

## Analysis of Replacement of Internal Combustion Engine with the Hydrogen Fuel Cell in Ship Powertrain

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### ABSTRACT

The article presents new propulsion concepts and related new energy sources of modern means of transportation. One of them is hydrogen fuel cells, widely regarded as one of the most promising and alternative solutions due mainly to their ecological nature. Also presented, the biggest problem associated with the development of fuel cells which is hydrogen. A huge energy input is used to produce it. In addition, the storage of hydrogen is highly problematic. With the introduction of increasingly stringent changes regarding toxic emissions into the atmosphere and the move toward emission-free transportation, the article examines the possibilities of converting a ship's reciprocating internal combustion engine propulsion system into an environmentally friendly one. In the rest of the article, legal aspects affecting the reduction of the environmental impact of exhaust emissions in the maritime industry are presented. Examples of fuel cell applications in current means of transportation are also discussed. In the main part of the article, the ship to be converted is presented, along with the planned voyage route. The main engine was converted to alternative electric motors, and a reduction gearbox in the main propulsion system was also selected. The power requirements for converting the ship's propulsion system were then determined. An inverter was selected to convert the generated direct current to alternating current and batteries to store the generated electricity. The final part of the article will analyse the feasibility of converting the propulsion of a Panamax-type bulk carrier with a piston internal combustion engine into an environmentally friendly propulsion system using a hydrogen fuel cell. The analysis will be carried out in terms of cost-effectiveness and technical feasibility. The article ended with conclusions.

**Keywords:** hydrogen fuel cell, unconventional energy sources, ECA zones, ship propulsion.

### INTRODUCTION

Nowadays there are various methods and means of transporting goods, but traditional sea transport is still used on a large scale. Sea transportation is not currently one of the fastest modes of transportation, but it is nevertheless very popular, mainly due to its relatively low prices. This is one of the most important advantages of this method of transporting cargo [1, 2]. Therefore, due to the growing popularity of this mode of transport, alternative propulsion systems are being sought that meet increasingly stringent regulations to protect the environment [3, 4].

Increasingly stringent environmental regulations and rising fuel prices have led to increasing

attention to design and anticipated operating costs when designing new units and retrofitting older ones [5]. Besides, with the development of means of transport, new concepts of their propulsion systems and related new energy sources are being developed [6, 7]. Researchers around the world are working hard to implement new systems and technological solutions [8]. One of them is hydrogen fuel cells, which are now widely regarded as one of the most promising alternative solutions for decarbonising the maritime and world economies due to the possibility of replacement of fossil fuels [9, 10]. A fuel cell produces electricity from fuel supplied continuously. The power fuel is hydrogen, but the wide range of fuel cell capabilities also allows the use of fuel containing a

large amount of this element, such as natural gas or even methanol [11, 12].

The biggest problem before the development of fuel cells is the fuel itself, namely hydrogen. Hydrogen is the fuel of the future, but a huge energy input is used to produce it. In addition, the storage of hydrogen itself is highly problematic, as hydrogen gas stores at a pressure of 250 ÷ 700 bar and it takes a huge amount of additional energy to store it. The second way is to store hydrogen in a liquid state at -240.18 °C (the critical temperature of hydrogen), but like the first way, it needs a large energy requirement to maintain its temperature [13, 14].

The average lifespan of a ship is between a dozen and several decades, and during such a period, increasingly stringent changes are being made regarding the emission of toxic compounds into the atmosphere. In order for a vessel to continue to perform its tasks in the changing reality, it must be constantly modernized and adapted to new conditions.

Accordingly, the purpose of the analysis presented in the article is to test the feasibility of converting the propulsion of a Panamax-type bulk carrier with a piston internal combustion engine into an environmentally friendly propulsion system using a hydrogen fuel cell. The analysis will be carried out in terms of cost-effectiveness and technical feasibility.

## BACKGROUND

### Legal aspects

Maritime shipping was, and still is today, fundamental to the proper functioning of the global economy. Comparing the maritime industry with alternative modes of transportation, the maritime industry has a relatively low impact on environmental pollution, but the impact is still noticeable and assessable in its effects.

Currently, the biggest issue for maritime organizations is the introduction of restrictions that will reduce greenhouse gas emissions. The big hope for shipowners who will have to comply with MARPOL is a nod to hydrogen as an alternative energy carrier.

For this reason, work and research are underway on the use of hydrogen fuel cells to propel ships, including seagoing vessels [16, 17].

The biggest advantage of a fuel cell is that it has high efficiency (depending on the type of fuel

cell, up to 70%) and, what is important nowadays, low environmental harm.

Despite the progress of recent years, the maritime sector still relies almost entirely on fossil fuels and is a significant source of greenhouse gas emissions and other harmful pollutants. For this reason, a preliminary agreement has been signed on the decarbonization of the Fuel EU Maritime sector. The initiative is part of the “Ready for 55” package presented by the European Commission on July 14, 2021 [18, 19].

The intensity of greenhouse gas emissions from energy currently used on ships is to be reduced by promoting the use of cleaner renewable and low-emission fuels by ships calling at EU ports. In doing so, the smooth operation of maritime traffic and the non-disruption of the internal market are to be ensured [20].

### Methods of producing hydrogen and their impact on the environment

For hydrogen to successfully replace, or be one of the alternatives, there is a need to develop a cheap, fast and efficient method to produce it. Currently, 48% of hydrogen is produced by steam reforming of methane, 30% from oil, 18% from coal, and the remaining 4% from the electrolysis of water. The most well-known methods of obtaining hydrogen are: natural gas reforming, coal or coke gasification, plasma technology, water electrolysis, photo electrolysis and biological method [21, 22].

