

REDUCTION OF CO₂ EMISSIONS FROM OFFSHORE COMBINED CYCLE DIESEL ENGINE-STEAM TURBINE POWER PLANT POWERED BY ALTERNATIVE FUELS

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ABSTRACT

Diverse forms of environmental pollution arise with the introduction of materials or energy that exert adverse effects on human health, climate patterns, ecosystems, and beyond. Rigorous emission regulations for gases resulting from fuel combustion are being enforced by the European Union and the International Maritime Organization (IMO), directed at maritime sectors to mitigate emissions of SO_x, NO_x, and CO₂. The IMO envisions the realisation of its 2050 targets through a suite of strategies encompassing deliberate reductions in vessel speed, enhanced ship operations, improved propulsion systems, and a transition towards low and zero-emission fuels such as LNG, methanol, hydrogen, and ammonia. While the majority of vessels currently depend on heavy fuel or low-sulphur fuel oil, novel designs integrating alternative fuels are gaining prominence. Technologies like exhaust gas purification systems, LNG, and methanol are being embraced to achieve minimised emissions. This study introduces the concept of a high-power combined ship system, composed of a primary main engine, a diesel engine, and a steam turbine system, harnessing the energy contained within the flue gases of the main combustion engine. Assumptions, constraints for calculations, and a thermodynamic evaluation of the combined cycle are outlined. Additionally, the study scrutinises the utilisation of alternative fuels for ship propulsion and their potential to curtail exhaust emissions, with a specific focus on reducing CO₂ output.

Keywords: ship power plants, alternative marine fuels, greenhouse gases, CO₂ emissions, combined power systems, diesel engines, steam turbine, gas turbine

Nomenclature

CO ₂	Carbon dioxide	EUA	EU Allowance
CCU	Carbon capture and utilisation,	GHG	Greenhouse gas
CCS	Carbon capture and storage	GTL	Gas to liquid
CTL	Coal to liquid	HFO	Heavy fuel oil
DF	Diesel-ignited engines with pilot fuel injection	IMO	International Maritime Organization
EEX	European Energy Exchange	LBSI	Lean-Burn Spark-Ignited gas engine
EEXI	Energy Efficiency Existing Ship Index	LMG	Liquefied methane gas
EGR	Exhaust gas recirculation	LNG	Liquefied natural gas
		LP	Low-pressure
		LPG	Liquefied petroleum gas

LSFO	Low sulphur fuel oil
MARPOL	The International Convention for the Prevention of Pollution from Ships
MFO	Marine fuel oil
MGO	Marine gas oil
MDO	Marine diesel oil
NOX	Nitrogen oxides
SCR	Selective catalytic reduction
SOX	Sulphur oxides
VLSFO	Very low sulphur fuel oil

INTRODUCTION

Decarbonisation has already become a reality but the pace of its implementation is much slower than originally assumed. The direction to take, in terms of selecting the best technology and energy sources to replace conventional fuels, is also not entirely clear. There is also no clear path for choosing the best methods of their storage and, in the case of some sources, such as liquid hydrogen, a proven method of transporting them. This will particularly apply to wind energy, hydrogen energy and the storage of carbon dioxide. These activities are strongly influenced by the 2015 Paris Agreement, which aims to limit global warming to 1.5°C by 2100, thus reducing the amount of CO₂ released into the atmosphere [1].

Environmental pollution can be defined and classified in various ways. According to the Act of 17 January 1980 on the protection and shaping of the environment, as amended (1994), environmental pollution means the introduction of solid, liquid or gaseous substances or energy into the environment in such quantities or such compositions that may adversely affect human health, climate, living nature, soil, or water, or cause other changes in the environment [2].

Increasingly stringent standards for the emission of gases from fuel combustion on floating plants, mainly SO_x, NO_x and CO₂, are being introduced by the EU (Directive 2012/33/EU) and IMO – MARPOL Annex VI [3]. The International Convention for the Prevention of Pollution from Ships, known as MARPOL 73/78 (Marine Pollution), has a global character and covers all seas [2]. Poland is a party to the Convention. The Convention applies only to pollution from ships and it divides sea areas into two categories:

- special areas, and
- other areas.

Current environmental conditions increase the need to reduce CO₂ emissions, the main factor responsible for global climate change. The most commonly considered technologies to reduce CO₂ emissions are CCS technologies, which consist of the separation of CO₂ and its transport, as well as its underground storage. CCU technologies aimed at the use of captured carbon dioxide and its conversion into other substances or products (e.g. plastic, concrete, biofuel) are also being considered [4].

The maritime industry has set ambitious targets to reduce CO₂ emissions in the future. The IMO aims to reduce the ratio of CO₂ emissions from propulsion by at least 40% by 2030 and up to 70% by 2050, compared to 2008 levels (Fig. 1).

