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Abstract. According to the International Maritime Organization (IMO) Greenhouse Gas (GHG) Strategy, the shipping industry by 2050 aims to reduce by at least 50% of GHG emission level in 2008. Among various alternative energy sources, biofuels illustrate potential as a drop-in fuel using existing shipboard technologies, bunkering infrastructure, and a new fuel replacing conventional fossil-based fuels. However, the decision to adopt biofuel in vessels depends on various factors. Biofuels may be derived from different feedstock and production routes and thus demonstrate different economic and environmental performances. The compatible type of engines also differs across biofuels, implying differences in capital cost. In addition, a high carbon tax may push the usage of a more expensive biofuel, while a low carbon tax may not drive the switch from fossil fuel. This study aims to analyse biofuel adoption pathways under carbon tax to achieve a net 50% GHG emission reduction for cargo vessels, including bulk carriers, container vessels and tankers. The study focuses on the following types of fuels: low sulphur fuel oil (LSFO), marine gas oil (MGO), Liquefied natural gas (LNG), biodiesel in the form of palm methyl ester (PME), hydrotreated vegetable oil (HVO), and bio-LNG.

Keywords: Ship emission, Greenhouse gas, Biofuel adoption, Carbon tax

1. Introduction

Maritime shipping is indispensable to global trade and the economic development of countries. Over 80% of world trade is transported by sea. The cost of shipping operation involves heavily in cost of energy required for ship powering. During the past two centuries, ocean-going vessels for commercial trade have evolved from using wind till the early 19th century to engines fuelled by coal, and later to diesel engines fuelled by oil from the second half of the 20th century. Among various oil products, heavy fuel oil (HFO) has become the dominant choice of fuel in the shipping industry due to its cost efficiency, ease of handling, and applicability. It is estimated that about 98% of vessels are driven by diesel engines nowadays [1].

Currently, more than 62,000 vessels in the world trading fleet are operating using fossil fuels. These ships account for about 250 to 300 million tonnes of fossil usage per year, about 3% of the world's fossil fuel consumption. Currently, international shipping is responsible for about 3% of total anthropogenic CO2 emission or 11% of global CO2 emission in the transport industry [1]. If no measures were taken, the emission of CO2 might increase by about 50% to 250% by 2050. To further enable the reduction of GHG emissions from ships and better align with the Paris Agreement, MEPC 72 established the "Initial IMO Strategy on Reduction of GHG Emissions from Ships" in 2018 [2]. In this strategy, various levels of ambitions are set as follows:

1. To implement further phases of the energy efficiency design index (EEDI) for new ships with the percentage improvement for each phase to be determined for each ship type, as appropriate;
2. To reduce CO2 emissions per transport work by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008; and
3. 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.

It is most unlikely to meet IMO's ambitious goal by 2050 without the help of alternative energy sources. Examples of such energy sources include fuels containing lower carbons, biogenic carbons, recycled carbons from carbon capture technology, and ultimately zero carbons. Among various alternative energy sources, biofuels illustrate potential as a drop-in fuel using existing shipboard technologies, bunkering infrastructure, and a new fuel replacing conventional fossil-based fuels. Yet, according to IEA's latest tracking report on international shipping [3], almost no low-carbon fuels are used today, with biofuel accounting for only 0.1% of the final energy consumption in shipping. Based on the current progress, IEA estimated that low- or zero-carbon fuels could only account for 5% of the final energy consumption by 2050, falling severely short of the expected 83% to meet the IEA's Net Zero Scenario.

A plausible explanation for the projected low adoption of biofuel in shipping is that the decision to adopt biofuel in vessels depends on various factors that are complex and uncertain. Biofuels may be derived from different feedstock and production routes and thus demonstrate different economic and environmental performances. The compatible type of engines also differs across biofuels, implying differences in capital cost. In addition, a high carbon tax may push the usage of a more expensive biofuel, while a low carbon tax may not drive the switch from fossil fuel. This study aims to analyse biofuel adoption pathways under cargo tax to achieve a net 50% GHG emission reduction for cargo vessels, including bulk carriers, container vessels and tankers. The study focuses on the following types of fuels: low sulphur fuel oil (LSFO), marine gas oil (MGO), Liquefied natural gas (LNG), biodiesel in the form of palm methyl ester (PME), hydrotreated vegetable oil (HVO), and bio-LNG.

