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Procedia Computer Science 217 (2023) 1386–1395

Procedia Computer Science

www.elsevier.com/locate/procedia

4th International Conference on Industry 4.0 and Smart Manufacturing

A fast feasibility tool for the assessment of fuel switch in the concept design of merchant ships

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Abstract

Due to the utmost importance of international maritime transport within the global economy, shipping contributes substantially to the emission of pollutants and Greenhouse Gases. Consequently, it is called to reduce its environmental impact, in accordance with the regulations that will enter into force in the next years. In this framework, innovative technologies can find fruitful applications in new constructions, but there is still a significant number of operating ships that needs to be technologically updated. Nonetheless, since these ships may be already in the middle of their service life, revamping operations must take into account the purpose of both reducing pollution and avoiding long and expensive interventions. The sustainability-oriented production is one of the most discussed topics and in this paper, the authors aim at describing the potential technologies and solutions to adapt operating ships to the future emission threshold limits. Then, they propose a tool for supporting energy conversion studies on ships. The tool was tested on an Oil Tanker selected as a case study; different layouts exploiting the use of liquefied natural gas, ammonia, and methanol as alternative fuels were analysed. The considered technological solutions were compared on the basis of both technical and economic aspects. Indeed, technological feasibility and economic viability represent the most important discriminants for the diffusion of such innovations on a wide scale and in particular for commercial vessels employed predominantly in long and international voyages.

Keywords: Maritime transport, Pollutant emissions, Energy conversion, Alternative fuels, Oil Tanker.

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10.1016/j.procs.2022.12.337

1. Introduction

The protection of the environment is one of the main concerns of modern society. However, the approach that is most frequently followed by Governments and Institutions is not always supported by adequate scientific studies and the availability of enabling technologies [1]. An example can be obtained from the automotive market, where instead of an ecological transition we are witnessing a phenomenon of delocalization of air pollution from the cities near the power plants [2,3]. Even the shipping sector has not shied away from this process: new climate neutrality targets for maritime transport have been imposed at an international level, involving not only new constructions, but also ships in operation [4–6]. If the principles underlying this revolution can be widely and rightly shared, their application sometimes seems to mask an opportunity to tighten the tax regime of shipping companies. That is, if the ecological transition of cars is practically entirely borne by private citizens, the ecological transition of ships will be entirely borne by shipowners.

In any case, maritime shipping is a fundamental component of the global economy. In fact, at least 80% of world goods and several tens of millions of passengers are handled by ships [7]. Although shipping emits less carbon dioxide per tonne-km compared to other forms of transport, the shipping industry is responsible for emitting approximately 1.1 Gt of carbon dioxide (3% of global greenhouse gas emissions), as well as 2.3 Mt of sulphur dioxide and 3.2 Mt nitrogen oxides per year [8,9]. The international goal is to reach *climate neutrality* that consists in reducing Greenhouse Gases (GHGs) emissions as much as possible [10]. The challenge to reduce the environmental footprint of ships — with reference also to the aforementioned regulatory obligations — necessarily involves the identification of appropriate technical and operational solutions to increase the energy efficiency of ships [11–15]. The problem lies in the fact that only some of the solutions identified can be effectively applied also to ships in operation both for technical reasons and for economic convenience. Paradoxically, for certain types of ships, it may be more convenient to scrap the ship rather than thinking about a green refit.

It is easy to imagine that the most lasting solution is the fuel switch towards green alternative fuels. Therefore research efforts must be concentrated more in this direction, always taking into great consideration the applicability of technologies to ships in operation and at the same time evaluating the economic convenience. The choice of alternative fuel, however, is linked to the greater uncertainties related to both the technologies available on the market for maritime application and to the global presence of an effective logistics chain for bunkering. In fact, all alternative fuels have a lower energy density than traditional HFOs, so the volume of alternative fuels necessary to ensure the same autonomy/range to the ship will be much larger and it is not always available on the market. It must be considered that the maritime sector represents about 6.1% of global world fuel oil demand and 49.5% of total global residual fuel oil demand, for a total of about 300 million tons per year [4]. Bulk carriers, tankers and container ships make up the majority of large and very large vessels, carrying over 85% of the shipping trade and representing 70% of the fuel demand of maritime sectors [16]. Recent studies reported the trend of GHG emissions from crude oil tankers [17] and bulk carrier [18] and showed interesting future scenarios.

