Feasibility Study for the Fuel Switch of a Fast Ferry

Donato PADOLECCHIA[a,1], Samuele UTZERI[a], Alberto MARINÒ[a], Vittorio BUCCI[a]
[a] *Department of Engineering and Architecture, University of Trieste*

Abstract. Liquefied Natural Gas (LNG) has recently become a popular fuel in the shipping industry due to its low emissions and high energy density. However, it requires one or more bulky cryogenic tanks for storage onboard. Considering a traditional fast ferry, it is hard to find onboard a location for tanks, thus hindering the retrofit of existing ships. In this context, Compressed Natural Gas (CNG) might be a viable solution, since it can be more flexibly stored onboard and has greater availability in minor ports compared to LNG. Hence, this article investigates the feasibility of retrofitting the propulsion system of a fast ferry to employ CNG as fuel. After a review of the pros and cons of CNG and LNG as alternative fuels to marine diesel oil (MDO), a critical analysis of the technical requirements for retrofitting a fast ferry with CNG propulsion systems is carried out. Defined the layout and changes of the refitted unit, its performances are assessed on a test operative scenario. The study concludes that CNG retrofitting is technically feasible and provides several benefits, including lower emissions, higher levels of performance and higher reliability compared to LNG. Nevertheless, the retrofit requires significant changes to the ship layout and its fuel system to fit the required number of CNG cylinders.

Keywords. Liquefied Natural Gas, Compressed Natural Gas, Fast ferry, Alternative fuels

1. Introduction

At present, one of the most critical environmental concerns is global warming, which is primarily driven by a substantial increase in Global Greenhouse Gases (GHGs) resulting from the use of fossil fuels [1], [2]. Notably, carbon dioxide (CO_2) is responsible for approximately 60% of the greenhouse effect. The transportation sector, in particular, has a significant impact on global CO_2 emissions, with about 25% of CO_2 stemming from this industry [3].
The issue of releasing harmful substances into the atmosphere also affects the maritime sector. Over the past few years, sea transportation of both goods and people has seen a considerable surge worldwide, with ships now accounting for more than 90% of freight transport. Consequently, maritime transportation contributes to 2.7% of CO_2 of total global anthropogenic emissions [4].
To address this problem, International Maritime Organizations (IMO) have been devising strategies for the short, medium, and long terms [5]. The strongest expression of the actions of IMO aimed at protecting the marine and coastal environment was embodied in Annex VI of the International Convention for the Prevention of Pollution

[1] Corresponding Author: Donato PADOLECCHIA, donato.padolecchia@phd.units.it.

from Ships: MARPOL [6] On April 13, 2018, the IMO Marine Environment Protection Committee – MEPC – announced an agreement among Member States' delegates to achieve the target of reducing the shipping sector's overall CO_2 emissions by approximately 50% by 2050. Moreover, they aim to reduce pollutant emissions promptly and continue efforts to eliminate carbon emissions entirely [7].. This provided for the introduction of Emission Control Areas (ECAs) [8], areas of the world where special restrictions on the release of pollutants into the atmosphere are in force; to date, these include the Baltic Sea, the North Sea, the English Channel, parts of the coasts of North America and its major lakes.
In light of the increases in maritime traffic in recent years and thinking about the consequences these could have on the environment, the IMO member states considered the possible extension of ECAs to the Mediterranean region in particular. This decision stems from the fact that around 19% of international maritime traffic passes through this sea. Reducing the emission of pollutants into the atmosphere is being achieved through the use of alternative fuels to oil-derived ones, including natural gas [9] or methanol [10]. With the delivery of 57 vessels1 in 2021 and seven in the first four months of 2022, the global LNG carrier fleet consisted of 641 active vessels1 as of end-of-April 2022, including 45 floating storage and regasification units (FSRUs) and five floating storage units (FSUs). This represents a 10% growth in the fleet size from 2020 to 2021, comparable to a 12% growth in the number of LNG voyages as trade recovered from COVID-19-induced demand reductions [11] .The following article aims at a feasibility study for the conversion of a fast monohull from conventional fuel to natural gas. The study compares the possible ways of storing natural gas on board and the choice of the most suitable one for the case under examination. The paper also proposes a possible placement of tanks on board after a technical and regulatory analysis.

