Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal 2022, 16(4), 48–55
https://doi.org/10.12913/22998624/151757
ISSN 2299-8624, License CC-BY 4.0

Received: 2022.06.20
Accepted: 2022.07.30
Published: 2022.09.01

Indication of the Target Alternative Fuel for Shipping

Jerzy Herdzik[1]

[1] Marine Propulsion Plants Department, Gdynia Maritime University, ul. 81-87 Morska, 81-225 Gdynia, Poland
E-mail: j.herdzik@wm.umg.edu.pl

ABSTRACT

The article presents the regulations of the International Maritime Organization aimed at reducing carbon dioxide emissions from international shipping. One of the main objectives is to search the alternative to fossil fuels. The main problem is the lack of indication of the target fuel for shipping. The current changes, forced by international regulations, are made by the decisions of shipowners who themselves are looking for an alternative fuel that will enable them to continue their activities. Attempts have been made to use fuels considered as transient, which will be used in the perspective of about 10 years. However, this is too short a time compared to the life of the ship (20–30 years). This will force another change in the type of fuel used on ships still in operation, which will result in additional costs associated with the adaptation of the ship's power plant fuel systems to a different type of fuel. The article evaluates the changes that currently taking place. Scenarios of the most likely directions of changes in a perspective of 2050 have been indicated.

Keywords: marine fuel, alternative fuel, shipping, emission into the atmosphere, environment protection.

INTRODUCTION

The basic fuels in international shipping are currently heavy and diesel oils from crude oil processing. Since 1st January 2000 the International Maritime Organization (IMO) has introduced a requirement to limit nitrogen oxides emission (as equivalent of N_2O) from marine diesel engines. Currently, in special areas there is a limit to a tier 3, in others to a tier 2 (for the ships were constructed on and after 1st January 2011) [1, 2]. Since 1st January 2020 the emission of sulfur oxides from marine fuels is limited to equivalent up to 0.5% of sulfur content in heavy oils and 0.1% for diesel oils. Thanks to this, the emission of sulfur oxides into the atmosphere has significantly decreased (about 6 times). The International Maritime Organization (IMO) has an ambition to halve the GHG emission from shipping by 2050 in a comparison to 2008 and to decarbonize shipping as soon as possible in this century [3, 4]. Currently, there are six mandatory requirements addressing the GHG emission: the Energy Efficiency Design Index (EEDI) for newbuilds [5, 6], the Ship Energy Efficiency Management Plan (SEEMP) for all ships above 400 GT in operation [7], the Fuel Oil Consumption Data Collection System (DCS), the Energy Efficiency Design Index for Existing Ships (EEXI) (entrance into force from January 1st, 2023) [8], the Carbon Intensity Indicator (CII) [9] and a strengthening of the SEEMP with mandatory content achieving the CII targets [10, 11, 12].

Carbon dioxide emissions have been limited by the Regulation on Energy Efficiency for Ships on and after 1st January 2013 [13]. In order to limit the effects of greenhouse gases on Earth climate, for which maritime transport accounts for about 3%, the IMO has set the objective of reducing carbon dioxide emissions, taking into account the transport effect, by at least 30% by 2030 and 70% by 2050 compared to 2008. Taking into account the equivalent carbon dioxide emission (as GHG effect), this is to be 50% by 2050 [14]. This is a challenge for shipbuilders to meet the demands set by the IMO. Solutions are being sought to increase the total efficiency of power plant and the