Metaphorically, the colors used to describe hydrogen carry information about how it is produced, the substrates and the energy sources used to obtain it. There are up to 7 distinguished categories/colors, but only three of them are of most interest today, namely grey, blue and green.

Currently, most of the hydrogen comes from natural gas (referred to as grey), but the process also produces a large amount of carbon waste. Most compounds in natural gas contain large amounts of hydrocarbons - hydrogen chemically bonded to carbon. Catalysts can break these bonds, but the excess carbon then forms CO<sub>2</sub>.

The formation of blue hydrogen is based on the same process as grey hydrogen, with the additional capture and storage of carbon dioxide. This eliminates the emissions produced by grey hydrogen and thus the negative environmental impact of hydrogen production. The higher cost of producing blue hydrogen

relative to gray hydrogen is associated with the installation of carbon capture, which is not present in the case of grey hydrogen [23].

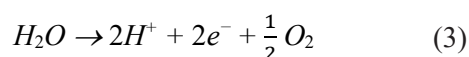
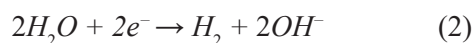
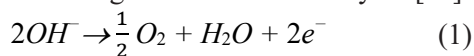
An alternative promoted by major countries is to be blue hydrogen, whose production also relies on gas. However, according to studies conducted at Cornell University and Stanford, the carbon footprint of blue hydrogen, which is derived from natural gas, is up to 60% higher compared to burning diesel fuel. Consequently, the carbon footprint of its production compared to gray hydrogen is only 9–12% lower. The researchers add that when the unabsorbed carbon dioxide is taken into account, as well as the large emissions of unburned methane associated with the use of natural gas during the production of blue hydrogen, the carbon footprint of its production is more than 20% higher than that of burning natural gas or coal [24].

The recommended hydrogen production is green hydrogen production, where only water and energy are needed, but not energy obtained from fossil fuels, but from renewable sources (RES). No carbon dioxide is produced at any stage during green hydrogen production – so it is zero-emission production. Obtaining hydrogen has disadvantages related to low efficiency of 30% resulting in high electricity requirements of 50 kWh/kg of hydrogen. Processes that use RES to produce hydrogen account for a negligible percentage of the global production of this gas, but provide an alternative to processes that use fossil fuels for this purpose. One of the rapidly developing forms of hydrogen production is the process of water electrolysis [23].

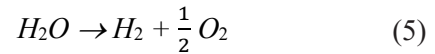
#### Hydrogen extraction from electrolysis

Water electrolysis plays a key role in hydrogen generation based on the use of RES. Electricity supplied to electrolyzers is used to break water into two components - oxygen and hydrogen.

Equations 1 and 2 show the course of reactions on the anode (positive electrode) and cathode (negative electrode) of an alkaline electrolyzer, respectively. Equations 3 and 4 show the reactions occurring on the anode and cathode, respectively, of a proton exchange membrane electrolyzer [15]:



The sum reaction for the electrolysis process of water is presented by the Equation 5:



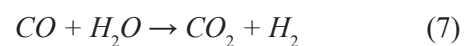
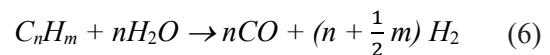
Hydrogen produced by electrolysis has a very high purity, and the process is uncomplicated and easy to operate. However, hydrogen generators using water electrolysis are still expensive devices with relatively low power output in relation to the market demand for hydrogen production. Hydrogen production by electrolysis is only justified if the process is powered solely by renewable energy sources.

#### Hydrogen extraction from hydrocarbon fuels

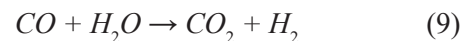
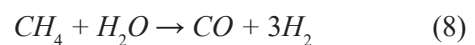
Hydrogen extraction processes from hydrocarbon fuels are based on the use of fossil fuels such as natural gas, oil and coal. At the moment, they are the main source of hydrogen supply for industry. There are three main hydrogen extraction technologies for processes using hydrocarbon fuels: steam reforming, partial oxidation of hydrocarbons (POX) and autothermal reforming (ATR).

#### Steam reforming

About 50% of the hydrogen is obtained by steam reforming of hydrocarbons. The reactions occurring during this process are described by the Equations 6 i 7 [15]:



The most commonly used fuel in the steam reforming process is methane. The reaction equations for the steam methane reforming (SMR) process (8) and (9) are of the form:

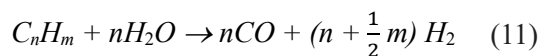
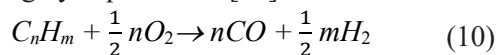


Processing hydrocarbons under such conditions produces significant amounts of pollutants emitted into the atmosphere, including greenhouse gases such as carbon dioxide. It is possible to sequester carbon dioxide through carbon capture and storage (CCS) facilities, which significantly reduces the adverse environmental impact of SMR facilities.

#### Partial oxidation of hydrocarbons

The process of partial oxidation of POX hydrocarbons is another method to produce hydrogen in processes using conventional fuels. The

reactions occurring during catalytic reforming are described by Equation 10, and for non-catalytic reforming by Equation 11 [15]:

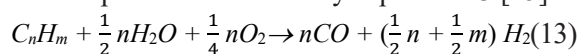


The reactions taking place in the reactor responsible for the conversion of carbon monoxide to CO<sub>2</sub> follow a course analogous to that of the steam reforming process. If the element carbon is inserted into the equations of reactions occurring in the partial oxidation of hydrocarbons, then the equation of reactions occurring in the carbon gasification process, which also plays a significant role in the production of hydrogen, is obtained. This reaction is shown by the relation (12):

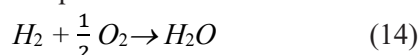


#### Autothermal conversion

For this process, steam and air are fed into the reforming process, and the reactions characterizing the ATR process are shown by Equation 13 [15]:



The essence of the energy conversion process in fuel cells is the direct conversion of the chemical energy of the fuel (hydrogen) into electrical energy. The theoretical efficiency value for typical fuel cells is 83% [15], while the reaction occurring during energy conversion in these devices is shown by the Equation 14.