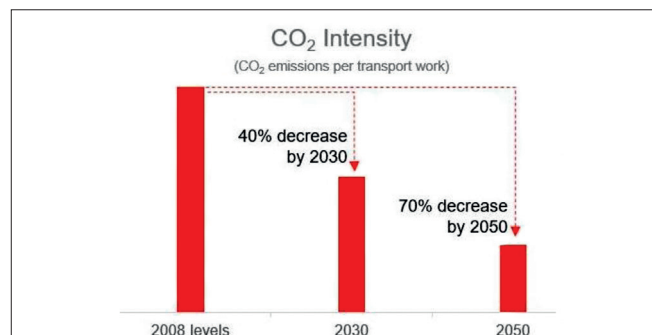


Fig. 1. Significant decreases in the carbon intensity of international shipping
Source: International Maritime Organization (November 2020).
Reducing greenhouse gas emissions from ships (Article). Retrieved from <https://www.imo.org/>

At the meeting in November 2020, the IMO's Marine Environment Protection Committee (MEPC 75) agreed on the following measures to achieve the above-mentioned targets [5]:

- the introduction of the Energy Efficiency Existing Ship Index (EEXI), with the aim of making older ships perform to a similar standard as newer tonnage,
- energy-efficient technologies/designs,
- alternative low-emission fuels,
- reduction in ship speed.

In July 2021, the European Commission [3] presented its legislative proposal to enable the European Union (EU) to meet its 2030 goal of reducing EU-wide greenhouse gas emissions by at least 55% compared to 1990. The 'Fit for 55' package includes 10 proposals, four of which are directly related to the maritime economy:

1. the inclusion of shipping in the EU Emissions Trading System (EU ETS) Directive from 2023;
2. the FuelEU Maritime regulation, new policy measures to switch to low-emission fuels, introducing requirements to gradually reduce the carbon intensity of marine fuels from 2025;
3. revision of the Alternative Fuels Infrastructure Directive: LNG and shore-side electricity in major ports by 2025 (LNG) and 2030; and
4. revision of the Energy Taxation Directive on the abolition of the tax exemption for marine fuels.

The IMO's target for 2050 is expected to be achieved through the simultaneous introduction of [6, 7]:

- slow-steaming ships – a reduction of the sailing speed of merchant ships (cargo ships) leading to a simultaneous reduction in fuel consumption and carbon emissions;
- better management of ship operations;
- improved propulsion efficiency;
- a massive shift to low and zero-emission fuels, such as LNG, LPG, methanol, hydrogen, ammonia (and other e-fuels), and biofuel; and
- the use of electricity for short sea shipping and port stops.

Today, the vast majority of the fleet runs on marine heavy fuel (HF) or low-sulphur fuel oil (LSFO) but significant orders have recently been placed for new designs that use alternative fuels.

Ship owners can achieve low emission levels in various ways through the use of exhaust gas cleaning systems, LNG

or low-sulphur fuels. The Polish shipbuilding industry engages in the manufacture or collaboration in the construction of LNG-powered floating structures. The availability of an LNG-powered ship bunkering service does not require additional investment in the construction of complex onshore infrastructure in Polish ports [8].

Not only LNG, but also methanol, has stepped into the spotlight. Currently, less than 1% of the existing fleet uses alternative fuels. Currently, the main alternative fuels available in the marine industry are [9]:

- LNG (and LPG), which can reduce CO₂ intensity by 15-25%. LNG technology is well-developed and the rapid growth of LNG bunkering infrastructure can also be observed. Methanol, usually produced from natural gas, reduces CO₂ intensity by about 10%.
- In addition to carbon-based fuels, the use of ammonia as a fuel is being extensively developed, and suitable engine technology is expected to be commercially available from 2024 onwards. The use of biofuels and synthetic fuels (also known as electrofuels or e-fuels) could provide opportunities to replace the above hydrocarbons with their low-emission equivalents.
- The supply of electricity from quays to merchant ships, while in port, is intended to eliminate the operation of ship's generator sets (reducing noise and pollution in the port area, caused by exhaust gases).

Changing macro-environmental conditions, greater customer requirements, as well as intensifying competition, forces economic entities to take systematic actions to increase the efficiency of their functioning. Making accurate decisions without access to reliable technical and economic information is not feasible. Nevertheless, the mere possession of this information is insufficient to assess the effectiveness of a company's operations. A reliable assessment can be obtained by analysing the financial and environmental impacts using technical and economic information.

THE CONCEPT OF A MOBILE FLOATING POWER PLANT

The proposed concept [10, 11] of electricity production in floating power plants for coastal regions has the following advantages (Fig. 2):

- it provides environmental protection;
- it reduces CO₂ and NO_x emissions, increasing system efficiency, and lower emissions result from the engine design. In addition, there is a reduction of SO_x emissions through the use of desulphurisation systems;
- diversification of primary energy sources reduces coal consumption in favour of liquid fuels;
- there is no slag and ash;
- there are no complications with condenser cooling water and a low impact on the environment related to water management;
- there is an increase in electricity production in northern Poland;

- there is shorter construction time, compared to conventional power plants and the possibility of starting it in stages;
- general mobile capabilities of the power plant complex – floating platform.

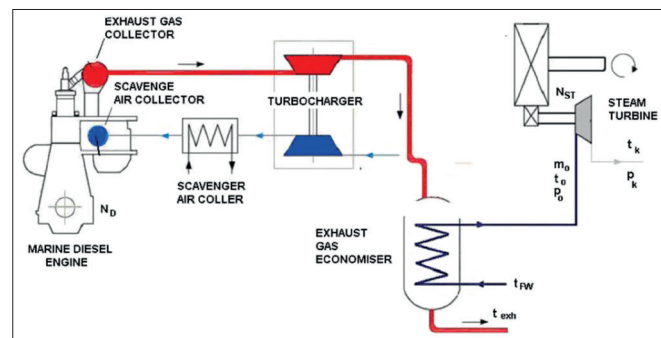


Fig. 2. Combined mobile floating power plant with a diesel engine and a steam turbine system. [10]

LOW-SPEED MARINE DIESEL ENGINES IN THE COMBINED CYCLE

MAN B&W MC-S two-stroke engines, designed by MAN Diesel, are low-speed engines with unit outputs of up to 80 MW. The low-speed two-stroke engines meet all the requirements of medium and large power units, up to 250-300 MW. They are suited to combust all liquid and gaseous fuels with high efficiency and good reliability.