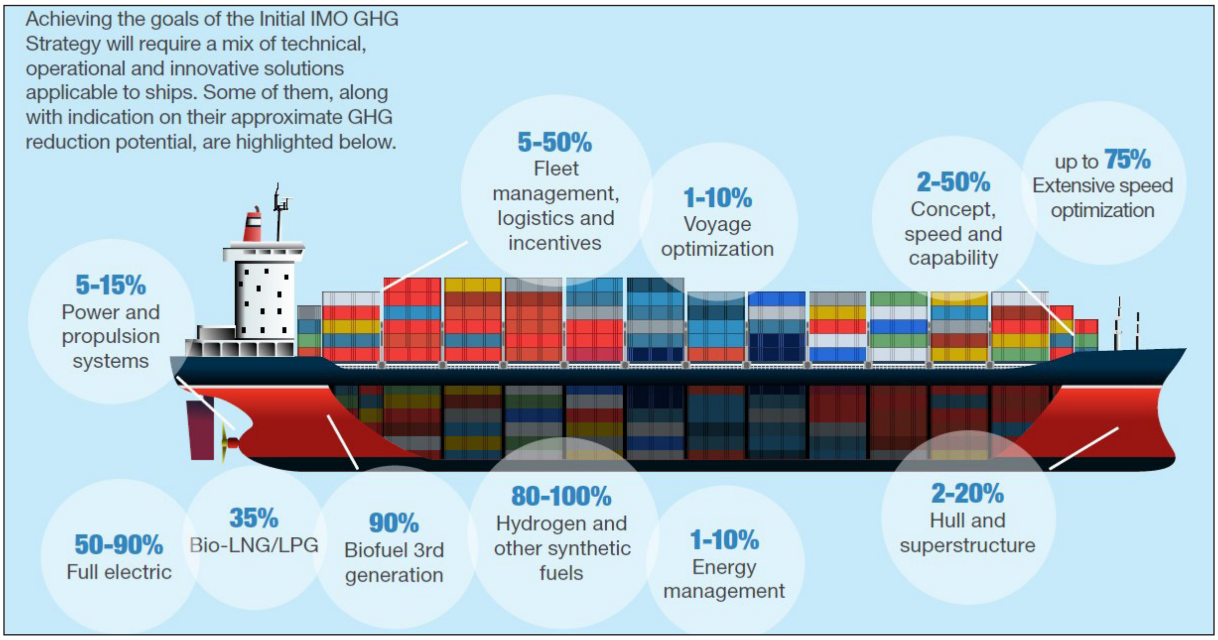

Fig. 1. A wide variety of design, operational and economic solutions [3]

overall efficiency of the propulsion. Improving the transport effect can be achieved by increasing the transport capacity of ships, preferably by increasing their size. IMO suggestions for improving transport efficiency are presented in Fig. 1.

The presented proposition of a mix of technical, operational and innovative solutions applicable to ships gives the possibilities of GHG emission reduction for each factor separately. The implementation of several factors will not bring benefits that are their algebraic sum. The upper values of the benefit may apply to vessels which no improvement action has been taken so far. In some, they are impossible to achieve, because many additional aspects have been omitted, which significantly reduce the benefits, e.g. a 35% reduction in emission for LPG is impossible due to only about 5% reduction in a carbon content of the gas, for LNG a direct reduction in emissions as a result of the direct combustion process is taken into account, but the effects of methane leaks from the fuel installation and in unproper combustion processes are not taken into account. A methane slip of 1.5% nullifies environmental benefits. Above this value is unfavorable [15].

The regulations adopted by the IMO are successively implemented and become obligatory for shipowners for existing ships being in operation as well. During every five-year periods, the company must obtain for the ship documents entitling to further operation (documents for the renewal of the class). At this point, the ship must comply with all current regulations for a given type of vessel, taking into account its age [12]. The inability to meet the requirements forces the shipowner for scrap it.

ALTERNATIVE FUELS IN SHIPPING

Attempts shall be made to use as marine fuels other non-petroleum products. A change in the type of fuel is necessary in view of the exhaustion of existing crude oil, gas and coal reserves. However, this is a period of about 50–100 years. There are many voices of leaving these resources to the next generations. Commitments made to reduce carbon dioxide emissions require a shift to other types of fuels [16–19]. Attention was paid mainly to so-called bio-fuels, i.e. fuels produced by chemical processes from biomass such as biogas and alcohols or from vegetable oils and animal fats, e.g. rapeseed oil esters or fatty acid methyl esters (FAME) [17]. A summary of selected fuels parameters is presented in Table 1.

The demand for marine fuels is about 370 million tons of heavy fuel oil per year and increases on average 2–3% per year. Assuming that the same efficiency of marine engines is maintained for other fuels, it is possible to estimate the demand in the form accumulated chemical energy and then, due to other lower heating value of these fuels, for an equivalent demand. This turns out to be impossible to meet for all alternative fuels.

