Technical University of Varna
Annual Journal
https://doi.org/10.29114/ajtuv.vol7.iss1.293
Vol.7 Issue 1 (2023)
Published: 2023-06-30
ISSN 2603-316X (Online)

Retrofitting measure of an ageing multi-purpose ship exposed to short-sea LNG operation

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Abstract. *The objective of the present study is to analyse the retrofitting measure needed for an ageing multi-purpose ship exposed to a short sea LNG operation in the Black Sea region. Different technical aspects of the retrofitting related to using LNG as fuel for short-sea shipping, including the required volume of the liquefied natural gas, the appropriate type of tanks and the location of tanks on the ship, changes in the main engine and needed additional equipment, are discussed. The cost-benefit feasibility analysis is performed considering the historical and current price of LNG fuel and different taxes related to the generated* CO_2*, examining the Varna-Poti-Varna and Varna-Istanbul-Varna routes.*

Keywords: ship; ageing; short sea shipping; eco-friendly fuel; retrofitting

1 Introduction

Various disruptions marked maritime transport and trade by sea in the past year as they had to adapt to the requirements related to preventing climate change. According to the 2022 Review of Maritime Transport (UNCTAD, 2022), there are six key trends in shipping.

The first one is the energy transition and decarbonisation; only about 6 per cent of funding to reducing greenhouse gas emissions. The second trend for supply chains is shaped by best-cost versus lowest-cost considering national security. This requires a gradual and flexible LNG approach, with cooperation and coordination of diversification, safety stocks, vertical integration, longer-term relationships, additional facilities and suppliers using digital technologies.

The third key trend is the creation of new consumption patterns with the advent of e-commerce. In the last two years, starting from 2019, global e-commerce, as a share of total retail sales, increased 1.4 times (from 15 to 21 %). The last three trends are digitalisation, the new roles of shipping and ports to cope with changes and building resilience.

The international maritime community, represented by the IMO, has been active in reducing shipping emissions for over ten years. The latest measures were adopted at the 79th Marine Environment Protection Committee (MEPC) session in 2022 (ABS, 2022a). Concerning the IMO strategy on GHG emissions, the primary consideration is the revision of the strategy for GHG reduction. The revised plan will include further enhancements to energy efficiency and carbon intensity.

Following the transition of the Mediterranean Sea (Fig. 1) into a SOx Emissions Control Area (ECA), significant progress will be made in reducing emissions and increasing energy efficiency. The vessels operating in this new ECA must use fuel oil of 0.10% m/m sulphur content. The amendments will enter into force on the 1st of May 2024, but ships operating in this ECA will be exempt from compliance during the first 12 months immediately following the amendment's entry into force.

Another significant result at the end of the 2022 year is the agreement of the EU's legislative bodies on including shipping in its Emission Trading System (EU ETS) (DNV, 2023b). Starting in 2024, commercial ships carrying cargo or passengers in the EU with GT over 5,000 GT are expected to obtain and relinquish allowances for their CO_2 emissions. Additionally, offshore ships will be encompassed in this requirement from 2027 onwards.

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Fig. 1. The Mediterranean SOx ECA area (in blue) (MEPC, 2022b)

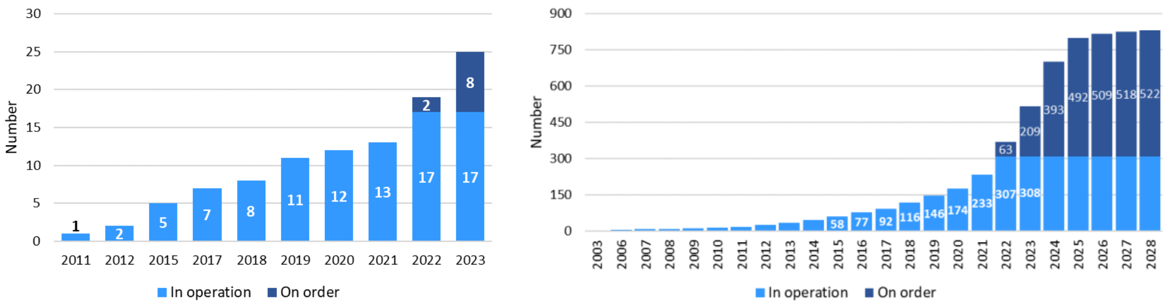

Fig. 2. Retrofitted (left) and new build (right) ships using LNG (DNV, 2022)

Along with introducing new regulatory documents, comprehensive measures to reduce emissions from shipping are underway. Generally, they can be divided into four groups (Xing et al., 2020), i.e. technical and operational measures, environmentally friendly fuels and unconventional power sources.

Although the benefits and drawbacks of alternative fuel implementation are slow, investments in the transition (fossil) fuel LNG have recently increased. In August 2022, the share of the fleet capable of using LNG increased from 2.0 to 2.4 per cent, with deadweight orders rising from 21 to 31 per cent (UNCTAD, 2022). However, almost 40 per cent of the order book (March 2022) was of vessels capable of running on alternative fuels (UNCTAD, 2022). LNG remains the most available alternative fuel in sufficient quantities; therefore, the number of refitted and newly built ships is growing (**Fig. 2**).

The new Emission Control Areas are seriously hampering shipowners engaged in Short Sea Shipping (SSS). The vessels from SSS operate entirely in such areas, and shipowners are forced to use more expensive fuels or make investments to comply with the imposed requirements. Assumptions are made, and analyses are carried out of the cases where ships will bypass these areas and likely travel long distances that will have no abatement effect (Morten, 2018), (Chen et al., 2018).

The issue of short-sea shipping and shipping emissions in the Black Sea is the subject of research as part of a logistics chain of cargo from Asia to Europe and subsequent intermodal land transport (Garbatov & Georgiev, 2022), (Georgiev, 2022).

The present study deals with the technical aspects of retrofitting an ageing multi-purpose ship using LNG as fuel for short-sea shipping in the Black Sea region. It identifies the required liquefied natural gas, the appropriate type of tanks and the location of tanks on the ship, changes in the main engine and needed additional equipment. The economic feasibility and cost-benefit analysis are performed considering the current price trends of LNG fuel, examining the Varna-Poti-Varna and Varna-Istanbul-Varna routes. The study continues the initial work completed by Yalamov et al. (2022), reviewing different solutions as an alternative to fossil fuels for ships, including alternatives for reducing the air pollution generated by sea shipping. The work here presents additional technical detail for the study already presented by Yalamov et al. (2023) and performs a cost-benefit analysis using new data for the price of LNG fuel and different taxes related to the generated CO_2, examining the Varna-Poti-Varna and Varna-Istanbul-Varna routes. The present study shows that in 2021 and 2022, the deficiency in the recovery of

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the initial investment in retrofitting the ageing ships to LNG fuels is relatively high and is more pronounced for the fairest routes and with the fuel prices stabilised in 2023, it demonstrates a relatively lower use of the transportation income in paying the bank obligations for retrofitting.

2 Use of LNG as fuel

The suitability of LNG for use as fuel in short-sea shipping has been demonstrated in several studies for different vessels and conditions for a ferry, OSV (Offshore support vessel) and tug in (Merien-Paul et al., 2017), for Ro-Ro Passenger ferry in (Dimitrellou et al., 2020), for the traffic of HSC catamarans and monohulls, Ro-Pax, RO-RO cargo and tugs in (Di Natale et al., 2022). A study evaluated the effectiveness of cold ironing and LNG as measures to reduce SSS emission (Martínez-López et al., 2021)

The natural approach is to refit existing ships with proven efficiency in line with the specific conditions of the voyage. Fig. 3 shows the number of refitted ships by type for recent years, and the retrofitting orders are set for 2023.

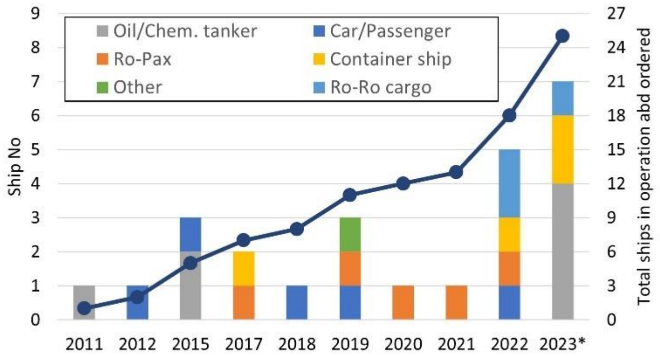

Fig. 3. Type and number of retrofitted ships, elaborated by data from (DNV, 2022), * - Orders for 2023

2.1 Physical properties and composition of LNG

LNG is a form of natural gas transformed into a liquid for storage and transportation, and its volume is about 1/600th that of natural gas. The exact composition of LNG includes methane, ethane, propane, butane, nitrogen and other hydrocarbons that determine its ability to become a liquid at an atmospheric pressure of approximately -162°C (-259°F). The composition's most significant percentage (87% - 99%) is methane (GIIGNL, 2009). The LNG's critical properties include its chemical composition, boiling point, density and specific gravity, flammability, and ignition and flame temperatures.

