TRANSNAV
http://www.transnav.eu
the International Journal on Marine Navigation and Safety of Sea Transportation
Volume 19
Number 3
September 2025

DOI: 10.12716/1001.19.03.04

A Technical, Environmental and Economical Comparison Among Traditional and Unconventional Marine Fuels

M. Acanfora[1], M. Altosole[1], F. Balsamo[1], L. Mocerino[1], F. Scamardella[1] & U. Campora[2]
[1] *University of Naples Federico II, Naples, Italy*
[2] *University of Genoa, Genoa, Italy*

ABSTRACT: The study presents a comprehensive comparison among traditional marine fossil fuels and seven alternative unconventional solutions: fossil-based fuels (natural gas (NG) and methanol), biological (HVO, bio-NG, and bio-methanol), and synthetic fuels (NG and methanol). The comparison evaluates technical, economic, and environmental aspects. The case study focuses on the mechanical propulsion system performance of a small luxury passenger ship, simulated by using a mathematical model developed in a Matlab-Simulink environment. In the simulation, the ship's original engines have been replaced with alternative engines of comparable power and RPM, which are compatible with the fuels under consideration. In addition to GHG evaluation, the study uses International Maritime Organization parameters such as the EEXI and the CII to assess the environmental impact of fuels. From an economic perspective, the vessel's propulsion system has been evaluated based on CAPEX and OPEX indices, providing a holistic view of the feasibility and sustainability of each fuel option.

1 INTRODUCTION

In a blue maritime economy perspective [1], to reduce greenhouse gases (GHG), the International Maritime Organization (IMO) has indicated the goal of net-zero emissions by 2050 [2]. In recent years, both researchers and the shipping industry have increasingly explored new fuel types—renewable and low-carbon fossil fuels—as potential energy sources for marine engines, including both propulsion and onboard electricity generation [3]-[14]. Alternative fuels, for drop-in solutions and retrofitting strategies, seem to be an interesting solution for drastically reducing emissions [3]-[25]. These alternative marine fuels are available in two primary physical states under ambient conditions: liquid and gaseous. Liquid alternative fuels include methanol, ethanol, as well as biological and synthetic liquid fuels. The main gaseous alternative fuels are natural gas, propane, hydrogen, ammonia, and biological and synthetic gas fuels [9], [11], [17]. As well known, in marine applications, emissions are categorized into GHG, including Carbon Dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which contribute to global warming, and non-GHG pollutants, such as sulfur oxides (SOx), nitrogen oxides (NOx), and particulate matter (PM), which impact air quality and human health. The IMO MARPOL Annex VI set limits on both types to reduce the environmental footprint of shipping. In this framework of non-GHG pollutants production, SECA (Sulfur Emission Control Areas) and NECA (Nitrogen Emission Control Areas) are designated maritime zones where stricter limits on sulfur oxide (SOx) and nitrogen oxide (NOx) emissions apply, respectively. Established by the IMO under MARPOL Annex VI, these zones currently include regions such as the Baltic Sea, North Sea, North American coast, and the U.S. Caribbean. On the other hand, as part of its strategy to reduce GHG emissions from ships, the IMO has introduced two key regulatory measures: the Energy Efficiency Design Index (EEDI), Energy Efficiency Existing Ship Index (EEXI), and the Carbon Intensity Indicator (CII) [1]-[2]. As part of the mid-term measures to reduce greenhouse gas (GHG) emissions, the International Maritime Organization (IMO) has introduced several mandatory frameworks targeting ship energy efficiency. The Energy Efficiency Design Index (EEDI), implemented in 2013, applies to newly built ships above 400 gross tonnage (GT). It measures energy efficiency at the design stage and aims to reduce CO_2 emissions by promoting improved vessel design. The IMO introduced the Energy Efficiency Existing Ship Index (EEXI) for existing ships in 2021. Like the EEDI, the EEXI targets ships above 400 GT, but focuses on ensuring existing vessels meet a minimum energy efficiency standard. Compliance became mandatory in 2023, and ships may need to undergo modifications or retrofitting to meet the required performance levels. In addition, the Carbon Intensity Indicator (CII) came into force in January 2023. It applies to ships above 5,000 GT and evaluates their operational carbon intensity. Vessels receive annual ratings from A to E indexes, with the system designed to incentivize ongoing improvements in energy efficiency during actual operation [19]. A more detailed description of the calculation methods for both indices will be presented later in the paper. Additionally, the recent FuelEU Maritime Regulation, taking effect from 1 January 2025, sets well-to-wake GHG emission intensity requirements for energy used on board ships over 5,000 GT transporting cargo or passengers for commercial purposes in the EU or European Economic Area (EEA) [20]. The International Maritime Organization (IMO) has, indeed, introduced the concepts of Well-to-Wake (WTW) and Tank-to-Wake (TTW) in its guidelines for assessing GHG emissions across the entire lifecycle of marine fuels. These concepts were formalized in Resolution MEPC.391(81) (2024), adopted during the 81st session of the IMO's Marine Environment Protection Committee (MEPC) [20]. The guidelines cover emissions from WTT, TTW, and WTW for all potential marine fuels and energy sources used onboard ships. For marine applications, WTW is crucial for comparing alternative fuels like LNG, biofuels, ammonia, and hydrogen, as it provides a more holistic view of their sustainability and carbon footprint. The TTW approach only considers the direct emissions from fuel combustion onboard the ship. It does not account for emissions produced during fuel production and transportation. TTW is often used for regulatory compliance, such as IMO regulations, but it does not fully reflect the overall environmental footprint of different fuels. The WTW approach evaluates the entire lifecycle emissions of fuel used in marine applications. This includes Tank-to-Wake and Well-to-Tank, which cover fuel extraction, production, processing, and transportation to the vessel. WTW is the most comprehensive metric for assessing the total environmental impact of fuel, considering both upstream and downstream emissions. In a WTW approach, according to the IMO, the required reduction in GHG intensity is set at 2% by 2025, 6% by 2030, 14.5% by 2035, 31% by 2040, 62% by 2045, and 80% by 2050 [2]. These GHG intensity targets will gradually force ships sailing into EU/EEA ports to shift fuels, including adopting new technologies, to reduce GHG emissions. In the framework of alternative fuels, LNG stands out as the most balanced choice, offering high energy density, well-established technology, and strong safety. Its fuel supply infrastructure is relatively advanced, though its availability as a green fuel remains limited. Methanol also performs well in several aspects, particularly in energy density and technological maturity. However, it does not reach the same level of safety as LNG and faces challenges with fuel supply infrastructure. The biggest limitation for methanol is its low availability in green form, making it less attractive from a sustainability perspective. Demonstration projects have already been in progress since before 2025, and commercial availability is expected to grow steadily into the 2030s. Just for example the Stena Germanica, a 1500-passenger ferry [26], [27], from 2015 is a notable demonstration project in methanol practical use in shipping. In 2018, also the tanker vessel (50000 deadweight tonnage) engine was converted to methanol use as fuel [28]. Ammonia and Hydrogen share similar challenges. Both have moderate energy density and are still developing in terms of technological maturity. Safety concerns are more pronounced for Ammonia, which poses significant risks compared to the other fuels. Additionally, both Ammonia and Hydrogen face major obstacles in fuel supply infrastructure, making widespread adoption difficult. Their availability as green fuels is also quite limited, further restricting their feasibility as sustainable alternatives. For Ammonia, the first demonstration projects for both ICE and fuel cell applications begin around 2025, with commercial applications expected to expand significantly after 2030 [22]. Hydrogen follows a similar pattern, with its first demonstration projects occurring before 2025. However, the timeline for commercial adoption appears to be slightly more extended, indicating potential technological or infrastructure challenges before full-scale implementation [22]. Batteries, as a different form of energy storage, offer advantages in sustainability but struggle in other key areas. Their energy density is much lower than traditional fuels, limiting their suitability for applications requiring long-range power. While battery technology is developing, it is not as mature as other alternatives [29]. Despite being considered a safer option, batteries still face infrastructure challenges. However, their greatest strength lies in their strong potential for green energy use, making them an attractive option for future sustainability. Overall, LNG remains the most viable fuel, balancing efficiency, safety, and infrastructure, while methanol presents a reasonable alternative with some limitations. Ammonia and hydrogen still have significant barriers to overcome, particularly in safety and availability, whereas batteries, despite their green energy potential, currently lack the necessary energy density and infrastructure to be a dominant energy solution. According to DNV [22] the vast majority of the world's fleet still relies on conventional fuel, with only 0.50% of ships in operation using alternatives such as Methanol (0.01%), LNG (0.19%), and Battery technology (0.30%). However, the trend is shifting, for the ships in order category. The percentage of ships relying on conventional fuel decreases to 88.16%, while alternative fuel adoption grows significantly to 11.84%. Within this group, Battery-powered ships account for 3.85%, LNG for 6.10%, and Methanol for 0.30%, with smaller shares for Hydrogen (0.06%) and Ammonia (0.02%) [29], [30]. This suggests an increasing interest in cleaner energy sources, particularly LNG and