#### Hydrogen fuel cells in marine and land applications

Fuel cells are seen as one of the most promising solutions for reducing harmful pollution. Already, the technology can power ships sailing short distances, as well as provide an auxiliary energy source on larger vessels. ABB and Hydrogène de France (HDF) plan to jointly produce megawatt fuel cell systems capable of powering ocean-going ships [25].

The first example is the hydrogen plant together with the LNG-fueled plant on the Viking Lady ship designed by Wärtsilä. The fuel cell system can operate in parallel with conventional propulsion and relieve the energy burden on generators. During periods of low energy demand, this system can replace the operation of auxiliary engines [26]. Another application is the use of fuel cells to produce

electricity to power a shunting locomotive. This allows it to perform its operating tasks close to a hydrogen refueling station. The locomotive is equipped with a fuel cell module, hydrogen tanks and energy batteries [27].

Applications of the hydrogen system show the direction in which the entire maritime industry and other non-maritime industries are heading. At the moment, the hydrogen installation is not sufficiently developed to fully base ship propulsion on it, but in the near future seagoing ships should be powered by hydrogen. For the moment, only tugboats in ports and shunting locomotives are pioneering examples, which are used to work in close proximity to hydrogen refueling stations or access to hydrogen bottle swaps [28, 29].

#### CONVERSION OF CONVENTIONAL PROPULSION TO HYDROGEN PROPULSION OF A PANAMAX BULK CARRIER

The ship selected for conversion was the bulk carrier of Polish Shipping “Giewont”. It is a Panamax-type bulk carrier, which is mainly designed to carry dry-type bulk cargoes or semi-bulk cargoes by means of transmission belts, pumps, etc. It also transports coal, soybeans, rye, timber, etc. The basic parameters of the ship are shown in Table 1, while a graphic depicting the ship is shown in Figure 1.

#### Duration of the cruise

The ship’s route as adopted is entirely within the ECA control zone, according to the initial assumptions. The ship on the route Gdansk – Oslo has 540 nautical miles to travel. The ship’s full voyage is shown in Figure 2.

**Table 1.** Basic information of the ship m/v Giewont [30]

Vessel name	m/v Giewont
Number IMO	9452593
Dimensions	229×32 m
Carrying capacity	79649 tons
Gross tonnage	43506 tons
Vessel type	Bulk Carrier
Engine speed	127 rev/min
Main engine power	11 060 kW
Construction year	2010



Figure 1. Photo of the ship m/v Giewont [30]

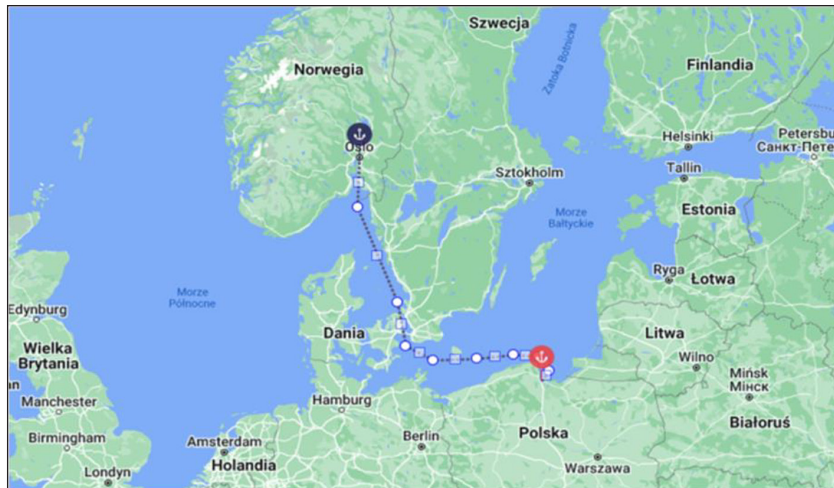


Figure 2. The assumed route of the ship [31]

Equation 15 shows the total duration of the ship’s voyage according to predetermined guidelines [32]:

$$\tau_c = \tau_{jm} + \tau_p = \tau_j + \tau_m + \tau_p \quad (15)$$

where:  $\tau_c$  – total cruise duration [h],  $\tau_{jm}$  – ship’s stay at sea [h],  $\tau_j$  – ship sailing time [h],  $\tau_p$  – ship’s stay in ports [h],  $\tau_m$  – duration of maneuvers at sea [h].

Knowing the vessel’s sailing range, i.e. 540 Mm, the vessel’s sailing time can be calculated from the formula 16:

$$\tau_j = \frac{R}{v_{ex} - \Delta_v} \quad (16)$$

where:  $\tau_j$  – ship sailing time [h],  $R$  – sailing range [Mm],  $v_{ex}$  – operational speed of the ship (assumed 12 kt),  $\Delta_v$  – average speed drop due to worse weather conditions, negative effect of hull entrainment, etc. (for a laden voyage it was assumed  $\Delta_v = 1$ kt).

By substituting data into the formula 16:

$$\tau_j = \frac{540 \text{ Mm}}{12 \text{ kt} - 1 \text{ kt}} = 42 \text{ h.}$$

Thus, the sailing time  $\tau_j$  is 42 hours.