The boiling point of LNG is (-162) °C, compared with water at 100 °C and Hydrogen (at-252°C). The density of LNG varies slightly between 430 kg/m^3 and 470 kg/m^{3,} and LNG will float if spilt on water.

The gas or vapour concentration range in which LNG can ignite and burn upon introducing an ignition source is called its "flammable range". The limits known as the “Lower Flammable Limit” (LFL) and the “Upper Flammable Limit” (UFL) for Methan, the main constituent of LPG, are 5 and 15%, respectively (GIIGNL, 2009)

The auto-ignition temperature is the lowest temperature at which a gas or vapour in the air (e.g., natural gas) will ignite spontaneously without a spark or flame. The auto-ignition temperature of Natural Gas is 599°C which is higher than the temperature for Diesel Oil (260-371°C) and Gasoline (226-471°C). LNG generates more significant heat upon combustion because its heat of combustion is 50.2 MJ/kg, whereas gasoline's heat of combustion is only 43.4 MJ/kg. Upon combustion, LNG primarily produces carbon dioxide and water vapour.

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2.2 LNG pressure vessels and tanks

One of the essential components of the system for supplying LNG as fuel is the fuel storage system, particularly the LNG tank. Due to the low storage temperatures, the inner shell of tanks is made from nickel steel sheets, austenitic steel, carbon-magnesium steel, aluminium alloys, and other materials resistant to cryogenic temperatures. In the event of a leak, LNG is not allowed to contact the ship's structure under any circumstances because, at cryogenic temperatures, the metal becomes very brittle and cracks or even splitting of the ship's hull can quickly form. The International Code of Safety for Ships defines the tank construction and safety requirements using Gases or other Low-flashpoint Fuels (IGF Code). Containment systems for LNG carriers have been classified as presented in (Tu et al., 2019).

C-type tanks are mainly used to retrofit ships using LNG. A series of tanks are available in different sizes and layouts (Table 1). In principle, the vertical arrangement of LNG storage tanks has the following advantages (ZEC, 2014):

- Stress Distribution: The cylindrical vertical storage tank ensures a uniform pressure distribution by eliminating stress points in horizontal and square tanks.
- Stability: A cylinder tank can be placed directly on a solid, level surface by positioning its base, resulting in a significantly improved stress distribution compared to a tank placed horizontally. In the case of being on board, liquid in the tank will have a less free surface effect.
- Cost Savings for Material and Construction: Tanks are usually constructed to have a greater height than the diameter, which results in thinner walls. This design requires less material for the tank's construction, and only the bottom plate needs to be thicker to support the hydrostatic load than the cylindrical walls.
- Increased Efficiency: The greater the height of a vertical tank, the higher its potential energy, which can be leveraged to lower pumping expenses by relying on gravity.
- Reduction in Footprint: By utilising vertical storage tanks, the area required for storage is significantly reduced, resulting in a smaller overall footprint. This allows for a more considerable amount of workspace to be available, which can be utilised for additional equipment or other purposes.

Table 1. MAN Cryo tank sizes (MAN, 2016)

Type	**Volume,** m^3	**Diameter,** m	**Length, including ColdBox,** m	**Weight,** t
Horizontal	30	3.6	8.8	26
	75	3.6	14.8	40
	115	4.2	14.5	50
	125	3.6	19.9	55
	201	5.3	15.5	80
	234	5.5	16.9	95
	300	5.5	16.9	115
Vertical	86	4.5	8.6 (height)	45
	230	6.4	10.8 (height)	95
	300	6.4	13.5 (height)	115
	400	6.9	16.9 (height)	175

2.3 Location of LNG tanks

Seventeen of all 18 reported retrofitted vessels have Type C LNG tanks installed. The capacity and location of the tanks are presented in

Table 2(DNV, 2022).

On all Ro-Ro passenger ships (except one), the LNG tank is located below the main deck, which is related to the specific general arrangement of these ships. For other cargo ships, the tanks are usually located on the deck in the bow half, i.e., away from the superstructure or behind the superstructure in the aft half. In Fig. 4, the summary of the LNG tank and primary equipment location is presented.

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Table 2. List of retrofitted vessels and location of tanks

No	IMO No	Ship Type	DW, t	Capacity m^3	On deck-Aft	On deck-Middle	On deck-Fwd	Below main deck
1	9286213	Chem/Oil tanker	4447	2 x 155			X	
2	9301873	Chem/Oil tanker	17557	2 x 255			X	
3	9309239	Chemical Tanker	24333	2 x 500			X	
4	9504059	Container ship	13200	2 x 45[1)]			X	
5	9234408	Dredger	13167	2 x 153		X		
6	9159933	Ro-Ro Cargo	5859	2 x 125	X[2)]			
7	9232278	Ro-Ro Cargo	22437	2 x 1100	X			
8	9008794	Ro-Ro Passenger	200	n.a.				X
9	8324622	Ro-Ro Passenger	452	1 x 45				X
10	8601989	Ro-Ro Passenger	524	1 x 53				X
11	9015668	Ro-Ro Passenger	2925	1 x 165				X
12	9030682	Ro-Ro Passenger	2925	1 x 165				X
13	9390367	Ro-Ro Passenger	4370	1 x 360				X
14	9498743	Ro-Ro Passenger	4520	1 x 425				X
15	9441130	Ro-Ro Passenger	5300	2 x 178	X			
16	9261542	Ro-Ro Passenger	7000	1 x 425				X
17	9243423	Ro-Ro Passenger	7500	1 x 425				X

Notes:[1)] - one of the tanks is intended for SNG (Synthetic Natural Gas); [2)] - the tanks are located vertically

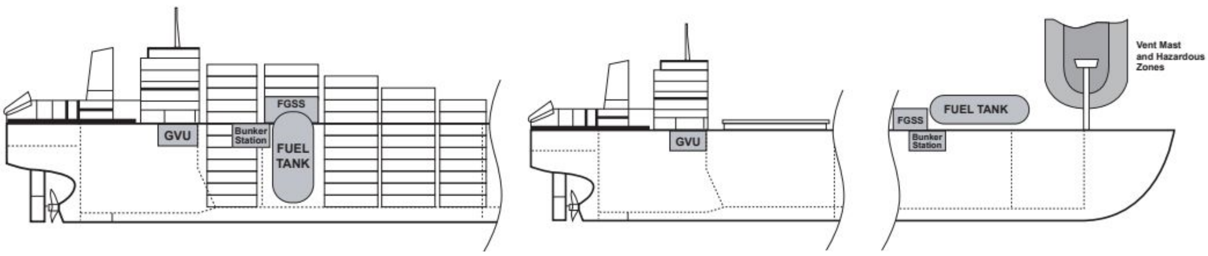

Fig. 4. Typical Examples for the location of LNG tanks and main equipment (ABS, 2022b)

The requirements for LNG tank location are included in the International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code) (MSC, 2015). The boundary of the fuel tank should not be located closer than distance *d* to the shell depending on the 100% of the gross design volume of the individual fuel tank at 20°C, including domes and appendages V_c (see also Fig. 5):

$$
\begin{array}{ll}
V_c \leq 1{,}000 m^3 & d = 0.80\, m \\
1{,}000\, m^3 < V_c < 5{,}000 m^3 & d = 0.75 + \frac{V_c 0.2}{1{,}000}\, m \\
5{,}000\, m^3 \leq V_c < 30{,}000 m^3 & d = 0.80 + \frac{V_c}{25{,}000}\, m \\
30{,}000\, m^3 \leq V_c & d = 2.00\, m
\end{array}
\quad (1)
$$

A study presented in (Ha et al., 2022) highlighted regulatory gaps between LNG carriers and LNG-fuelled ships to be considered.