In this paper, the authors present a spreadsheet-based tool, aimed at evaluating the feasibility of fuel switch for existing ships and consisting of a series of progressive actions shown in Figure 1. In particular, starting from the main characteristics of the reference ship and considering the volumes available on board for fuel and propulsion system, the quantity of alternative fuels to be embarked is calculated to assure the same range, or how the range is reduced with the same amount of fuel embarked.

2. Technologies for the reduction of emissions in shipping

The shipping industry can face the problem of limiting pollutant emissions by implementing two different approaches [19]. The first one is based on the technological update of the currently used propulsion systems and machinery based on traditional fossil fuels [20,21]. The installation of specific equipment aimed at lowering pollution may aid in ensuring compliance with the current emission regulations, but does not allow achieving carbon neutrality. The second measure available consists in adopting alternative fuels with lower carbon, sulphur and other pollutants content, capable of generating a lower amount of CO_2 during combustion and supporting the achievement of carbon neutrality. Among the others, these fuels include Liquefied Natural Gas (LNG), methanol (CH_3OH), ammonia (NH_3), and hydrogen (H_2) [22]. Both the strategies will be deeply described in the following sections.

2.1. Technological updates

Conventional propulsion systems and machinery used on-board merchant ships may benefit from the addition of specific equipment, whose aim consists in treating and managing exhaust gases and lowering pollutant emissions. Such solutions and technologies can be summarized as follows:

- *Direct Water Injection (DWI):* Method for reducing NO_x emission by the injection of water directly into the combustion chamber via a separate nozzle [23];
- *Exhaust Gas Recirculation (EGR*): Method for reducing NO_x emission, which involves diluting the intake air with recirculated exhaust gases [24];
- *Selective Catalytic Reduction (SCR):* Method for reducing NO_x emission by injecting urea into the exhaust stream through a specially designed catalyst [23];
- *Scrubber:* Method for reducing SO_x emission through spraying water on exhaust gases, in order to make the SO_x react with water to form sulphuric acid; in open-loop systems, the natural alkalinity of the seawater neutralizes the acid, whereas, in closed-loop systems, caustic soda serves for the purpose [23].

2.2. Alternative fuels

As a second way to reduce pollutant emissions in shipping, the use of alternative fuels must be deeply analysed on the basis of the properties of the fuels themselves. In particular, emissions from the combustion of alternative fuels can be divided into two categories.

The *First Category* includes fuels that have a lower carbon content than conventional marine fuels and can significantly reduce emissions of SO_x, NO_x, PM, but cannot lead to complete decarbonisation. The following fuels belong to this category:

- *Liquefied Natural Gas (LNG)* – it is composed by a mixture of gaseous hydrocarbons [Table 1] and is a proven technology, widespread within the maritime sector. It offers a competitive fuel price compared to MGO and a competitive OPEX compared to Scrubber and SCR [25];
- *Methanol (CH_3OH)* – it is the simplest substance among alcohols and offers the lowest content of carbon with the highest content of hydrogen when compared to other liquid fuels, thus ensuring a significant reduction of CO_2 emissions when produced by means of renewable resources *(green methanol)* [26].

Table 1. LNG composition.