2. Materials and Methods

The International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code) [12] establishes global standards for ships utilizing gas or low-flashpoint liquids as fuel, excluding vessels covered by the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) [13].
The main objective of the IGF Code is to provide compulsory guidelines for the layout and installation of machinery, equipment, and systems on these ships, aiming to minimize risks to the vessel, crew, and the environment, considering the specific characteristics of these fuels.
The development of the Code was based on sound naval architecture and engineering principles, incorporating operational experience, field data, and research and development. As new fuel technologies emerge, the IMO will periodically review and update the Code, integrating practical experience and technical advancements.
Regarding fuel containment tanks, they must be positioned to preserve their integrity or reduce damage in case of collisions or grounding. Therefore, the Code specifies that fuel tanks should be located at a minimum distance of B/5 or 11.5 m from the ship's sides and stern, measured within the plating and normal to the ship's centerline. For passenger ships, the tank walls should not be less than B/10 from the ship's sides and stern. The lowest point of the tank should be at a minimum distance of B/15 or 2 m from the bottom of the ship, measured within the plating and normal to the ship's centerline.

Natural gas is transported in two forms: Liquefied Natural Gas (LNG) and Compressed Natural Gas (CNG), depending on whether the gas is in a gaseous state at ambient pressure and temperature. Its boiling temperature at atmospheric pressure is -161°C.

2.1. LNG technologies

LNG storage on board ships can be achieved using various types of tanks, each with its specific characteristics:

- Integrated tanks: These tanks are structurally integrated into the ship's hull and bear the same loads as adjacent structures. They have a design pressure not exceeding 0.25 bar, which can be increased up to 0.7 bar if the hull is reinforced. Integrated tanks are suitable for products with a boiling temperature of at least -10°C.
- Membrane tanks: These tanks are self-supporting when empty, but rest against the ship's hull when loaded. They consist of a thin layer of insulating material and metal containment barriers. The design of the membrane prevents thermal stresses from affecting the vessel. The maximum design pressure for these tanks is 0.7 bar, which can be achieved with hull reinforcement.
- Semi-membrane tanks: Unlike membrane tanks, these tanks cannot support their own weight and rely on external hull structures for support. They also have a membrane designed to prevent thermal stresses from reaching the ship.
- Independent tanks: These tanks rest on the ship's bottom on appropriate saddles, ensuring no transmission of thermal or hull stresses. There are three categories of independent tanks:
  - Type A: Designed for steam pressures up to 0.25 bar.
  - Type B: Designed for steam pressures up to 0.7 bar.
  - Type C: Designed based on the expected strength limit depending on the transport pressure of the liquefied gas.

The construction materials for these tanks need to maintain good mechanical properties even at low temperatures, making stainless steel the most common choice. Spherical and cylindrical shapes are the most prevalent designs, with spherical tanks limiting heat exchange due to a reduced surface area. A typical tank consists of a stainless-steel container for the liquefied gas placed within a carbon-steel heat exchanger shell. Between the two containers, there is pearlitic insulation under high vacuum. The vessel is supported by tie-rods connected to the heat-retaining casing, which rests on a supporting platform. The vacuum and pearlitic layer minimize heat exchange through conduction and convection, allowing LNG to be stored for about one to two weeks without withdrawal.

2.2. CNG technologies

Compressed Natural Gas (CNG) is obtained by subjecting natural gas to compression processes. The risks associated with the high-pressure storage of highly flammable fuels and the technical difficulties involved in building tanks that can withstand pressures of around 200 to 250 bar at room temperature were the major brake on the spread of this technology in years past. Nowadays, however, technical developments have made it possible to make this transport safe; the introduction of composite tanks on the market, which are lighter and safer, has contributed to this. **Table 1** shows the main characteristics of Compressed Natural Gas.

Table 1 GNC main characteristics

Density at 15°C and 240bar (kg/l)	Storage pressure (bar)	Lower heating power (MJ/kg)	Ignition limit (%)	Volumetric equivalence to natural gas (m^3/m^3)
0.212	250	56.30	5:15	250

Tanks used for the storage of compressed natural gas are very robust components: this is related to the high operating pressures at which they will have to work.
CNG tanks are distinguished according to the material of construction and the structural reinforcements used.
Below is the classification given by ISO 11439 [14] (**Table 2**).