2. Biofuels for Shipping Sectors

In the search for energy sources alternative to using conventional fossil-based fuels for the shipping industry, a potential option is to adopt biofuels. In this context, the term "biofuel" refers to liquid or gaseous fuels for the transportation sector that is predominantly produced from biomass [4]. Biomass is renewable organic material that comes from plants and animals [5][6]. The biomass feedstock can be categorised based on their sources into four major groups [7]. Through thermal, chemical and biochemical conversion processes, biomass can be converted into a variety of biofuel products. Biofuels provide several advantages over fossil fuels especially in the nature of the feedstock (i.e. biomass). Biomass tends to be more renewable, carbon-neutral, and evenly distributed on Earth than fossil fuel resources [4]. As such, biofuels tend to be associated with lower life-cycle GHG emissions. After coal and oil, biomass stands as the third-largest energy source in the world [8]. There is a wide range of biofuel products produced from different sources of feedstock (as described in Table 1) through several conversion routes. The biofuel products include (but are not limited to) bio-oil, biodiesel (Fatty Acid Methyl Ester, FAME), synthetic diesel (hydrotreated vegetable oil), Fischer-Tropsch diesel (F-T diesel or BTL), bio-alcohol and biohydrogen. Given the varieties of biofuels and in view of IMO's 50% emission reduction target by 2050, a research question that remained unanswered in the existing literature would be which biofuel adoption pathway is more feasible at certain conditions. This study focuses on the first-generation biofuels as a start, namely: biodiesel in the form of palm methyl ester (PME) and hydrotreated vegetable oil (HVO).

Table 1. Biomass as feedstock for biofuel production

Type	Source	Biofuel Products	Note
First generation (1G)	Vegetable oils & animal fats and plants containing sugar & starch	Biodiesel (Fatty acid methyl ester, FAME), synthetic diesel (hydrotreated vegetable oil) and bioethanol	- Conflict of 1G biofuels with food supply - The use of only 2% of the planet's arable land to produce the 1G biofuels had a significant impact on food and animal feed price.
Second generation (2G)	Lignocellulosic biomass	A wide range of biofuels, i.e. bio-oil, synthetic diesel, FT diesel (or BTL), biomethane, bio-ethanol, bio-methanol and biohydrogen	- Costly pre-treatment and advanced technologies are needed for biomass conversion to biofuels.
Third generation (3G)	Algae (macro and microalgae)	A wide range of biofuels, i.e. bio-oil, synthetic diesel, FT diesel (or BTL), biomethane, bioethanol, bio-methanol and biohydrogen	Macroalgae: areas for their cultivation Microalgae: Oil content in microalgae, harvesting, oil extraction
Fourth generation (4G)	Wastes and genetically modified algae (Waste includes municipal waste, food processing waste, sewage, plastic, organic waste, etc.)	A wide range of biofuels, i.e. bio-oil, synthetic diesel, FT diesel (or BTL), biomethane, bio-ethanol, bio-methanol and biohydrogen	To eradicate the constraints in 2G biofuel production

3. Methodology

The evaluation of the adoption of alternative fuels is performed mainly based on economic criteria, Relative Net Present Value, designated as NPV, to justify whether ship owners will adopt biofuels instead of continuing using conventional fuel.

$$NPV = \sum_{t=0}^{T} \frac{Fuel\ cost_{FO} - Fuel\ cost_{Biofuel}}{(1+r)^t} - CAPEX$$