Component Name	Chemical Formula	Composition (Molar Percentage)	Average Composition* (Molar Percentage)
Methane	CH4	84% to 99%	90.4%
Ethane	C2H6	0.1% to 14%	6.4%
Propane	C_3H_8	0% to 4%	1.8%
Butane	C_4H_{10}	0% to 2.5%	0.9%
Nitrogen	N	0% to 1.8%	0.5%
Other	-	< 1%	0%

The *Second Category* includes fuels that do not contain carbon. For this reason, they can be considered Zero-GHG-emitting; furthermore, they guarantee also a valuable reduction of SO_x, NO_x, and PM emissions when produced by means of renewable resources *(green fuels)*. In this category, the most known and interesting fuels are the following:

- *Ammonia (NH_3)* - it is produced by the union of hydrogen (H_2) and nitrogen (N_2), does not contain carbon and therefore does not release CO_2 when used as fuel [27];
- *Hydrogen (H_2)* - it is a non-polluting gas that can be produced by thermochemical processes, electrolytic processes, or biological processes aimed at extracting it in its pure form since it is usually found in solution with other compounds [25].

The possibility of using alternative fuels for merchant vessels must be carefully analysed, since these ships are characterised by peculiar service conditions that significantly differ from those of ferries and passenger ships. Indeed, merchant ships are used on international voyages, where the route of each voyage, in most cases, is different from the previous one. For this reason, the main factors able to affect the selection of exploitable fuels are their availability for bunkering in ports, their reliability, the presence of an adequate supply chain, the technology maturity, and their cost [29]. In this framework, the fuel environmental footprint is still important and represents an additional factor able to direct the choice of shipowners and shipping companies as well as the aforementioned aspects.

3. Modelling tool

The feasibility of a fuel switch process has been here carried out with an in-house built tool shaped as shown in Figure 1. First, some quantities regarding the existing vessels are assessed. In particular, data shall be acquired regarding ships, main particulars, capacity plan, general arrangement and main machinery. Then, the operative profile shall be defined including both navigation (at a reference speed) and loading/unloading operations. For the operative profiles, the required power and fuel consumption are assessed for conventional fuel, including the energy stored on-board and the ship range. Then, considering only the mass and energy density of alternative fuels, a preliminary comparison of the volumes/weights required to store the same amount of energy is provided. This comparison can help to exclude unreasonable options and to highlight the challenges connected to each alternative.

In the second step, each fuel switch option under analysis is detailed up to a feasibility study level. Considering ship layout and current/draft rule requirements, a hypothesis about positioning, volume and mass of the new fuel storage is done. Besides, from a database of solutions on the market or under development, an energy conversion technology (e.g. internal combustion engines, fuel cells + electric motor +batteries, etc.) is also selected. Then assuming a set of fuel characteristics (in the present study the ones provided in Table 2) and considering eventual additional systems (e.g. craking for ammonia, SCR, etc.), the energy balance and efficiency of the propulsion/electric generation systems are assessed in the different operative scenarios. Then, fuel consumption is assessed and, combining it with the tested fuel storage layout, the range of the vessel is evaluated.

Multiple layouts/technologies can be tested in separate feasibility studies and then compared through tables and graphs. Finally, the selection of the preferred option is carried out based on the computed range and additional considerations about the technological maturity, measured by the Technology Readiness Level (TRL), of the applied technologies and on the uncertainties regarding the rule framework for the considered fuel. This information is essential to evaluate the technical feasibility of a solution. Besides, here focus has been made on technical feasibility only, but it is acknowledged that the study shall be complemented with the economic effort required for the fuel switch as well as the availability of bunkering facilities in the considered regions.

Table 2. LNG, methanol, ammonia and hydrogen characteristics [28].

