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RESEARCH ARTICLE

A discussion on alternative fuel criteria for maritime transport

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ABSTRACT

Alternative marine fuels are considered an important solution for reducing ship emissions from fossil fuels. These fuels have similar energy content with fossil fuels, but they create much less environmental burden during their use due to the elements they contain (or not), the ratio of elements to each other and different combustion characteristics. On the other hand, for these fuels to replace fossil fuels, they must meet a number of important criteria and conditions. These are divided under four main titles: Economic, technical, environmental, social and other. In addition, examining the environmental impacts of alternative fuels from a life-cycle perspective is also important for determining the holistic and cumulative impacts. In this study, the criteria determined for alternative marine fuels were evaluated from the life cycle perspective and it was investigated which criterion is the most important in terms of life cycle. Thus, it is aimed to summarize the assessments of the criteria for acceptance of the alternative fuels.

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Introduction

Ships are responsible for 6.8% of the world's total energy demand (IEA, 2020) and 2.89% of the total anthropogenic emissions generation, and moreover, if the current situation is not changed, the total ship-related emission amount will increase by 90-130% and 50% in 2050 compared to 2008 and 2018, respectively (Faber et al., 2020).

Of the ship-related emissions, the total number of which is thought to be around 450 (Kollamthodi et al., 2008), only a few are produced in quantities worth examining. They are also the pollutants with the greatest environmental risk. Emissions evaluated by the International Maritime Organization (IMO) within the scope of the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78) are ozone-depleting substances (ODSs), nitrogen oxides (NO_x),

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sulphur oxides (SO_x), particulate matter (PM) and volatile organic compounds (VOCs).

Among these emissions, which are evaluated within the scope of MARPOL Annex-VI, ODSs are completely prohibited on ships as of 1 January 2020 with the rules introduced by Regulation 12, and Regulation 15 imposes restrictions on the production of VOCs. In addition, various restrictions have been placed on NO_x and SO_x emissions through Regulation 13 and Regulation 14, respectively, in special regions called Emission Control Areas (ECA) covering the coasts of North America, the Caribbean waters of the USA, the Baltic Sea and the North Sea. The constraints are shown in Table 1 and Table 2 (IMO, n.d.-a, n.d.-c).

In addition, according to the rules brought by the European Union (EU), as of January 1, 2020, all ships sailing in EU waters other than ECA should use fuel containing up to 0.5% sulphur. In 2018, China declared ECA to cover the Yangtze and Xi-Jiang Rivers and all territorial waters, and as of January 1, 2020, the sulphur content of the fuel used by each ship sailing in these regions should not be higher than 0.1% (Zhao et al., 2021). Sulphur restrictions for regions currently in the world are presented in Figure 1.

With its Initial IMO Strategy on Reduction of GHG Emissions from Ships report published in 2018, IMO has set the chart for the next decade for the decarbonization of the maritime industry. The report has been prepared in line with the United Nations (UN) Sustainable Development Goals (SDGs) and reveals ways to reduce ship-related carbon dioxide (CO_2) emissions by 40% by 2030 and by 70% by 2050 (IMO, n.d.-b, 2018; United Nations, 2020). Short, medium and long-term methods are presented in Table 3.

According to Table 3, alternative fuels are introduced and accepted as an important solution in all short, medium and long-term measures. On the other hand, there are serious obstacles to the acceptability of these fuels, which have significant disadvantages as well as great advantages. While most of the studies on alternative fuels primarily focus on environmental impacts, economic impacts have recently been taken into consideration in a comprehensive manner. On the other hand, alternative fuels must meet various criteria in order to be accepted in all respects. In this study, alternative fuels were briefly introduced and an evaluation of the acceptance criteria was made, and this is the first study in which only the criteria were evaluated and interpreted from a life cycle perspective.

Assessment of Criteria for Alternative Marine Fuels

Although the use of alternative fuel is only one of the various methods used to reduce and zero ship-related emissions, it is the only method that can achieve 100% success in emission reduction, and its applicability and market acceptability is extremely high. On the other hand, it is a difficult process for conventional fossil fuels to be replaced by new fuels due to their strong infrastructure, popularity and widespread usage networks. Alternative fuels must meet some very important criteria in order to replace conventional fossil fuels. These criteria can be summarized under six titles as economic, technical, environmental, social, demand and other:

Alternative fuels can be classified as; ammonia, biofuels (especially biodiesel), dimethyl ether, ethanol, hydrogen, liquefied natural gas (LNG), liquefied petroleum gas (LPG), and methanol.