2.4 Bunkering of LNG

There are 29 European bunkering ports (Yalamov et al., 2022) with three basic methods for bunkering LNG-fuelled ships: Terminal Tank - Vessel; Truck - Vessel; Vessel – Vessel and alternative – Portable Tank transfer as was discussed (ABS, 1996).

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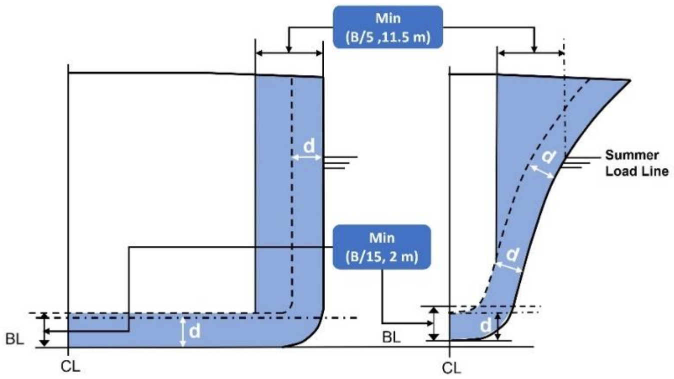

Fig. 5. Limits for tank location (based on (MSC, 2014))

Table 3. FEU ISO tank container for LNG (Taylor-Wharton, 2017)

Item	Value
ISO container Dimensions Lx B x H	12,192 x 2,438 x 2,591 mm
Maximum Loading Volume	39,100 L
Calculated Inner Volume	43,445 L
Maximum Loading Capacity	12,494 kg
Tank Container Gross Weight	30,480 kg
Design temp. of Cryogenic Tank	-196°C
Natural Evaporation Loss	Less than 1%/day

In 2019, the valuation of the worldwide LNG bunkering market stood at $0.38 billion, but it is expected to reach $5.14 billion in 2027 (Saurabh et al., 2021). Vessel - Vessel type bunkering accounted for the largest share of around 60.5% in 2019, and this type is expected to maintain its dominance until 2027.

Portable tanks are ISO tank containers, and they are delivered by truck or train to the port and replace those discharged from the ship, which are taken back for loading. The principal dimensions of the FEU ISO tank container are presented in Table 3. The maximum LNG payload is 90% of the total volume at a 460 kg/m^3 density.

3 Case studies

While most new ships are being built with new technologies for reducing exhaust emissions, ageing ships must be competitively capable. Most deep-sea ships are constructed with a lifespan of 25 years or beyond. To avoid having immobile resources, the shipping industry should take steps to adapt to this transition promptly. For instance, operating costs for fossil fuel-powered ships would rise dramatically as market-based policies to promote zero-emission shipping are implemented. Fossil fuel ship owners can pay to offset their emissions, upgrade their vessels, or retire their ships earlier than planned.

According to (RETROFIT, 2015), retrofitting is "*…the onboard installation ships of state-of-the-art or innovative components or systems and could in principle be driven by the need to meet new regulatory energy and emission standards or by the ship owner interest to upgrade to higher operational standards*."

In choosing a case study, the following circumstances were considered:

- The vessel is suitable for short-distance sea transport and operating in the Black Sea,
- The ship was built in Bulgaria, and the most detailed ship documentation is available, contributing to the analyses' reliability,
- When choosing a ship, look for a dual-fuel engine that is a close alternative to the existing one,
- Consider possible alternatives to account for the lack of bunkering with liquefied natural gas in the Black Sea,
- To analyse the longest route in the Black Sea and the most intensive for the export and import of cargo there.

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Vol.7 Issue 1 (2023)
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3.1 Main particulars of the ship

The study ship is a 9,870 multi-purpose vessel (MPV) constructed at the Bulgarian Shipyard in 2009. The main particulars are presented in Table 4, and a side view of the ship is in Fig. 6.

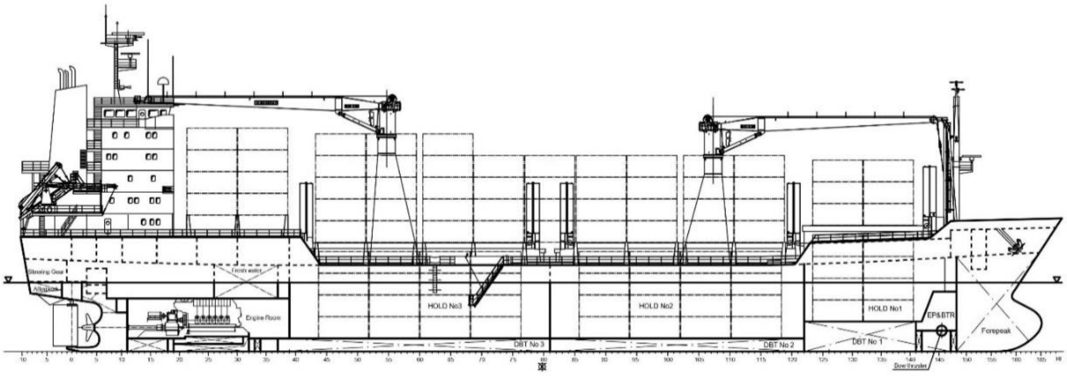

Fig. 6. Side view of the ship for retrofitting (Yalamov et al., 2023)

Table 4. Main ship particulars

Item	Value
Length overall, m	125.89
Length b/w perpendiculars, m	113.75
Breadth, m	20.00
Depth, m	10.40
Draught, m	8.292
Displacement, t	14,114
Deadweight	9,870
Gross tonnage -	7,775
Net tonnage -	3,441
Container capacity, TEU	631
Main engine, type	6M43C MAK-Caterpillar
Power/speed, kW/min^{-1},	5,400/500

The ship is intended to carry various general, dry bulk and heavy cargos, including 40 pcs of refrigerating containers on deck and grain. The navigation area is unrestricted.

3.2 Routes in the Black Sea

The volume of transported cargo through SSS increased in most European countries between 2010 and 2019. Bulgaria has a high percentage of SSS from total sea transport, exceeding 80%, due to the distance from the main sea motorways and the limited water depth in the ports (Georgiev, 2022).

Efforts towards developing transport corridors between Asia and Europe are ongoing. The Central Asia Regional Economic Cooperation (CAREC) Program has laid out a strategic plan for 2030, which serves as a guide. Bulgaria has concluded that the Trans-Caspian International Transport Route, which extends to the Georgian ports of Poti and Batumi, remains significant. Transforming goods through the Black Sea to Bulgarian ports is crucial for the multimodal transport chain.

According to (Zasiadko, 2022), the projection for container transport in the Black Sea in 2022 is for a 10% increase in throughput in Romania and 2.5% for Bulgaria and Georgia. Turkey remains the leader in transport containers, which increased in 2021 compared to 2020 by 6.6% to 9,614,000 TEU (https://ec.europa.eu/eurostat). Considering these trends, the analysis examines the Varna-Poti-Varna and Varna-Istanbul-Varna routes.

3.2.1 Varna-Poti-Varna (V-P-V) route

The distance between the ports of Varna and Poti-Georgia is 617.5 nm. Therefore, the distance Varna-Poti-Varna is 1235 nm. The distance from the Varna quay to the pilot station is 10 nm, and from the pilot station Poti to the Poti quay is 7.5 nm is included in the study at 50% of the Ship Power Plants load and 10 knots speed. Therefore, 35 nm for each passage are with a 50% load and the rest of 1200 NM with a 75% load.

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The ship is assumed to be loaded on each course, making the passage with 75% engine load 4,050 kW and a 14.3 knots average speed where 1200 nm will be carried out at that speed, and the distance will be covered in 84 hours. A period of 30 minutes has been allotted for both stopping and sailing from the ports of Varna and Poti, which will invariably involve the use of either diesel or heavy fuel but will have no impact on the analysis. If the average loading and unloading in the two ports take 21 hours, it can be calculated that the ship will have the following cycle of operation (Table 5) with a total time of 129.5 hours.