	Methane (LNG)	Methanol (CH_3OH)	Ammonia (NH_3)	Hydrogen (H_2)
Boiling temperature	-162 °C	64.7 °C	-33 °C	-253 °C
Density at boiling temperature	450 kg/m^3	748 kg/m^3	680 kg/m^3	71 kg/m^3
Flammability limits is air by volume	5-15%	6.7-36%	15-28%	4-75%
Auto – ignition temperature	595 °C	470 °C	651 °C	571 °C
Lower Heating value	49.6 MJ/kg	19.9 MJ/kg	18.6 MK/kg	119 MJ/kg
CO_2	- 45%* (up to)	-75%* (up to)	-100%*	-100%*
NO_x	- 85% (up to)	-60% (up to)	?	-85% (up to)
SO_x	- 100%	-90%	-100%	-100%*
Particulate matter	- 98%	-95%	?	-100%*
Other characteristics	Cryogenic, Risk of explosion in confined space, Risk of asphyxiation in confined space	Toxic, Flammable and corrosive gas, Risk of explosion in confined space	Toxic, Risk of explosion in confined space, Corrosive gas, Cold gas or high pressure	Cryogenic, Extremely flammable, Risk of explosion in confined space, Danger risk of asphyxiation

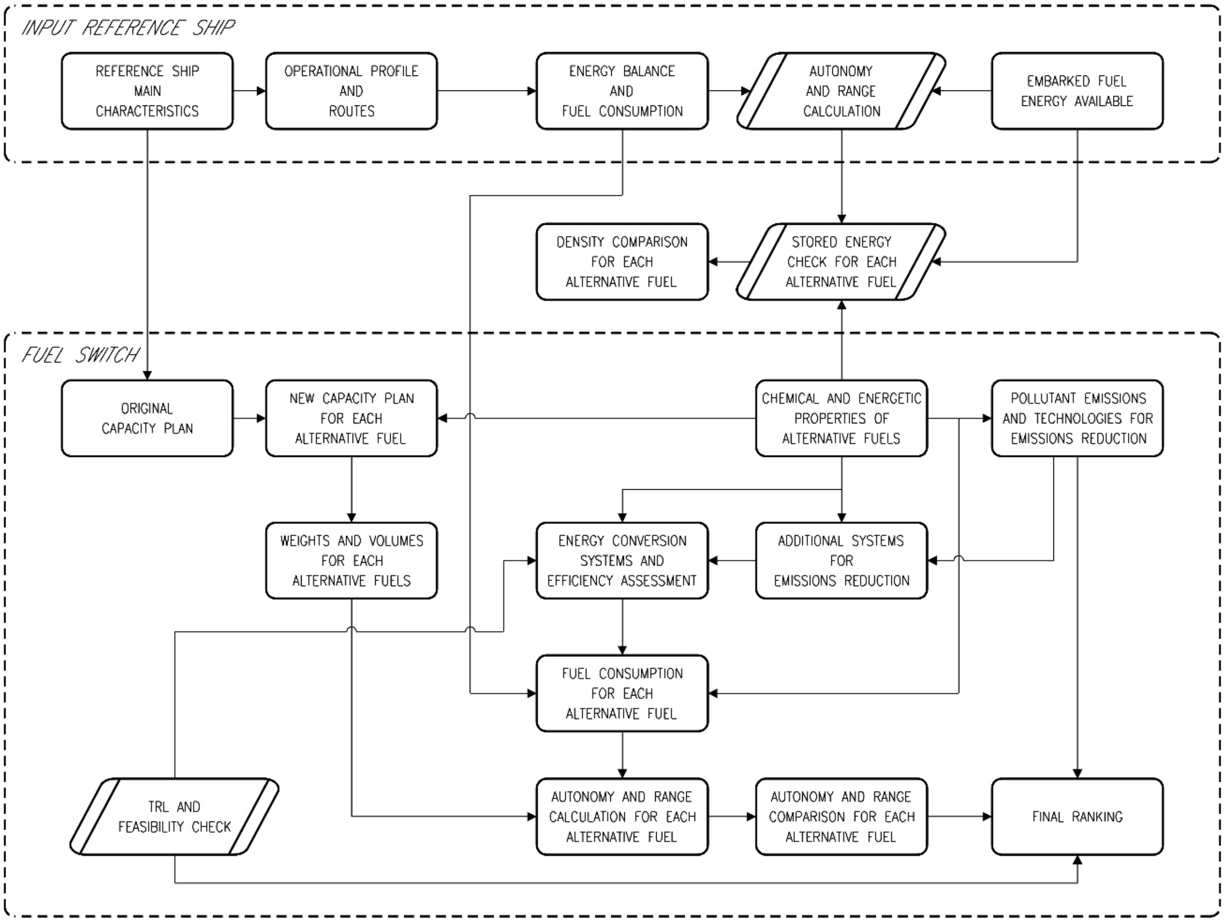


Fig. 1. Flowchart showing the components and processes included in the developed tool for assessing fuel switch.