Such engines can operate at a low load without restriction, up to approximately 10% of the maximum continuous rated output. In addition, they can operate at 10% overload for approximately one hour every 12 consecutive operating hours. The installation of such engines can be justified in mobile floating power plants, as it shortens the construction time of the power unit, reduces space requirements, and reduces investment, operating and maintenance costs while ensuring high efficiency, reliability and rapid relocation.

The engine manufacturer WinGD is designing marine engines with CCS technology, which will be available commercially in 2024 and 2025. The engines will be multi-fuel and use zero-emission or carbon-neutral fuels, such as ammonia and methanol, providing ship owners with reduced greenhouse gas (GHG) emissions and CO₂ emissions by up to 50%.

New engine designs launched in 2021 [2] are expected to reduce the loss of methane, which is considered a greenhouse gas when it enters the atmosphere:

- Two-stroke engines: For high pressures – 23% reduction in GHG emissions; for low pressures – 14% reduction in GHG emissions.
- Four-stroke engines (both low pressure): – DF engines with diesel ignition and pilot fuel injection: 6% reduction in GHG emissions. LBSI engines: 14% reduction in GHG emissions.

Methanol-fuelled diesel engines operate on the same principles as dual-fuel gas engines. A small pilot fuel injection, usually less than 5% of the total energy consumed, is required to ignite the methanol-air mixture [12]. The design of the MAN ME-LGI 2-stroke engine [13], which is already in operation, is

not significantly different from conventional diesel engines; its methanol-fuelled engine is at least as efficient, the lower energy density of methanol means that fuel consumption will be higher by volume or mass. ME-LGI can switch to MGO fuel mode without any speed or load limits. They can combust liquid and gaseous fuel in almost any ratio without affecting their power or efficiency. The use of methanol as a fuel reduces NO_x emissions by 30-50% and slightly improves engine efficiency in comparison to MGO fuel. EGR systems or SCR catalysts can be installed to reduce NO_x emissions further, to comply with NO_x Tier III standards.

Due to global climate change and various international agreements on CO₂ emissions, there has been a growing interest in the use of various liquid biofuels of animal or plant origin in the last few years. MAN B&W low-speed two-stroke diesel engines are a viable option for use wherever reliable and economical diesel installations are required, especially if the fuel is scarce and of poor quality.

THERMODYNAMIC ANALYSIS OF THE COMBINED CYCLE OF A MOBILE POWER PLANT

One solution for a mobile floating power plant could be to combine a diesel engine with a gas turbine and steam turbine cycle into a combined cycle using the waste heat contained in the flue gases of the main combustion engine [14]. Such a solution was presented by the authors of this article, in papers [10] and [11]. The leading engine in this system is a low-speed diesel engine.

A low-speed diesel engine combusting heavy fuel (HFO) was used for the main propulsion. Nowadays, the efficiency of such engines reaches 45-50%. With the high power of propulsion engines, the fuel gases leaving the engine contain large amounts of heat that can be further utilised. Table 1 shows the basic parameters of a low-speed marine engine.

Tab. 1. Basic ship parameters of a low-speed diesel engine

Company		MAN DIESEL & TURBO
Engine type		9K98 MC, Two- Stroke
Power	kW	48,762
Ambient air temperature	°C	25
Exhaust gas mass flow	kg/s	134.25
Exhaust gas temperature	°C	232.8
Fuel	kJ/kg	42,700
Fuel mass flow	kg/s	2.369

Combined systems of a steam turbine, in combination with a single-pressure or dual-pressure exhaust gas collector, were analysed (Figs. 3 and 4).

In the single-pressure system (Fig. 3), one exchanger was used in the steam system, namely a de-aerator heated by steam from the steam turbine exhaust.

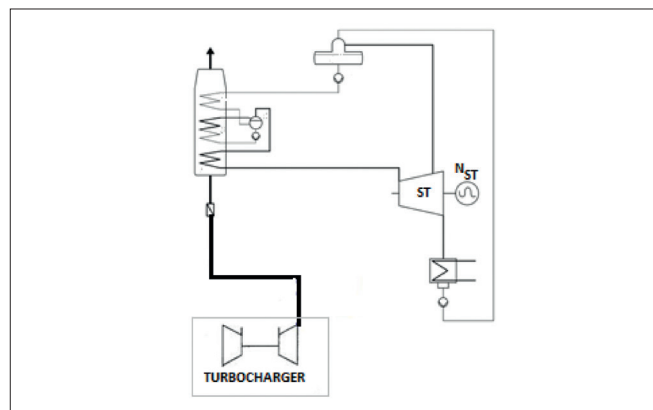


Fig. 3. Flow diagram of a single pressure system [10]