The share of the total of all alternative fuels in the mass of marine fuels does not currently

Table 1. Parameters of selected marine, alternative and biofuels [own elaboration]

Type of fuel	Density [kg/m^3]	Lower Heating Value [MJ/kg]	Equivalent energy volume capacity to HFO=1	Equivalent demand per year [million tons]
Heavy fuel oil	940	39	1	370
Marine diesel oil	870	41.5	1.015	348
Marine gas oil	840	43	1.015	336
Bio-diesel	880	37.2	1.120	388
Renewable diesel	780	44.1	1.066	327
Fatty acid methyl esters	765	43	1.206	336
Methanol	794	22	2.099	656
Ethanol	789	28	1.660	515
Ammonia	682	18.6	2.890 / 3.468*	776
Propane	493	46.6	1.596 / 2.075*	310
Methane (LNG, SNG)	460	50	1.594 / 2.551*	289
Hydrogen (liquid)	71	120	4.303 / 8.606*	120

Note: *Additional volume for thermal insulation.

exceed 5%. They are mainly used on ships sailing inside special areas (Annex VI of MARPOL Convention), primarily on ferries. Switching to alternative fuels are actions taken by ship-owners to comply with the regulations introduced by IMO. However, these are ad hoc actions, because alternative fuels such as bio-diesel, FAME, synthetic LNG reduce the emission of pollutants such as sulfur and nitrogen oxides, particulate matter, but carbon dioxide emission do not meet the requirements after 2025 [20, 21, 22, 23, 24]. One way out of this situation remains, to recognize that carbon dioxide emission from these fuels do not fall into within these requirements – they do not come from the combustion of fossil fuels.

This is where you get to the level absurdity or political decisions. The negative social and environmental impacts of biofuel production are becoming increasingly apparent and the promised environmental benefits are lacking.

Table 2 presents the estimated effects of emissions into the atmosphere on different fuels from well-to-wake. Assuming the presented estimates in Table 2 as reliable, conclusions can be drawn in contrast to actions taken by IMO and shipowners.

Table 2. Well-to-wake emission factors for each pollutant (EF_{WTW}) and associated carbon dioxide equivalent factors (CEF_{WTW}) [on a base 25]

Fuel type	Engine type	Well-to-wake [g/g fuel]					
		EF_{WTW}				CEF_{WTW}	
		CO_2	CH_4	N_2O	BC	CO_2^{e100}	CO_2^{e20}
Heavy fuel oil	SSD	3.545	0.00404	0.00018	0.00019	3.915	4.553
	MSD	3.545	0.00404	0.00017	0.00049	4.182	5.510
VLSFO	SSD	3.734	0.00453	0.00019	0.00019	4.124	4.787
	MSD	3.734	0.00453	0.00018	0.00049	4.391	5.744
Marine diesel oil	SSD	3.782	0.00466	0.00019	0.00004	4.043	4.367
	MSD	3.782	0.00466	0.00018	0.00024	4.237	5.068
LNG	Otto MSD electronic	3.280	0.05336	0.00014	0.00002	5.259	8.023
	Otto MSD crankcase	3.280	0.05977	0.00014	0.00002	5.490	8.580
	Otto SSD electronic	3.280	0.03499	0.00014	0.00002	4.600	6.427
	Otto SSD crankcase	3.280	0.04175	0.00014	0.00002	4.844	7.015
	LBSI electronic	3.280	0.04438	0.00014	0.00002	4.936	7.242
	LBSI crankcase	3.280	0.05079	0.00014	0.00002	5.167	7.799

Note: VLSFO – very low sulfur fuel oil, LNG – liquefied natural gas, SSD – slow speed diesel engine, MSD – medium speed diesel engine, BC – black carbon, LBSI – lean-burn spark- ignited engine, e100 – a hundred year equivalent, e20 – twenty year equivalent.