Table 1. The limits for NO_x (IMO, 2020a)

Tier	Ship Construction Date on or after	Total Weighted Cycle Emission Limit (g/kWh) n=Engine's Rated Speed (RPM)		
		n<130	*n=130-1999*	*n≥2000*
Tier I	1 January 2000	17.0	$45 \times n^{-0.2}$	9.8
Tier II	1 January 2011	14.4	$44 \times n^{-0.2}$	7.7
Tier III (ECA)	1 January 2016	3.4	$9 \times n^{-0.2}$	2.0

Table 2. The limits for SO_x (IMO, 2020b)

Outside an Emission Control Area	Inside an Emission Control Area
4.50% prior to 1 January 2012	1.50% prior to 1 July 2010
3.50% on and after 1 January 2012	1.00% on and after 1 July 2010
0.50% on and after 1 January 2020	0.10% on and after 1 January 2015

Table 3. IMO Initial Strategies (adopted from IMO (2018))

Period	Strategies
2018-2023	— Developing the existing energy efficiency framework with a focus on EEDI and SEEMP, — Developing technical and operational energy efficiency measures for new and existing ships, — Assessment of methane (CH_4) and VOCs emissions, — Developing national action plans and policies for the reduction of GHGs in accordance with IMO rules, — Using shore-side electricity from renewable sources, establishing infrastructure for alternative low and zero carbon fuels, — Establishing research and development units covering ship propulsion, alternative low and zero carbon fuels and innovative technologies to increase ship energy efficiency, — Increasing life-cycle GHG studies for alternative low and zero carbon fuels, — Further studies on emission reduction cost and alternative low and zero carbon fuels
2023-2030	— Developing an application program for the efficient use of alternative low and zero carbon fuels, — Implementing operational energy efficiency measures for new and existing ships, — Developing new and innovative emission reduction mechanisms
2030-	— Following the development of zero-carbon fuels to assess decarbonization in the second half of the 21st century, — Providing incentives for the development of other new and innovative emission reduction mechanisms

The economic criterion most basically includes a pricing policy that can compete with conventional fossil fuels. In addition, necessary machinery (and machinery equipment) modifications, specialist personnel (and training) costs, infrastructure costs, and life-cycle costs, including production, distribution, storage and bunkering processes, are also important factors (Brynolf, 2014; Thomson et al., 2015; Svanberg et al., 2018; Hansson et al., 2019, 2020; Andersson et al., 2020). What makes this criterion more important than the others is that the cost is placed first by the shipowners (Eise Fokkema et al., 2017). The most important advantage of conventional fossil fuels compared to alternative fuels is that they have a strong infrastructure based on centuries of experience. Conventional fossil fuels are not expected to incur additional costs, as their operational responses are well known. Personnel are trained on these fuels and do not require additional training costs. For all these reasons, the economic criterion is seen as the first hurdle to be overcome for the use of an alternative fuel in global scale. It is also the most difficult obstacle because it creates a vicious circle in which demand remains limited, as the costs in the supply system cannot be reduced without an increase in demand. For this reason, governmental incentive may be required in order to exceed the economic criterion at the desired level.

The technical criterion relates to the use of the fuel on board and includes machinery (and machinery) modifications, fuel storage conditions, supply and infrastructure constraints (Brynolf, 2014; Thomson et al., 2015; Svanberg et al., 2018; Hansson et al., 2019, 2020; Andersson et al., 2020). One study concluded that technical conditions are accepted as the most important criteria by shipowners (Mandić et al., 2021). Technical conditions of alternative fuels need to be at least close to conventional fossil fuels' level to overtake them. Conventional fossil fuels do not present unusual surprises as they are used under proven conditions and almost all existing ship systems have been developed for conventional fossil fuels. The engines have been designed, the storage conditions have been adjusted, and the other engine equipment has been arranged according to the characteristics of conventional fossil fuels. Moreover, infrastructure and supply facilities are designed to meet the needs of conventional fossil fuels. Since the technical infrastructure required by the majority of alternative fuels is very different from that of conventional fuels, any technical arrangement that needs to be made mean an additional cost and loss of time. Moreover, new regulations bring the risk of mistakes and may cause additional and unpredictable costs.