Using Equation 17, we can determine the duration of maneuvers during the entire trip:

$$\tau_m = a_m \cdot \tau_j \quad (17)$$

where:  $\tau_m$  – duration of maneuvers at sea [h],  $a_m$  – maneuvering time factor, depending largely on the number of ports and other variables, etc. (assumed  $a_m = 0.15$ ),  $\tau_j$  – ship sailing time [h].

Substituting the data into the formula, we get (17):

$$\tau_m = 0.15 \cdot 42 \text{ h} = 6 \text{ h}$$

Thus, the duration of the maneuvers is 6 hours.

Another component of time in a ship’s voyage is the time spent in the vessel’s port, we can

calculate this from Equation 18. Of course, this correlation varies with the type of vessel, the modernity of unloading and loading facilities and many other variables:

$$\tau_p = (1 - \alpha_{jm}) \cdot \tau_c = \frac{1 - \alpha_{jm}}{\alpha_{jm}} \cdot \tau_{jm} \quad (18)$$

where:  $\tau_p$  – ship’s stay in ports [h],  $\alpha_{jm}$  – coefficient of the time a vessel stays at sea (for bulk carriers assumed  $\alpha_{jm} = 0.8$ ),  $\tau_c$  – total cruise duration [h],  $\tau_{jm} = \tau_j + \tau_m$  [h].

By substituting the data into Equation 4, it was obtained:

$$\tau_p = \frac{1 - 0.8}{0.8} \cdot 48 \text{ h} = 12 \text{ h}$$

The ship’s total time in port is 12 hours.

Adding up all the components calculated earlier and substituting them into Equation 15, we get the total duration of the voyage:

$$\tau_c = \tau_{jm} + \tau_p = 48 \text{ h} + 12 \text{ h} = 60 \text{ h}$$

Thus, the total duration of the cruise is 60 hours.

Due to the fact that the ship is designed for hydrogen propulsion during the voyage, it should be taken into account that there will be possible inter refueling, but on the chosen route such breaks are not necessary.

#### Actual specific fuel consumption and CO<sub>2</sub> emissions

The fuel with a sulphur content of 0.1% and a density of  $\rho = 863.4 \text{ kg/m}^3$ , which is used in the ECA zones, was accepted for the calculations. The value of the specific fuel consumption of the MAN B&W 7S50MC-C engine, which results from the technical and operational documentation, is  $g_e = 175 \text{ g/kWh}$ . The actual specific diesel consumption was calculated from the formula [32]:

$$g_e^{on} = \beta \cdot g_e \frac{w_d^u}{w_d^{on}} [\text{g/kWh}] \quad (19)$$

where  $\beta$  – coefficient of limiting fuel consumption above the normative value, given and guaranteed by the engine manufacturer,  $\beta = 1.03$  was assumed,  $g_e$  [g/kWh] – specific, nominal consumption of contractual fuel given by the manufacturer of the engine,  $w_d^u$  [kJ/kg] – calorific value of contractual fuel given by the manufacturer of the engine,  $w_d^u = 42700 \text{ kJ/kg}$ ,  $w_d^{on}$  [kJ/kg] – assumed calorific value of diesel oil,  $w_d^{on} = 42600 \text{ kJ/kg}$ .

$$g_e^{on} = 180.67 \text{ g/kWh.}$$

#### Fuel consumption during the cruise

Nominal consumption of light fuel by the main engine ( $G_g^{on}$ ):

$$G_g^{on} = g_e^{on} \cdot N_n^* \cdot 10^{-6} [\text{t/h}] \quad (20)$$

where:  $g_e^{on}$  – actual specific light fuel consumption by the main engine ( $g_e^{on} = 180.67 \text{ g/kWh}$ ),  $N_n^*$  – nominal power of the main engine ( $N_n^* = 11060 \text{ kW}$ ).

After inserting into the formula 23 the nominal fuel consumption is respectively:

$$G_g^{on} = 1.99 \text{ t/h.}$$

With information that this vessel will sail 42 hours on the route Gdansk – Oslo, you can count the fuel consumption:

$$G_g^{on} = 42 \cdot 1.99 \frac{\text{t}}{\text{h}} = 83.58 \frac{\text{t}}{\text{route}}$$

Due to the fact that the vessel operates this route 2 times a week and the year consists of an average of 52 weeks, you can estimate the fuel consumption for a year:

$$G_g^{on} = 83.58 \cdot (2 \cdot 52) = 8692.32 \frac{\text{t}}{\text{year.}}$$

Suppose that the vessel will sail more for 10 years, the fuel consumption has been calculated for this period:

$$G_g^{on} = 8692.32 \cdot 10 = 86923 \frac{\text{t}}{10 \text{ year.}}$$

Assuming the world price of low-sulphur fuel is fixed and amounts to \$600 per ton [33] it is possible to estimate the cost of fuel consumed for a given period (10 years):

$$86923 \text{ t} \cdot 600 \$ = 52153800 \$.$$

To the cost of fuel, you have to add charges related to CO<sub>2</sub> emissions, since shipping is covered by the EU emissions trading system (ETS) as of January 1, 2024. Operating costs for an average bulk carrier emitting about 16000 tons of CO<sub>2</sub>, assuming it trades only between EU ports, will increase by \$1.4 million annually, [34], i.e. \$14 million over 10 years. The total cost of fuel and CO<sub>2</sub> fees is, assuming the price does not change significantly:

$$52153800 + 14000000 = 66153800 \$.$$

#### Calculation of the current level of CO<sub>2</sub> emissions (carbon footprint)

Low-sulphur light diesel, that is used to propel the ship, has density of  $\rho = 863.4 \text{ kg/m}^3$ , therefore:

$$0.863 \text{ kg fuel} = 1 \text{ dm}^3 \text{ fuel}$$

$$G_g^{on} = 86923t = 86923000 \text{ kg,}$$

$$G_g^{on} = 100721900 \text{ dm}^3.$$

According to [35] 1 dm<sup>3</sup> of diesel produces 2.68 kg of CO<sub>2</sub>, so the current level of CO<sub>2</sub> emissions is:

$$\begin{aligned} CO_2 \text{ emissions} &= 100721900 \cdot 2.68 = \\ &= 261745662.56 \text{ kg} = 261745.66 \text{ t.} \end{aligned}$$