THE PROBLEM OF TARGET FUEL FOR SHIPPING

IMO regulations aimed at reducing emissions of harmful substances into the atmosphere from maritime transport are in line with the expectations of many international organizations. The course of action is known. However, the problem of achieving these goals remains. Switching the type of marine fuel requires many actions enable its use:

- technical possibilities of production of a given fuel;
- improvement the fuel production to minimize the environmental effect (energy consumption) and decrease the fuel price as low as possible as a unit of cumulative storage energy (a price of 1 GJ/m^3);
- adaptation of ship power plant systems for a given fuel, including fuel reserve tanks (ship's autonomy);
- positive tests of different marine engines on this type of fuel;
- construction of a network of production, transport and storage fuel in the ports (fuel availability);
- infrastructure and bunkering systems in ports.

Fuel costs in maritime transport reach 70–90% of the total cost of operation of the ship. As a result, the price of marine fuel will be a decisive factor of the cost of transport by sea, and they on many parameters of the world economy. Changing the type of fuel, even to synthetic fuel, similar in composition to those currently used, is at least related to suitability of the tested fuel for the existing installation and the engine. There is no fuel system on the ship that automatically adapts to a change of liquid fuel. Currently, it is possible to switch from heavy fuel to diesel oil and vice versa. This process requires 1 to 4 hours to heat or cool the components of fuel system, primarily injection pumps and injectors, to stabilize the viscosity in the required range. It is a prerequisite for the proper operation of the system and proper fuel spraying during injection to the combustion chamber. Slight differences in the lower heating value of these fuels up to 10%, can be compensated by changing the fuel dose administered by the injection pump to maintain the assumed engine load. However, the problem of adequate fuel quality that meets the requirements specified for liquid marine fuels remains. If other fuels are attempted, the engine and fuel system of the new fuel shall be adapted to power the engine. Due to the fact that in emergency situations it is necessary to be able to switch the engine to work on liquid fuel, a separate fuel system is built for the new fuel. Attempts have been made to keep the boilers, main and auxiliary engines running only on liquefied natural gas (a part of new passenger cruise liners design and build after 2019), but this requires additional solutions and safeguards for emergency states, e.g. leaks in the gas fuel system [15, 26, 27]. The environmental benefits of switching to LNG are limited, due to significant carbon dioxide emission. Attempts have been made to produce synthetic LNG and use it as a marine fuel, expecting that carbon dioxide emission from this source will not be counted as emission subject to limits. It remains debatable whether this will be the case. The environmental costs of producing synthetic LNG are significant (mainly the consumption of energy and raw materials), which may suggest that there will be a change in the ecological assessment of this fuel.

Pure biofuel seems to be straight vegetable oils (SVO) which have been extracted from plants. The direct use of SVO generates many problems for marine diesel engines due to the SVOs' higher viscosity and high boiling point, the creation of carbon deposits inside the engines and damage to the engine lubricants [22]. It has been found that SVOs may be used in blends with conventional fuels in order to mitigate these problems, but we get a mixture of fuels. The content of SVO does not exceed 25%.

Some shipowners, mainly passenger-car ferries, have begun to adapt ship's fuel systems (relatively low costs) or build new ferries to use only biofuels (mainly FAME) or mixtures of marine fuels and biofuels, in order to meet carbon dioxide emission requirements. It was considered that emissions from biofuels do not count towards equivalent carbon dioxide emission. This road is probably the blind way, because it is enough to change the regulations and all the expenditure will be lost (the main loss will be the cost of building infrastructure for the production and distribution of biofuels). From the point of view of environmental effects, the opinion that these are not ecological fuel may prevail.

Similar problems occur where switching to methanol [17, 27, 28, 29] or ethanol. They can be obtained by chemical synthesis or as biofuels. The latter source seems to be more attractive in terms of ecology. In order to balance the energy demand for maritime transport contained in alcohol, around 656 million tons of methanol or 515 million tons of ethanol would have to be allocated (Table 1).