4. Case study

The tool presented in the previous section was validated through a case study based on an Aframax Oil Tanker, whose main characteristics are shown in Table 3. Specifically, the authors analyzed three different propulsion solutions capable of reducing the emissions produced by the tanker without changing the original operative mission. The attention was focused on LNG, Ammonia, and Methanol as alternative fuels. The full-hydrogen case was not considered due to the low volumetric energy density, which requires unreasonable storage tanks or too limited range.

The Main Engine is a two-stroke Mitsui MAN B&W 760 MC; plus, three Diesel Generators from Daihatsu are installed on-board. The vessel is equipped with dedicated tanks for the storage of HFO and MGO.

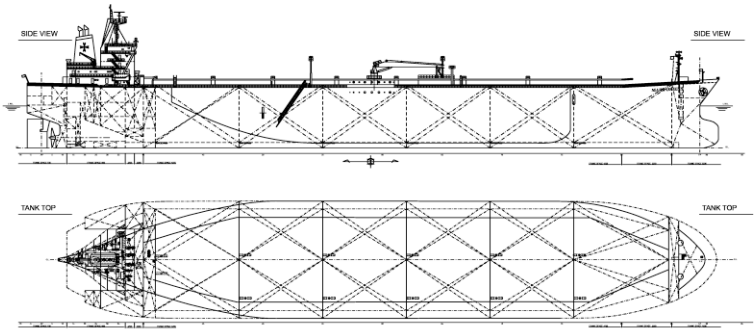
Considering the current HFO storage tanks having a capacity equal to 2860.4 m^3 and MGO storage tanks having a capacity equal to 1181.4 m^3, the volume and masses of the considered alternative fuels necessary to achieve the same amount of energy stored on-board were estimated [Fig. 2]. Henceforth, for the solutions based on LNG and Ammonia, the fuel storage system must be considered complete with all the necessary characteristics as regards construction materials, thickness, filling limits, and loaded volume, which have not been covered here for the sake of brevity.

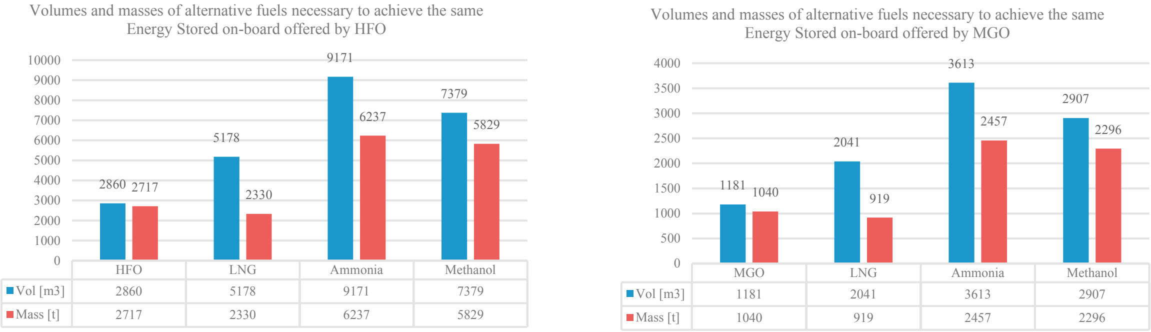
For the purposes of the study and of the fuel consumption calculation [Table 4], the vessel's operational profiles were defined on the basis of the following conditions:

- Voyage of the vessel in Laden Condition from Fujairah (UAE) to Singapore - distance equal to **3334 nm**, at the average speed of **12.5 kn** [Fig. 3];
- Discharging operations carried out in the Port of Singapore for a duration of **22 hours**.