Battery technology, as the shipping industry moves toward sustainability. Recently, Hydrotreating Vegetable Oil (HVO), a biological fuel [29], has begun to be used to power fast marine engines [31]. HVO is a renewable diesel produced through the hydroprocessing of vegetable oils or animal fats. Unlike conventional biodiesel FAME (Fatty Acid Methyl Esters), HVO has a chemical structure nearly identical to fossil diesel, which allows it to be used as a drop-in replacement without engine modifications. The use of HVO contributes to lower CO_2 lifecycle emissions, reduced particulate matter, and improved air quality, especially in coastal and port areas. Its compatibility with existing marine diesel engines and infrastructure makes HVO a practical interim solution on the pathway to full maritime decarbonization. In recent studies, the authors have developed thermodynamic simulation models for four-stroke marine engines fuelled by Heavy Fuel Oil (HFO), Natural Gas (NG), and methanol [32],[33]. This paper integrated these engine models into a previously developed simulation model tested on a small luxury passenger ship [34]. Using the three versions of the ship's propulsion model and considering the vessel's actual service route, this study compares three alternative marine fuels (NG, methanol, and HVO) against a conventional marine fuel (HFO). For a comprehensive analysis, NG and methanol are considered in their fossil, bio-based, and synthetic forms [3], [4], [22], [24], [25], [35]-[37] while HVO is assessed as a biofuel [29]. The fuel comparison covers technical aspects (lower heating value, onboard storage requirements, engine efficiency), environmental impact (GHG emissions), and economic factors (specific fuel costs, engine and onboard storage expenses, carbon tax). Beyond the ship's in-service GHG emissions, the study also evaluates the fuel-related environmental impact using the EEXI and CII. Finally, CAPEX (Capital Expenditure) and OPEX (Operational Expenditure) indicators are applied for the economic assessment.

2 FUELS

The fuels considered in this study include conventional, alternative, and renewable options for maritime applications. The reference fossil-based fuel is Ultra Low Sulphur Fuel Oil (ULSFO) [38], which complies with emission regulations by reducing sulfur content. Liquefied natural gas has been analyzed in three forms: fossil-based Liquefied Natural Gas (LNG), bio-derived Liquefied Biological Gas (LBG), and Liquefied Synthetic Methane (LSM), produced using renewable energy. Methanol has been considered in its fossil (Methanol), biological (bio-Methanol), and synthetic (e-Methanol) forms. Additionally, the renewable biofuel, Hydrotreating Vegetable Oil (HVO) [38], [39] has been included as a drop-in alternative since it is compatible with existing marine engines. These fuels are compared in terms of technical feasibility, environmental impact, and economic viability for maritime propulsion. Table 1 presents the main parameters of the considered fuels [38], [39].

Table 1. Fuels main parameters

Fuel parameters	ULSFO	HVO	LNG, LBG, SM	Foss-Meth, bio-Meth, e-Meth
Ambient conditions state	liquid	liquid	gas	liquid
Density [kg/m3]	890	780	0.717	781
Carbon contents [wt%]	86.88	-	75	37.5
Sulphur content [wt%]	0.1	0	0	0
Lower Heating Value (LHV) [kJ/kg]	42700	43700	49000	19600
Stoichiometric air fuel ratio	14.5	14.9	17.5	6.5

3 INPUT AND METHODOLOGY

3.1 *Engine*

To the scope, two four-stroke Rolls-Royce marine Bergen engines have been selected (C25:33L8P with 2665 kW at 1000 rpm and C26:33L9PG with 2430 kW at 1000 rpm); these engines are normally fuelled both with diesel fuel (ULSFO) and LNG [15]. According to the manufacturer, the main design characteristics of the two engines are reported in Table 2.

Table 2. Main data and performance (at MCR) for the selected engines and fuels

Engine parameters	C25:33L8P	C26:33L9PG
fuel type	ULSFO-HVO	NG/simulated METHANOL
cylinders number	8L	9L
bore [mm]	250	260
stroke [mm]	330	330
brake power [kW]	2665	2430
(b.m.e.p.) [bar]	24.7	18.5
speed [rpm]	1000	1000
efficiency [%]	46.3	47.7/46.2
charge air pressure [bar]	4.2	2.8/4.2
charge air temperature [°C]	55÷60	55/56

Authors have already developed and validated the thermodynamics simulator of the Bergen engines fuelled with diesel and NG [32], [33]. The same engine has been fuelled with methanol in simulation environments (see Table 2). The engine's efficiency (E_{eff}), reported in Figure 1 and Table 2, are determined by eq (1):

$$E_{eff} = \frac{P_E}{M_f \, FLHV} \tag{1}$$

where: P_E is the engine-delivered power; M_f and $FLHV$ are the fuel mass flow rate and its lower heating value respectively. In particular, the data in Table 2 shows a very similar diesel and methanol engine efficiency, while that of the NG engine is about 1.5 percent higher. Figure 1 reports the working engine curves versus the ship's speed, in the figure the black curves are pertinent to the propulsion power only, while the blue one considers also the shaft generator's mechanical power. To define this last curve, 10% of sea margin and 15% of the engine margin are considered. According to manufacturer data, Figure 1a and Figure 1b display the efficiency curves for diesel and NG configurations on a power-speed chart. Figure 1c presents the same information for the methanol configuration based on simulation results [32], [33]. The diesel engine simulator maintains almost the same MCR efficiency [32], whether fed with ULSFO or HVO (the difference in MCR engine efficiency is less than 0.1 %); this is due to the very similar characteristics of these two fuels (see Table 1). Based on this consideration, the constant efficiency curves for the diesel engine reported in Figure 1a are considered valid for both fuels. Regarding NG and methanol, the use of fuel from fossil, biological, or synthetic origin does not show any difference in the simulation model and results, as the characteristics of these fuels are the same regardless of their origin (see Table 1).