The environmental criterion is the reason for the emergence of alternative fuels and includes the regulation of total life cycle emissions, and in particular, emissions during operation. In addition, human health indirectly falls within the scope of this criterion (Brynolf, 2014; Thomson et al., 2015; Svanberg et al., 2018; Hansson et al., 2019, 2020; Andersson et al., 2020). The environmental criterion is most accepted among academics

(Mandić et al., 2021). This criterion constitutes a very important basis for the existence of alternative fuels, and the compliance of alternative fuels with existing and then potential environmental regulations has a primary priority. The existence of alternative fuels is very important for the reduction of carbon emissions (decarbonization), which is the main cause of global climate change, and also for the zeroing or reduction of other ship-related emissions (SO_x, NO_x, PM, etc.). Although these fuels are generally quite successful from an environmental point of view during the operation process, more rigorous studies are required on the emissions that occur throughout their life cycle.

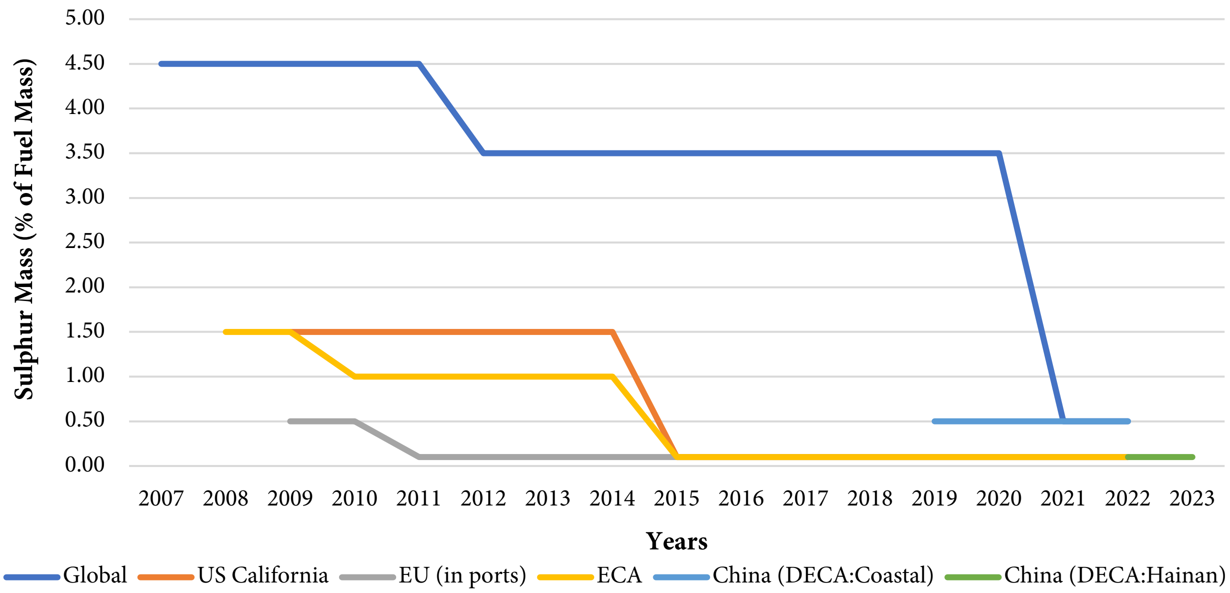

Figure 1. National and international sulphur content limits (adopted from Fan et al. (2021))