An attractive alternative fuel seems to be ammonia [30, 31]. Its main advantage is that it does not contain carbon in its molecule, as a result, there is no carbon dioxide emission after burning. Due to a very slow process of burning ammonia (the speed of flame propagation is about 0.09 m/s, about 5–10 times too slow), it cannot be used as pure gas. Additional, pre-injection of liquid fuel (10–30% of the total dose) and its ignition accelerates the speed of flame propagation after ammonia injection. In that case, a small level of carbon dioxide emission will occur (below required limits up to 2050). Trials at tested benches and engines from MAN and Wartsila (the main manufacturers of marine engines) proved promising. Engines can work correctly on this type of fuel [32, 33, 34]. The basic problem is that ammonia is obtained mainly by chemical synthesis. Currently used methods consume significant amount of energy, which in terms of environmental effects means about twice the equivalent emission of carbon dioxide. It is much more expensive than currently used marine fuels. The production of synthetic ammonia is relatively small, accounting for about 20% of the energy demand in maritime transport, which means that its production must be increased by at least 6 times. It seems to be necessary to find the technology for the production of ammonia at several times lower costs.

Another potential fuel that does not contain carbon in the molecule is hydrogen. Due to very low density of hydrogen vapors and liquids and problems with its storage after production, it is advisable to look for ways to concentrate it calorific value per unit volume. The combustion of hydrogen gas in marine engines causes a number of unsolvable problems due to too high speed of flame propagation [35, 36]. Positive have been made to burn mixtures of hydrogen with other gaseous or liquid fuels. This method significantly complicates the fuel system, including installations for its long-term storage. As a result, this method has not yet found application outside laboratory for marine engines. To indicate the substantial differences, the parameters of selected alternative fuels are summarized in Table 3.

Particularly large differences occur for critical temperature values, which affects the conditions of long-term storage – very low requirements for ammonia (it is a liquid at ambient temperatures), important for methane (generally fully refrigerated, cooled from -162 °C to about -155 °C) – the tanks need thermal insulation and very difficult for hydrogen (cryogenic temperature about -250 °C) – the tanks (cisterns) need a special solution of thermal insulation [35].

Burning hydrogen in marine internal combustion engines seems to be a not very beneficial way to get energy. Their thermal efficiency reaches value of about 50% with deep recovery waste heat up to 60% and their future development will not ensure efficiency above 60% (70% as the total energy efficiency of the marine power plant). Higher efficiency values can be achieved by using fuel cells. If the technology allows the use of cells with a capacity of 10÷100 MW with a compact volume, reasonable mass and price, the era of marine internal combustion engines will come to the end.

Table 3. Comparing the parameters of potential alternative marine fuel [own elaboration]

Parameter/type of fuel	LNG		Ammonia	Hydrogen
	Fossil	Synthetic	Synthetic	Different sources
Purity [%]	87–97 CH_4	Almost 100	Almost 100	Almost, depends on the type of source
Boiling temperature at 1 at_{ph} [°C]	-162	-162	-33.4	-253
Density of gas at normal conditions [kg/m^3]	0.714–0.740	0.714	0.760	0.089
Critical temperature [°C]	-82.56	-82.56	132.4	-240.15
LEL-UEL [%]	5–15	5.4–14	16–25	4–75
GWP^{20} [1], ODP [1]	84, 0	84, 0	0, 0	6-30 (24), high (during estimation)
Slip [%]	0.5-6	0.1–2	0.5–3	1–10

Note: LEL – low explosive limit, UEL – upper explosive limit, GWP^{20} – twenty-year global warming potential, ODP – ozone depleting potential.

In fuel cells, primary source may be methanol (due to the lack of problems with its long-term storage), from which hydrogen is produced in the final stage to feed the cells.

INDICATION OF THE TARGET FUEL FOR SHIPPING

The development of hydrogen technologies, and in particular the reduction of the price and conditions of storage and transport, may have a significant impact on marine fuel market [31, 35, 37]. It seems that after 2035 there should be an influential increase in the share of hydrogen as a marine fuel (mostly in short voyages), and in 2050 its share will be still below 10% (Fig. 2). The production of hydrogen from waste, redundant and renewable energy, which cannot be used directly (decreased demand) to store it as an energy storage for use in situations of rapid increase in demand for electricity or in emergency states in failures resulting in a power grid loss, will be of significant importance for the development of hydrogen technologies. This will justify the spread of hydrogen as a target fuel.