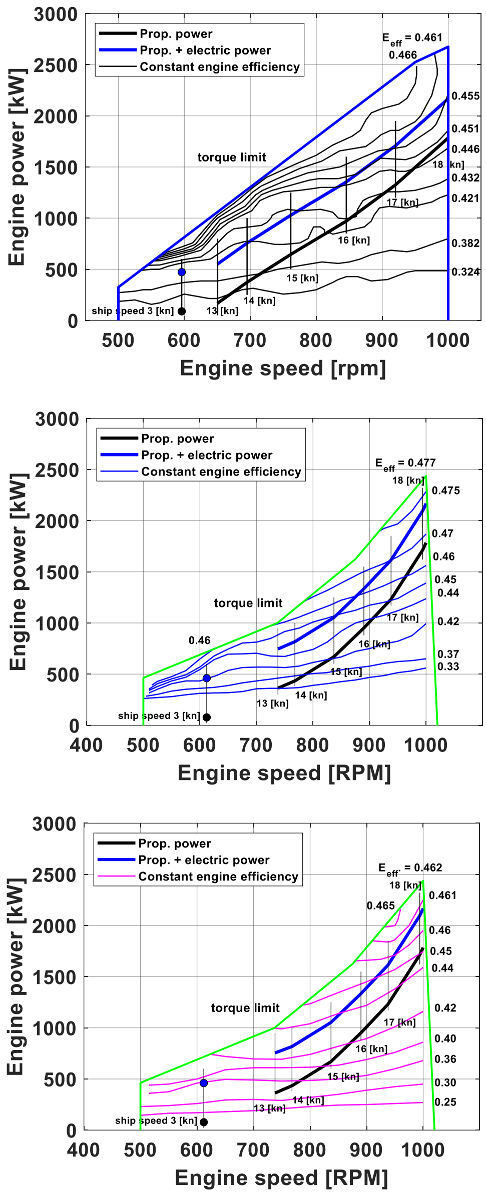


Figure 1. Diesel (a), NG (b), and methanol (c) engines efficiency

3.2 *Engine*

A small cruise ship, called Spirit of Oceanus owned by the Cruise West company, has been chosen as a case study vessel. The main data of the ship and the original propulsion plant are reported in Table 3. According to Figure 2, the vessel's actual nine-day cruise to Alaska starts in Seattle and includes stops at the ports of Ketchikan, Juneau, and Skagway, along with a low-speed cruise through Endicott Arm Fjord, before returning to Seattle. The cruise schedule is reported in Figure 3. A harbor departure and arrival time of 1h is considered, with the vessel operating at an average speed of 3 knots during these segments. Despite the whole route being within an ECA area [40] all the tested fuels can be used as conventional fossil ULSFO has a sulfur content of less than 0.1% while the other tested fuels contain no sulfur. Finally, a total of 30 cruises/ per year are considered. The vessel propulsion plant diagram is shown in Figure 4 [41]; according to this figure, the ship has two shaft lines, each equipped with a four-stroke diesel engine (MAIN-DE) that drives a Controllable Pitch Propeller (CPP) through a reduction gear (G). In the navigation configuration, the vessel's hotel electric load is supplied by a Shaft Electric Generator (SEG), which is directly connected to each engine shaft. The two diesel-electric generators (DE-EG) are used only when the ship is at the harbor. A bow thruster (364 kW electric load) is used for port maneuvers.

Table 3. Case study

Dimensions	Overall length	90.6 m
	Breadth	15.3 m
	Draught	3.9 m
	Gross tonnage (GT)	4200 t
Speed	Maximum speed (design draught)	18.5 kn
Propulsion and electric load	Propulsion diesel engines MCR power	2x2289 kW at 1050 rpm
	Shaft electric generators	2x800 kWe
	Diesel generators	2x1050 kWe
	Hotel electric load	889 kWe
	Manoeuvre electric load	1637 kWe
	Harbors stop electric load	698 kWe
Passenger and crew	Passenger	127
	Crew	85

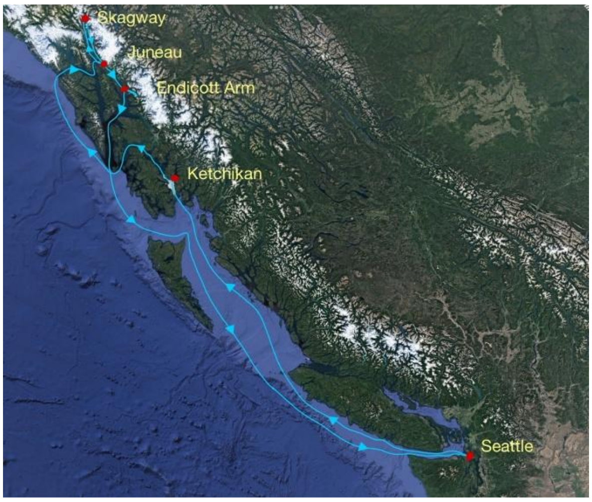


Figure 2. Actual ship route for the Alaska cruise

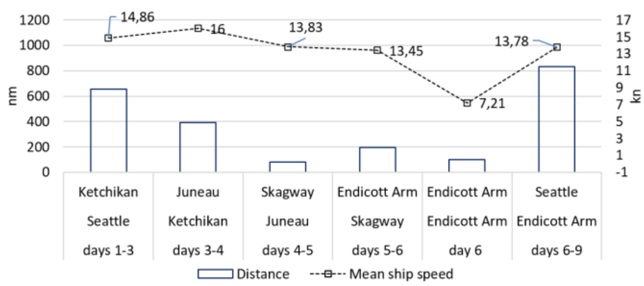


Figure 3. Travel segments for the Alaska cruise

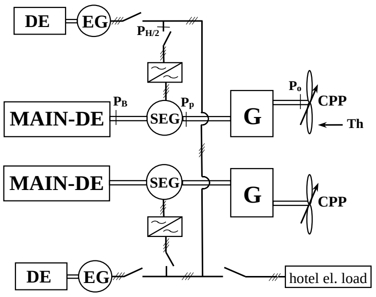


Figure 4. Ship propulsion plant

The original ship propulsion plant MCR engine power and speed (Tab. 3) are similar to those of the Bergen selected engines to fuels comparison (Tab. 2), then, in the propulsion system simulator the two original propulsion engines are replaced with the Bergen engine (in different versions fed with ULSFO or HVO (both diesel fuels), NG or Methanol, depending on the tested fuel). Since the diesel and NG-methanol engine's different torque limit curves (see Figure 1), diverse propeller P/D laws versus shaft speed are considered, see (Figure 5).