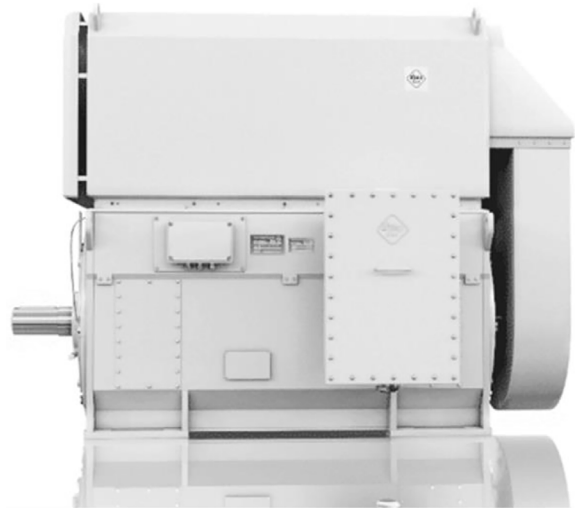
### Main engine and its replacement with alternative electric motors

Variables characterized by a certain range of values were selected to be as close as possible to the tool values MAN & Turbo recommends. The computerized engine application system (CEAS) performs all the necessary calculations, as well as the dimensioning for the main drive, interacting with the installations based on the basic data entered [36]. Based on system-generated calculations and data, the designed fuel cell plant will be converted from the systems, parameters and equipment generated by CEAS for conventional propulsion. The design assumptions are presented in Table 2.

Already knowing the power of the conventional main engine selected by CEAS, alternative electric motors can be selected to serve as the ship’s main propulsion system. The MAN B&W 7S50MC-C main engine generates 11060 kW and has a speed of 127 rpm. Standard electric motors produced in series reach power outputs of up to a few kW, depending on the manufacturer. In this case, to meet the needs of the ship’s engine room and the ship as a whole, it is necessary to select motors that will match the power output of the conventional main engine. Accordingly, based on the calculations of the CEAS program, 2 high-voltage electric motors VYBO 5500 kW H27R shown in Figure 3. were selected, while its basic parameters are shown in Table 3 [37].

**Table 2.** Design assumptions [36]

Engine model	MAN B&W 7S50MC-C
Type of engine supercharging	Conventional (turbocharger)
Load adjustment	High load
Thruster type	4-wing fixed pitch screw
Cooling water system	Central cooling system
Cooling water temperature	25 °C (condition ISO)
Normal working conditions	100%



**Figure 3.** View of the high-voltage electric motor VYBO 5500 kW H27R [37]

**Table 3.** Basic parameters of the VYBO 5500 kW H27R engine [37]

Engine name and model	VYBO 3700 kW H27R
Power	5500 kW
Nominal voltage	3 kV
Frequency	60 Hz
Rotational speed	2900 rev/min

### Reduction gear on the main drive train

Getting rid of the MAN B&W 7S50MC-C diesel main engine and inserting two VYBO 5500 kW H27R electric motors in its place, the reduction gearbox in the ship’s main propulsion system must be modified. In order not to generate additional costs, the main drive system remains unchanged with the only modification being the replacement of the reduction gearbox. The reduction gear must be selected so that the drive system can be driven by two electric motors that operate at 2900 rpm, while the thrust shaft can remain at the optimal speed it was designed for, which is 100–127 rpm. A multi-stage reduction gearbox will ensure the optimum speed of the drive train shaft.

### Power requirements for converting conventional motors to electric motors

The auxiliary engines that were on the ship should be replaced with electric motors powered by fuel cell energy. These engines are deliberately selected independently of the main engines in order to be able to operate independently during operation. In

place of conventional motors, 3 electric motors will be installed, so that, as in the previous application, as many motors can be loaded as electric power is required. Knowing the power of the motor, it is easy to calculate from relation (24) the power of electricity (formula proposed by Michalski) [32]:

$$N_{el} = 0.08912 \cdot N_n + 812.7 \quad (21)$$

where:  $N_{el}$  – estimated power of the ship’s power plant [kW],  $N_n$  – nominal power of the selected main motor [kW], 0.08912 – directional coefficient of the trend line, 812.7 – coefficient resulting from the intersection with the axis of ordinates of the trend line [kN].

Thus, substituting the data from Table 1 into the formula, we get the result:

$$N_{el} = 0.08912 \cdot 11060 \text{ kW} + 812.7 \text{ kW} = 1798.7 \text{ kW}$$

### Fuel cell module

The fuel cell module is intended to replace the main and auxiliary engines on a Panamax marine vessel. In order to select the appropriate module, as well as their quantity, it is necessary to add up the total power produced by one MAN B&W 7S50MC-C main engine and three Wärtsilä 645W4L20 auxiliary engines. For this purpose, the relationship (25) was used:

$$N = N_{el} + N_n \quad (22)$$

where:  $N_{el}$  – estimated power of the ship’s power plant [kW],  $N_n$  – nominal power of the selected main motor [kW],  $N$  – the sum of the power of the main engine and the ship’s power plant [kW].