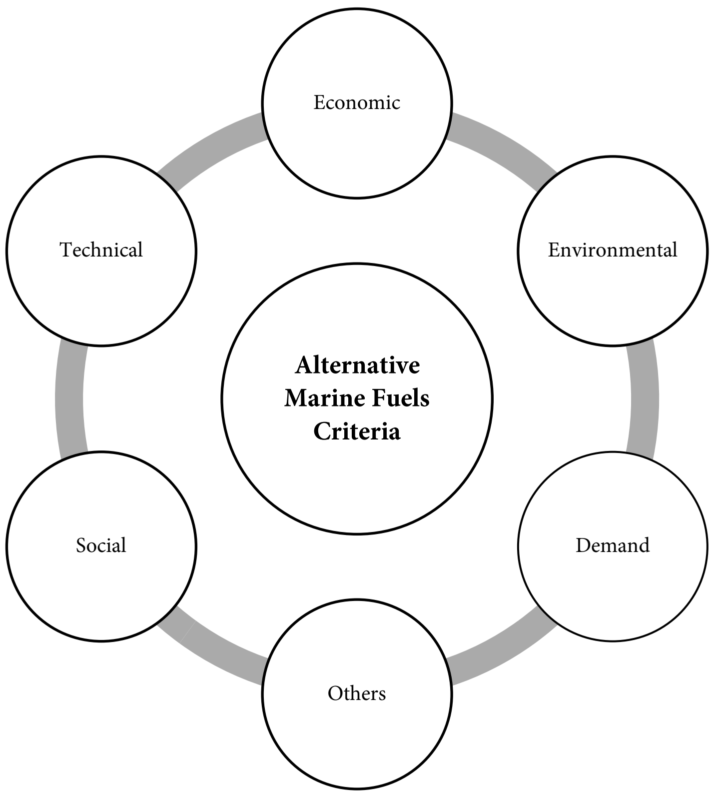

Figure 2. Alternative marine fuel criteria

Table 4. The summary of alternative fuel selection criteria

Title	Criteria	Reference
Economic	Initial investment Operational cost Fuel cost	Brynolf (2014), Thomson et al. (2015), Svanberg et al. (2018), Hansson et al. (2019, 2020), Andersson et al. (2020)
Technical	Infrastructure Supply chain Fuel and propulsion system	Brynolf (2014), Thomson et al. (2015), Svanberg et al. (2018), Hansson et al. (2019, 2020), Andersson et al. (2020)
Environmental	Climate change Human health Life cycle emissions	Brynolf (2014), Thomson et al. (2015), Svanberg et al. (2018), Hansson et al. (2019, 2020), Andersson et al. (2020)
Social	Safety	Hansson et al. (2019, 2020)
Demand	Price competition	Thomson et al. (2015)
Other	Logistics Ethics Politics	Brynolf (2014), Andersson et al. (2020)

Note: Fuels that successfully meet all these criteria are called drop-in Hsieh & Felby (2017).

The social criterion includes the risks that may occur especially during the operation (Hansson et al., 2019, 2020). Cargo and passenger transportation must, above all, ensure the safe transport of cargo and passengers (and crew). For this reason, it is necessary to determine the risks that may occur and take the necessary precautions sensitively. While the well-known characteristics of conventional fossil fuels and the extensive training process will minimize the risks that may arise, the elimination of new risks arising from the different characteristics of alternative fuels, some of which are quite difficult to overcome, will require some additional measures.

Other criteria include logistics, public opinion, ethics, and political and strategic perspective (Brynolf, 2014; Andersson et al., 2020). An alternative fuel accepted by the society is a fuel with high environmental performance and does not increase the product price due to its transportation cost, and public pressure is a significant force. The ethical approach focuses on whether it would be right to allocate the lands to be used for food production, especially for bio-based fuels, for fuel production. The political and strategic approach examines the effects of governments and companies on the creation of new jobs and the strengthening of local fuel producers with a long-term view. The summary of these criteria is presented in Table 4.

Results and Discussion

80-85% and 15-20% of the fuels currently used are residual fuels (Heavy Fuel Oil-HFO) and distillate fuels (Marine Diesel Oil-MDO and Marine Gas Oil-MGO) (Ammar, 2019). In a more recent study, these rates are given as 72% and 26%, respectively (DNV GL, 2021). Alternative fuels are expected to replace especially MDO and MGO, and the criteria listed above have emerged as a result of the comparisons made with these two fuels.

Ammonia can be used directly as fuel in internal combustion engines or alkaline fuel cells (Dimitriou & Javaid, 2020; Julia Hansson et al., 2020). Ammonia does not contain carbon and sulphur, thus, it is not a source of CO_2, CO, and unburned HC emissions, as well as SO_x and PM emissions (Hansson & Fridell, 2020). On the other hand, the greatest problem with ammonia is to be inhaled by the crew due to its high toxicity (Trivyza et al., 2020). Besides, a ship that uses ammonia as a fuel needs 1.6-2.3 times more volume and 1.4-1.6 times more weight (Kim et al., 2020). Also, the production cost of ammonia is higher than fossil-based fuels (IEA, 2019).

Hydrogen has a low flash point, high flame speed, a wide flammability range, and high diffusibility and can be used with other fuels (Pan et al., 2014; Kim et al., 2020). Hydrogen produces zero emissions when produced from renewable sources (Ryste, 2019). On the other hand, it is very reactive (Konnov, 2019; Elishav et al., 2020) and has major difficulties in handling and high transportation cost (Plana et al., 2010; Valera-Medina et al., 2017; Nemanič, 2019; Taccani et al., 2020).

