study because battery-electric propulsion is an important technology that can be and has already been applied to vessels to reduce GHG emission.

LNG

LNG has the potential to reduce CO2 emissions up to 26% compared to heavy fuel oil (HFO) and produces no SOx emission and low NOx emission. Compared to other alternative fuels, LNG has competitive feedstock price, more infrastructure for ships and commercially available technologies. However, LNG should be stored in insulated tanks, and uncontrolled methane slip may offset the reduced CO2 (DNV-GL 2019). The most critical disadvantage of LNG is that this fuel alone cannot comply with the Initial Strategy of IMO that requires 50% CO2 reduction.

Hydrogen

Hydrogen can be used in combination with fuel cells, which enable zero-emission propulsion with up to 60% of energy efficiency. The energy density of liquefied hydrogen is almost three times the energy density of HFO, and long-distance transportation infrastructure may not be required because hydrogen can be produced from electrolysis near the ports. However, the volumetric density of liquefied hydrogen is lower than HFO, and the price of hydrogen is about 2.7 to 3.5 times the price of HFO. In addition, there is neither available hydrogen-fuelled piston engine nor bunkering infrastructure for ships. Hydrogen should be stored at an extremely low temperature, so storage tanks will be significantly more expensive than other alternative fuels (DNV-GL 2019), and hydrogen is an extremely flammable gas with very wide flammability bandwidth (from 4% to 74%) (de Vries 2019).

Ammonia

Unlike hydrogen, ammonia can be used in various prime movers: diesel engines, spark-ignition engines, and gas turbines, as well as fuel cells. Ammonia can be stored at significantly lower pressure and/or higher temperature than liquefied hydrogen and LNG. Ammonia is the top three chemicals transported annually, so ammonia has already been transported by ships, and there are world-wide storage and delivery systems (NH3FUEL Association 2010). The major disadvantages of ammonia are the toxicity and environmental impact. Ammonia is toxic if inhaled, and exposure to ammonia causes severe skin burns and eye damage. When liquid ammonia is spilled directly into water, it kills most living organisms in a close area, and a significant amount of time is required to restore to its natural state. Ammonia is hard to ignite

(compared to conventional fuels), so hydrogen needs to be added when ammonia is used in internal combustion engines (de Vries 2019).

Biofuel

Biofuels can be carbon-neutral energy sources and the CO₂ reduction potential on life cycle is up to 88%. The greatest advantage of biofuels is that this fuel is compatible with existing infrastructure and engine systems of ships. However, the production of biofuels is more expensive than conventional fossil fuels, depletes the soil quicker over time, and may compete with food production directly and/or indirectly. Another critical disadvantage is the limited production volume of biofuel (DNV-GL 2019; Somerville 2007).

Electricity produced by battery

Batteries enable zero-emission propulsion and are up to twice as efficient as a typical diesel generator set. Battery-powered propulsion systems have lower noise and vibration compared to conventional propulsion systems, and the OpEx can be lower than conventional fossil fuels in some regions where electricity prices are low. Battery prices are decreasing rapidly and the performance improvement is significant. The major disadvantage of batteries is the low energy density of mass (about 150 times lower than diesel) and low volumetric density (about 100 times lower than diesel). The manufacture of batteries is energy-intensive and the CapEx of large battery system is significantly higher than conventional propulsion system (DNV-GL 2019).

Summary

The key advantages and disadvantages of each alternative marine fuel are summarized in Table 2.

Necessity of integrated evaluation for alternative fuels

As investigated in "Alternative marine fuels" section, each alternative fuel has different advantages and disadvantages in various aspects, which can be classified into three main categories: environmental impact, risk to human and business value.

Environmental impact

The main aim of the Initial Strategy of IMO is to reduce GHG emission, so the GHG reduction potential of each alternative fuel, of course, needs to be evaluated firstly. For instance, ammonia combustion engines generate no CO₂ emission, but may cause higher NO_x emission. The overall environmental impact of each alternative fuel should be evaluated. In addition, we need to consider

Table 2. Key advantages and disadvantages of alternative marine fuels.