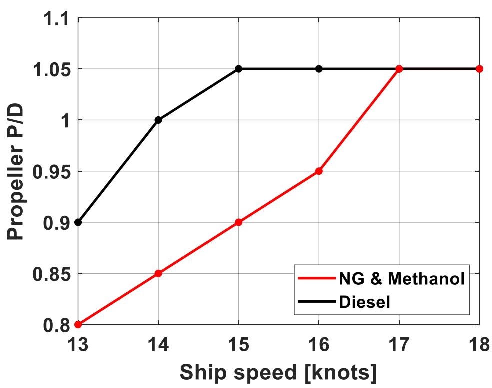


Figure 5. Diesel, NG, and methanol engines propeller P/D laws vs ship speed

For the harbour condition, for the diesel-electric generators engine (DE-EG blocks in Figure 4), in the case of ULSFO or HVO fuels, the four-stoke high-speed MTU 8V 4000 M 63 diesel engine has been adopted (1 MW MCR power at 1800 rpm and 727 kW mechanical power at 1500 rpm [42]) to satisfy the electric load at 50 Hz, with 41% of engine efficiency. In the case of NG fuel, the same electric energy is satisfied by the four-stoke high-speed MTU 8V 4000 GS engine (1.065 MW MCR power at 1500 rpm, 35% of efficiency) [43]. Due to a lack of information, an efficiency of 34% has been assumed for methanol configuration according to the engine data used for NG, with the correct efficiency value based on the data of the Bergen engines reported in Figure 1 (MTU 8V 4000 GS).

4 RESULTS AND COMPARISONS

As declared before, the considered fuels are compared between them from different points of view: technical (engine efficiency, and fuel consumption), GHG emissions (CO_{2eq}, *EEXI*, and *CII index*), and economical (*CAPEX, OPEX, AK*).

4.1 *Technical aspect*

Figure 6 reports the efficiency of the engine versus the ship's speed referred to the propeller plus shaft generator electric power (blue curve in Figure 1). Results show that the diesel and methanol engine efficiency are similar at a certain speed, except for 13 knots, where the methanol engine efficiency is about 1.5% higher than the diesel engine. NG engine is characterized by about 1.5-2.5% greater efficiency compared to the other two engines, for all ship speeds considered. In addition, Figure 7a shows the overall fuel consumption, distinguishing between navigation, maneuvering, and stay in port; overall annual fuel consumption, based on 30 cruises/y, is reported in Figure 7b; the lower HVO consumption, compared to the ULSFO one, is due the ULSFO less lower heating value (see Table 1), referring the HVO one, assuming equal the engine efficiency. Finally, Figure 7b shows the higher methanol consumption, due to its very low LHV compared to the other fuels.

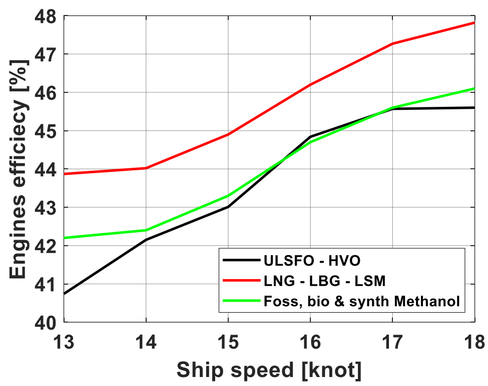


Figure 6. Engine efficiency (propeller and electric load) as a function of ship speed for the different fuels.

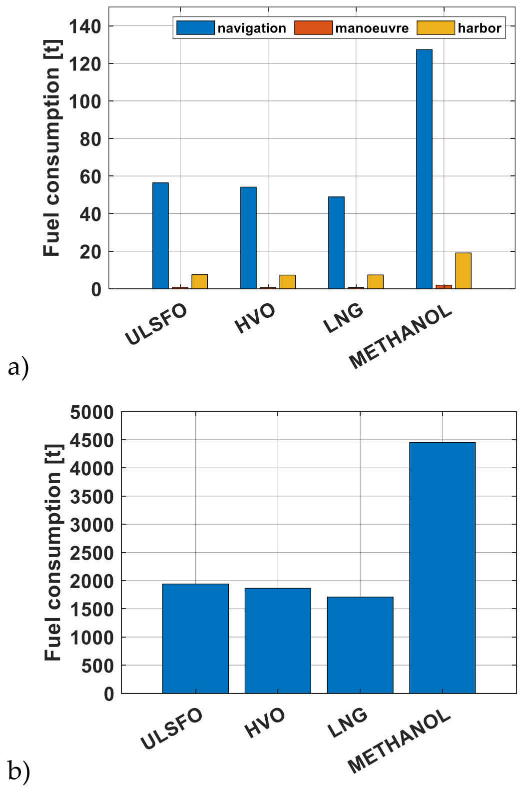


Figure 7. Ship fuel consumption: cruise (a) and annual (b).

4.2 *GHG emissions comparison*

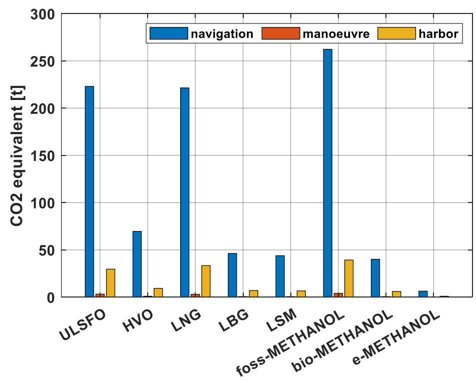
Table 4 reports the fuel Carbon factors (CF) in t_{CO2eq}/t_{fuel} for the considered fuel and Life Cycle Assessment (WTT, TTW, and WTW) [22],[38]. In the same table, for some fuels, are reported also the TTW CF value reported in the IMO report [44].

Table 4. Fuels carbon factors

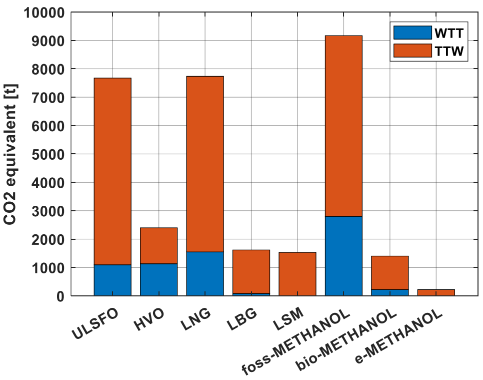
Carbon factors [t_{CO2eq}/t_{fuel}]	ULSFO	HVO	LNG	LBG	LSM	foss-Meth	bio-Meth	e-Meth
WTT	0,564	0.607	0.636	0.049	0	0.630	0.265	0
TTW	3.390 (3.114 IMO)	0.679	3.621 (2.750 IMO)	0.897	0.897	1.430 (1.375 IMO)	0.050	0.050
WTW	3.954	1.286	4.527	0.946	0.897	2.060	0.315	0.050

Based on the carbon factors reported in Table 4 and the fuel consumption data presented in Figure 7, the well-to-wake (WTW) estimated CO_2eq emissions for navigation, maneuvering, and port stays have been calculated (Figure 8a). The results show that fossil fuels (ULSFO, LNG, and fossil methanol) have significantly higher CO_2eq emissions compared to bio-based and synthetic fuels. Among the non-fossil fuels, HVO has the highest emissions, but still shows approximately 75% lower CO_2eq emissions than fossil methanol, and about 66% lower than ULSFO and LNG. Synthetic methanol (e-methanol) has the lowest CO_2eq emissions of all the fuels considered—only 2.4% of the emissions from fossil methanol, which is the most carbon-intensive option.