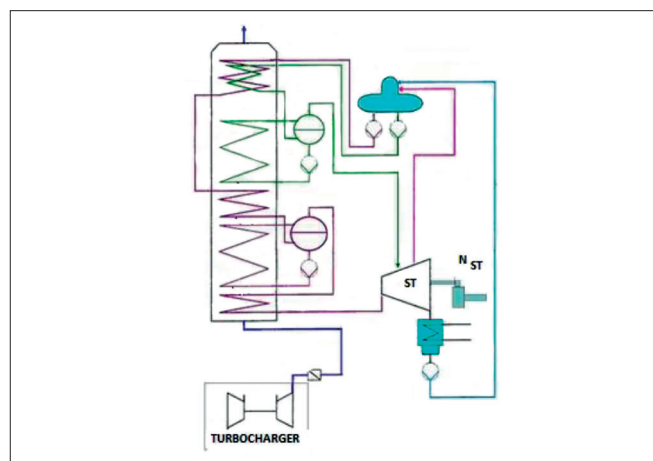


Fig. 4. Flow diagram of a two-pressure system [10]

In the two-pressure system (Fig. 4), two steam pressures were applied in the evaporators, with saturated steam ($x = 1$) in the low-pressure evaporator feeding the steam turbine. One regenerative exchanger was also applied, with a de-aerator heated by the steam from the turbine exhaust.

Both steam turbine circuits used a condensing type steam turbine, with the condenser cooled by seawater.

In the calculations, the temperature of the fresh steam in the steam turbine system was assumed to be 10°C lower than the flue gas temperature of the diesel engine. The condenser pressure was the same for the single and two-pressure system.

The calculation results for other variants of the combined system are presented in the papers [10], [11] and [4].

Fig. 5 shows the course of the steam turbine power, depending on the fresh steam pressure for a constant feed water temperature and the circuit with a single or double-pressure boiler for boiler feed water temperatures of 85°C and 120°C. The charts show that the two-pressure boiler for both engines provides the maximum steam turbine power with an appropriately adjusted low-boiling evaporator pressure. Increasing the pressure of the low-boiling evaporator reduces the steam turbine power. In both cases, the maximum steam turbine power of the single-pressure boiler is less than the maximum power of the two-pressure boiler. At the same time, the optimum fresh steam pressure of a single-pressure boiler

is lower than the fresh steam pressure of a two-pressure boiler. For a lower feed water temperature, the steam turbine power parameters for both variants are higher than the assumed higher feed water temperature. For a lower feed water temperature, the de-aerator will be more expensive and its operation will be more difficult because it works at lower than atmospheric pressures.

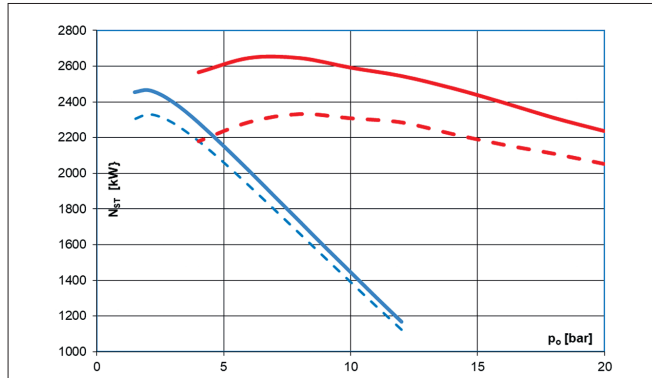


Fig. 5. The power of the steam turbine for constant feed water temperature (MAN Diesel & Turbo engine 9K98MC) $t_{FW} = 85^{\circ}\text{C}$
 — Single-Pressure System — Two-Pressure System $t_{FW} = 120^{\circ}\text{C}$
 - - - Single-Pressure System - - - Two-Pressure System

Calculations of combination systems consisting of a diesel engine with a steam turbine circuit show that [10, 11]:

- it is possible to use a combined system, consisting of a diesel combustion engine as the main engine and a steam turbine circuit using the heat contained in the flue gas of the diesel engine;
- Such systems achieve thermodynamic efficiencies comparable to combined circuits of gas turbines with steam turbines;
- Depending on the variant and load of the main engine, the use of a combined system makes it possible to increase the power of the power plant by 7-15%, compared with a conventional power plant for the same fuel stream;
- The additional power of the system is possible because of the recovery of energy contained in the flue gases of the diesel engine; and
- The combined system reduces specific fuel consumption by 6.4-12.8%, compared to a conventional power plant.

Using a combined system for the propulsion of a mobile floating power plant increases the propulsion system's efficiency, thereby reducing specific fuel consumption and increasing the propulsion power; this results in additional environmental benefits.

Tab. 2. 2017 electricity production forecast by fuel (%) [15]

	2010	2015	2020	2025	2030	2035	2040	2045	2050
coal	0.558	0.457	0.432	0.405	0.382	0.381	0.387	0.359	0.334
lignite	0.309	0.368	0.302	0.265	0.184	0.050	0.049	0.047	0.046
natural gas	0.043	0.037	0.066	0.063	0.063	0.083	0.076	0.102	0.091
renewable energy sources	0.074	0.130	0.191	0.197	0.251	0.276	0.284	0.294	0.328
nuclear energy	0.000	0.000	0.000	0.063	0.113	0.204	0.198	0.193	0.194
other	0.017	0.009	0.008	0.007	0.007	0.006	0.006	0.006	0.006
total	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

ALTERNATIVE FUELS

The EU Directive '2012/33/EU' defines alternative fuels as fuels or power sources which serve, at least partly, as a substitute for fossil oil sources in the energy supply which have the potential to reduce the dependence of EU Member States on oil imports and contribute to the decarbonisation and improvement of environmental performance in this sector [3].