Alternative fuel	Advantages	Disadvantages
LNG	<ul style="list-style-type: none"> Competitive fuel price Available infrastructure and technologies 	<ul style="list-style-type: none"> Must be stored at insulated tanks Cannot comply with 50% CO₂ reduction
Hydrogen	<ul style="list-style-type: none"> Enable zero-emission (with fuel-cell) Can be produced from electrolysis near ports 	<ul style="list-style-type: none"> High fuel price No available piston engine and infrastructure Must be stored at extremely low temperature (liquefied hydrogen)
Ammonia	<ul style="list-style-type: none"> Can be used in various combustion engines as well as fuel cells Can be stored relatively low pressure and high temperature (liquefied ammonia) 	<ul style="list-style-type: none"> Toxicity and environmental impact when leaked Need to add hydrogen when used for internal combustion engines
Biofuel	<ul style="list-style-type: none"> Can be carbon neutral Compatible with existing infrastructure and engine systems 	<ul style="list-style-type: none"> High fuel price Limited production volume
Electricity produced by Battery	<ul style="list-style-type: none"> Enable zero-emission High efficiency 	<ul style="list-style-type: none"> Low energy density of mass and volumetric density High CapEx

a couple of more environmental impacts of each alternative fuel.

As introduced in "Ammonia" section accidental spill of ammonia would cause serious environmental damage that requires a significantly long time to be restored (de Vries 2019). It is needed to analyse and compare how much we gain from GHG emission reduction, and how much we may lose from accidental fuel spill at sea of each alternative marine fuel. Otherwise, operation vessels on alternative marine fuels can result in sacrificing the marine environment to reduce GHG emission onboard, in the worst case.

The environmental impact for the entire life cycle of alternative fuels also needs to be considered. As indicated in "Electricity produced by battery" section, battery production requires a huge amount of energy, and disposal of batteries can contaminate the environment. Hydrogen and ammonia are fuels with a wide range of carbon footprint depending on the production methods (DNV-GL 2019). If we do not consider the environmental impact for the entire life cycle, we may reduce GHG emission only onboard, while the rest of the environment is contaminated, in the worst case.

Risk to human

Risk to human onboard is another important aspect that must be considered for alternative marine fuels. As introduced in previous sections, hydrogen gas is highly flammable and ammonia gas is extremely toxic than other fuels. Fire and gas explosion of batteries are also threatening human lives onboard. We need to

take consideration the risk to human when we select alternative marine fuels, in order not to sacrifice human lives to reduce GHG emission.

Kim, Haugen, and Utne (2013) argued that an effort to improve environmental performance might sometimes result in reduced human safety. An example of this conflict is increased loss of propulsion at California coast. A new sulphur emission regulation of the California Air Resource Board (CARB) came into effect in July 2009, which requires fuel switching near the California coast (Cowan 2011). However, the fuel switching may lead to shut down of the main engine, if it is not properly prepared and executed (Gard 2009). As a result, the propulsion loss incidents increased significantly in a couple of years as shown in Figure 1, and the U.S. Coast Guard issued a Maritime Safety Alert, "Fuel Switching Safety" in 2011 (Edinger 2009; USCG Fuel Switching Safety (Maritime Safety Alert 11-01) 2011).

The latest example is the fire and explosion of a diesel-electric hybrid passenger ferry, MF Ytterøyningen (International Institute of Marine Surveying 2019). A small fire occurred in the battery room on 10 October 2019. Passengers and crew evacuated to shore, and the ferry returned to harbour under its own propulsion. However, a serious gas explosion occurred overnight. It was reported that 12 firefighters were exposed to hazardous gases from the batteries and taken to the hospital. Norwegian Maritime Authority issued warning to all ship owners with vessels that have battery installations, as a result.

Business value

The main barrier to operate vessels on alternative fuels is the cost. Almost no additional CapEx is required for

biofuels, but the OpEx is higher than HFO. The CapEx and OpEx of hydrogen and ammonia can vary in a wide range depending on the various propulsion system and production method of the fuels. For instance, both CapEx and OpEx can be increased for ammonia combustion engines, because we need to remove high NOx emission when we burn ammonia. The OpEx of batteries can be competitive in some regions, but CapEx is higher than conventional propulsion system (DNV-GL 2019).

Fuel availability is another aspect to be considered for alternative fuels. Limited production volume and fuel availability are the main challenges when operating vessels on biofuels with regards to an increased use of biofuel (Opdal and Hojem 2007; Tyrovola et al. 2017).