- Type 1: Cylinders with a metal body, generally steel.
- Type 2: Cylinders with a metal body, reinforced in the circumferential direction only, by a composite liner.
- Type 3: Cylinders with a thin metal body, fully reinforced by a composite liner.
- Type 4: Cylinders with a plastic body, fully reinforced by a composite liner.

Depending on the material of which the cylinder body is made and the material of which the filament is composed, the maximum pressure which the container will be able to withstand, will change.

Table 2 CNG tanks ISO 11439

	Type 1	Type 2	Type 3	Type 4
Steel	450	\	\	\
Fiberglass	\	500	700	730
Aramid fibres	\	470	600	620
Carbon fibres	\	470	470	470

3. Application

The conversion of Liberty Lines' Aquastrada TMV 47 for dual fuel was studied, analyzing the main modifications to be carried out.
In particular, it is a single-hull vessel intended for fast passenger transport, entirely built in aluminum alloy, so as to contain weight and guarantee high performance. **Table 3** shows its main characteristics.
One of the main pieces of information that heavily influenced the outputs of the conversion project is the definition of the route on which the vehicle operates and consequently the autonomy it must withstand.
In **Figure 1**, the route under study is highlighted in red: it is the connection between the city of Milazzo and the island of Stromboli. The ship makes four stops as shown in **Table 4**. The ship then heads towards Stromboli for a total of 56 nautical miles. This route is repeated twice during the day, so the nautical miles considered for the range are approximately 224.

Table 3 Ship characteristics

	Units	Value
Length overall	(m)	46.00
Length at waterline	(m)	37.20
Beam	(m)	7.600
Design draught	(m)	1.200
Displacement	(t)	147.0
Maximum speed	(kn)	36
Service speed	(kn)	34
Engines	(/)	2 MTU 16V396TE74L
Installed power	(kW)	4000

Figure 1. Route study

Table 4 Route analysis

		Travel distance (nm)	Travel time (min)
Start	Milazzo	0	0
1st Stop	Vulcano	20.2	45
2nd Stop	Lipari	23.8	65
3rd Stop	Salina	32.7	100
4th Stop	Panarea	43.7	135
Arrival	Stromboli	56	175

A comparison of the specific energies of diesel and liquefied natural gas was made to calculate the amount of gas to be stored on board. Given the specific energies of the two fuels and taking into account the difference in density between diesel and compressed natural gas (under specific pressure and temperature conditions), a volumetric equivalence factor was derived. This value makes it possible to derive, given the quantity of diesel initially stored, the equivalent volume of compressed natural gas that will need to be loaded on board. **Table 5** resumes the assumptions.

Table 5 Equivalence factor at 15°C and atmospheric pressure

	Specific energy (MJ/kg)	Density (kg/m^3)	Specific energy ratio (/)	Density ratio (/)	Equivalence factor (/)
MDO	48.50	890.0	1	1	1
NG	53.60	212.5	0.905	4.187	3.789

Thus, it can be stated that 1 m^3 of marine diesel stored at 15°C and at atmospheric pressure will be energetically equivalent to 3.8 m^3 of natural gas stored at the same temperature but at a pressure of 250 bar.

4. Results and discussion

There are two storage solutions to choose from, namely natural gas in liquefied and compressed form. The main items on which to base the comparison between the two alternatives are as follows:

- Fuel availability: what most influences this choice is the route the ship will follow and the availability of any bunkering stations along the path. The ship in question operates in an area that is completely uncovered as far as LNG distribution is concerned; the only viable alternative is the construction of a CNG refueling station, to be connected directly to the national methane pipeline network.
- Materials to be used for the construction of the bunkering station and the fuel supply plant: in the event that the ship is propelled with LNG, the storage temperature, -163°C, will make necessary the construction of rooms and structures at risk of spillage with special materials that can withstand the low temperatures and that are not subject to embrittlement if they come into contact with the cryogenic liquid. This would not have to be done in the case of CNG storage.