These fuels include:

- electricity;
- hydrogen;
- biofuels;
- synthetic and paraffin fuels;
- natural gas (including biomethane) in the form of compressed natural gas (CNG) and liquefied natural gas (LNG); and
- liquefied petroleum gas (LPG).

Synthetic fuels can be divided according to the raw material used:

1. natural gas-derived fuels (GTL);
2. coal-derived fuels (CTL);
3. biomass-derived fuels; and
4. plastic-derived fuels (municipal waste).

The use of synthetic fuels does not involve the construction of new refuelling infrastructure in ports.

Table 2 presents data from a Polish government report [15], forecasting the structure of fuels in electricity production. In 2050, only 38% of electricity is expected to be produced from fossil fuels (coal and lignite) whereas, in 2020, solid fuels constituted 78% of electricity production.

In terms of environmental protection, marine fuels (existing, emerging and future marine fuels) [16] are divided into:

- Grey: Fossil fuels – typically used today, such as HFO, LNG, LPG, methanol, hydrogen (H_2), and ammonia – produced from natural gas/coal;
- Blue: Hydrogen, ammonia – produced from natural gas/coal with CCS, e-fuels – produced with CO_2 from carbon capture during another combustion process;
- Green: Hydrogen (H_2), ammonia – produced from carbon-free electricity, e-fuels – produced with CO_2 directly extracted from the atmosphere, and biofuels – (sustainability requirements apply).

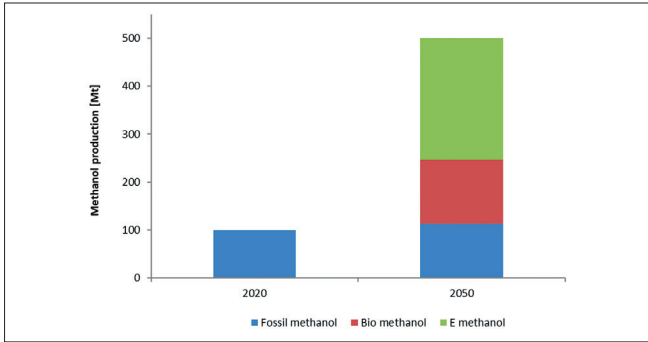


Fig. 6. Current and future methanol production by source
Source: www.methanol.org/join-us

We consider the production of methanol as an example. Depending on the technology used, grey, blue or green fuel can be obtained. Fig. 6 shows the methanol production capacity by fuel type for each year. In 2020, only methanol derived from fossil fuels was available and the widespread use of methanol as

bio or e-fuel was dependent on production capacity. Methanol produced from natural gas increases greenhouse gas emissions by a few per cent (2-3%) when produced from LNG, although emissions are reduced by 10 to 25%, depending on the technology applied. When methanol is produced from LPG, it typically leads to a 17% reduction in greenhouse gases. The production of green methanol as bio and synthetic e-methanol is currently very limited. In 2050, methanol, as a low-carbon fuel, will account for 80% of production. In the decarbonisation of exhaust gases, it is important to use low and zero-emission fuels. Their production depends on the available technologies and legal regulations, as well as safety standards for the transport and use of these fuels on floating facilities. Fig. 7 presents the possibilities for the use of a given fuel on floating facilities, enabling the safe use of such fuels. The technology of using hydrogen in transport is the least developed of all alternative fuels; however, commercial development is expected by around 2040-2050 [12], [15].

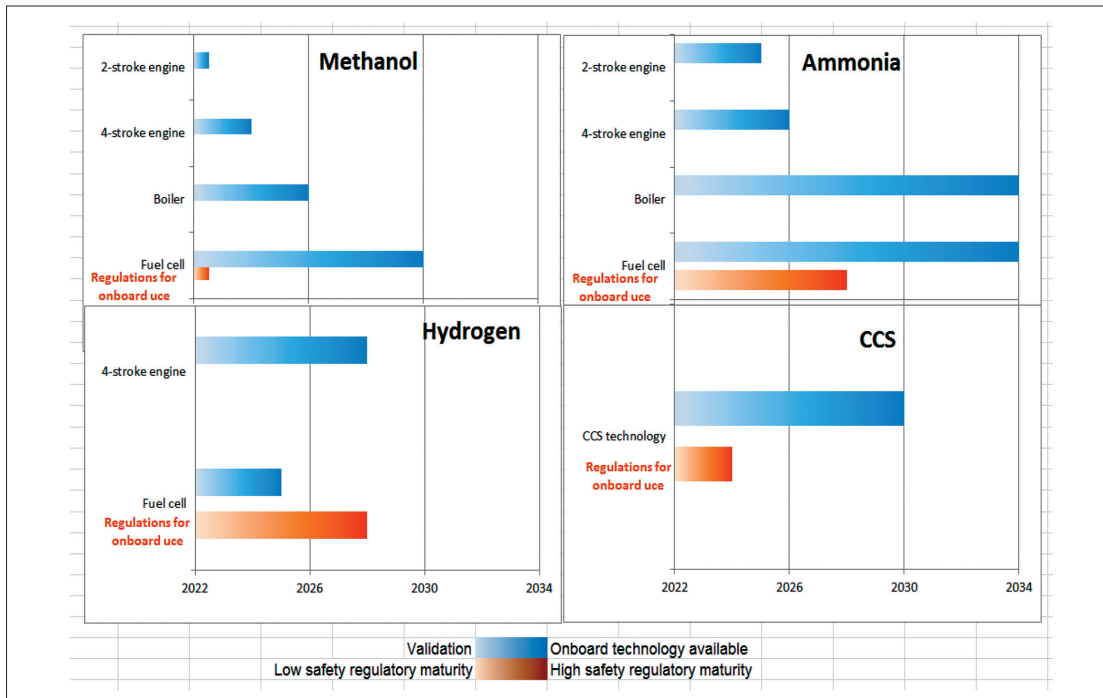


Fig.7. Estimated maturation timelines for energy converters onboard CCS technologies and corresponding safety regulations for onboard use.
Source: <https://www.dnv.com/maritime/publications/maritime-forecast-2022/index.html>