Table 3. Main characteristics of the Aframax Oil Tanker Vessel selected as case study. improve the clarity of the drawing

Main characteristics	
Length, overall	245.56 *m*
Length, between perpendiculars	235.72 *m*
Breadth, moulded	42.00 *m*
Moulded depth	21.51 *m*
Draught, scantling	14.95 *m*
Deadweight, summer draught	110295 *t*
Gross Tonnage	59611 *GT*
Engine	**Power**
Main Engine	14280 *kW*
Diesel Generators	3 x 720 *kW*
Vessel Consumption in Laden condition	
Service Speed	*14.9 kn*
Range	19600 *nm*





(a) (b)

Fig. 2. Volumes and masses of alternative fuels necessary to achieve the same Energy Stored on-board offered by HFO (a) and MGO (b).

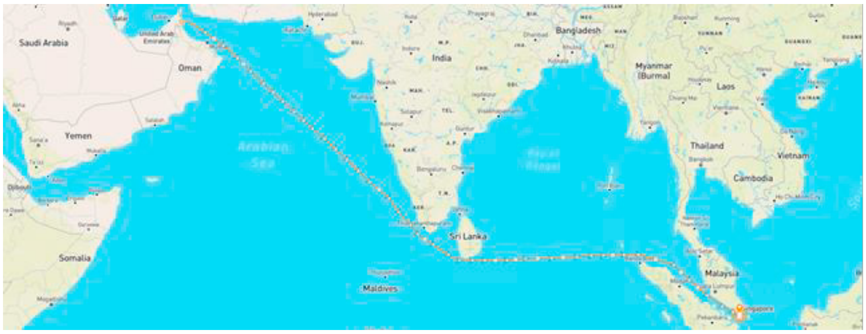


Fig. 3. Route from Fujairah (UAE) to Singapore.

Table 4. Consumption of two operational profiles.

Consumption during voyage	
Voyage distance	3334 *nm*
Reference speed	12.5 *kn*
Main Engine Consumption	34 *t/day*
DG Consumption	2.5 *t/day*
Voyage days	~11 *days*
ME Consumption	~374 *t*
DG Consumption	~28 *t*
Consumption during discharge	
Time for discharging	22 *hours*
Boiler Consumption	54 *t*
DG Consumption	5 *t*

4.1. LNG solution

The LNG solution for the ship conversion implies that LNG would represent the primary fuel, while MGO would be used as a pilot fuel in dual-fuel (DF) engines or in back-up situations for the emergency generators. Consequently, appropriate tanks for the MGO storage should be maintained, even though with smaller capacities than the reference ship. As regards the LNG storage tanks, two C-Type tanks shall be located on the main deck in front of the accommodation superstructure, as shown in Figure 4. The tanks' capacity has been evaluated on the basis of the space available on the main deck [Table 5].

From the calculations carried out, the implementation of the LNG solution causes a reduction of the range of the vessel at the reference speed. However, for the specific case study, the vessel would be able to perform both the voyage and the discharge operations, plus having still enough fuel to perform another route without the necessity of bunkering.

(a) (b)

Fig. 4. Arrangement of the LNG C-Type tanks as seen from a transversal section (a) and in a rendering (b).

Table 5. Main characteristics of Vessel propulsion with LNG.

Main characteristics - Consumption during voyage	
LNG Tank	2 x 2004 m^3
Total Fuel	~1800 *t*
MGO Tank	410 m^3
Reference speed	14.9 *kn*
Range	~13500 *nm*
Autonomy	*~38 days*
Consumption during discharge	
Time for discharging	22 *hours*
Tot Consumption	51 *t*

Considering the large volumes of natural gas available worldwide [29], there are no principal limitations to the production capacities that could limit the use of LNG as vessel fuel. Therefore, with the adequate development of infrastructures, the vessel should be probably able to do bunkering of LNG in almost all the international ports without facing limitations on routes. In addition, for tanker vessels, the fuel storage tanks allocated on the main deck would allow freeing space in the engine room that could be optimized for other uses.