Analyzing the two considerations above, it can therefore be concluded that the best solution for the ship under analysis is to supply it with CNG.
Noting the daily volume of diesel consumed, equal to 6807 kg, and considering that in gas mode the engine uses only 5% of the total fuel as pilot fuel, the amount of gas to be stored on board was estimated at 27.54 m^3. For this study, a possible location on board for the pressurized tanks following the IGF code was also provided. Possible locations for these tanks are on the main deck, inside the hull under the main deck and in the double bottom.

4.1. Main deck

The area of the upper deck affected by the modifications is the area between frame 2 and frame 6, as shown in **Figure 2**: the tanks have been installed in two parallel rows of six units each. They are close to passenger spaces, so, as required by the regulations, the separation wall must be made with an A60 class subdivision; to obviate this need without having to modify the ship's structures, it was decided to place the pressurized tanks inside a box built with the characteristics in question.

4.2. Lower deck

The lower deck underwent significant changes, including carving out a special room between frame 7 and frame 8 to accommodate four additional tanks. As a result, the last row of seats originally present in frame 8 had to be removed to make space for the tanks (**Figure 3**).

4.3. Double bottom

The ship's double bottom, originally designed for diesel fuel storage, provided ample space for retrofitting 34 pressurized tanks with a 25-inch diameter. The tanks were installed horizontally between the ship's frames, leaving the required minimum distance from the bottom (760 mm). A containment system using cradles welded directly to the ship's frames was implemented to secure the tanks in place (**Figure 4**).

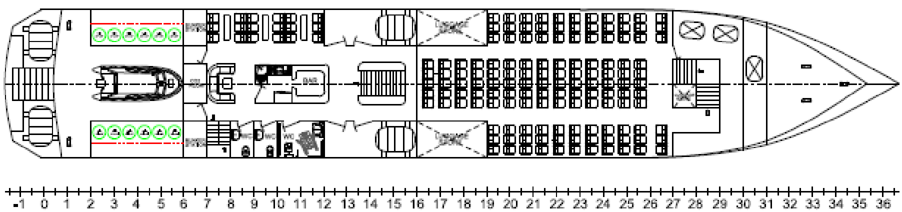

Figure 2. Tanks positioned on the main deck

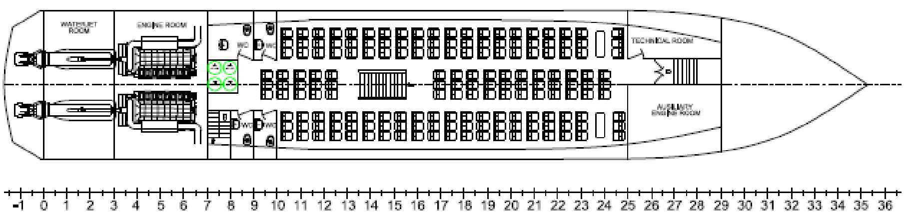

Figure 3. Tanks positioned on the lower deck

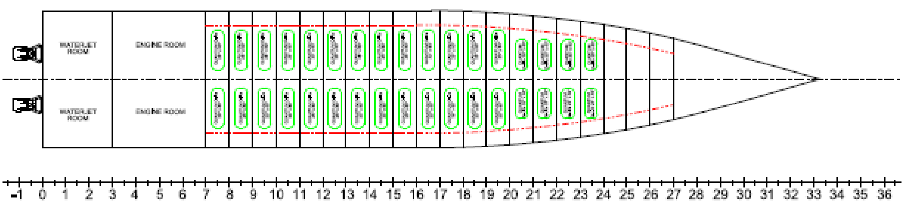

Figure 4. Tanks positioned in the double bottom

5. Conclusion

In conclusion, this article explored the feasibility of retrofitting the propulsion system of a fast ferry to utilize CNG as a fuel alternative to Liquefied Natural Gas LNG and MDO. While LNG has gained popularity in the shipping industry for its low emissions and high energy density, the challenge of accommodating bulky cryogenic tanks on a traditional