Table 5. Descriptors of Varna-Poti-Varna route

Item	Varna Port	Varna Canal	Sail	Port Station	Poti Port	Port – Station	Sail	Varna Canal	Summary		
									To/From ports	Sail	In Ports
Distance, nm	0	10.0	600.0	7.5	0	7.5	600.0	10.0	35.0	1200.0	
Engine Load, %	0	50	75	50	0	50	75	50	50	75	
Speed, kn	0	10	14.3	10.0	0	10.0	14.3	10.0	10.0	14.3	
Time, h	21.0	1.0	42.0	0.75	21.0	0.75	42.0	1.0	3.50	84.0	42.0
Time from the start, h	21.0	22.0	64.0	64.75	85.75	86.5	128.5	129.5		129.5	
									2.7%	64.9%	32.4%

3.2.2 *Varna - Istanbul - Varna (V-I-V) route*

The distance between the ports of Varna and Haidar Pasha - Istanbul is 165 nm and includes 137 nm between the Pilot stations of Varna Port and Istanbul Port. For each cycle, the following additional data are considered: 10 nm from Varna Port to Pilot station Varna at an average speed of 10 kn and 50% engine load; 18 nm from the Pilot station and Port of Haidar Pasha at an average speed of 10 kn and 50% load.

Additionally, 2 hours are provided for crossing the Bosphorus and manoeuvring to moor to the quay in Istanbul since often strong currents can adversely affect the ship's speed. This time is obtained considering 30 minutes for final mooring to the quay, where the ship will run on heavy fuel/diesel oil and 1 hour and 30 minutes in manoeuvring mode at 10 kn speed at 50% load. For Varna port, this time is 1 hour and 30 minutes.

If the average loading and unloading at the port of Istanbul take 10 hours and 20 hours at the port of Varna, the cycles of routes are shown in Table 6.

Table 6. Descriptors of Varna-Istanbul-Varna route

Item	Varna Port	Varna Canal	Sail	Bosphorus	Istanbul Port	Bosphorus	Sail	Varna Canal	Summary		
									To/From ports	Sail	In Ports
Distance, nm	0	10.0	137.0	18.0	0	18.0	137.0	10.0	56.0	274.0	
Engine Load, %	0	50	75	50	0	50	75	50	50	75	
Speed, kn	0	10	14.3	10.0	0	10.0	14.3	10.0	10.0	14.3	
Time, h	21.0	1.0	9.6	1.8	11.0	1.8	9.6	1.0	5.6	19.2	32.0
Time from the start, h	21.0	22.0	31.6	33.4	44.4	46.2	55.8	56.8		56.8	
									9.9%	33.8%	56.3%

The ship is assumed to operate in both routes 24 hours per day, 30 days, i.e., 720 hours per month. Based on this and considering the time per cycle, the remaining voyage parameters are determined and presented in Table 10.

Table 7. Monthly parameters of the routes

Parameter	**V-P-V**	**V-I-V**
Total time per cycle, h	129.5	56.8
Cycles per month,	5.6	12.7
Time at 75% Engine Load ($T_{75\%}$), h	5644.8	2926.1
Time at 50% Engine Load, ($T_{50\%}$), h	235.2	853.4

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4 Modifications

4.1 LNG tank

The necessary amount of LNG is determined by route parameters and the main engine's specific fuel consumption (SFC), given by the manufacturer (Table 8). The gas consumption in g/kWh is calculated by a Lower Calorific Value (LCV) of 49.5 kJ/g. The density of LNG used is 450 kg/m^3.

Table 8. Specific fuel consumption of chosen dual-fuel main engine.

Load, %	Power, kW	Specific fuel consumption		
		Diesel, g/kWh	Gas+Pilot, kJ/kWh	(g/kWh)
100	5.400	186	7.400	149.5
85	4.590	185	7.524	152.0
75	4.050	187	7.457	150.6
70	3.780	188	7.551	152.5
65	3.510	189	7.646	154.5
60	3.240	190	7.740	156.4
50	2.700	192	7.929	160.2
25	1.350	213	9.379	189.5
NOx-Emission, g/kWh		10.3	2.6	

The fuel consumption per cycle of diesel (d) or natural gas (g) $FC^{(d),(g)}$ (t/cycle) is estimated as:

$$FC^{(d),(g)} = T_{\%}.P_e.SFC^{(d),(g)} \tag{2}$$

where $T_{\%}$ is the time at the corresponding percentage of engine load, P_e is the power of the main engine at the corresponding load, $SFC^{(d),(g)}$ is the specific fuel consumption of used fuels or diesel, (g) – LNG at corresponding load, g/kWh. Table 9 presents the data for fuel consumption for one cycle and one year for both routes.

Table 9. Fuel consumption data for routes.

Characteristics	Varna-Poti-Varna	Varna-Istanbul-Varna
Distance per cycle, NM	1235	330
VLSFO consumption per cycle, t	65.4	17.4
Natural gas consumption per cycle, t	52.7	14.1
Natural gas consumption per cycle, m^3	117.1	31.3
VLSFO consumption per month, t	366.2	221.0
Natural gas consumption per month, t	295.1	179.1
VLSFO consumption per year, t	4,394.9	2,651.8
Natural Gas consumption per year, t	3,541.4	2,148.8

Assuming autonomy of 15% (for severe weather), the required amount of LNG per cycle is 135 m^3 based on consumption for longer routes Varna-Poti-Varna. The required amount of LNG is provided by one standard tank (Table 1) and 4 LNG ISO containers (Table 3). The total volume of LNG is 30.0 + 4x39.1 = 186.4 m^3.

The tank with attached TCS is installed in place of 4 TEU on the poop deck (Fig. 7).

The platform is located 4 meters from the stern of the ship and is specifically designed to accommodate ISO containers. This platform has a capacity of 250 tons and can hold up to 4 FEU fully loaded containers. Standard foundations and quick-release fittings secure the containers.

With this arrangement of the main stationary LNG tank, the distance from the tank structure to the ship's side is 7.5 m. The length and width of the metal platform are estimated to be 12.2 m and 4.92 m, respectively, and the loading and unloading of the adjacent rows of containers will not be hindered. 8 TEU reduces the container stowage capacity on the poop deck.

Technical University of Varna
Annual Journal
https://doi.org/10.29114/ajtuv.vol7.iss1.293
Vol.7 Issue 1 (2023)
Published: 2023-06-30
ISSN 2603-316X (Online)

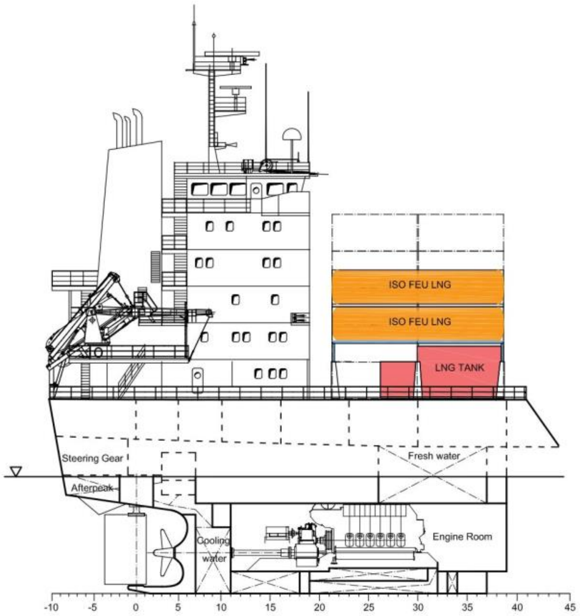

Fig. 7. Positioning of MANcryo LNG tank and LNG ISO containers.

The connection between the portable containers and the main LNG tank is through quick standardised connections that are double-walled with a gas leak detector and a quick disconnect in case of a leak.

All equipment and systems for regular operation and processing of LNG are installed inside the TCS, which in the present case is part of the stationary tank. The TCS serves as a secondary protective layer to prevent any potential leakage of LNG from affecting the ship's hull. It is constructed using stainless steel and is a gas-tight, enclosed system with separate ventilation from other areas. The equipment installed inside the TCS is designed to operate continuously and be controlled remotely, so it is unnecessary to access its interior under normal operating conditions. The main equipment included is the MGE-main gas evaporator, PBE-booster evaporator, glycol cooling system, and valve system.

The Main Evaporator converts the LNG into gas, delivering it to the gas valve block before the engine. In this device, LNG is vaporised and heated to a suitable temperature by the heat provided by a water-glycol mixture. The main evaporator works whenever the engine consumes gas as fuel.

For the operation and consumption of gas from both the stationary and the four portable container tanks, connections will be made between the four containers and the TCS using four pneumatic valves, which will be part of the remote control of the TCS. This way, the operator can turn off or on a randomly selected tank for consumption.