Figure 8b presents the annual well-to-tank (WTT) and tank-to-wake (TTW) CO_2eq emissions for the various fuels, based on 30 cruises per year. LSM and e-methanol have zero WTT emissions; e-methanol total emissions are much lower than those of LBG and bio-methanol, while are similar to LSM case (refer to the corresponding carbon factors in Table 4).



a



b

Figure 8. Ship CO_{2eq} emissions Cruise (a) and annual (b)

4.3 *EEXI and CII*

According to the IMO regulation, the attained *EEXI* (*$EEXI_{att}$*) value must be lower than the required *EEXI* (*$EEXI_{req}$*), both expressed in $gCO_2/t/nm$. For ships without energy recovery systems the *$EEXI_{att}$* index can be calculated according to the following formula [45]:

$$EEXI_{att}=\frac{\left(f_j\sum P_{ME(i)}\ C_{FME}\ SFC_{ME(i)}\right)+\sum P_{AE(i)}\ C_{FAE}\ SFC_{ME(i)}}{f_c\ Capacity\ V_{ref}} \qquad (2)$$

where: PME and SFC_{ME} are the main engines with 75% MCR power and specific fuel consumption; P_{AE} and SFC_{AE} are the auxiliary engine power and its specific fuel consumption [45]; C_{FME} and C_{FAE} are the main engines and auxiliary engine TTW fuel Carbon factor respectively; Capacity is the ship capacity defined as function of ship type [46] (GT for passenger's vessel); V_{ref} is the vessel speed (at 75% MCR); fj and fc are constant-coefficient set to 1 for passenger ships [45]. The required index ($EEXI_{req}$) can be determined as [46]:

$$EEXI_{req}=\left(1-\frac{y}{100}\right)\cdot\left[170.84\cdot GT^{-0.214}\right] \qquad (3)$$

Both the reduction factor (y=0) and the EEDI reference value (square brackets in the eq. 3), depending on vessel type, can be obtained from an exponential regression based on GT value [46]. In the same way, for the CII calculation customized for passenger's vessels, to meet the CII regulations, the attained values (see eq.4 for CII_{att}) [46]-[49] must be lower than the required one (see eq.5 for CII_{req}):

$$CII_{att}=\frac{CO_2\ \text{annual mass}}{GT\cdot D} \qquad (4)$$

where D is the ship annual distance travelled (nm)

$$CII_{req}=\left(1-\frac{z}{100}\right)\cdot 930\cdot Capacity^{-0.383} \qquad (5)$$

where: z is the reduction factor relative to 2019, its values are: 5% to 2023, 7% to 2024, 9% to 2025, and 11% to 2026.

As a result, Figure 9a shows that for all fuels, the attained $EEXI_{att}$ is always lower than the required $EEXI_{req}$, with a significantly larger margin for HVO, biological and synthetic fuels.

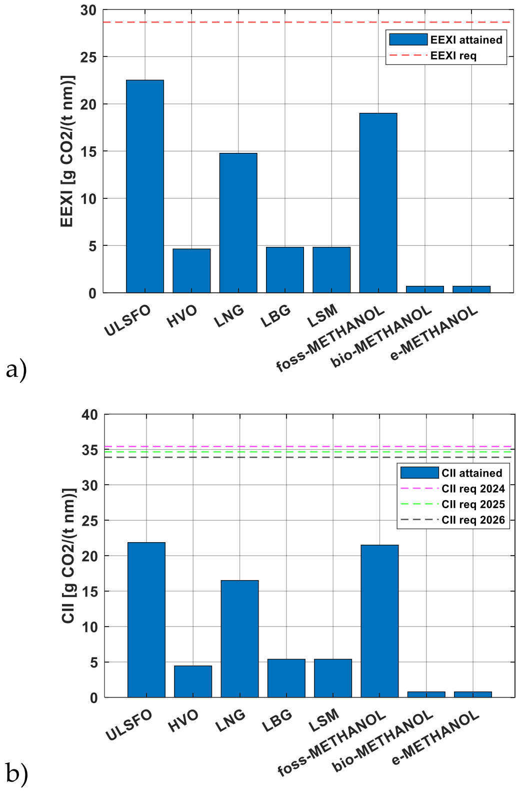


Figure 9. EEXI (a) and CII (b) results

Similar trends can be identified for the CII evaluation. For all fuels, the attained CII_{att} values are lower than the required CII_{req} values, with a much larger margin for HVO, biological and synthetic fuels compared to fossil ones.

4.4 *Economical comparison*

To make the economic comparison between the considered fuels, the ship's Annual Costs (AC) are determined. AC is the sum of Capital Expenditure (CAPEX, see eq. 6) and Operational Expenditure (OPEX, see eq. 7) [50]-[54]

$$CAPEX=IC \cdot R \frac{(1+R)^n}{(1+R)^n -1} \tag{6}$$

where *IC* is the Investment Cost determined based on the specific cost of the propulsion plant's main components (see Table 5) [23], [51], [52]; *R* is the discount rate, set at 12 [53]; *n* is the investment lifetime set at 20 years.

Table 5. The main propulsion plant component's specific costs

Component	Specific cost [USD/kW]
Diesel Internal Combustion Engine (fossil, bio) (2,665-1 MW)	370 - 450
LNG, LBF, LSM ICE (2,43-1 MW)	515 - 630
Methanol ICE (fossil, bio, synth) (2,43-1 MW)	405 - 490
LNG tank and equipment	430
Electric generator – shaft generator	140 - 180
CPP and shaft line	320
AC/AC converter	195

$$OPEX = AFC + ALC + AMC\ (+CTAX) \tag{7}$$

where AFC is the annual fuel cost; ALC and AMC are the annual lubrication oil and maintenance costs, respectively, which are assumed to be equal for all the considered fuels. Consequently, their contribution is not included in the fuel comparison. CTAX represents the carbon tax (if considered). The European Union has included shipping in the Emissions Trading System (ETS) [54], [55] starting in 2025, which involves the payment of a carbon tax based on a vessel's CO_2 emissions. The purpose of this tax is to discourage the use of high-carbon fuels and to reduce CO_2 emissions [56], [57]. For shipping, the carbon tax will come into force in 2025 (the year of entry into the ETS). In the first year, operators will be required to pay for 40% of their emissions. This percentage will rise to 70% in the second year (2026) and to 100% in the third year (2027) [55], [58]. To include the carbon tax in the OPEX calculation, a second economic analysis was carried out, considering the cost of CO_2 emissions. Currently, there are no precise indications regarding the cost per ton of emitted CO_2 (Carbon Tax Price – CTP). Therefore, an average value of 80 USD/t was assumed based on a review of the literature [56]-[62]. The CTAX value was obtained by multiplying the CTP (80 USD/t) by the yearly fuel consumption, as reported in Figure 7b. The specific costs of the fuels considered are reported in Table 6.