fast ferry hindered its widespread adoption. CNG emerges as a promising solution due to its flexible storage options onboard and greater availability in minor ports.
After conducting a thorough review of the advantages and disadvantages of CNG and LNG, along with a critical analysis of the technical requirements for retrofitting a fast ferry with CNG propulsion systems, the study confirmed that CNG retrofitting is technically feasible. The refitted unit exhibited numerous benefits, including reduced emissions, improved performance, and increased reliability compared to LNG.
However, it is crucial to acknowledge that the retrofitting process necessitates significant changes to the ship layout and fuel system to accommodate the required number of CNG cylinders. Despite this challenge, the advantages offered by CNG as a cleaner and more accessible fuel make it a compelling option for the shipping industry's sustainable future.
The successful implementation of CNG retrofitting in the maritime sector could bring about a positive transformation, reducing vessels' environmental impact while maintaining high performance standards. To fully unlock the potential of CNG as an effective and efficient fuel choice, further research and innovation in this area will play a crucial role.

References

[1] S. Bertagna, L. Braidotti, V. Bortuzzo, A. Marinò, e V. Bucci, «A fast feasibility tool for the assessment of fuel switch in the concept design of merchant ships», *Procedia Computer Science*, vol. 217, pp. 1386–1395, 2023, doi: 10.1016/j.procs.2022.12.337.

[2] C. Walsh *et al.*, «Trade and trade-offs: Shipping in changing climates», *Marine Policy*, vol. 106, p. 103537, ago. 2019, doi: 10.1016/j.marpol.2019.103537.

[3] D. Tong *et al.*, «Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target», *Nature*, vol. 572, fasc. 7769, pp. 373–377, ago. 2019, doi: 10.1038/s41586-019-1364-3.

[4] K. Mersin, İ. Bayirhan, e C. Gazioglu, «Review of CO2 emission and reducing methods in maritime transportation», *Therm sci*, vol. 23, fasc. Suppl. 6, pp. 2073–2079, 2019, doi: 10.2298/TSCI190722372M.

[5] I. S. Seddiek e M. M. Elgohary, «Eco-friendly selection of ship emissions reduction strategies with emphasis on SOx and NOx emissions», *International Journal of Naval Architecture and Ocean Engineering*, vol. 6, fasc. 3, pp. 737–748, 2014.

[6] «MEPC.1-Circ.795-Rev.7 - Unified Interpretations To Marpol Annex Vi (Secretariat).pdf».

[7] D. Padolecchia, S. Utzeri, L. Braidotti, e A. Marino, «A Hybrid-Electric Passenger Vessel for Inland Waterway», in *2023 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC)*, Venice, Italy: IEEE, mar. 2023, pp. 1–6. doi: 10.1109/ESARS-ITEC57127.2023.10114841.

[8] K. Cullinane e R. Bergqvist, «Emission control areas and their impact on maritime transport», *Transportation Research Part D: Transport and Environment*, vol. 28, pp. 1–5, 2014.

[9] S. Bertagna, I. Kouznetsov, L. Braidotti, A. Marinò, e V. Bucci, «A Rational Approach to the Ecological Transition in the Cruise Market: Technologies and Design Compromises for the Fuel Switch», *JMSE*, vol. 11, fasc. 1, p. 67, gen. 2023, doi: 10.3390/jmse11010067.

[10] S. Bertagna, V. Bucci, A. Marinò, G. Sulligoi, e A. Vicenzutti, «Impact of Fuel Switch to Methanol on the Design of an all Electric Cruise Ship», in *2023 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC)*, Venice, Italy: IEEE, mar. 2023, pp. 1–6. doi: 10.1109/ESARS-ITEC57127.2023.10114852.

[11] «2022 World LNG Report», International GAS Union, London, lug. 2022.

[12] International Maritime Organization, *IGF Code: international code of safety for ships using gases or other low-flashpoint fuels*, 2016 edition. in IMO publication. London: International Maritime Organization, 2016.

[13] International Maritime Organization, A c. di, *IGC Code: international code for the construction and equipment of ships carrying liquefied gases in bulk*, 2016 edition, Second edition. in IMO publication. London: International Maritime Organization, 2016.

[14] «ISO 11439 - Gas cylinders - High pressure cylinders for the on-board storage of natural gas as a fuel for automotive vehicles». 2013.