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Analysis of Alternative Configurations of Ship Power Systems Using Biofuels and Renewable Energy

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ABSTRACT: The requirements to reduce emissions of carbon dioxide and other greenhouse gases from maritime transport require taking actions aimed at increasing the overall efficiency of the propulsion system, optimal and rational use of electricity and heat. Taking such actions is necessary in order to demonstrate the improvement of the energy efficiency index of a ship in operation or an already existing one (EEOI and EEXI), which will allow to obtain category A or B emissions for a given ship. Obtaining similar energy efficiency effects is also possible after switching to fuels containing less carbon in the molecule and the use of renewable energy. Attempts are made to create new configurations of combined energy systems so as to obtain maximum benefits related to the use of various energy sources in order to ensure the production of energy in quantities consistent with the current demand of the ship in the operating condition.

1 INTRODUCTION

The International Maritime Organization (IMO) recommended that on 1 January 2013 all convention ships (with a capacity equal or above 400) apply procedures limiting carbon dioxide (CO_2) emissions, which are included in the previously prepared by shipowners Ship Energy Efficiency Management Plan (SEEMP) .

The main source of carbon dioxide emissions on ships is the combustion of fuels containing the element carbon.

The primary solution for reducing carbon dioxide emissions is the use of carbon-free or low-carbon fuels. However, this is very difficult to implement, the marine fuels used (Tab.1) contain carbon as the main component. The CO_2 emission factor for the amount of fuel burned - c_F is also given.

Table 1. Carbon content of marine fuels and carbon dioxide emission factor – c_F

Type of marine fuel	Reference	Carbon content (averaged)	CO_2 emission factor - c_F [kg CO_2/kg of fuel]
Gas oil or distilled fuel	ISO 8217, from DMX to DMB	0.8744	3.206
Marine diesel oil	ISO 8217, from RMA to RMD	0.8594	3.151
Heavy fuel oil	ISO 8217, from RME to RMK	0.8493	3.1144
LPG	Propane	0.8182	3.000
LPG	Butane	0.8284	3.030
LNG, CNG, methane	Methane	0.7500	2.750
Ammonia	Ammonia	0	0/0.4727*

* with 15% pilot dose of marine diesel oil

Another basic method should be applied - reducing fuel consumption by the elements of the ship's power system. This can be achieved by:

- reducing the demand for mechanical energy from the ship's propulsion system, electrical energy and heat energy receivers;
- use of high-efficiency energy devices and maintaining their good technical condition during operation;
- use of waste energy recovery systems (deep waste heat recovery systems);
- reduction of the ship's operating speed (however, it extends the duration of the voyage, additional costs of ship operation and crew costs arise).

The engine crew has the greatest number of actions that can be taken to reduce fuel consumption (and reduce the value of Energy Efficiency Operational Index – EEOI, or for existing ships - EEXI). Examples of actions it should consider, assess the impact and take:

- selection of the type of fuel supplied directly to power devices. Basically, it will be the choice of the cheapest fuel, as long as it can be used in a given area of the sea. The shipowner's recommendations, which reduce the ship's operating costs (fuel in this case), are followed first. This also often leads to a reduction in carbon dioxide emissions, but this is a secondary effect;
- emergency states of power systems force actions limiting energy consumption. For the safety of the ship and the crew, this is an emergency situation, but from the point of view of the EEOI value, it may be beneficial;
- energy generation should take place in devices that are in good technical condition. The type and number of operating devices should be appropriate to the energy demand so that they work on economic loads;
- there are more and more complex systems on ships that have the ability to recover (recycle) waste energy. This applies mainly to the energy contained in the exhaust gases from the main and auxiliary engines, thermal energy obtained as a result of cooling the charging air, engine cooling water and lubricating oils. Waste energy is recovered in utilization boilers by producing heating steam and/or power steam for turbogenerators, power gas turbines are sometimes used (utilization for diesel exhaust fumes), technical water is produced (as distillate from sea water) in evaporators using from thermal energy from engine cooling systems, etc. In high-power power plants (above 40 MW), the so-called deep utilization of waste heat. A number of additional problems arise for the engine crew. Most of the disposal devices can be started only after the port departure maneuvers (from coastal waters) are completed, when the loads on the main engine are stabilized. This requires a number of additional maintenance activities, for which the limited engine crew may not have time;
- if the ship is located in areas with controlled emission of harmful substances into the atmosphere from ship engines (ECA areas), the requirements allowing the ship to stay in these zones must be met in the first place, e.g. secondly, actions are taken (provided that there are technical and time possibilities) related to the recovery of waste heat;
- commissioning of some systems may take place after consultations between the captain and the chief engineer, e.g. the ship's air-conditioning system. Due to its energy consumption, they can only be switched on after obtaining permission. During the operation of the air-conditioning system, a number of rules must be observed to limit the load on this system, e.g. closing windows, portholes and external doors on the ship;
- load sharing between power devices operating in parallel should ensure their proper load, which will ensure, among others, their minimum total fuel consumption.

Generally speaking, the engine crew should ensure the operation of appropriate power devices supplying the required amounts of individual types of energy, with the minimum total fuel consumption. Lower fuel consumption translates into lower carbon dioxide emissions into the atmosphere.

The basic task of the ship's crew is to reduce the demand for energy, i.e. to save. This also applies to activities related to the reduction of hull resistance. Improper operation of the rudder (excessive rudder deflections causing the ship to yaw) causes not only lengthening of the ship's path, but also an increase in hull resistance. Only for this reason, the load on the main engine increases, while reducing the speed of the ship from 0.5 to 2 knots. It is common to use the so-called automatic pilot, but it is worth taking care of its correct adjustment.

In heavily trafficked sea areas, it will sometimes be necessary to adjust the vessel's speed (in order to reduce the risk of collision traffic) so that vessels can pass, overtake, let a vessel with the right of way pass, etc. at an appropriate distance, in a manner that is legible to other ships, in compliance with safety rules. In doubtful situations, a ship should be called by radio, as to whose behaviour we have ambiguities, specify and agree on a common behaviour. The smaller the speed and/or road correction is, the less time we will lose for additional maneuvers.

Most of the important devices for ship safety are duplicated (in some cases there are even triple solutions). Only one of them, e.g. only one hydraulic pump of the steering gear, should operate under normal ship operation conditions. The backup device is turned off, but left in the standby position, with the possibility of automatic activation in most cases. Maintaining the operation of redundant devices generates additional energy demand without significantly increasing the level of ship operation safety.

In order to limit the effects of greenhouse gases on Earth climate, for which maritime transport accounts for about 3%, the IMO has set the objective of reducing carbon dioxide emissions, taking into account the transport effect, by at least 30% by 2030 and 70% by 2050 compared to 2008. Taking into account the equivalent carbon dioxide emission (as GHG effect), this is to be 50% by 2050 [1].

2 BIOFUELS AND RENEWABLE ENERGY

In order to comply with IMO regulations, a transformation of marine fuels and a wider use of renewable energy sources, primarily wind and solar energy, must be carried out.

2.1 *Biofuels*

It is possible to meet the limits limiting CO_2 emissions by using fuels recognized as biofuels (e.g. FAME, methanol, ethanol), alternative fuels from sources other than crude oil (e.g. gaseous fuels - LNG, LPG) and, above all, synthetic fuels (synthetic LNG - SNG, ammonia) or acting as excess energy storage (electrolysis of hydrogen, storage and use as fuel) and fuel cells.

One of the remedies for reducing CO_2 emissions is the use of biofuels. Although they contain carbon particles, CO_2 emissions from these sources are not included in the emissions to the atmosphere. A comparison of selected parameters of fuels considered as marine fuels is presented in Table 2.