If significant amounts of bio-methane can be produced and carbon dioxide emissions from this source are still considered as not being included in the emission limits, then this type of fuel will be dominate the marine fuel market up to about 2040, in later years the share will decrease. In the case of synthetic methane, there will be no significant development of these technologies, which will mean that the share in the fuel market will not matter. On the other hand, e-ammonia and bio-methanol and bio-ethanol together should also compete. A proposition for a scenario of ongoing changes in the use of alternative fuels is presented in Fig. 2. The author suggests far-reaching changes in the marine fuel market. Due to IMO requirements, several types of fuels will be used during the transition period, but which do not meet the requirements for 2050. Legal regulations will have a decisive impact on the speed of changes taking place. Countries with large number of ships representing a large share of world tonnage and ship-owners who will be lobby for an extension of the transition periods will have some impact on slowing down this process.

Ships using electricity stored in batteries or produced in fuel cells as the primary source for

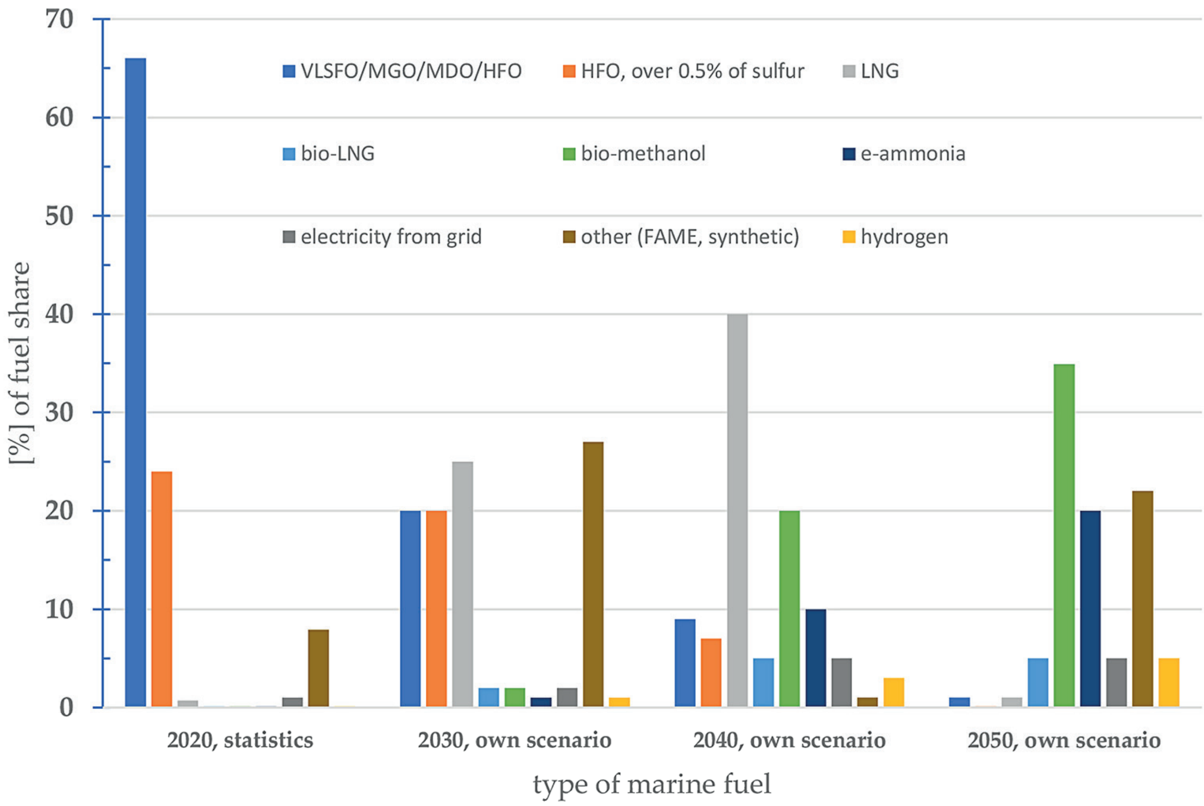

Fig. 2. Statistics from 2020 and possible scenarios for the distribution of different marine fuels types to the shipping market by 2050 [own elaboration]

propulsion will not represent significant change in trends. It will only be coastal and ferry shipping for the distances up to about 100 km (50÷60 nautical miles). The requirement for the ships to connect to the land power grid in the port will be of some importance, but this is not revolutionary, the emission will be transferred to another place where electricity is generated. In addition, for ships with high sailing autonomy (more than 10 days), it will not be crucial importance in the quantity of emitted equivalent carbon dioxide.