Where,
T = Remaining service year (years). The remaining service year of a ship is derived from the lifespan of a ship (typically 25 years) with subtraction of ship age.
CAPEX = Conversion cost (USD) from using conventional fuels to adopt alternative fuel. It includes engine and its system with their installation.
Fuel $Cost_{FO}$ = Annual fuel cost for ship operation when using conventional fuel (USD/year). It can be calculated from annual fuel consumption (tonnes) multiplied by fuel cost per tonne (USD/tonne). Annual fuel consumption (tonnes) is the product of operational power of the ship (kW), operational hours (hours) and specific fuel consumption (tonnes/kWh).
Fuel $cost_{Biofuel}$ = Annual fuel cost for ship operation when adopting biofuel (USD/year). Its calculation can be performed in a similar approach to that of fuel oil.
r = Discount rate (%). The discount rate of investment used in this study is based on the weighted average cost of capital (WACC) of the Global Shipbuilding and Marine Industry.

Table 2. Pathways for the adoption of biofuels for the shipping industry

Pathway	Description	Input		Results
1 Fossil dominance	New-built vessels continue using fossil fuels (i.e., LSFO/MGO and LNG) [1.1 Conventional marine fuel; and 1.2 LNG]	Cost:	CAPEX, fuel cost, and space loss	1. CO_2 monetary value to enable the adoption 2. Fuel requirement: types and amounts 3. Emission of CO_2 (onboard and LCA)
		Fuel:	Characteristics including energy density, density as well as onboard and LCA emission factors	
		Ships:	Specifications, operating profiles, SFOCs	
2. Biodiesel (in the form of PME)	Consideration of the adoption of B30	Cost:	CAPEX, fuel cost, and space loss	1. CO_2 monetary value to enable the adoption 2. Requirement of B30 3. Emission of CO_2 (onboard and LCA)
		Fuel:	Characteristics including energy density, density as well as onboard and LCA emission factors	
		Ships:	Specifications, operating profiles, SFOCs	
3. HVO	Consideration to substitute fossil fuels using HVO	Cost:	CAPEX, fuel cost, and space loss	1. CO_2 monetary value and desirable HVO cost to enable the adoption 2. Requirement of HVO 3. Emission of CO_2 (onboard and LCA)
		Fuel:	Characteristics including energy density, density as well as onboard and LCA emission factors	

		Ships: Specifications, operating profiles, SFOCs	
		Aim: Targeted amount of CO2 to be reduced to meet IMO target by 2050	

4. Results and Discussion

Table 3 presents the results of pathways for the adoption of biofuels in the shipping industry with CO2 monetary value. Pathway 1.1 is the fossil LSFO pathway. This pathway involves ships' operation without implementing CO2 monetary value, i.e., (cost of CO2, expressed in the unit of USD/ton CO2). The shipping industry continues using fossil fuels in this pathway, including LSFO, MGO and LNG. Although the adoption of fossil-LNG can be observed, a majority still continue using conventional fuel oils (LSFO) due to the economic decision. If following this pathway, the shipping industry will not achieve IMO GHG emission reduction target by 2050. Therefore, the pathway is considered not sustainable.

Pathway 1.2 is the fossil LNG pathway. The monetary value of CO2 is introduced to this pathway now. It could be seen that the shipping industry will adopt fossil-LNG when CO2 monetary value is set at 70 USD/tons. The existing ships will continue using conventional marine fuels, i.e., LSFO. In contrast, the adoption rate of fossil LNG increases over the period of time due to the implementation of CO2 monetary value. If following this pathway, the shipping industry will not achieve IMO GHG emission reduction target by 2050 for both SSPs. Therefore, the pathway is also considered not sustainable.

Pathway 2 is the biodiesel B30 pathway. The monetary value of CO2 is introduced now in order to enable the adoption of B30. The adoption of B30 can be seen as early as 2022. It could be seen that the shipping industry will adopt B30 when CO2 monetary value is set at 200 USD/tons. In addition to B30, the shipping industry will also adopt fossil LNG in this pathway. This is purely based on the economic decision. With reference to the current production of biodiesel (40 million tons per year), the requirement of B30 will be around 0.9 million tons and, consequently, B100 of 0.28 million tons. The supply should be sufficient to support the shipping industry. However, the pathway cannot facilitate the industry to meet IMO target by 2050. Therefore, the pathway is considered not sustainable.