Table 2. Selected parameters of alternative marine fuels and biofuels [own elaboration]

Type of fuel	Density [kg/m³]	Lower Heating Value [MJ/kg]	Equivalent energy volume capacity to HFO=1	Equivalent demand per year [million tons]*
Bio-diesel	880	37.2	1.120	388
Renewable diesel	780	44.1	1.066	327
Fatty acid methyl esters	765	43	1.206	336
Methanol	794	22	2.099	656
Ethanol	789	28	1.660	515
Ammonia	682	18.6	2.890 / 3.468**	776
Propane	493	46.6	1.596 / 2.075**	310
Methane (LNG, SNG)	460	50	1.594 / 2.551**	289
Hydrogen (liquid)	71	120	4.303 / 8.606**	120

* To cover energy demand for marine transport compared to 2020
** Additional volume for thermal insulation

In 2021, petroleum fuels accounted for 98% of the consumption of marine fuels in maritime transport. The main benefit for the marine environment was the introduction of the requirement to use de-sulphurised heavy fuels below the threshold of 0.5% for heavy fuels and 0.1% for diesel and gas oils.

The IMO regulations oblige shipowners to reduce the consumption of petroleum fuels by achieving a reduction in CO_2 equivalent emissions for a specific transport effect [2]. The process of switching to alternative fuels is inevitable, but it raises a number of problems during the transition period. The initial stage is the use of mixtures of petroleum fuels with biofuels with a content of up to 25%. It is possible to adapt marine engines by their manufacturers to burn such mixtures. Another solution that allows the combustion of crude oil derived and alternative fuels is the construction of dual- and tri-fuel engines, in which it is possible to switch from one fuel to another during engine operation. Due to other parameters of alternative fuels, it is necessary to build additional tanks and an additional fuel supply system for them. With a high autonomy of the ship (over 10 days), this results in an increase in space for additional tanks, due to the lower density of the fuel, lower calorific value of the fuel or the need for thermal insulation of the tanks (Table 2).

2.2 *Renewable energy for marine transport*

The beginnings of sea transport were possible thanks to the use of wind energy. However, it is a source with a number of disadvantages in order to use this energy in the form of sails. It may blow too weakly or too strongly, as well as from directions that make it impossible to keep the ship on the required course. Sailing ships sailed on such courses to such regions of the seas where a suitable wind was expected, in order to reach the intended destination as a result, although it was not usually the shortest route.

Currently, attempts are being made to use wind energy in the form of building appropriate masts and sails (Figure 1), which are used in the case of favourable wind directions, and the energy obtained supports the traditional mechanical propulsion of the ship, reducing the total fuel consumption.

Figure 1. Automatically set rigid sails support the ship's propulsion [3]

A similar solution is to develop a sail in the form of a kite, which at the appropriate height uses wind energy to support the main propulsion of the ship. In both cases, in order to maintain the ship's intended course, it is necessary to correct the rudder position in order to limit the lateral drift of the ship's hull. With favourable wind directions and a properly placed sail, the load on the main engine (and fuel consumption) can be reduced by 5-15% (Figure 2).

Figure 2. A kite-sail supports the main propulsion of the ship [4]

Another proposal is a device mounted on the ship's bow or along the ship's sides. The Rotor Sail solution consists of a tall cylinder made of glass and carbon fibre, which rotates around its axis thanks to an electric motor driving it. A spinning cylinder exposed to the wind creates a lift force perpendicular to the wind direction based on the Magnus effect (Figure 3). Typically consisting of two or three cylinders, the system can be retrofitted to existing vessels or integrated into new designs. Once installed on the ship, the solution is completely maintenance-free. The intelligent system independently monitors weather conditions and rotates the mechanism in such a way as to maximize the benefits of its use. Additional thrust allows to increase the ship's speed or at a given speed of the ship allows for reducing the load on the main engine and its fuel consumption.