Substituting the data from relation (22) and the power of the MAN B&W 7S50MC-C main engine, we get the following result:

$$N = 1798.7 \text{ kW} + 11060 \text{ kW} = 12858.7 \text{ kW}$$

Thus, the estimated power of the main engine and the ship’s power plant is 12858.7 kW, for further consideration, the power was taken as 13000 kW.

Knowing a ship’s power requirements makes it easy to select the fuel cell modules needed to convert conventional propulsion to hydrogen propulsion. Ballard offers Ballard’s FC wave fuel modules, which are adapted for use in the marine industry.

One Ballard’s 1000 kW FC wave fuel cell module generates a power rating of 1000 kW, so 13 such modules will be required to meet the ship’s needs, for a total of 13,000 kW. These modules can be

installed in place of the main engine, as the dimension of one such module is 1209×741×2195 mm. An additional advantage of using fuel cells is that more fuel cell modules can easily be added if the ship needs more power. Ballard’s modules are cooled by liquid, more precisely by a mixture of water and glycol in a 50/50 ratio. For this purpose, the existing cooling system of the main engine can be successfully used. Thus, if the average hydrogen consumption for a 1000 kW module is 16 ÷ 18.6 kg/h [38], so from the simple relationship (26), you can calculate the hydrogen consumption for all modules [38]:

$$G_{wm} = 13 \cdot G_{jm} \quad (23)$$

where:  $G_{wm}$  – average hydrogen consumption of all fuel cell modules [kg/h],  $G_{jm}$  – average hydrogen consumption of one fuel cell module [kg/h].

So, substituting the data into equation (26), we get the result:

$$G_{wm} = 13 \cdot 16 \frac{\text{kg}}{\text{h}} = 208 \frac{\text{kg}}{\text{h}}$$

and

$$G_{wm} = 13 \cdot 18,6 \frac{\text{kg}}{\text{h}} = 241,8 \frac{\text{kg}}{\text{h}}$$

The average hourly hydrogen consumption at rated power by all ship modules is 208 ÷ 241.8 kg/h, which is approximately 208 ÷ 242 kg/h.

### Hydrogen storage tanks

Referring to the introduction in the article, it can be noted that hydrogen is a problematic medium for transportation as well as storage. In order to convert conventional propulsion to hydrogen propulsion, heavy fuel oil (HFO) and marine diesel oil (MDO) fuel tanks will prove unnecessary. They will be able to serve as additional ballast tanks, or in the future with the development of the hydrogen storage system converted to hydrogen storage tanks.

On the ship, the first cargo hold will have to be adapted to store hydrogen storage. The hold is an ideal location, as the hydrogen tanks, according to the PRS regulation, should be located away from the entire hydrogen cell installation. Dutch company H2 storage has standard shipping containers with hydrogen storage tanks in its offer. The composite hydrogen storage cylinder is manufactured from resin and carbon fiber. As assured by the manufacturer, such a solution



provides greater storage capacity relative to steel and aluminium tanks.

A shipping container with standard dimensions of 1200cm×260cm×239cm will be equipped with 100 such cylinders. The entire container will be capable of storing 1400 kg of hydrogen stored at 700 bar. The containers can be connected in series through the manufacturer’s specially adapted installation, providing a large fuel buffer on board. The only limitation is the payload capacity of the containers on the ship. A cross-section of the entire container is shown in Figure 4 [39].

Already knowing the possibility of storing hydrogen in shipping containers, one can proceed with calculations. One container can store 1400 kg of hydrogen. Based on the results from the previous calculations according to formulas (21) and (26), it is possible to calculate the hydrogen demand for the entire duration of the voyage from relation (27). The upper limit of the average hourly hydrogen burn will be used for the calculation to ensure an adequate safety buffer.

$$G_{cr} = \tau_c \cdot G_{wm} \tag{24}$$

where:  $G_{cr}$  – average hydrogen consumption during the entire voyage [kg],  $\tau_c$  – total cruise duration [h],  $G_{wm}$  – average hydrogen consumption of all fuel cell modules [kg/h].

The upper limit of the average hourly hydrogen combustion will be used in the calculations to provide an adequate safety buffer. By substituting the previously calculated data into Equation 27, we get the following:

$$G_{cr} = 60 h \cdot 242 \frac{kg}{h} = 14520 kg$$

Thus, the average hydrogen consumption during the entire cruise is 14 520 kg. Then, from a

simple calculation (28), the number of hydrogen containers to be placed in the hold for the duration of the voyage can be calculated:

$$L_k = \frac{G_{cr}}{W_{wk}} \tag{25}$$

where:  $L_k$  – number of containers,  $G_{cr}$  – average hydrogen consumption during the entire voyage [kg],  $W_{wk}$  – weight of hydrogen in one container [kg].

By substituting the data into Equation 28, we get the result of the number of containers:

$$L_k = \frac{14520 kg}{1400 kg} = 10.38$$

The number of containers needed to meet the ship’s hydrogen needs is approximately up to the top figure gives 11 containers of hydrogen.

Of course, the number of hydrogen containers may change during different routes of the ship. The value given was calculated on the basis of the Gdansk-Oslo route.

#### Hydrogen consumption and CO<sub>2</sub> emissions

Due to the fact that the ferry operates this route 2 times a week and the year consists of an average of 52 weeks, you can estimate the hydrogen consumption for a year:

$$G_{cr} = 14.52 \cdot (2 \cdot 52) = 1510.08 \frac{t}{year}$$

Suppose that the vessel will sail yet for 10 years, the hydrogen consumption has been calculated for this period:

$$G_{cr} = 1510.08 \cdot 10 = 15100.8 \frac{t}{year}$$

Assuming the world price of hydrogen is fixed and amounts to 2\$ per kg [40] it is possible to estimate the cost of fuel consumed for a given period (10 years):

$$15100.8 \cdot 2000 = 30201600 \$$$



Figure 4. Cross-section of a hydrogen storage shipping container from H2 storage [39]

The total CO<sub>2</sub> emissions from hydrogen consist of production, storage and transportation.