4.2 Main engine modifications

The primary power source of the current vessel is a diesel engine with four-stroke and medium-speed capabilities. This engine cannot be reversed and relies on a gas turbine set to achieve supercharging. It is designed to function using heavy fuel oil with a viscosity of 380 cSt at a temperature of 50°C. The cylinder jackets and covers are cooled with fresh water, and LO cools the pistons. The engine type is 6M43C of Catterpillar-MaK with main parameters: number of cylinders 6; cylinder diameter 430 mm; piston stroke 610 mm; contract maximum continuous rating (CMCR) 5,400 kW and revolutions at CMSR 500 min^{-1}.

A ship with this engine is highly suitable for retrofitting. It is feasible to convert the current M43C engines to the new M46DF engines as they share the exact dimensions and footprint. This conversion can be easily accomplished while retaining crucial components like the engine block, crankshaft, air cooler, and turbocharger, as seen in Fig. 8 and Table 10

Technical University of Varna
Annual Journal
https://doi.org/10.29114/ajtuv.vol7.iss1.293
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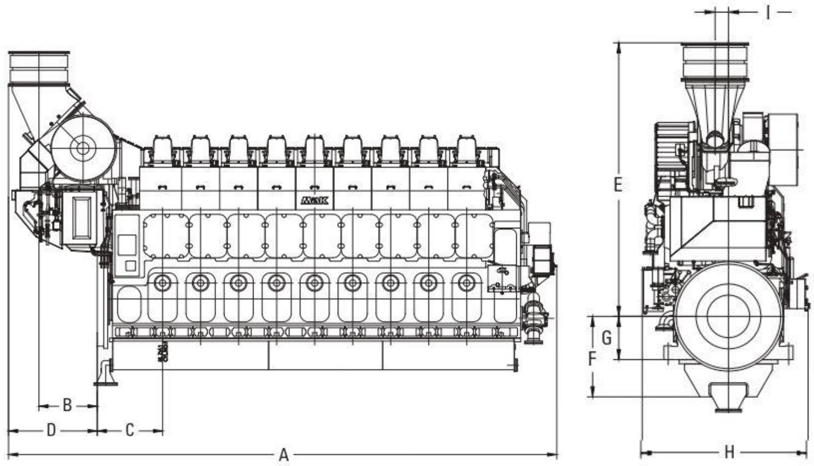

Fig. 8. Scheme and dimensions of M46 DF of MaK Caterpillar (Caterpilar, 2012)

Table 10. Main dimensions of 6M43C and 6M46DF engines

Engine type	Dimension, [mm]									Weight
	A	B	C	D	E	F	G	H	I	[t]
6 M 43 C	8,251	1,086	1,255	1,583	4,258	1,399	750	2,878	215	94
6 M 46 DF	8,271	1,086	1,255	1,638	4,258	1,396	750	2,878	215	94

4.3 Additional equipment

Even though both engines have the same size, there are discrepancies in the auxiliary machinery and devices required for each one. The dual-fuel engine necessitates extra equipment, including a ventilation module, pre-ignition module, GVU - Gas Valve Unit module, glycol-GU module, BS bunker station, and slow engine rotation module. When adding up the weight of this additional equipment, the dual-fuel engine is roughly 4 tonnes heavier, but this extra weight will not impact the engine's performance. These are the only parts that will remain in place, as the rest will be replaced with M46DF components.

The primary focus of engine modification is to enlarge the cylinder bore size from 430 mm to 460 mm. As a result, several components will require replacement, including cylinder liners, cooling water jackets, pistons, cylinder heads, gas fuel lines, and engine electronics. The upgrade will also include temperature monitoring for the significant end bearing and main bearing and timing sensors for the camshaft gear wheel and flywheel to enhance the engine's performance.

4.4 Extra components in engine room

For the engine to run on gas, several components need to be situated near it:

- GVU (Gas Valve Unit). The function of this component is to regulate the pressure of the gaseous fuel directed to the engine and guarantee secure performance via the implementation of dual block and bleed valves and ventilation options. To ensure safety in a gas leak, the gas pipe must have two walls, and the unit must be situated within a maximum distance of 10 meters from the primary engine.
- IFM unit (Ignition Fuel Module). The purpose of this unit is to guarantee that a sufficient amount of filtered fuel oil is supplied to the pilot fuel injection system. The pilot fuel injection system then uses this fuel to ignite the gaseous fuel.
- Vacuum pump unit. The engine's fuel gas line and the portion between the GVU outlet and the engine have a double-wall construction. This setup generates pressure in the double wall barrier to detect leaks. The extracted air is monitored for CH_4 content and then expelled outside.
- Exhaust ventilation module. To avoid the buildup of a combustible mixture in the exhaust pipe, it is necessary to flush the exhaust pipe downstream of the turbocharger in case of an emergency engine shutdown while in gas mode.

Technical University of Varna
Annual Journal
https://doi.org/10.29114/ajtuv.vol7.iss1.293
Vol.7 Issue 1 (2023)
Published: 2023-06-30
ISSN 2603-316X (Online)

- Slow turn the device. As a result of the way the engine is built, there are no indicators or over-pressure valves installed on the cylinder heads. A slow-turn device is affixed to the engine to identify the presence of water on the piston, which rotates it gradually before starting.

These are the major components required to convert the engine from diesel to Dual Fuel mode. Besides this, the ship is to be equipped with gas storage tanks, the master gas valve on deck, transfer pumps suitable for LNG, safety devices according to the IGF codes such as ex-safety zones, double wall gas piping throughout enclosed spaces, inert gas production, storage, and deployment equipment.

5 Environmental norms and regulations

5.1 Energy Efficiency Operational Indicator (EEOI)

The EEOI (MEPC, 2009), which stands for the ratio of the annual fuel consumption to transport work, represents the annual average efficiency of a ship under its actual operating state. It considers actual speeds, draughts, distance covered, capacity utilisation, the impact of hull and machinery degradation, and weather conditions.

The EEOI is computed per journey, with a journey being characterised as the duration starting from departing a port until leaving the following port. EEOI for a voyage is determined, and the average value for a period of several voyages is as follows:

$$EEOI = \frac{\sum_j FC_j \times C_{Fj}}{m_{cargo} \times D} \quad (3)$$

$$Average\ EEOI = \frac{\sum_i \sum_j (FC_{ij} \times C_{Fj})}{\sum_i (m_{cargo,i} \times D_i)} \quad (4)$$

where j is the fuel type, i is the voyage number, FC_{ij} is the mass of consumed fuel j at voyage i, C_{Fj} is the fuel mass to CO_2 mass conversion factor for fuel j (see Table 11), m_{cargo} is cargo carried or work done (number of TEU or passengers), and D is the distance in nm corresponding to the cargo taken or work done. The measurement unit of EEOI is [t CO_2/(t. nm)].

The maximum number of shipping containers (limited by the ship stability) is 168 FEU with a gross weight of 30.4 tonnes and 8 TEU with a gross weight of 24 tonnes. This is equivalent to 344 TEU. It is assumed that 70% of the maximum number of containers are carried in each cycle, or that is 482 container TEU. The EEOI for both routes for one voyage is presented in Table 12.

Table 11. Coefficient for converting fuel mass into mass of CO_2 emissions. (MEPC, 2018a)

Type of fuel	Reference	Carbon content, m/m	CF, t-CO_2/t-Fuel
Diesel / Gas Oil	ISO 8217 Grades DMX through DMC	0.875	3.20600
Light Fuel Oil	ISO 8217 Grades RMA through RMD	0.860	3.15104
Heavy Fuel OIL	ISO 8217 Grades RME through RMK	0.850	3.11400
LPG	Propane	0.819	3.00000
	Butane	0.827	3.03000
LNG		0.750	2.75000

Table 12. EEOI estimates for the routes

Characteristics	Varna-Poti-Varna		Varna-Istanbul-Varna	
Fuel type	VLSFO	LNG	VLSFO	LNG
Consumption per cycle, t	65.4	52.7	17.4	14.1
CF	3.114	2.750	3.114	2.750
Cargo (number TEU)	482		482	
Distance, nm	1235		330	
EEOI	3.42E-04	2.43E-04	3.41E-04	2.44E-04
EEOI reduction using LNG	28.8%		28.4%	

Technical University of Varna
Annual Journal
https://doi.org/10.29114/ajtuv.vol7.iss1.293
Vol.7 Issue 1 (2023)
Published: 2023-06-30
ISSN 2603-316X (Online)

5.2 Attained EEXI

The IMO targets reducing a ship's greenhouse gas emissions by introducing the Energy Efficiency Existing Ship Index (EEXI) (MEPC, 2022a). The EEXI pertains to a ship's technical design, and ships are required to obtain EEXI approval during their lifetime, with the latest periodical survey deadline set for 2023. For ships of a particular size and type, specific requirements must be met:

$$Attained\ EEXI \leqq Required\ EEXI \tag{5}$$

For general cargo ships, the requirement applies to ships with GT > 400 and DWT > 3,000 tonnes. The required EEXI (MEPC, 2018b) is estimated as follows:

$$Required\ EEXI = \left(1 - \frac{Y}{100}\right) \times EEDI\ Reference\ Line \tag{6}$$

where Y is the reduction factor depending on ship type. For general cargo ships, 0 for DWT = 3,000 tonnes and 30 for DWT=15,000 tonnes. For intermediate deadweight values, linear interpolation is used.