Figure 3. Norsepower designed and developed Rotor Sail. Flettner rotor produces an additional thrust to support the propulsion system of the ship [5]

The use of photovoltaic cells on small vessels, e.g. boats, catamarans, small yachts, is already quite a common practice. Especially on vessels with few people, the demand for electricity is relatively low (power below 100 kW). An advantageous solution is the ability to accumulate excess energy in batteries to use this source at night. This is important for devices such as GMDSS, which are powered by a UPS anyway, which provide uninterruptible power to these devices, and at the same time have an accumulated supply of electricity.

Ships with a much larger capacity are used in sea transport. The power demand for the main drive ranges from 1-100 MW and in the range of 0.1-10 MW of electric power. It should be noted that the generation of power of the order of 1 MW consumes about 200 kg of fuel per hour with the emission of about 620-630 kg of CO_2. Production of electricity from renewable sources (mainly the use of solar energy in photovoltaic panels is being considered) will reduce fuel consumption and CO_2 emissions in proportion to the given indicator.

Obtaining an electrical power of 10-100 kW from photovoltaic panels is basically possible on every ship. This requires an appropriate design to place these panels on the ship's superstructures or decks and to connect them to the ship's energy system. An example of application is shown in Figure 4.

One kilowatt of peak nominal power of typical photovoltaic modules is obtained from 6-9 m^2 of surface. In order to estimate the required area of photovoltaic panels for typical power in real conditions, a value of 10-12 m^2/kW should be assumed. To obtain a power of 100 kW, the estimated area of the panels should be about 1000-1200 m^2. This may only be achievable for a relatively large ship. With a ship length of 150 m and a width of 30 m, the area of the main deck will be approximately 4,000 m^2. The panels are set in a position approximately perpendicular to the direction of the sun's rays, which allows them to be arranged in several rows, but so that they do not cover each other.

The problem can be reversed by knowing the area available for the panels and estimating the expected electric power from these panels.

Figure 4. The use of photovoltaic panels and a kite-sail to reduce the ship's energy demand [6]

Several different types can be used to increase the share of renewable energy sources in the ship's energy demand.

2.3 *Fuel cells and electricity for marine transport*

Fuel cells are a great hope in many fields of energy, including the generation of energy for the needs of the ship. If renewables are used to produce the hydrogen fuel, the entire energy chain will be clean, providing a true zero-emission fuel. They can produce electricity with greater efficiency than current heat engines. There's no combustion involved, as the fuel cell converts fuel directly to electricity and heat. Several fuel cell technologies have been developed. One of the most promising emission-free technologies is the proton exchange membrane fuel cell (PEMFC) (Figure 5).

So far, the primary limitation has been the available power from fuel cells. In the power range of 10-100 kW, it does not capable of powering ocean-going vessels. ABB has signed a Memorandum of Understanding with hydrogen specialist Hydrogène de France (HDF) with the intent to jointly manufacture megawatt-scale fuel cell systems [7].

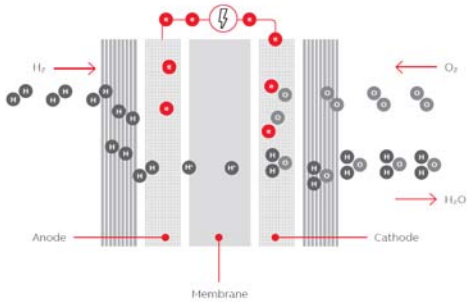

Figure 5. The idea of the working principle of the fuel cell [7]

Obtaining power in the range of 1-10 MW may be an alternative solution for generating energy on ships, preferring them in order to obtain lower emission indicators (EEOI, EEXI) from maritime transport. The idea of future marine applications for larger ships powered by fuel cells is shown in Figure 6.