The production of one ton of hydrogen generates about ten tons of CO<sub>2</sub>[41], therefore:

$$[\text{CO}_2]_{\text{production}} = 15100.8 \cdot 10 = 151008 \text{ t.}$$

Currently, 76% of the hydrogen sourced is gray hydrogen sourced from fossil sources by which they contribute to high greenhouse gas emissions (including CO<sub>2</sub>). After hydrogen is produced, it has to be stored and transported to the end-users. Currently, two storage methods exist, physical hydrogen storage (high-pressure hydrogen storage, liquid hydrogen storage and cryo-compressed hydrogen storage) and chemical hydrogen storage.

On the ship, the hydrogen will be stored in tanks in gaseous form, for which, during storage and transport, CO<sub>2</sub> emissions are, according to [42], about 500 kg of CO<sub>2</sub> per ton of hydrogen per 100 km. The ship has a distance to travel of 540 Mm, or 1,000 km. This means that CO<sub>2</sub> emissions along this route will be 5 t per ton of hydrogen and eventually:

$$[\text{CO}_2]_{\text{storage + transport}} = 15100.8 \cdot 5 = 75504 \text{ t.}$$

$$[\text{CO}_2]_{\text{p+s+t}} = 151008 + 75504 = 226512 \text{ t.}$$

### Inverter to convert direct current to alternating current

An inverter is an electrical device that converts direct current into alternating current. Fuel cells produce direct current, but the entire electrical system on the ship and all the electric motors run on alternating current, so the hydrogen system needs the aforementioned inverter. The device will be selected for hybrid operation, i.e. with batteries and the ship's power grid. Knowing the power of the fuel cell modules from relation (10), we can calculate which inverter should be used on the ship [43]:

$$0.7 \cdot P_{\text{MAX(MOD)}} < P_{\text{NOM(INV)}} < 1.2 \cdot P_{\text{MAX(MOD)}} \quad (26)$$

where:  $P_{\text{NOM(INV)}}$  – converter power [kW],  $P_{\text{MAX(MOD)}}$  – power of fuel cell modules [kW].

Knowing the total power of the fuel cell modules calculated relation 6, we get the condition 10:

$$0.7 \cdot 1300 \text{ kW} < P_{\text{NOM(INV)}} \text{ kW} < 1.2 \cdot 1300 \text{ kW},$$

$$9100 \text{ kW} < P_{\text{NOM(INV)}} \text{ kW} < 15600 \text{ kW}.$$

Based on these calculations, an inverter from INGECON SunPowerstation CON40 NA/NA/FA was selected. It is a power station with a maximum capacity of 4920 kVA, i.e. 3936 kW, equipped with a transformer and electrical switchgear. The most important aspect is the possibility of installing several such inverters in one installation. Figure 5 shows the selected inverter in the form of a shipping container. The ship will require three INGECON SunPowerstation CON40 NA/NA/FA inverters, which will operate in parallel [43].

### Batteries in the hydrogen system

Knowing the energy requirements of the ship, it is necessary to select the appropriate batteries and their capacity. The task of batteries in a ship's hydrogen system is mainly to secure the ship in electricity in the event of a total failure of the fuel cells. In addition, the batteries will compensate for temporary energy requirements.

The voltage that the fuel cells will generate is 650 VDC, so the 12-volt batteries will be connected in series, resulting in a summation of voltages while maintaining the original capacity. In order to extend the life of the batteries, their capacity should be doubled to avoid deep discharge. Connecting 54 batteries in series will result in a rounded 650 volts.



Figure 5. Station view INGECON SunPowerstation CON40 NA/NA/FA [43]

Formula 11 allows you to calculate the capacity of the batteries:

$$C = \frac{2 \cdot (N \cdot \tau_c)}{U} \quad (27)$$

where:  $C$  – battery capacity [kAh],  $N$  – the sum of the power of the main engine and the ship’s power plant [kW],  $\tau_c$  – total cruise duration [h],  $U$  – system voltage [V].

When substituted into the formula, we get:

$$C = \frac{2 \cdot (13000 \text{ kW} \cdot 60 \text{ h})}{650 \text{ V}} = 2400 \text{ kAh}$$

Based on the calculated capacity, a 12 kWh lithium-iron-phosphate battery from Fronius Solar Battery was selected. The battery is characterized by short charging time, possible deep discharge, which is important for battery life. Fronius assures that it can select the parameters of the battery for a specific project on special request. A block diagram of the hydrogen system created for a Panamax-type ship, using all the selected components, is shown in Figure 6.