CONCLUSIONS

Unfortunately, neither the IMO nor any other widely known international organization has indicated a route for the transition to target marine fuel. Many international and advisory organizations justify the need to use transitional fuels (LNG, ammonia), the continued use of which after 2035 seems doubtful. It seems that the current trend of switching to LNG as a marine fuel will have to be stopped after 2035 (maybe synthetic natural gas will be used longer), due to the need to directly reduced carbon dioxide emissions by about 90%. The eventual shift to the use of ammonia as a marine fuel is possible, once cheaper and more environmentally friendly technologies have been developed. If this happen, the era of ammonia will be short, until the era of hydrogen and the use of fuel cells as an energy source on ships occurs.

The main problem is a lack of indication of the target fuel for 2050 and beyond. In the opinion of the author of the article, there is no alternative to hydrogen. An energy revolution on a epochal scale will be the mastery of nuclear fusion technology. However, it is not known when this will happen.

Currently shipowners are facing a serious challenge, changing marine fuel to one that will meet the requirements imposed by IMO. Shipowners take the risk of switching to a particular type of fuel without being sure that they have chosen the right path.

REFERENCES

1. IMO. 2000. Emission control areas (ECAs) designated under MARPOL Annex VI, http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Emission-Control-Areas-(ECAs)-designated-under-regulation-13-of-MARPOL-Annex-VI-(NOx-emission-control).aspx
2. IMO. 2000. Sulfur Oxides. Ammonia as Marine Fuel, Sustainability Whitepaper, October 2020. http://imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Sulphur-oxides-(SOx)-%E2%80%93-Regulation-14.aspxABS
3. IMO Action. 2017. IMO Action to Reduce Greenhouse Gas Emission from International Shipping, https://www.gcca.eu/sites/default/files/2020-06/2017%20IMO%20Action%20to%20Reduce%20GHG%20Emissions%20from%20International%20Shipping.pdf.
4. IMO. 2020. MEPC 75/7/15, Reduction of GHG Emissions from Ships. Fourth IMO GHG Study 2020 – Final report. Dated 29 July 2020.
5. IMO. 2012. Resolution MEPC.215(63). Guidelines for Calculation of Reference Lines for Use with EEDI; International Maritime Organization: London, UK, 2012.
6. IMO. 2021. Resolution MEPC.332(76) – Amendments to the 2018 Guidelines on the method of calculation on the attained energy efficiency design index (EEDI) for new ships (Resolution MEPC.308(73), as amended by Resolution MEPC.322(74).
7. IMO. 2012. MEPC.59/24/Add.1, Annex 19. Guidance for the Development of a Ship Energy Efficiency Management Plan, SEEMP; International Maritime Organization: London, UK, 2012.
8. IMO. 2021. Resolution MEPC.333(76) – 2021 Guidelines on the method of calculation the attained energy efficiency existing ship index (EEXI).
9. IMO. 2021. Resolution MEPC.336(76) – 2021 Guidelines on operational carbon intensity indicators and the calculation methods (CII Guidelines, G1).
10. IMO. 2021. Resolution MEPC.337(76) – 2021 Guidelines on the reference lines for use with operational carbon intensity indicators (CII Reference lines guidelines, G2).
11. IMO. 2021. Resolution MEPC.338(76) – 2021 Guidelines on the operational carbon intensity reduction factors relative to reference lines (CII Reduction factor guidelines, G3).
12. IMO. 2021. Resolution MEPC.339(76) – 2021 Guidelines on the operational carbon intensity rating of ships (CII Rating guidelines, G4).
13. IMO. 2018. MEPC 72/INF.5. (2018), Reduction of GHG from Ships. Understanding CO_2 Emissions and Challenges in Assessing the Operational Efficiency for Ships; International Maritime Organization: London, UK, 2018.
14. ICCT. 2018. The International Maritime Organization's initial greenhouse strategy, International Council on Clean Transportation.