Figure 6. Concept illustration of a large vessel powered by fuel cells [8]

The development of ship propulsion leads to the wider use of modern sources of electricity. A good example is a ship built in 2021, powered by 400 kW fuel cells, floating on the Rhône River [6]. It is estimated that it will take about 10-20 years to reach fuel cell capacities of 10-50 MW, which will provide the opportunity to compete with traditional shipboard heat engines, resulting in their gradual replacement. The efficiency of heat engines is limited by the maximum efficiency defined by the Carnot cycle. Obtaining higher efficiency from fuel cells will prefer their use due to the very high share of fuel costs in ship operation. However, there are some issues that need to be considered and resolved. The main problem is the source of obtaining new fuels (methanol, ethanol, and mainly hydrogen) so that they are considered clean fuels, the production of which does not emit greenhouse gases. Another is the fuel storage and distribution system, ship bunkering, the amount of space on the ship occupied by fuel tanks with the required autonomy of sailing and the total costs of the fuel system.

3 DUAL- OR TRI-FUEL MARINE DIESEL ENGINES - ADDITIONAL REQUIREMENTS IN THE DESIGN AND OPERATION OF THE SHIP'S ENGINE ROOM

Marine dual-fuel (tri-fuel) engines are adapted to work on traditional liquid fuels derived from the crude oil, and can also operate on gaseous fuels (mainly LPG, CNG, LNG, SNG). It is necessary to expand the system of fuel tanks divided into heavy fuels, diesel fuels and gaseous fuels. The gas fuel system is an independent system and requires additional protections specified by the regulations of classification societies. Engines start on liquid fuel and may run without time limits. Depending on the vessel's operating state, the engine may be switched to the second type of fuel.

There are basically 3 modes of operation for dual fuel marine engines used on-board ships:

1. when engine is well supplied with natural gas, amount of pilot fuel injected is corresponding to about 6% of the total engine load. In other words major contributor to the engine load is natural gas.
2. when gas supply to the engine is constant and limited, then engine is said to be in "Specified Gas Mode". Here gas supply is constant, but fuel oil quantity injected varies to meet changing engine load demand.
3. in "Fuel Oil Only" mode, gas supply will not be available, and engine runs only on fuel oil. This mode is used when engine is unstable, such as during restricted waters, heavy weather, manoeuvring, etc.

International Association of Classification Societies (IACS) require following safeties in dual-fuel engines [7]:

- use oil fuel only while starting the engine;
- use oil fuel only during unstable engine conditions, such as manoeuvring, restricted waters, etc.;
- engine should continue to run on fuel oil even when gas supply stops;
- crankcase relief valves to be fitted in way of each crank throw;
- construction and operation of pressure relief valve of engine units should consider gas leak inside the engine and subsequent pressure rise;
- exhaust gas system of the engine to be independent and not to be mixed with any other systems;
- starting airline to each unit to be fitted with flame arresters;
- flame arrester to be fitted at the inlet of the gas supply valve to the units;
- apart from automatic shutdown system, gas supply must be able to shut manually from engine starting platform or other control stations.

4 USE OF RENEWABLE ENERGY SOURCES TO REDUCE CO_2 EMISSIONS IN SHIP OPERATION

The use of renewable energies supporting the energy demand by the ship's propulsion and energy system improves its emission indexes and may be considered as meeting the requirements of energy efficiency of a given type of ship [2, 9-13]. This may enable further operation of the ship and, depending on the conditions of using renewable energy sources, reduce the costs of generating energy for the ship's needs. Due to the change in the efficiency of electricity generation in a generator driven by a diesel engine depending on its load, there is a situation where additional energy obtained from renewable sources does not cause a linear change in fuel consumption by the engine. The differences are so small that it can be estimated that this relationship is linear. As a result, if 3% of electricity demand is generated from renewable sources, it is said that fuel consumption and emissions into the atmosphere have decreased by 3% as well.