Table 6. Fuel-specific cost

Fuel type	ULSFO	HVO	LNG	LBG	LSM	foss-Meth	bio-Meth	e-Meth
Specific cost [USD/t]	637 [63]	640 [64]	706 [39]	1758 [35]	7175 [14]-[65]	488 [66]-[67]	574 [66]	2298 [14]

Starting from the data reported in Tables 5 and 6, the overall propulsion system investment cost (IC) is determined and reported in Table 7, where the ratio relative to the plant cost (using ULSFO as fuel) is also shown.

Table 7. Propulsion plants overall IC

Propulsion plant type	Plant cost [MUSD]	Ratio plant/ref. plant
Diesel ICE (foss, bio) (ref. plant)	4.94	1.00
LNG, LBF, LSM ICE	7.96	1.56
Methanol ICE (foss, bio, synth)	5.03	1.02

Comparisons show that the system employing biological diesel fuel (HVO) has a cost equal to the reference one and that the systems powered by methanol (fossil, biological, and synthetic) have only a small surcharge (2%) compared to the reference plant. On the contrary, the plant using natural gas (NG) (fossil, biological, and synthetic) involves a 56% surcharge; this significant difference is due to increased costs related to the engine and the fuel tank (see Table 5), which, in the case of diesel and methanol fuels, have been neglected (since they are similar to the reference one).

As reported above, a second economic comparison of fuels is carried out, also considering the effects of the carbon tax (although the vessel's route is not in the application area of this tax [56]). Figure 10 shows the difference between the reference fuel (ULSFO) Annual Cost (AC) minus the considered fuel's AC, all multiplied by the ship's service lifetime (n = 20 years).

In the graphs, at t = 0, the starting points of the lines are given by the ULSFO Investment Cost (IC) value minus that of the considered fuel (all IC values are reported in Table 7). As is normally done in this type of analysis, over the 20 years considered, the fuel and system component costs are assumed constant [50], [63].

Figure 10a shows that, compared to ULSFO fuel, HVO entails a saving of 0.9 million USD, and when considering the carbon tax (CTAX), the saving increases to 9.2 million USD.

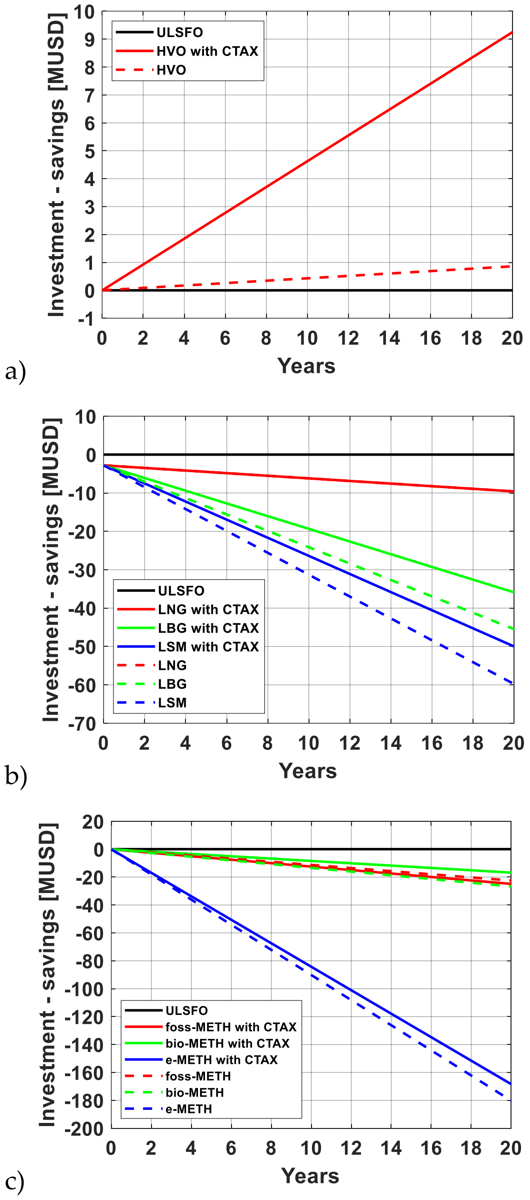


Figure 10. Fuels AC comparison versus reference fuel (ULSFO) with and without the Carbon tax

Due to its higher investment cost (IC), LNG consistently results in greater operating costs compared to ULSFO. Over a 20-year period, the additional cost of LNG amounts to USD 9.6 million, regardless of the carbon tax (CTAX), since the CO_2-equivalent emissions of LNG and ULSFO are nearly identical (see Figure 8b). Bio-NG (LBG, green dotted line in Figure 10b) and e-NG (LSM, blue dotted line) are associated with even higher 20-year costs compared to ULSFO—USD 45.5 million and USD 58.8 million, respectively. When CTAX is considered, these additional costs are reduced to USD 35.9 million for LBG and USD 50.0 million for LSM (solid lines). The fossil methanol (foss-Meth) option (red dotted line in Figure 10c) shows additional costs of USD 22.5 million without CTAX and USD 24.9 million with CTAX (solid red lines), both relative to ULSFO. In this case, the application of CTAX leads to greater economic loss, as fossil methanol produces higher CO_2-equivalent emissions than ULSFO (see Figure 8b). Biological methanol (bio-Meth) (green lines in Figure 10c) involves additional costs of USD 26.7 million without CTAX and USD 16.8 million with CTAX (dotted and solid green lines, respectively). Finally, e-methanol, due to its high specific cost (see Table 6), results in a substantial cost increase of USD 180.2 million over 20 years (blue dotted line in Figure 10c), only slightly mitigated by CTAX, which reduces the cost to USD 168.4 million (solid blue line). As a final observation, Figures 8b and 10 illustrate that fuels with lower CO_2-equivalent emissions than the reference fuel (ULSFO) consistently benefit more economically from the application of CTAX.

5 CONCLUSIONS

In this paper, a comprehensive comparison of eight marine fuels was conducted, evaluating their technical performance, GHG emissions, and economic impact. The analysis was applied to a small cruise ship used as a case study. The comparison between non-conventional fuels and the reference fossil fuel (ULSFO) led to the following key findings:

– The ship powered by traditional fuel (ULSFO), HVO, and methanol (fossil, biological, and synthetic) exhibits very similar engine efficiencies across the entire operating range. In contrast, when fueled with natural gas (NG—fossil, biological, or synthetic), the same engines operating under identical conditions achieve higher efficiency—ranging from 1.5% to 2.5% more.
– In terms of GHG emissions, the ranking of fuels from best to worst is as follows: e-methanol, bio-methanol, LBG, LSM, HVO, ULSFO, LNG, and fossil methanol. LNG's emissions are nearly equivalent to those of ULSFO, while fossil methanol emits approximately 15% more. HVO emissions amount to just 31.2% of those from ULSFO, while e-methanol—by far the best performer—achieves emissions equal to only 2.9% of ULSFO's. These results are largely corroborated by the EEXI and CII index evaluations.
– From an economic standpoint, and excluding the carbon tax (CTAX), the fuels rank from most to least cost-effective as follows: ULSFO, HVO, LNG, fossil methanol, bio-methanol, LBG, LSM, and e-methanol. Among the synthetic fuels—generally the most expensive—LSM shows an annual cost (AC) 2.5 times higher than ULSFO, while e-methanol's cost is 5.74 times higher.