15. Herdzik J. Methane Slip during Cargo Operations on LNG Carriers and LNG Fueled Vessels, New Trends in Production Engineering. 2018; 1(1): 293–300.
16. Andersson K., Brynolf S., Hansson J., Grahn M. Criteria and Decision Support for A Sustainable Choice of Alternative Marine Fuels, Sustainability. 2010; 12: 3623. DOI: 10.3390/su12093623
17. DNV-GL Maritime. 2019. Assessment of Selected Alternative Fuels and Technologies, June 2019.
18. Lloyd's Register Marine. 2021. Global Marine Fuel Trends 2030; Lloyd's Register: London, UK, 2021.
19. MAN B&W. 2013. Emission Project Guide. Two-stroke Marine Engines, MAN Diesel & Turbo, 2013.
20. Directive. 2015. 2015/757 of the European Parliament and of the Council of 29 April 2015, as amended by Delegated Regulation 2016/2071, On monitoring, reporting and verification of carbon dioxide emissions from maritime transport, and amended Directive 2009/16/EC.
21. Directive. 2018. 2018/410 of the European Parliament and of the Council of 14 March 2018 amending Directive 2003/87/EC To enhance cost-effective emission reductions and low-carbon investments, and Decision (EU) 2015/1814.
22. DNV. 2018. Bio Diesel: Emissions Depend on the Production Method; DNV GL: Bærum, Norway, 2018.
23. Herdzik J. Decarbonization of Marine Fuels – the Future of Shipping, Energies. 2021; 14: 4311. https://doi.org/10.3390/en14144311
24. Stenersen D., Thonstad O. GHG and NOx emissions from gas fuelled engines, SINTEF Ocean AS Maritim. 2017. https://midc.be/wp-content/uploads/2018/06/methane-slip-from-gas-engines-mainreport-1492296.pdf
25. Comer B., Osipova L. Accounting well-to-wake carbon dioxide equivalent emissions in maritime transportation climate policies, International Council on Clean Transportation. 2021.
26. IMO. 2015. Resolution MSC 39(95), Adoption of the International Code for the Ships Using Gases other Low-Flashpoint fuels (IGF Code). Adopted 11 June 2015.
27. Transport & Environment. 2018. Roadmap to decarbonizing European Shipping. A study by Transport & Environment. November 2018. On-line at: https://www.transportenvironment.org/publications/roadmap-decarbonising-european-shipping.
28. Liu M., Li C., Koh E.K., Ang Z., Lam J.S.L. Is methanol a future marine fuel for shipping? IOP Conf. Ser. J. Phys. 2019; 1357. DOI: 10.1088/1742-6596/1357/1/012014
29. Andersson K., Salazar C.M. 2015. Methanol as A Marine Fuel Report, Methanol Institute, 2015.
30. ABS. 2020. Ammonia as Marine Fuel, Sustainability Whitepaper, October 2020.
31. IMO. 2020. CCC 7/INF8, Forecasting the alternative fuel. Ammonia. Dated 10 July 2020.
32. MAN Energy Solutions. Engineering the future two-stroke green-ammonia engine. On-line at https://man-es.com/docs/default-source/marine/tools/engineering-the-future-two-stroke-green-ammonia-engine.pdf?sfvrsn=2b4d9d8a_10
33. DNV-GL. 2020. Ammonia as A Marine Fuel, Safety Handbook, Green Shipping Programme.
34. Hansson J., Brynolf S., Fridell E., Lehtveer M. 2020. The Potential Role of Ammonia as Marine Fuel – Based on Energy System Modelling and Multi-Criteria Decision Analysis, Sustainability. 2020; 12: 3625; DOI: 10.3390/su12083265
35. DNV. 2021. Rising to the Challenge of Hydrogen Economy; DNV: Bærum, Norway, 2021.
36. BP. 2021. Statistical Review of World Energy, 70th edition, https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf
37. DNV. 2022. Hydrogen forecast to 2050, Energy Transition Outlook, 2022.