The reference value is estimated by:

$$Reference\ line\ value = a \times b^{-c} \tag{7}$$

where for general cargo ships a = 107.48, b is the $DWT$of the ship and c=0.216.

The concept formula for EEXI (ClassNK, 2022) is as follows:

$$EEXI\ [g/t.mile] = \frac{CO2\ Conversion\ factor \times SFC[g/kW.h] \times Engine\ Power\ [kW]}{Capacity\ [ton] \times EEXI\ Speed\ (V_{ref})[knots]} \tag{8}$$

where the CO_2 conversion factor (CF)corresponds to the fuel used when determining SFC, SFC is the fuel consumption at 75% MCR (M/E) and 50% MCR (A/E), the $Engine\ Power$ is 75% of the rated installed power (MCR), the $Capacity$ is the deadweight (for containerships, 70% of the deadweight) and $EEXI\ Speed\ (V_{ref})$ is ship speed at 75% MCR under the draught condition corresponding to the capacity.

The V_{ref}, is determined by the speed-power curve. If this curve is not accessible or the sea trial report lacks information about the EEDI or design load draught condition, an estimated value for the ship's speed, V_{ref}, can be derived using a statistical analysis. This estimated value, referred to as $V_{ref,app}$, is obtained by calculating the mean of the distribution of ship speed and engine power, as defined below (MEPC, 2022a):

$$V_{ref,app} = (V_{rev,avg} - m_V) \times \left[\frac{\sum P_{ME}}{0.75 \times MCR_{avg}}\right]^{1/3} \tag{9}$$

where m_V is the performance margin of a ship, which should be 5% of $V_{ref,avg}$, alternatively, one knot, whichever is lower, $V_{ref,avg}$ is the statistical mean of the distribution of ship speed in a given ship type and ship size, to be calculated as follows:

$$V_{ref,avg} = A \times B^C \tag{10}$$

where A, B and C are parameters defined for the general cargo ship as A = 2.4538, B is the DWT and C=0.18832. MCR_{avg} is the statistical mean of the distribution of MCRs for main engines, to be calculated as follows:

$$MCR_{avg} = D \times E^F \tag{11}$$

where for general cargo ships D = 0.8816, E is the DWT and F= 0.92050.

The numerator of Eqn (8) includes the CO_2 emissions from the operation of the auxiliary engines. The ship has two diesel generators, ZJMD-MAN 6L16/24, P=506 kWe, n=1000 min^{-1} and a shaft generator with P = 640 kW, n=1,500 min^{-1}. The shaft generator provides the power of auxiliary equipment

https://doi.org/10.29114/ajtuv.vol7.iss1.293
Vol.7 Issue 1 (2023)
Published: 2023-06-30
ISSN 2603-316X (Online)

at sea and, therefore, for the estimation of CO_2 emissions SFC_{AE} equal to SFC_{ME} at 50% MCR is accepted.

According to Eqns (9)-(11), the considered ship speed, $V_{ref,app}$ is 14.34 kn. The EEXI using VLSFO is 18.48 g/t.mile, and using LNG is 13.84 g/t.mile. The required EEXI according to Eqns (6)-(7) is 12.21g/t.mile.

Thus, initial calculations show that the required EEXI for a particular ship cannot be achieved solely by switching to LNG as fuel.

5.3 EU ETS Shipping Carbon Tax

The EU Emission Trading System (EU ETS) restricts the release of greenhouse gases by establishing a maximum limit on some regions of the economy. It provides a limited amount of EU Allowances (EUAs) for yearly trading. The goal is to reduce GHG emissions and reach a 55% reduction by 2030 and net zero by 2050. Each EU Allowances permits companies to emit GHG emissions equivalent to one tonne of CO_2 (DNV, 2023a).

The legislative entities of the European Union have come to a consensus regarding the addition of shipping to the EU Emission Trading System (EU ETS). Pending final approval, commercial ships weighing over 5,000 GT that transport passengers or cargo within the EU will need to obtain and use emission allowances for their CO_2 emissions starting in 2024 (DNV, 2023b).

Starting from 2024, ships above 5,000 GT will need to comply with EU regulations on emissions, with a phase-in period of three years increasing in scope from 40% to 70% in 2025 and 100% in 2026 (DNV, 2023a). The EU ETS will initially cover CO_2 emissions and will be expanded to include methane and nitrous oxide from 2026. Smaller ships may also be included in the future. The EU ETS applies to all emissions generated during voyages and port visits within the EU/EEA and half of the emissions produced during voyages to or from the EU/EEA.

6 Cost-benefit analysis

To assess the viability of retrofitting measures, a conventional discounted cash flow methodology is employed, with net present value as the benchmark. This entails calculating the expected future cash inflows minus the initial investment, which must be recouped along with interest and depreciation costs. The cash flow is the difference between the VLSFO and LNG fuel expenditures and associated eco-taxes related to decarbonisation. The capital expenditure of the retrofitting, related to the engine and associated equipment and LNG tank storage, is assumed to be 3,500,000 USD$, and its own capital of 500,000 USD$ is invested as provided in (Yalamov et al., 2023). The required net profitability rate is assumed as 2%, the resting years of ship operation are about 15 years, the depreciation time is eight years, and the time for performing the retrofitting in the dry dock is four months. Additionally, the average annual inflation rate is assumed as 3%, and the income tax rate is 15%, which leads to a capital recovery of 7.78% (Georgiev & Garbatov, 2021). To calculate the cash out-flow $Cash_{outflow}$ various factors are considered, including the taxes associated with CO_2 emissions (Yalamov et al., 2023) as:

$$Cash_{outflow} = V_{sc} LF_{CO2} C_{CO2} (W_{VLSFO} EF_{VLSFO} - W_{LNG} EF_{LNG} + (C_{VLSFO} W_{VLSFO} - C_{LNG} W_{LNG}) \quad (12)$$

where V_{sc} is the voyage scope (50% or 100% depending on if the voyage is in or outside the EU), LF_{CO2} is the load CO_2 factor, C_{CO2} is the taxes for C_{CO2} emissions, W_{VLSFO} weight consumption of VLSFO, EF_{VLSFO} is the emission factor for VLSFO, W_{LNG} is the weight consumption of LNG, EF_{LNG} is the emission factor of LNG, C_{VLSFO} is the price of the VLSFO fuel and C_{LNG} is the price of LNG fuel.

Several years of tax relaxation are introduced at the beginning of the retrofitted ship's service. Once the tax reduction period ends, to recover the invested capital for retrofitting following the net-present value approach, 900,572 USD$ needs annually to be returned to the bank. Depending on the difference in the price of the diesel and LNG fuels, the banking obligations may require a part to be paid by the income from the transportation activities of the ship.

The objective is to define the out-flow of 900,572 USD$ exceedance frequency per year of retrofitting the multi-purpose ship with an investment of 3,500,000 USD$. This out-flow will yield a different

Technical University of Varna
Annual Journal
https://doi.org/10.29114/ajtuv.vol7.iss1.293
Vol.7 Issue 1 (2023)
Published: 2023-06-30
ISSN 2603-316X (Online)

deficiency in a lifetime of 8 years, during which the investment recovery is planned conditional on the economic and banking conditions.

A series of the stock market price of LNG-380e, VLSFO and the cost of CO_2 permits were collected, as can be seen in Fig. 9 and Fig. 10. Each stock market price of LNG, VLSFO and CO_2 permits results in a cash-outflow that is used to analyse the recover the retrofitting investment.