By using currently available devices for generating electricity or thrust (kites, Flettner rotors, sails) from solar and wind energy, it is possible to reduce the ship's energy demand by 1 to 30%. On average, it is 3-10%. In this case, it is not possible to meet the IMO requirements for improving the transport effect of the ship. Significant benefits can be obtained as a result of optimization of sea voyage planning (use of available travel time), reduction of hull resistance, better use of the ship's carrying capacity, shortening of stays on roadsteads and ports, logistics activities regarding loading and unloading, etc. It is always important to use all optimization possibilities total fuel consumption, increasing the overall efficiency of the drive, and even reducing the demand for energy (savings). The most important, necessary action, however, will be the transition to alternative or carbon-free fuels to decarbonise maritime transport.

Table 1 presents the CO_2 emission factor for marine fuels derived from crude oil. Fuels obtained through synthesis (ammonia, synthetic NG) and biofuels can be (currently are) considered as fuels from which CO_2 emissions do not count towards the determined emission factors. In the case of designating the so-called equivalent CO_2 emissions (emissions of other greenhouse gases, e.g. SOx, NOx, particulate matter, hydrocarbons from fuel leaks or misfires in engine cylinders are taken into account), this indicator will be higher than zero, but still several times smaller if CO_2 emissions are taken into account. In the case of switching from oil-derived fuels to biofuels with a share of 50% each or using fuel mixtures, it may turn out that the ship is able to meet the IMO "Fit for 55" requirements to a limited extent until around 2035. In 2050, the share of biofuels would have to reach the threshold of 85% or 50% for carbon-free fuels [14].

5 CHANGES IN THE CONFIGURATION OF SHIP POWER SYSTEMS

The ship's energy system is located in a watertight space called the engine room. In most cases it is located at the stern of the ship. In special cases of certain types of ships, they are located in the fore part (ro-ro ferries) or amidships (diesel electric engine room e.g. for passenger ships, cruise liners). For large container ships, two independent power plants separated by a watertight bulkhead and ships with dynamic positioning systems, which can have up to four independent power plants, were built. The choice of the type of engine room is always conditioned by the type of ship and the type of cargo carried by it. Generation of electrical or mechanical energy (thrust) by devices using solar energy or wind, are located on the ship's main deck or its superstructures. Supplying the generated electricity to the ship's main power system is not a major technical challenge, as is distributing the power supply to all receivers of this energy located in different parts of the ship. After its production and possible processing (from direct current to alternating current with specific parameters in the main network), protection of the network against the risk of short-circuit, overload, fire, synchronization with the main network, etc., it was led through switchboards to power receivers. Apart from the expansion of the power grid with additional elements, this does not constitute a significant change in the solutions already in use.

The biggest changes to the fuel system are necessary for dual-fuel engines. The gaseous fuel supply system must be independent of the liquid fuel from the service tank to the direct injection of gas into the intake duct during the intake stroke (four-stroke engines) or gas injection into the combustion chamber (two-stroke engines). An example of an additional gas supply installation with the required protections is shown in Figure 7.

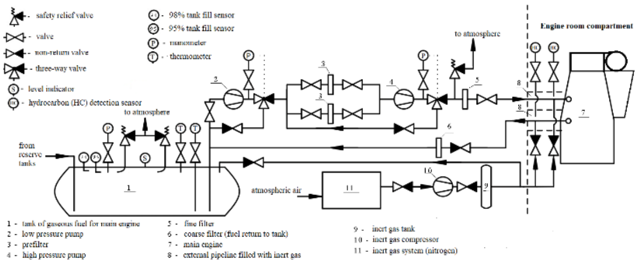

Figure 7. Additional gaseous fuel system for dual-fuel main engine

5.1 *Analysis of alternative configuration of ship power systems for offshore vessels*

Offshore vessels usually operate at a short distance from land (up to 200 nautical miles) and their autonomy does not exceed 30 days. This causes ships to have limited fuel reserves. If the period of stay at sea is extended and it is not possible to enter the port for bunkering fuel, it is possible to bunker them at sea under acceptable weather conditions for such operations. On ships of this type, diesel de-sulphured fuel is commonly used (they usually work in special areas), which simplifies the construction of the fuel system. The need to reduce emission factors makes it necessary to look for solutions that would improve this situation. Attempts are made to use photovoltaic cells, biofuels or mixtures of petroleum fuels and biofuels (up to 25% of biofuel content, most often it is possible to operate the engine without adaptation changes) and to use electricity batteries charged from the land grid and fuel cells. The combination of several solutions allows for a significant improvement in the emission index, up to the achievement of category A [9]. This enables the operation of these ships in waters where more stringent environmental protection regulations have been introduced or it is a condition for signing a contract.