The inclusion of CTAX does not significantly alter the ranking, with the notable exception of HVO: its cost ratio relative to ULSFO improves from 0.97 (without CTAX) to 0.82 (with CTAX) (see also Fig. 9a).

In terms of GHG emissions, e-methanol represents the most environmentally favorable solution, albeit with an annual fuel cost 827% higher than that of

ULSFO (excluding CTAX). HVO, emitting only 31.2% of ULSFO's GHGs and with a fuel cost 3.48% lower (without CTAX), emerges as the best compromise between emissions and economic sustainability. This advantage becomes even more pronounced when CTAX is applied.

ACKNOWLEDGMENTS

This research was developed within the “CN-MOST – Spoke 3 (Waterways)” research activity, funded under the National Recovery and Resilience Plan (NRRP) of the Italian Ministry of University and Research (MUR); funded by the European Union – NextGenerationEU. The authors wish to gratefully acknowledge the Rolls-Royce England technical office and engineer Andrea Cerutti of Rolls-Royce Italy for the received support.

REFERENCES

[1] H. N. Psaraftis and C. A. Kontovas, “Decarbonization of maritime transport: Is there light at the end of the tunnel? ” Sustainability, vol. 13, no. 1, p. 237, 2020.
[2] T. H. Joung, S. G. Kang, J. K. Lee, and J. Ahn, “The IMO initial strategy for reducing Greenhouse Gas (GHG) emissions, and its follow-up actions towards 2050,” Journal of International Maritime Safety, Environmental Affairs, and Shipping, vol. 4, no. 1, pp. 1-7, 2020.
[3] S. Brynolf, E. Fridell, and K. Andersson, “Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol,” Journal of Cleaner Production, vol. 74, pp. 86-95, 2014
[4] Z. Wang, T. Paulauskiene, J. Uebe, and M. Bucas, “Characterization of biomethanol–biodiesel–diesel blends as alternative fuel for marine applications,” Journal of Marine Science and Engineering, vol. 8, no. 9, p. 730, 2020.
[5] N. R. Ammar, “An environmental and economic analysis of methanol fuel for a cellular container ship,” Transportation Research Part D: Transport and Environment, vol. 69, pp. 66-76, 2019.
[6] A. G. Elkafas and M. R. Shouman, “Assessment of Technical and Environmental Performance of Marine Alternative fuels for Container Ships,” Arab Academy for Science Technology and Maritime Transport College of Maritime Transport and Technology, 2021. Available: https://doi.org/10.21203/rs.3.rs-745573/v1.
[7] D. Delneri, “Combustion system optimization for alternative fuels,” in 17th Conference The Working Process of the Internal Combustion Engine, 2019.
[8] MAN, The Methanol-fuelled MAN B&W LGIM Engine, MAN Energy Solutions, 2021.
[9] MAN, MAN B&W S50ME-C9.6-LGIM Project Guide Electronically Controlled Dual Fuel Two-stroke Engines, Jan. 2022.
[10] Wartsila, Wartsila 32 Methanol, Wartsila report, 2021.
[11] G. Benvenuto, U. Campora, M. Altosole, and F. Balsamo, “Numerical modelling and analysis of the ambient conditions influence on the performance of a marine diesel engine,” in Maritime Technology and Engineering 5 Volume 2, CRC Press, pp. 463-474, 2021.
[12] R. Verbeek, P. T. Hart, J. F. J. Pruyn, and J. Bergsma, “Assessment of alternative fuels for seagoing vessels using heavy fuel oil,” 2020.
[13] M. Altosole, U. Campora, L. Mocerino, and A. Scamardella, “Comparison between high-efficiency propulsion systems in electric ship applications,” in 2022 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), June 2022, pp. 634–639, IEEE.
[14] E. Lindstad, B. Lagemann, A. Rialland, G. M. Gamlem, and A. Valland, “Reduction of maritime GHG emissions and the potential role of E-fuels,” Transportation Research Part D: Transport and Environment, vol. 101, p. 103075, 2021.
[15] A. G. Elkafas, M. Khalil, M. R. Shouman, and M. M. Elgohary, “Environmental protection and energy efficiency improvement by using natural gas fuel in maritime transportation,” Environmental Science and Pollution Research, vol. 28, no. 43, pp. 60585-60596, 2021.
[16] O. V. Nilsen, “LNG Regulatory Update ‘Best Fuel of the Future’,” Internationalisation Conference on LNG Project & the Baltic Sea Region LNG Cluster, Bergen, 10-12 April 2018. Available: http://www.golng.eu/files/Main/20180417/2.%20Ole%20Vidar%20Nilsen%20-0DNV%20GL.pdf.
[17] Rolls-Royce, Diesel and Gas Engines Generator Set and Propulsion Systems, Report, 2012.
[18] MAN, 51/60 DF IMO TIER II / IMO TIER III, project guide – Marine, 2015.
[19] https://www.imo.org/en/MediaCentre/HotTopics/Pages/EEXI-CII-FAQ.aspx
[20] https://transport.ec.europa.eu/transport-modes/maritime/decarbonising-maritime-transport-fueleu-maritime_enwwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.391(81).pdf
[21] Wartsila, 50 DF project guide, 2016.
[22] DNV, Use of Methanol as fuel, DNV-GL. Methanol as marine fuel: Environmental benefits, technology readiness, and economic feasibility, Report no. 2015-1997, Rev. 2, Jan. 20, 2016.
[23] D. Nelissen, A. Kleijn, and J. Faber, FuelEU Maritime and EU ETS Sound incentives for the fuel choice?, Delft, CE Delft, Feb. 2022. Available: www.cedelft.eu.
[24] Y. Wang and L. A. Wright, “A comparative review of alternative fuels for the maritime sector: Economic, technology, and policy challenges for clean energy implementation,” World, vol. 2, no. 4, pp. 456-481, 2021.
[25] G. Zang et al., “Synthetic methanol/Fischer–Tropsch fuel production capacity, cost, and carbon intensity utilizing CO2 from industrial and power plants in the United States,” Environmental Science & Technology, vol. 55, no. 11, pp. 7595-7604, 2021.
[26] Stena Line Scandinavia AB, “Stena Germanica’s methanol conversion,” 2018. Available: https://www.stenalinefreight.com/news/Methanol-project.
[27] S. Verhelst, J. W. Turner, L. Sileghem, and J. Vancoillie, “Methanol as a fuel for internal combustion engines,” Progress in Energy and Combustion Science, vol. 70, pp. 43-88, 2019.
[28] FCBI Energy, Methanol as a Marine Fuel, Report, Oct. 2015.
[29] https://www.dnv.com/maritime/publications/alternative-fuels-for-containerships-methanol-and-ammonia-download/
[30] Waterfront Shipping Company Limited, “Methanol-fueled vessels mark one year of safe, reliable, and efficient operations,” 2018. Available: https://www.wfs-cl.com/news/2017/04/methanol-fueled-vessels-mark-one-year-safe-reliable-and-efficient-operations.
[31] H. Aatola, M. Larmi, T. Sarjovaara, and S. Mikkonen, “Hydrotreated vegetable oil (HVO) as a renewable diesel fuel: trade-off between NO_x, particulate emission, and fuel consumption of a heavy duty engine,” SAE International Journal of Engines, vol. 1, no. 1, pp. 1251-1262, 2009.
[32] Marine Biofuels, what to expect in the 2020s, Alfalaval, 2020.
[33] M. Altosole, G. Benvenuto, U. Campora, M. Laviola, and R. Zaccone, “Simulation and performance comparison between diesel and natural gas engines for marine applications,” Proceedings of the Institution of

Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, vol. 231, no. 2, pp. 690-704, 2017.
[34] M. Acanfora, M. Altosole, F. Balsamo, U. Campora, and F. Scamardella, "A Methanol Fueled Marine Engine Simulator for Fast Craft Applications," in HSMV 2023, pp. 117-125, IOS Press, 2023.
[35] T. P. Zis, H. N. Psaraftis, F. Tillig, and J. W. Ringsberg, "Decarbonizing maritime transport: A Ro-Pax case study," Research in Transportation Business & Management, vol. 37, p. 100565, 2020.
[36] D. Nelissen, "Availability and costs of liquefied bio-and synthetic methane," 2020.
[37] Y. Wang and L. A. Wright, "A comparative review of alternative fuels for the maritime sector: Economic, technology, and policy challenges for clean energy implementation," World, vol. 2, no. 4, pp. 456-481, 2021.
[38] International Maritime Organization (IMO), Train the Trainer (TTT) Course on Energy Efficient Ship Operation (EEDI and EEOI), Module 2 – Ship Energy Efficiency Regulations and Related Guidelines, London, Jan. 2016.
[39] R. Laursen et al., "Update on potential of biofuels for shipping," American Bureau of Shipping, CE Delft and Arcsilea, 2022.
[40] IMO, Emission Control Areas (ECAs) designated under regulation 13 of MARPOL Annex VI (NOx emission control), [Online]. Available: https://www.imo.org/en/OurWork/Environment/Pages/Emission-Control-Areas-(ECAs)-designated-under-regulation-13-of-MARPOL-Annex-VI-(NOx-emission-control).aspx.
[41] G. Benvenuto, U. Campora, M. Altosole, and F. Balsamo, "Numerical modelling and analysis of the ambient conditions influence on the performance of a marine diesel engine," in Maritime Technology and Engineering 5 Volume 2, CRC Press, pp. 463-474, 2021.
[42] MTU, 8V 4000 M 63 project guide, confidential report, 2022.
[43] MTU, 8V 4000 GS project guide, confidential report, 2023.
[44] V. M. Domínguez, J. J. Hernández, Á. Ramos, B. Giménez, and J. Rodríguez-Fernández, "Exploring the effect of methanol and ethanol on the overall performance and substitution window of a dual-fuel compression-ignition engine fueled with HVO," Fuel, vol. 359, p. 130529, 2024.
[45] International Maritime Organization (IMO), Resolution MEPC.333/76, 2021 Guidelines on the Method of Calculation of the Attained Energy Efficiency Existing Ship Index (EEXI), London, June 17, 2021.
[46] Maritime Organization (IMO), Resolution MEPC.328/76, 2021 Amendments to the Annex of Protocol of 1997 of Amend the International Convention for the Prevention of Pollution from Ships, 1973, as Modified by the Protocol of 1978 Relating Thereto, 2021 Revised MARPOL Annex IV, MEPC 76/15/Add. 1, 2021.
[47] International Maritime Organization (IMO), Resolution MEPC.336/76, 2021 Guidelines on Operational Carbon Intensity Indicators and the Calculation Methods (CII Guidelines, G1), June 17, 2021.
[48] International Maritime Organization (IMO), Interim Guidance on the Use of Biofuels Under Regulations 26, 27 And 28 of MARPOL annex VI (DCS and CII), MEPC.1/Circ.905, London, UK, July 24, 2023.
[49] International Maritime Organization (IMO), Resolution MEPC.337/76, 2021 Guidelines on the Reference Lines for Use of Operational Carbon Intensity Indicators (CII Reference Lines Guidelines, G2), June 17, 2021.
[50] International Maritime Organization (IMO), Resolution MEPC.336/76, 2021 Guidelines on Operational Carbon Intensity Reduction Factors relative to reference Lines (CII Reduction Factors Guidelines, G3), June 17, 2021.
[51] O. E. Karaçay and O. A. Özsoysal, "Techno-economic investigation of alternative propulsion systems for tugboats," Energy Conversion and Management: X, vol. 12, p. 100140, 2021.
[52] G. A. Livanos, G. Theotokatos, and D. N. Pagonis, "Techno-economic investigation of alternative propulsion plants for Ferries and RoRo ships," Energy Conversion and Management, vol. 79, pp. 640–651, 2014.
[53] G. Theotokatos, A. Rentizelas, C. Guan, and I. Ancic, "Waste heat recovery steam systems techno-economic and environmental investigation for ocean-going vessels considering actual operating profiles," Journal of Cleaner Production, vol. 267, p. 121837, 2020.
[54] A. Dotto, U. Campora, and F. Satta, "Feasibility study of an integrated COGES-DF engine power plant in LNG propulsion for a cruise-ferry," Energy Conversion and Management, vol. 245, p. 114602, 2021.
[55] European Commission, EU Emissions Trading System (EU ETS), 2005. Available: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/what-eu-ets_en.
[56] DNV, EU ETS – Emissions Trading System, Available: https://www.dnv.com/maritime/insights/topics/eu-emissions-trading-system.
[57] F. M. J. Venmans, "The effect of allocation above emissions and price uncertainty on abatement investments under the EU ETS," Journal of Cleaner Production, vol. 126, pp. 595-606, 2016.
[58] T. Jong, O. Couwenberg, and E. Woerdman, "Does EU emissions trading bite? An event study," Energy Policy, vol. 69, pp. 510-519, 2014.
[59] International Transport Forum (ITF), "Carbon Pricing in Shipping," International Transport Forum Policy Papers, No. 110, OECD Publishing, Paris, 2022.
[60] Climate Leadership Council, Carbon Pricing in the Shipping Industry, [Online]. Available: https://clcouncil.org.
[61] China Dialogue, "EU carbon tax puts a price on shipping emissions," [Online]. Available: https://chinadialogue.net/en/transport/eu-carbon-tax-puts-a-price-on-shipping-emissions/.
[62] H. Wang, M. Z. Aung, X. Xu, and E. Boulougouris, "Life cycle analysis of hydrogen powered marine vessels—case ship comparison study with conventional power system," Sustainability, vol. 15, no. 17, p. 12946, 2023.
[63] US Gulf Coast Ultra-Low Sulfur No 2 Diesel Spot Price, ycharts.com.
[64] E. Van Thuijl, C. J. Roos, and L. W. M. Beurskens, "An overview of biofuel technologies, markets and policies in Europe," Energy research Centre of the Netherlands, ECN Policy Studies Report No. ECN-C--03-008, 2003.
[65] S&P Global, [Online]. Available: https://www.spglobal.com.
[66] Y. Wang and L. A. Wright, "A comparative review of alternative fuels for the maritime sector: Economic, technology, and policy challenges for clean energy implementation," World, vol. 2, no. 4, pp. 456-481, 2021.
[67] Methanex, [Online]. Available: https://www.methanex.com.