Necessity of integrated evaluation

As explored previous sections, each alternative marine fuel has its own advantages and disadvantages, and these various properties can vary depending on the type, size, and route of a ship. In order to build and operate sustainable vessels for the environment, for the economy, and for the people, an integrated evaluation for the various aspects of alternative fuels needs to be preceded. Otherwise, we may sacrifice the environment other than atmosphere, human lives, and/or our economy to reduce GHG emission only, in the worst case. For instance, the risk to human of ammonia leakage would be significantly greater for passenger ships compared to merchant cargo ships because a large number of untrained passengers can be exposed to the toxic gas if ammonia leaks on a passenger ship. The risk of hydrogen leak can be greater for the cargo ships that carry dangerous cargos compared to the cargo ships with non-dangerous cargo, because the fire/explosion led by hydrogen leak can be escalated into the fire/

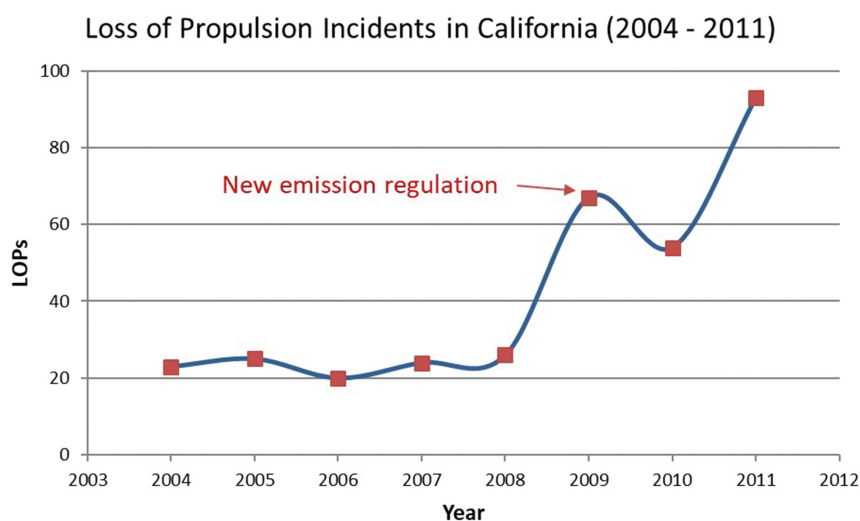


Figure 1. Loss of propulsion incidents in California from 2004 to 2011.

Table 3. Criteria for integrated evaluation of alternative marine fuels.

Category	Criteria for integrated evaluation
Environmental impact	<ul style="list-style-type: none"> ● GHG emission reduction potential ● Impact of accidental fuel spill ● Environmental footprint
Risk to human	<ul style="list-style-type: none"> ● Risk caused by fire/explosion ● Risk caused by fuel leakage ● Risk caused by propulsion loss
Business value	<ul style="list-style-type: none"> ● CapEx ● OpEx ● Fuel availability