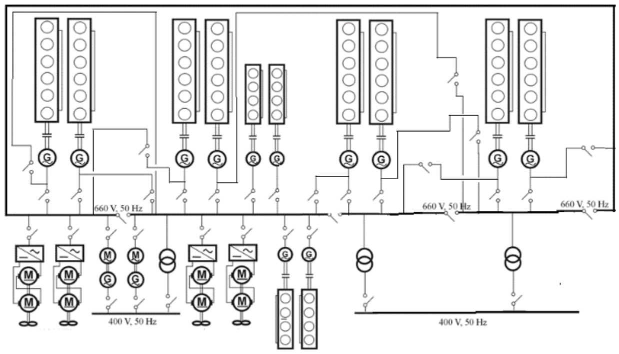

Figure 8. Schematic diagram of the ship's power system with 12 generating sets and the possibility of division into 4 main switchboards

The power system type diesel-electric (D-E) can be very extensive and contain from 4 to 16 generating sets. In such a case, the main switchboard has the possibility of switching off part of the busbars due to their damage, short-circuit, flooding of the watertight compartment, etc. and connecting each of the generating sets to two independent sections. Figure 8 shows a schematic diagram of such a network. Expansion and protection of the main switchboards are required, among others, on ships with dynamic positioning systems.

5.2 *Influence of marine fuel type on a configuration of ship power systems*

The choice of marine alternative fuel is necessary by shipowners, but it carries a high risk. The selection decision lacks indications from IMO, classification societies and consulting companies. Making a choice has many consequences [15-18]. One of them was changing the configuration of the ship's energy system, starting from the fuel storage tanks to the fuel supply system for the engines. As a result, shipowners' actions are conservative. They introduce ad hoc changes in order to meet the imposed requirements with an indication of time, but they do not decide on significant changes for fear of excessive costs that may be misguided and expose the shipowner to a financial crisis or bankruptcy of the company. Therefore, the changes will be evolutionary. Pro-environmental solutions will be introduced, improving emissivity to meet the requirements, but not going too far, in the expectation that the future will show the direction of appropriate changes.

6 CONCLUSIONS

The configuration of the ship's energy system is most influenced by the type of ship and the sailing area. The autonomy of swimming has a significant impact on the solutions of the fuel system and the fuel supply. Another factor is the degree of expansion of the energy system using alternative or carbon-free fuels. This affects the expansion of the fuel system, especially in power plants with dual- and tri-fuel engines. The use of dual-fuel engines requires additional qualifications of the engine crew related to the process of bunkering gaseous fuels with a flash point below 60oC (IGF code requirements), its storage, operation of the gaseous fuel system supplying the engine and procedures for switching from one fuel to another.

The use of gaseous fuels requires additional explosion and fire protection, additional ventilation systems and the use of inert gas. The transition to the use of only gaseous fuels will require further operational experience and raising the reliability index to the level currently achieved for power plants with conventional fuels. The least changes in the configuration of the ship's energy system are caused by systems using solar or wind energy. They either work independently or slightly expand the existing energy system. Due to the relatively small power in relation to the energy required by the ship, they can support the energy system and improve the emission indicators, but it will not be possible to further operate the ship on petroleum fuels. In order to meet the "Fit for 55" limits, at least 50% of energy production will have to use carbon-free fuels, and in the case of alternative fuels, their share will have to be around 70-80%.

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