Pathway 3 is the HVO pathway. The monetary value of CO2 is introduced with immediate effect. The CO2 monetary level of 262 USD/ton is required in order to enable the adoption of HVO. With the implementation of CO2 monetary value, the first adoption of HVO can be observed in 2025. In addition, the adoption of fossil LNG and bio-LNG can also be observed. Although the pathway has the potential for the shipping industry to meet IMO GHG emission reduction target by 2050, there will be an issue with the supply of HVO with limited feedstock. In order to fulfil this pathway, the industry requires HVO of around 160 million tons/year. Without 4th generation feedstock, i.e., algae, this pathway is likely to be "unrealistic".

Table 3. Results of pathways for the adoption of biofuels in the shipping industry with CO_2 monetary value

Description	**1.1. Fossil LSFO Pathway**			**1.2. Fossil LNG Pathway**			**2. Biodiesel B30 Pathway**			**3. HVO Pathway**		
	2020	**2030**	**2050**	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**
Fossil-fuel demand (million tons/year)												
LSFO requirement	222.76	258.9	345.9	222.76	204.6	115.6	222.76	180.7	72.6	222.8	180.7	72.6
LNG requirement	Negligible	1	4.8	Negligible	43.7	185.8	0	61.7	218.8	0	44.2	44.2
Biofuel requirement (million tons/year)												
B30	0	0	0	0	0	0	0	0.9	0.9	0	1.5	1.5
HVO	0	0	0	0	0	0	0	0	0	0	9	160.6
Bio-LNG	0	0	0	0	0	0	0	0	0	0	8.8	28.8
CO_2 emission (million tons/year)												
LCA CO_2	805.7	943	1,272.60	805.7	901.7	1,097.40	805.7	883.4	1064.5	805.7	840.1	696.2
Onboard CO_2 emission	693.4	808.9	1,090.20	693.4	757.1	870.9	693.4	734.3	829.8	693.4	687.5	350.8
CO_2 emission target by 2050 (50% of 2008 emission level)	NA	NA	354	NA	NA	354	NA	NA	354	NA	NA	354
Difference in CO_2 to meet target by 2050	NA	NA	**736.2**	NA	NA	**516.9**	NA	NA	**475.8**	NA	NA	**-3.2**
Required CO_2 monetary value (USD/ton)	**0**	**0**	**0**	**0**	**70**	**70**	**0**	**200**	**200**	**0**	**262**	**262**
Cost of biofuels (USD/ton)												
B30	702	702	702	702	702	702	702	702	702	702	702	702
HVO	1,474	1,357	1,122	1,474	1,357	1,122	1,474	1,357	1,122	1,474	1,357	1,122
Bio-LNG	1,437	1,369	1,234	1,437	1,369	1,234	1,437	1,369	1,234	1,437	1,369	1,234

5. Conclusion

This study performs an economic analysis on biofuel adoption pathways under carbon tax to achieve a net 50% GHG emission reduction for cargo vessels, including bulk carriers, container vessels and tankers. The study presents three pathways with a focus on the following types of fuels: low sulphur fuel oil (LSFO), marine gas oil (MGO), Liquefied natural gas (LNG), biodiesel in the form of palm methyl ester (PME), hydrotreated vegetable oil (HVO), and bio-LNG. The respective CO2 monetary value to enable the adoption of individual fuel is highlighted in this study. A key finding is that a minimum carbon value of USD 262 should be implemented as soon as possible to achieve IMO's 50% emission reduction target. A carbon value lower than that would either promote biofuels that could not meet IMO's emission target (e.g. biodiesel) or would not be enough to encourage the use of biofuels. Future research could apply the adoption model to other types of alternative fuels such as bio-methanol, BTL diesel, renewable ammonia, renewable hydrogen etc.

Acknowledgements

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