4.2. Ammonia solution

A first consideration as regards the implementation of the ammonia solution should deal with the lower energy content in both weight and volume when compared to the LNG; this causes great disadvantages in terms of storage volumes. Indeed, the same tanks hypothesized for LNG and offering a total capacity volume equal to 4008 m^3 can contain ammonia as well. However, due to its lower energy content, the total energy stored on-board significantly decreases, causing also a drastic reduction in the endurance capability of the ship, as shown in Table 6. As a result, the ammonia solution for fuel-switching reduces the range by almost half, if compared to the LNG solution.

Moreover, ammonia applications as fuel for ships are currently non-existent; the industry has been evaluating its use in combustion engines [29], but engines are still in development.

In any case, assuming the future availability of ammonia bunkering sites, the vessel would be able to perform both the voyage and the discharge operations, plus having still enough fuel to perform another route without the necessity of bunkering. Nevertheless, due to the remarkably reduced range and the probable slow construction of bunkering sites, the vessel will not be able to carry out all the international routes usually foreseen.

Table 6. Main characteristics of Vessel propulsion with ammonia.

Main characteristics - Consumption during voyage	
Ammonia Tank	2 x 2004 m^3
Total Fuel	~2700 *t*
MGO Tank	410 m^3
Reference speed	14.9 *kn*
Range	~7600 *nm*
Autonomy	~21 *days*
Consumption during discharge	
Time for discharging	22 *hours*
Tot Consumption	134 *t*

4.3. Methanol solution

Finally, the authors considered the possibility of using methanol as fuel. This offers a great advantage in comparison with LNG and ammonia, since it can be stored as traditional fuels in structural tanks. Furthermore, it also offers the highest energy density after LNG and Table 7 shows that it reduces the range by roughly 1/3 if compared to LNG.

As regards the supply chain, methanol is already available through existing and well-positioned global terminal infrastructures even though dedicated bunkering infrastructures for ships are currently limited [29]. However, for the specific case study, again the vessel would be able to perform both the voyage and the discharge operations, plus having still enough fuel to perform another route without the necessity of bunkering.

Table 7. Main characteristics of Vessel propulsion with Methanol.

Main characteristics - Consumption during the voyage	
Methanol Tank	~4040 m^3
Total Fuel	~3200 *t*
Reference speed	14.9 *kn*
Range	~9500 *nm*
Autonomy	~26 *days*
Consumption during discharge	
Time for discharging	22 *hours*
Tot Consumption	126 *t*

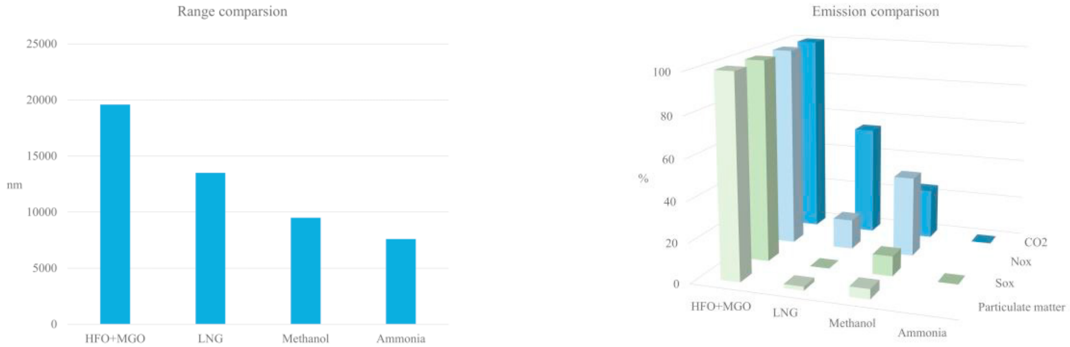
4.4. Results

For each alternative solution proposed, the range in nautical miles was estimated on the basis of the energy stored on-board (Fig. 5a). In order to perform a comparison with the reference ship fuelled with HFO+MDO, the following results in terms of the percentage of range achieved with respect to the conventional solution were calculated:

- LNG solution – 30% reduction of the range;
- Ammonia solution – 60% reduction of the range;
- Methanol solution – 50% reduction of the range.