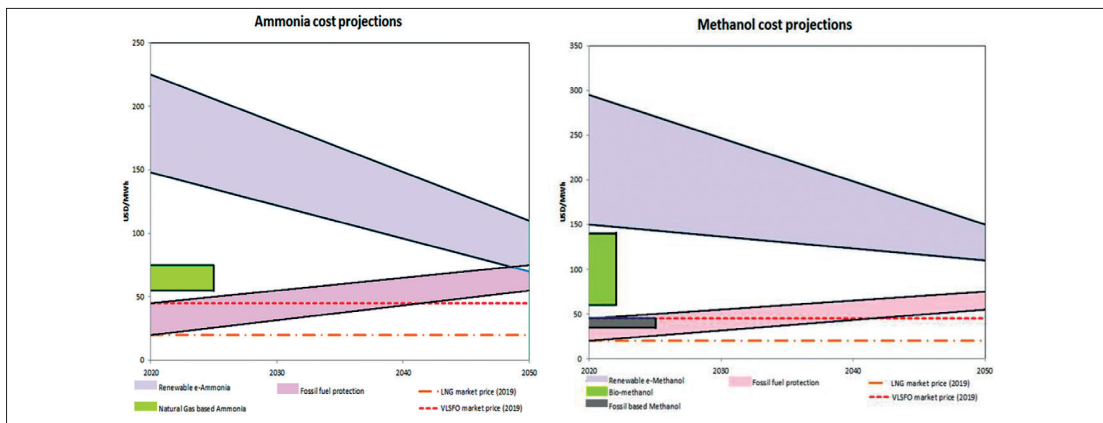


Fig. 8. Fuel cost projections. Source: A Pathway to Decarbonise the Shipping Sector by 2050 (International Renewable Energy Agency, 2021) www.methanol.org/renewable/

The cost of producing zero and low-carbon fuels will play a significant role in the use of alternative fuels. Ammonia is of great interest as a source of zero-emission fuel for shipping [17]. Fig. 8 shows the expenditure on the production of ammonia and methanol for various technologies. At the moment, the price of low and zero-emission fuels is high, compared to grey or fossil fuels. In the future, the prices of such fuels will be comparable to current fossil fuels. Almost all ammonia currently in use is produced from hydrocarbons and, as such, provides almost no benefit, in terms of reducing CO₂ emissions, but increases costs. In 2020, the costs of ammonia production in zero-emission e-fuel technology were three times higher than VLFSO fuel and it will be five times higher than LNG gas fuel in 2050. Their price is expected to fall, so that the cost will be two times higher than the cost of VLFSO fuel and 2.5 times more expensive than LNG gas fuel, respectively. This constitutes a barrier to the use of this fuel. Ammonia prices vary significantly over time and are not the same in all geographical regions. The cost of natural gas accounts for 70-85% of the cost of ammonia production. The cost of renewable ammonia production will largely depend on two parameters: the price of electricity and capital expenditure [10].

On the other hand, green ammonia (produced by electrolysis powered by renewable or nuclear energy) is an excellent source of zero-emission fuel, provided that the associated NO_x emissions are appropriately technology-dependent [18]. Greenhouse gas emissions will be close to zero.

There are many other alternative fuels that can be used in shipping, such as dimethyl ether, ethanol, biodiesel, electricity, liquefied biogas (LBG), hydrogen and nuclear power.

Synthetic fuels, produced from a combination of pure hydrogen and CO₂ obtained from the atmosphere or other biogenic processes, can also be carbon neutral at the cost of very high fuel prices. For this reason, the conversion of CO₂ into fuels appears to be a good way forward, both to dispose of CO₂ and to store renewable and excess electricity [19].

Options that will lead to a near 100% reduction in greenhouse gas emissions include nuclear fission reactors and onboard carbon capture and storage. The former is controversial and capital-intensive, while the latter is currently complex, expensive and dependent on the reception facilities in ports. Greenhouse gas emissions from electricity production, and even more from hydrogen, have the potential for virtually emission-free production from renewable energy. However, those energy carriers are difficult to store, which significantly limits the range of ships, in the case of battery propulsion and pressurised hydrogen storage.

THE USE OF ALTERNATIVE FUELS ON FLOATING FACILITIES

Ethanol fuel, like conventional fuel, causes the emission of toxic chemicals and greenhouse gases [11]. It is generally accepted that CO₂ emissions, during the use of ethanol fuel, are offset by CO₂ captured during its cultivation, compared to those powered by standard motor gasoline. A reduction of 54% NO_x emissions, 27% non-methane hydrocarbon emissions, and 18% CO₂ emissions has been shown, on average.