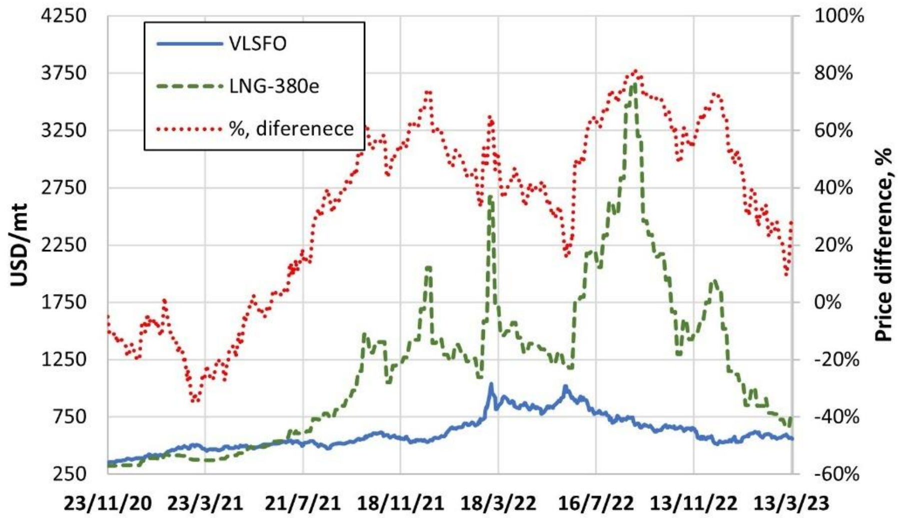

Fig. 9. Historical fuel prices of VLSFO and LNG-380e and percentage increase in price per LNG (right axis) (https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam)

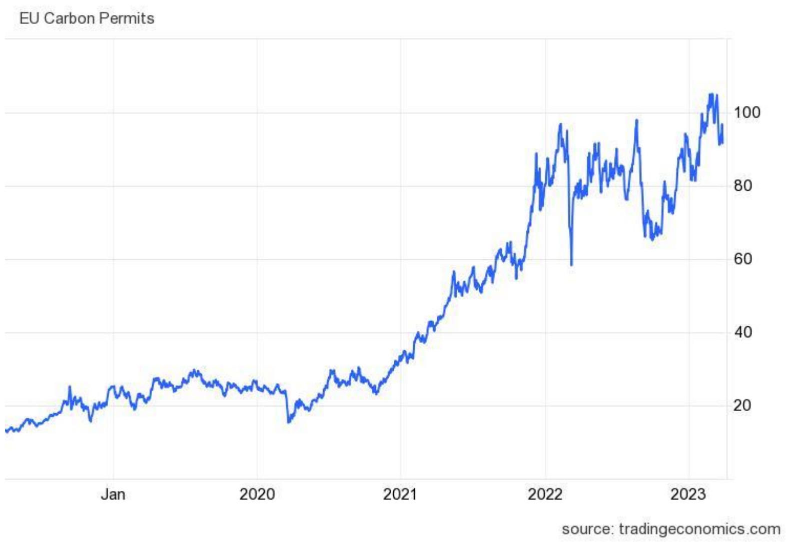

Fig. 10. Historical price of CO_2 permits (https://tradingeconomics.com/commodity/carbon)

https://doi.org/10.29114/ajtuv.vol7.iss1.293
Vol.7 Issue 1 (2023)
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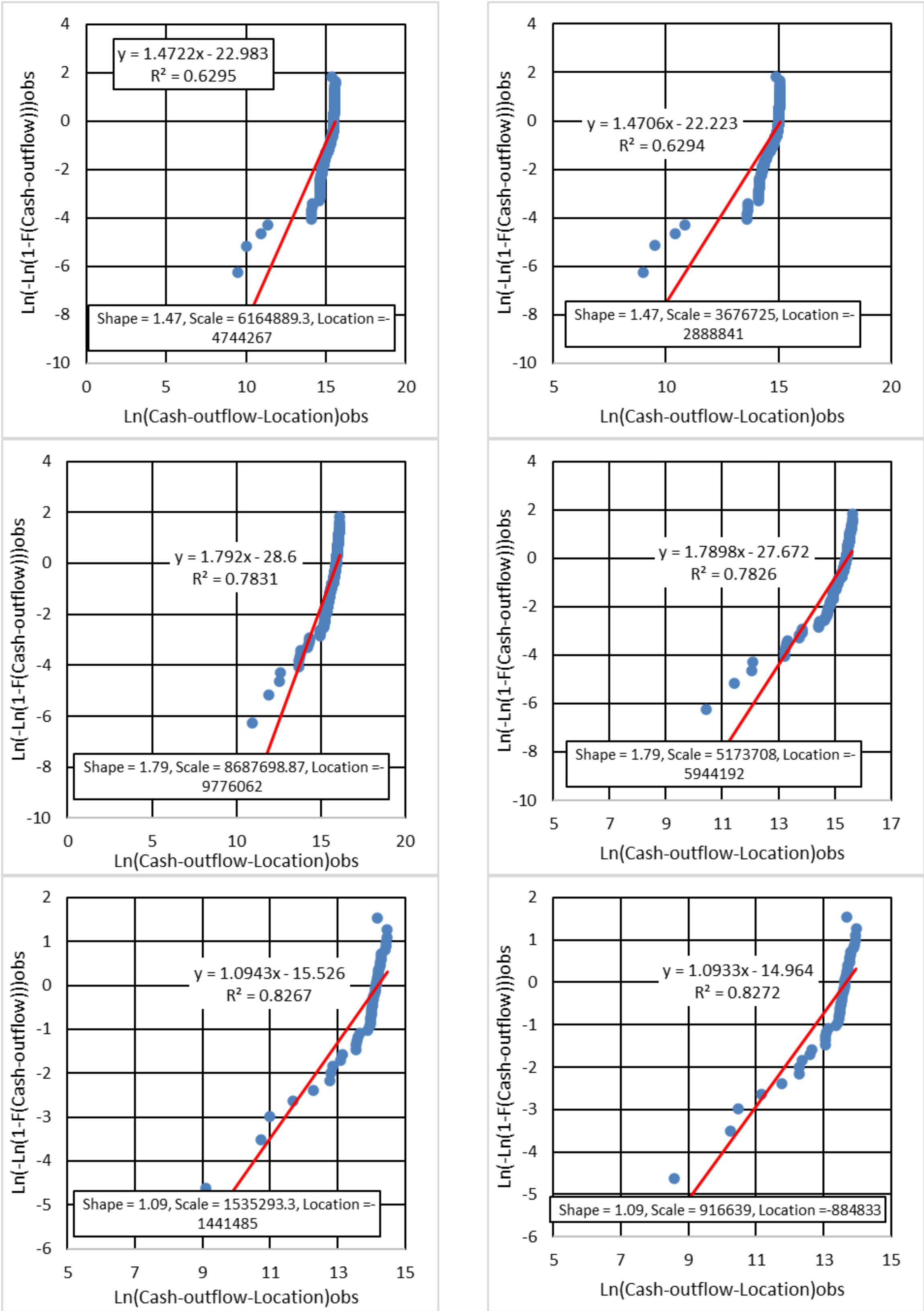


Fig. 11. Weibull descriptors of cash out-flow for Varna-Poti-Varna (left column) and Varna-Istanbul-Varna (right column) for 2021 (top), 2022 (middle) and 2023 (bottom)

Technical University of Varna
Annual Journal
https://doi.org/10.29114/ajtuv.vol7.iss1.293
Vol.7 Issue 1 (2023)
Published: 2023-06-30
ISSN 2603-316X (Online)

Three sets of one-year records for 2021, 2022 and 2023 year are used for the analysis, where the probability of any cash-outflow $C_{out-flow}^{a}$ of being equal to or less than a specific cash-out-flow $C_{out-flow}^{s}$ is defined as:

$$P_r = P_r(C_{out-flow}^{a} \leq C_{out-flow}^{s} \tag{13}$$

and the resulting probability of exceedance Q that $C_{out-flow}^{a}$ is greater than a specific cash-outflow $C_{out-flow}^{s}$ is defined as:

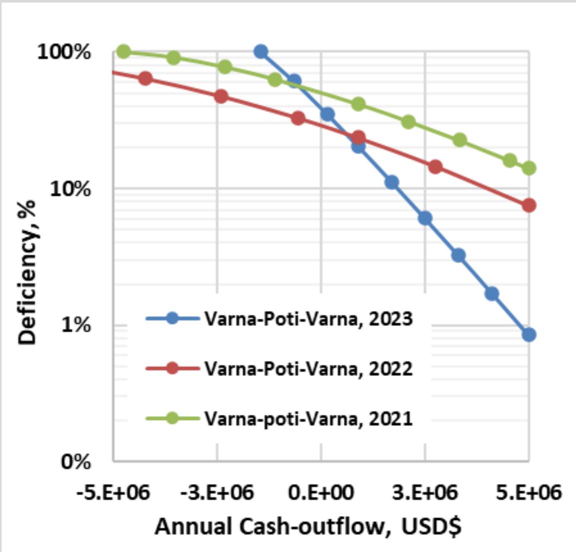
$$Q = Q\left(C_{out-flow}^{a} > C_{out-flow}^{s}\right) = 1 - P_r \tag{14}$$

To model extreme values of annual cash-outflow based on the daily historical fuel prices of VLSFO and LNG-380e (https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam) records, the Weibull distribution is used (Garbatov et al., 2022). The extreme values of the cash out-flow are used to estimate the probability of exceedance of a given $C_{out-flow}^{s}$. Plotting Q in a logarithmic scale, as seen in Fig. 11, the probability of exceedance of any given cash-outflow can be estimated.

By analysing the cash out-flow, different problems can be solved, including defining the minimum cash out-flow needed, conditional on the probability of exceedance for a period to satisfy an acceptable level of benefits due to the retrofitting. Knowing the cash-outflow level, the deficiency in the capital recovery due to retrofitting the propulsion ship system by using the LNG fuel can be estimated as follows:

$$R(T_r) = P_r\left(\left(C_{casj-outflow} \middle| T_r\right) < C_{lower\ limit}\right) \tag{15}$$

where $R(T_r)$ is the deficiency in a percentage for a period T_r, $C_{cash-outflow}$ is the cash out-flow, $C_{Lower\ limit}$ is the lower acceptable limit for recovering the retrofitting investment. The deficiency for 2021, 2022, and 2023 yrs for the route Varna-Poti-Varna and Varna-Istanbul-Varna can be seen in Fig. 12. Given that there is a favourable fuel market conditions, then the deficiency that $C_{out-flow}^{a} = 900{,}572\ USD\$$ can be collected annually can be estimated as presented in Fig. 13.



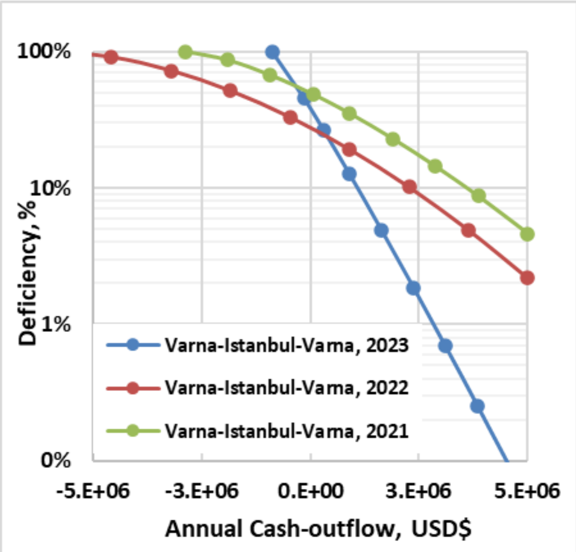


Fig. 12. Deficiency as a function of the annual cash-outflow, Varna-Poti-Varna (left) and Varna-Istanbul-Varna (right)

Technical University of Varna
Annual Journal
https://doi.org/10.29114/ajtuv.vol7.iss1.293
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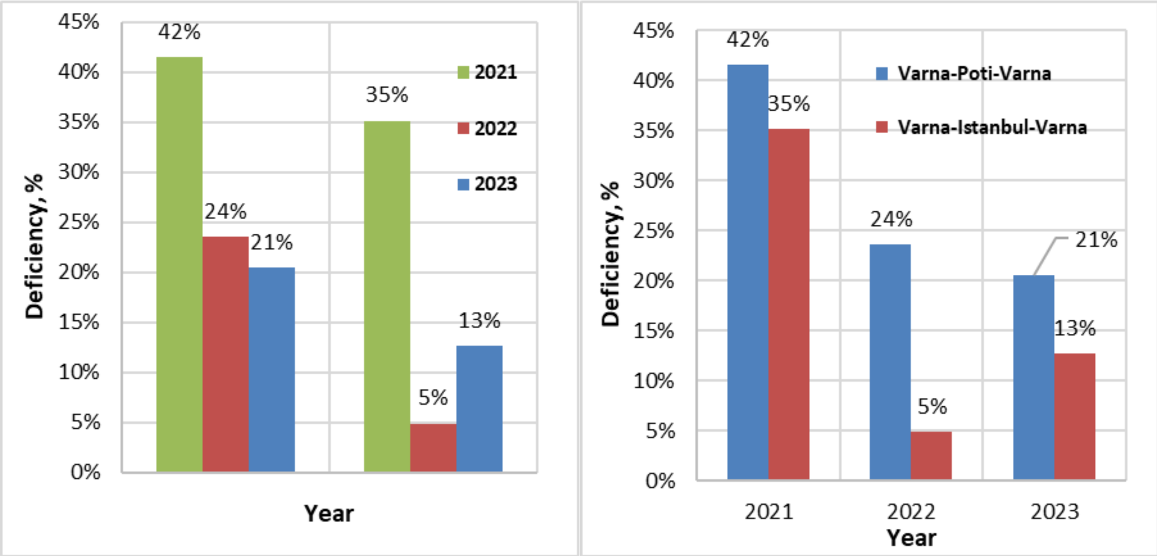

Fig. 13. Deficiency as a function of the routs (left) and years (right), conditional of the cash out-flow of 900,572 USD$

It can be noticed that in the years 2021 and 2022, due to the energy supply crisis, which raised the price of LNG fuel, the deficiency is relatively high and is more pronounced for the fairest route, Varna-Poti-Varna compared to the somewhat shorter way of Varna-Istanbul-Varna. Additional observation can be made that the fuel prices demonstrated a relatively stable level in 2023, which led to more benefits in the recovery of the capital investment due to the retrofitting with relatively lower use of the transportation income in paying the bank obligations.

The difference in the deficiency, risen in the different years and routes, can also be explained by the different portions of time the ships use dual fuel in the arriving and manoeuvring in the destination's ports and associated taxes.

7 Conclusions

The presented study analysed different technical aspects of the retrofitting of a multi-purpose ship for using LNG as fuel for short-sea shipping, including the required volume of the liquefied natural gas, the appropriate type of tanks and location of tanks on the ship, changes in the main engine and needed additional equipment, are discussed. Implementing LNG as fuel reduced the EEOI for the considered voyages reduced the EEXI by 25%. The migration to LNG as fuel is insufficient to reach the required EEXI, and the deficiency; is about 34% for the VLSFO fuel and 10% for the LNG fuel. Additional analyses and measures are needed to reach the required index. The cost-benefit feasibility analysis was performed considering the historical price of the LNG fuel and different taxes related to the generated CO_2, evaluating the Varna-Poti-Varna and Varna-Istanbul-Varna routes. The deficiency in a percentage between the cash out-flow and the lower acceptable limit for recovering the retrofitting investment was defined. The research indicates that during the years 2021 and 2022, there was a significant shortage of LNG fuel caused by an energy supply crisis. This crisis led to a rise in the price of LNG fuel, particularly affecting the fairest route, Varna-Poti-Varna, compared to the slightly shorter way of Varna-Istanbul-Varna. It is worth mentioning that the fuel prices stabilised in 2023, resulting in higher profits for capital investment recovery through retrofitting. This was possible due to relatively lower transportation expenses allocated towards fulfilling bank obligations. It is important to note that the analysis only considered the market data for the first quarter of 2023.

The positive effect of using LNG as a fuel should be assessed by estimating the ship's Carbon Intensity Indicator (CII).

https://doi.org/10.29114/ajtuv.vol7.iss1.293
Vol.7 Issue 1 (2023)
Published: 2023-06-30
ISSN 2603-316X (Online)

Acknowledgements

This work was performed within the Technical University of Varna Research Plan, funded by the State Budget under the contract NP13 for 2022.

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