It is evident that the alternative fuels proposed are not able to guarantee the same range and, consequently, autonomy, of the conventional solution based on HFO+MGO currently employed for the reference ship, with significant reduction for both ammonia and methanol.

In the current social, political, and financial context, an economic comparison among different solutions appears without scientific soundness due to a market heavily distorted by unjustified and very often deceptive speculations that may affect the supply of both fuels and components. However, it is not excluded that in the near future certain choices may be forced and therefore supported by Governmental fundings. In any case, for the case-study vessel, the authors estimated the investment cost for the installation of tanks of LNG and Ammonia, which turned to be about 28 M€ and 20 M€, respectively [28]. As for the operational cost, it has been estimated with reference to a range of 7600 nm: for methanol and Ammonia, it would be almost double than the value for HFO+MGO or LNG [28, 30, 31, 32]. Again, it should be considered that the current speculation is leading to ever-increasing prices, especially for LNG, and the analysis of operational costs is changing on a daily basis. This economic analysis underlined that investment costs and operational costs are extremely high for alternative fuels compared to conventional ones. On the other hand, emissions generated by the consumption of alternative fuels are significantly lower than those generated by the use of HFO+MDO (Fig. 5b) [28].



(a) (b)

Fig. 5. Range and emission comparison amongst the reference value (HFO+MGO) and the alternative solutions proposed.

5. Conclusions

The present work presents a spreadsheet-based tool, useful for assessing the technological and economic viability of fuel switch on a cargo vessel. Compared to the established literature, the new tool does not focus on the use of one technology over another but allows a quick and consistent analysis during the early-stage design of ships. The case study presented is of utmost significance since it deals with a type of ship often neglected by the current literature.

As a direct result of the study, the authors highlighted the impossibility of performing a conversion to alternative fuels by exploiting the useful space on-board without affecting the range. The vessel propelled by alternative fuels will need more refuelling stops and, in some cases, may have to perform shorter routes due to the lack of refuelling possibilities in some ports. Consequently, the underdevelopment of bunkering infrastructures remains a barrier to the use of alternative fuels for commercial vessels. Even if the infrastructures for both LNG and methanol bunkering are quite developed, it should be considered that these fuels are still not carbon-free. Otherwise, ammonia may play an important role in the decarbonization target, but fully developed bunkering chains and new technologies to optimize its storage on-board must still be implemented and studied. Furthermore, the present research shows that the range of the Ammonia-fuelled vessel is the smallest if compared to the other alternative fuels. Therefore, its use would considerably reduce all the emissions, but at the same time it would not allow commercial vessels to carry out all the international voyages planned, with a consequent increase of the employed ships for maritime transports.

In conclusion, ship-owners will have to deal from one side with both the investment cost of ships propelled with alternative fuels and the consequent reduction in range, and from the other, with the stricter regulations that will enter into force in the near future. As a result, charterers will be called to face the compromise between environmental sustainability and efficiency. It is clear that the final outcomes of this revolution in the shipping industry will be deeply affected by the development and availability of the supply chain, as well as by the cost of the new alternative fuels and the economic incentives for their use. At the end, the present work highlights that the transition to green fuels in the shipping industry cannot be immediate, and, in particular, it will consist in the use of more fuels, due to the impossibility to choose a single replacement for current fossil fuels suitable for all types of ships, at prices that are accessible and readily available in every port.

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