LNG gives the opportunity to reduce emissions of greenhouse gases (GHG) [5], NO_x and particulate matter (PM). NO_x emissions

can be reduced by 20-80%, depending on the technologies used, Exhaust Gas Recirculation (EGR) or Selective Catalytic Reduction (SCR) systems ensure that Tier III IMO NO_x levels are achieved. In greenhouse gases, both CO₂ and methane emissions should be considered, the latter being emitted as a result of incomplete combustion. Methane leaks throughout the entire chain of fuel installations (including fuel production, transportation and distribution), affecting the overall GHG footprint. The emission reduction depends on the type of engine used and it is: 95-98% for SO_x, 20-80% for NO_x and 14-25% for CO₂. In the case of internal combustion engines powered by LNG gas, additional pilot fuel is required (about 8% of MDO fuel) [20].

Methanol is the simplest alcohol, with the lowest carbon content and the largest amount of hydrogen. Methanol can be produced from several different feedstocks, mainly natural gas or coal, but also from renewable resources such as black liquor from pulp and paper mills, as a result of forest clearing or from agricultural waste, or even directly from CO₂ captured from power plants. It can also be converted into dimethyl ether (DME), which can be used as a fuel for diesel engines. Methanol requires modified engines. The key differences between methanol and HFO marine fuel are as follows:

- Methanol has a low flash point of 11-12°C compared to over 50°C for HFO.
- Emission reductions: SO_x (95-98%) and CO₂ (5-10%); but for green methanol: NO_x (25-80%); and with exhaust gas recirculation (EGR) or selective catalytic reduction (SCR) systems: CO₂ up to 80%.
- The volume of the methanol tank is 2.5 times that of HFO.
- Methanol engine technology is already available and in use.

Ammonia is an alkaline compound with a distinctly strong, suffocating odour. It is corrosive to certain materials, such as copper, copper alloys and zinc, and, therefore, care must be taken in the selection of motor construction materials. Ammonia has a lower air-fuel stoichiometric ratio compared to diesel and, with the same amount of air, more ammonia can be introduced to compensate for the lower energy content and maintain the motor power density. Additional fuel is required for internal combustion engines. Usually, MGO is used as a pilot fuel but it could also be renewable diesel (HVO) with about 60% lower GHG emissions. The use of ammonia as fuel, like LNG, almost completely eliminates particulate and soot emissions. However, there are NO_x emissions, which depend on the engine technology applied. In the case of ammonia, toxicity is a major concern but flammability and reduced temperatures also need to be considered. Ammonia is a zero-emission fuel that can potentially play an important role in the decarbonisation of marine propulsion systems. Although ammonia is toxic and has a lower energy density than currently used petroleum fuels, ammonia is preferable to hydrogen and may be a suitable option for future use in marine applications.

REDUCTION OF CO₂ EMISSIONS BY USING ALTERNATIVE FUELS

The calculations presented in [10, 11] apply to a combined cycle with a steam turbine system at a feed water temperature for a waste heat boiler $t_{FW} = 85^{\circ}\text{C}$ and $t_{FW} = 120^{\circ}\text{C}$. The fuel burned in the engine was Heavy Fuel Oil, HFO. The system with

a dual-pressure utilisation boiler has a higher steam turbine power compared to the system with a single-pressure boiler; however, the increase in the power of the steam turbine compared to the dual-pressure system is small, approximately 6%. A system with a single-pressure boiler in the steam turbine system is adopted in further considerations. This solution is cheaper and easier to use from the point of view of investment costs.

The temperature of a boiler feed water affects the power of the steam turbine and the design of the de-aerator: the lower the temperature, the more powerful the steam turbine but, also, the lower the pressure in the de-aerator. For a supply water temperature of 85°C, the de-aerator must be of a vacuum design, which causes more operational difficulties; it is a more expensive solution than

a positive pressure de-aerator. The increase in steam turbine power is small. Further calculations of the combined system will be carried out for a single-pressure utilisation boiler and a feed water temperature of 120°C (positive pressure de-aerator).

A combined system was analysed for different alternative marine fuels with the mass compositions and calorific values given in Table 2. The results were compared with a power plant powered by a low-speed marine engine without a steam turbine system and powered by MDO fuel.

The combined system was analysed under the following additional assumptions:

- engine efficiency and power were identical, regardless of the type of fuel;

Tab. 3. Fuel specifications

Fuel		MDO	LNG 1	LNG 2	methanol	ethanol	ammonia	dual fuel 8% MDO & 92% LNG 1
		in 1 kg						
C		0.829						0.06632
CH ₄			0.885	0.911				0.81420
H		0.122						0.00976
S		0.028						0.00224
O ₂		0.010						0.00080
N ₂		0.011		0.006				0.00088
CO ₂				0.005				
H ₂ O								
C ₂ H ₂			0.046	0.047				0.04232
C ₃ H ₈			0.054	0.017				0.04968
C ₄ H ₁₀			0.015	0.014				0.01380
CH ₃ OH					1			
C ₂ H ₅ OH						1		
NH ₃							1	
Lower calorific value [13] [21]	kJ/kg	42700	49170	48390	22693	26800	18600	48652

Tab. 4. Exhaust gas composition of a combined system for alternative marine fuels