LNG is a clean, colourless, odourless, non-toxic, and non-corrosive fuel and is compatible with IMO targets (Buhaug et al., 2009; Arteconi et al., 2010; EC, 2021). LNG usage lowers different types of emissions (Lehtoranta et al., 2021) but increase greenhouse gas emissions due the methane leakage during life-cycle (Schinas & Butler, 2016; Manouchehrinia et al., 2020; Ančić et al., 2020). Besides, LNG is competitively priced with conventional fuels but has a high initial investment cost (Brynolf et al., 2014).

Methanol can use the infrastructure of LNG (Andersson & Salazar, 2015; Verhelst et al., 2019; Ančić et al., 2020) but is toxic and corrosive (Ellis & Tanneberger, 2015; Ammar, 2019; Verhelst et al., 2019). Methanol produces low GHGs and other emissions (Tunér, 2015; Shahhosseini et al., 2018; Tunér et al., 2018) and has an acceptable initial cost (Ellis & Tanneberger, 2015).

While only 0.5% of the ships currently in operation are equipped with alternative energy systems, this rate has increased to 11.84% in the ships ordered (Lee et al., 2020). It is predicted that this rate will increase in the following years with the coming of new environmental regulations, but there are serious limitations that need to be overcome.

First of all, the ethical background encountered in the production process of bio-based fuels is a difficult problem to overcome. Farmers taking the route of producing fuel raw materials, which are more income-generating, can disrupt the local, regional and national food supply and this is an unacceptable problem in terms of its consequences. Despite their operational success, the impacts of alternative fuels (especially LNG) on life-cycle emissions are still not fully determined, and therefore it is likely to be frowned upon.

Considering life-cycle emissions should be a must-have approach to meet IMO's 2050 targets. Increasing the support for alternative fuels and breaking the vicious circle between supply and demand will be an important step in this direction. In this way, the necessary technical infrastructure will be established and a suitable environment will be created for the dissemination of alternative fuels.

Incentives to be applied to ships with alternative energy systems, project supports to be provided to institutions examining this issue, and various priorities to be provided to these ships will constitute a strong support point for the dissemination of alternative fuels.

More trained personnel would make the use of fuels safer, reduce unforeseen costs due to accidents and therefore make easier for shipowners to accept to use these fuels.

Informing the public is another important issue and it has been observed that South Koreans are ready to accept the additional costs caused by the environmental advantages of alternative fuels (Lee et al., 2020). Although it is not possible to expect this idea to be accepted by other societies, it seems possible to support the orientation of the public towards alternative fuels in cases where environmental and economic balance is achieved.

Conclusion

In today's world, where conventional fossil fuels are still in a very strong position, it is clear that effective measures must be taken in order to achieve environmental targets. Moreover, conventional fossil fuel prices are very sensitive to international crises, such as COVID-19 and Russo-Ukrainian War, whose effects are still not fully quantified. Developing alternatives that are just as powerful as conventional fossil fuels means that the world is not only making significant environmental gains, but also being stronger against potential energy crises.

This is the first study in which the criteria developed for the acceptance of alternative fuels were compiled holistically and examined from a life-cycle perspective. The most important obstacle for alternative fuels to replace fossil fuels is the lack of evaluation of whether these fuels are truly environmentally friendly, as the life cycle emissions of fuels have not yet been fully determined. According to the findings of the study, global acceptance of alternative fuels is possible within an optimization process of criteria with different dimensions. The criteria may come into conflict with each other. Therefore, the superiority of any criterion over the other is possible only from a subjective point of view, and there is no objective advantage. If the effects of the criteria are also examined from the life cycle perspective, it will be possible to get an idea of which one should be prioritized, and the evaluation errors within the criteria themselves can be eliminated. Recently, in addition to the economic dimension of environmentally beneficial practices, the social dimension has also been extensively included in scientific studies. Therefore, in the near future, more attention should be paid to the social dimension of an issue such as alternative fuels that may affect not only the maritime sector but also the lives of ordinary people.

In the light of the criteria evaluations, it is predicted that LNG will be preferred more in the near future due to environmental reasons as well as cost and infrastructure opportunities, but with the development of technology and decreasing costs in the medium term, hydrogen will play a more dominant role in the energy needs of the maritime sector.

Compliance With Ethical Standards

Conflict of Interest

The author declares that there is no conflict of interest.

Ethical Approval

The study involves no human participant. For this type of study, formal consent is not required.

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