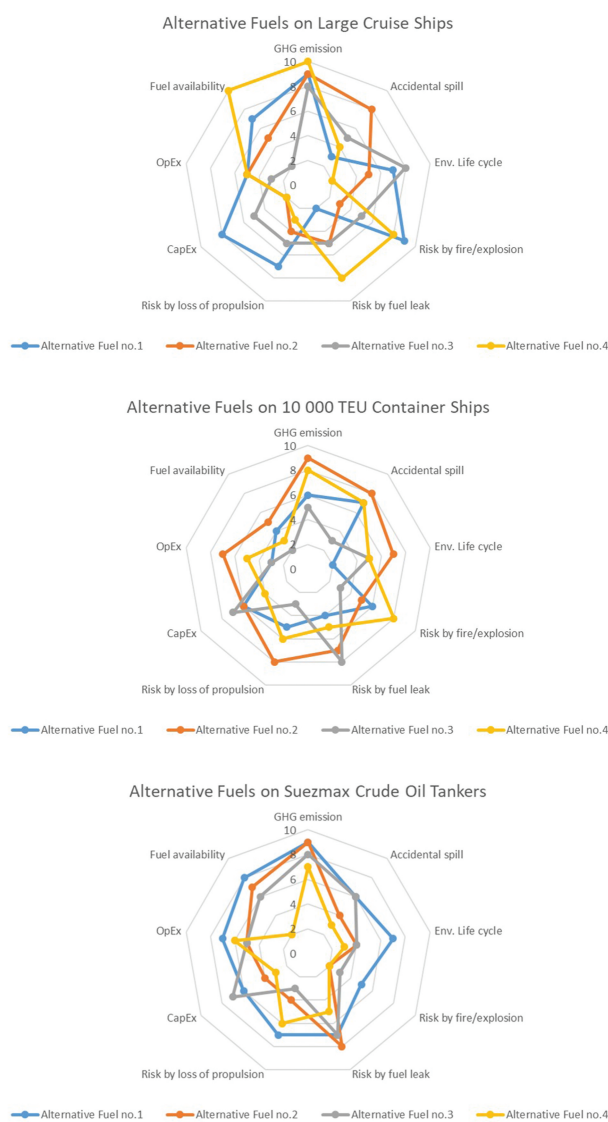
explosion of the dangerous cargos. Environmental impact can also vary depending on the type and size of the ship. The accidental spill of ammonia causes critical damage to the marine environment, and the frequency of collision accident that can lead to accidental fuel spill varies by the ship type and size. For instance, the collision accident frequency of crude oil tankers is 1.5 times higher than the collision frequency of container ships (MSC 83/INF 2007; MSC 58/INF 2008), and the collision accident frequency of Suezmax tankers is almost twice as high as the accident frequency of very large crude carriers (VLCCs) and ultra-large crude carriers (ULCCs). Therefore, the environmental impact caused by accident fuel spill may not be the same for different ship types and sizes. Business values can also vary in various aspects. One example is the OpEx of battery-powered ships. Even for same type and same size ships, the electricity price varies significantly by the route of the ship, because the electricity prices in EU vary up to three times from region to region (DNV-GL 2019).

We therefore need to develop an integrated evaluation model for alternative marine fuels, and the evaluation criteria can be (1) environmental impact, (2) risk to human and (3) business value, as explored above. The environmental impact includes GHG emission reduction potential, impact of accidental fuel spill, and environmental footprint over the life cycle of the fuel. The risk to human includes risk caused by fire/explosion, fuel leakage, and loss of propulsion. The business value includes CapEx, OpEx, and fuel availability. The criteria for the integrated evaluation of alternative marine fuels are categorized and summarized in Table 3.

Due to the various properties of alternative fuels that vary by many factors, it is not expected that a single alternative fuel is always optimal for every vessel. The optimal alternative fuel for a vessel can vary depending on the ship type, size, and route. We can select the optimal alternative fuel for each vessel, if we can conduct an integrated evaluation of alternative marine fuels in a variety of different aspects, as illustrated in Figure 2.

Concluding remarks and future works

The authors believe that the ultimate goal of the Initial Strategy of IMO is not to reduce onboard GHG emission

**Figure 2.** Examples of integrated evaluations of alternative fuels (illustration only).

only, but to build and operate sustainable vessels for the environment, for the economy and for the people. For this purpose, an integrated evaluation of alternative marine fuels needs to be developed, because each fuel has different properties, advantages, and disadvantages that vary by ship type, size, and route. A single alternative fuel cannot always be the optimal fuel for every vessel. Rather, the optimal alternative fuel may vary case by case. Without an integrated evaluation of alternative fuels, we could not select an optimal fuel for each ship, and in the worst case, we might sacrifice the environment, human lives, and our economy to reduce onboard GHG emission only. Developing an integrated evaluation model for alternative marine fuels is therefore an essential future work.

This study suggests three categories and nine criteria for the integrated evaluation as provided in Table 3, but there can be more aspects that need to be considered when we evaluate alternative fuels. For instance, LNG alone has low CO₂ reduction potential

and cannot achieve the Initial Strategy of IMO (50% CO₂ reduction), but onboard CO₂ capture system (CCS) can easily be combined with LNG propulsion system, because captured CO₂ can be cooled and liquefied using the low-temperature LNG (van den Akker 2017). Therefore, a possible synergy effect between alternative fuels and other GHG reduction technologies can be considered as another criterion for the integrated evaluation. Identifying additional criteria would be another important future work.

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