Fuel		Power of Steam turbine	Emission					Exhaust gases	Specific Fuel Consumption
			CO ₂	SO ₂	H ₂ O	O ₂	N ₂		
		kW	kg/kWh						
MDO	without steam turbine	0	0.5316	0.0098	0.1920	1.6984	7.4796	9.9114	0.1749
MDO	Combined cycle	2450	0.5062	0.0093	0.1829	1.6171	7.1217	9.4372	0.1665
dual fuel 8% MDO & 92% LNG 1		2820	0.4087	0.0007	0.2977	1.5733	7.0690	9.3493	0.1451
LNG 1		2740	0.4022	0.0000	0.3070	1.5733	7.0798	9.3623	0.1438
LNG 2		2740	0.4037	0.0000	0.3115	1.5687	7.0807	9.3646	0.1461
methanol		2730	0.4285	0.0000	0.3506	1.6716	7.0812	9.5319	0.3116
ethanol		2100	0.5111	0.0000	0.3136	1.6081	7.1689	9.6017	0.2672
ammonia		2260	0.0000	0.0000	0.5756	1.6472	7.4449	9.6676	0.3837

Tab. 5. Reduction of CO₂ emissions of a combined system with alternative marine fuels.

Fuel		MDO	MDO	dual fuel 8% MDO & 92% LNG 1	LNG 1	LNG 2	methanol	ethanol	ammonia
		without steam turbine	Combined cycle						
CO ₂	kg/kWh	0.5316	0.5062	0.4087	0.4022	0.4037	0.4285	0.5111	0.0000
ΔCO ₂ /CO ₂ MDO	%	0	-4.78	-23.13	-24.34	-24.06	-19.40	-3.87	-100.00

- the charge air was identical, irrespective of fuel type;
- fuel flow was variable and dependent on calorific value;
- engine exhaust gases were dependent on fuel stream; and
- temperature of the exhaust gases from the engine were identical, regardless of the type of fuel used.

With the above assumptions, a combined cycle was recalculated for different types of alternative marine fuel (Table 2). Two types of LNG-based fuel were adopted for different contents of methane, methanol, ethanol and ammonia. For a slow-speed engine [13], according to the manufacturer's requirements, a fuel consisting of 8% of MDO pilot fuel and 92% of LNG 1 gas was adopted.

The maximum power of the steam turbine was determined for each variant (Table 3). The power of the steam turbine, depending on the type of fuel, changed by +/- 14% in relation to the power of the steam turbine from the combined system variant fuelled with standard MDO fuel. Changes in the power of the entire combined drive system differed by +/- 0.7% in relation to the variant of the system powered by MDO fuel.

Greenhouse gas emissions for alternative fuels in the system are presented in Table 4; Table 5 presents the CO₂ reductions compared to a simple drive system without a steam turbine for the standard MDO fuel.

CO₂ gas emissions depend on the fuel composition. The use of a steam turbine for a simple drive with no fuel change (MDO) results in a 4.8% reduction in emissions. This is due to an increase in system efficiency and, thus, a reduction in specific fuel consumption. The use of low-emission alternative fuels further reduces CO₂ emissions. For low-emission fuels, the greatest reduction in emissions is the result of the use of LNG fuels at 23-24%. The use of the zero-emission fuel, ammonia, leads to the complete elimination of CO₂ from the exhaust gases.

SO_x gas emissions depend on the sulphur content in the fuel. The use of a combined system without changing the type of fuel (MDO) reduces emissions of sulphur compounds by approximately 5%. In dual-fuel engines fuelled with a mixture of LNG and MDO control fuel, this reduction reaches 93%, compared to the standard fuel. By using alternative sulphur-free fuels, sulphur compounds are completely eliminated.

The emission of water vapour H₂O, which is also a greenhouse gas for renewable low and zero-emission fuels increases, in relation to the system powered by standard fuel. Technologies can be used in this area to eliminate this problem.

This article does not consider NO_x emissions in a combined system. Emissions of these compounds can be reduced by using appropriate SCR engine technologies.

CONCLUSIONS

Based on the analysis conducted, the following conclusions can be drawn regarding the utilisation of mobile floating power plants in relation to greenhouse gas emissions.

- The adoption of a combined system powered by conventional fuel leads to a reduction in CO₂ emissions.
- Alternative fuels that replace the standard marine fuel, MDO, contribute to a decrease in CO₂ emissions. The specific type of fuel and the technologies employed for its production significantly influence the extent of CO₂ reduction.
- Low and zero-emission marine fuels, derived from environmentally friendly technologies and known as e-fuels, offer the potential to achieve CO₂ emission reduction in line with EU Directives and IMO Conventions within specified timeframes. Complete decarbonisation can be realised through the utilisation of zero-emission green ammonia.
- The surplus electricity production from offshore wind farms on the Polish Baltic Sea shelf (Offshore Wind Energy) will play a significant role in alternative fuel production (green technology).
- The incorporation of low-emission fuels within the maritime sector and mobile floating power plants has the capacity to eliminate or substantially reduce SO_x emissions.
- Alternative fuels containing methane necessitate appropriate technologies to prevent methane release into the atmosphere, as methane is classified as a greenhouse gas due to its potential escape through leaks in storage and power supply systems, as well as incomplete fuel combustion.
- The integration of slow-speed reciprocating engines within a combined system, encompassing steam and gas turbines in mobile floating power plants, results in reduced CO₂ and SO_x emissions when utilising conventional MDO fuels. The advantages of such emission reduction are further enhanced by the incorporation of low and zero-emission fuels within the combined system.

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