### ANALYSIS OF THE POSSIBILITY OF USING A HYDROGEN FUEL CELL TO PROPEL A PANAMAX BULK CARRIER

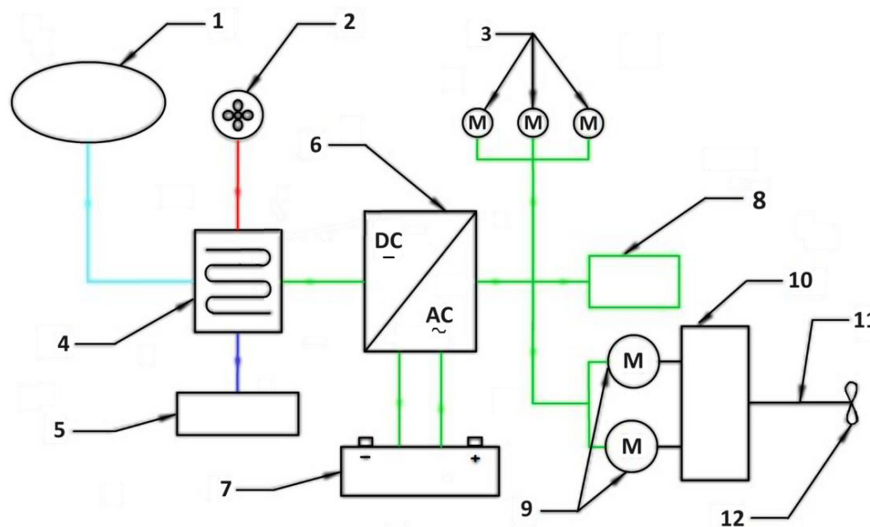
#### Technical analysis

The ship’s route as adopted is entirely within the ECA control zone. The ship on the route Gdansk - Oslo has 540 nautical miles to

cover. The total duration of the voyage with sailing time, with maneuvering and stopping in port is 60 hours. Due to the fact that the ship is designed for hydrogen propulsion during the voyage there may be possible inter refueling, but on the chosen route such breaks are not necessary. Knowing the power of the conventional main engine, alternative electric motors were selected to serve as the ship’s main propulsion system. The main engine generates 11060 kW of power, and its speed is 127 rpm. To meet the needs of the ship’s engine room and the ship as a whole, 2 high-voltage electric motors were selected to match the power output of the conventional main engine. The auxiliary engines that were on board the ship are to be replaced with electric motors powered by fuel cell energy. These motors are deliberately selected independently of the main engines in order to be able to operate independently during operation.

In place of conventional motors, 3 electric motors will be installed so that, as in the previous application, as many motors can be loaded as electric power is needed.

The fuel cell module is designed to replace the main and auxiliary engines on a ship. In order to select the right module, as well as their number, it is necessary to add up the total power produced by one main engine and three auxiliary engines. To meet the needs of the ship, 13 such modules will be required, which will have a total power output of 13,000 kW. These modules can be installed in place of the main



**Figure 6.** Block diagram of hydrogen system on Panamax ship: 1 – hydrogen tanks, 2 – air blower, 3 – electric electric motors, 4 – hydrogen fuel cell module, 5 – water tank, 6 – DC to AC inverter, 7 – batteries, 8 – other energy consumers, 9 – electric main engines, 10 – gearbox, 11 – propeller shaft, 12 – propeller, cyan – hydrogen, red – air, blue – water, green – electricity, black – shaft line

engine. Ballard’s modules are cooled by liquid, more precisely by a 50/50 mixture of water and glycol, and the existing cooling system of the main engine can be successfully used for this purpose.

The ship will need to adopt the first hold for hydrogen storage space. The cargo hold is an ideal location because the hydrogen tanks, according to the PRS regulation, should be in a place away from the entire hydrogen cell installation.

A sea container of standard dimensions will be equipped with 100 such cylinders. The entire container will be able to store 1,400 kg of hydrogen stored at a pressure of 700 bar. The containers can be connected in series through the manufacturer’s specially adapted installation, providing a large fuel buffer on board. The only limitation is the cargo capacity of the containers per ship. The number of containers needed to provide the ship’s hydrogen needs is approximately 11 containers of hydrogen.

It is also necessary to install an inverter, which converts direct current into alternating current. The power station will be equipped with a transformer and electrical switchgear. The most important aspect is the possibility of installing several such inverters in one installation. The unit will be sized for hybrid operation, i.e. with batteries and the ship’s power grid. Knowing the energy requirements of the ship, it is necessary to select the appropriate batteries and their capacity. The task of batteries in a ship’s hydrogen system is mainly to secure the ship in electricity in the event of a total failure of the fuel cells. In addition, the batteries will compensate for temporary energy requirements.

The voltage that the fuel cells will generate is 650 VDC, so the 12-volt batteries will be connected in series, resulting in a summation of voltages while maintaining the original capacity. In order to extend the life of the batteries, their capacity should be doubled to avoid deep discharge. Connecting 54 batteries in series will result in a rounded 650 volts.

Most of the hydrogen system’s equipment can be installed in place of existing ship power plant equipment. The main problem is hydrogen transportation and storage. Unfortunately, the HFO and MDO fuel tanks will be redundant after conversion. They can then serve as additional ballast tanks, or

in the future with the development of the hydrogen storage system converted to hydrogen storage tanks.

A major advantage of the solution of the hydrogen system on a ship is the possibility of expansion and continuous modification of the system. If the type of use of the ship changes and the energy demand of the ship increases, the energy potential of the installation can easily be increased by adding hydrogen tanks, fuel cell modules, batteries, inverters and electric motors one by one.

### Economic analysis

For the economic analysis, among other things, a comparison was made between fuel costs, namely light diesel and hydrogen. For diesel fuel, costs related to CO<sub>2</sub> emissions were also added. Further analysis focused on the aspect of converting a ship from conventional propulsion to alternative propulsion. The article analyzes selected environmental aspects, particularly those related to hydrogen, production and its application as a fuel. To this end, methods of producing hydrogen and their environmental impact were compared. CO<sub>2</sub> emissions from burning fossil fuel and CO<sub>2</sub> emissions from hydrogen production, storage and transportation were calculated. Additional costs were added to the price of diesel fuel due to CO<sub>2</sub> emissions as a fossil fuel, while the use of hydrogen for ship propulsion, regardless of the method of production, does not involve such charges.

The economic analysis of the transformation of a ship from conventional propulsion to hydrogen propulsion poses quite significant problems. Unfortunately, the total cost of such a conversion is not known at the moment. The construction of a conventionally powered Panamax-type bulk carrier costs about \$30 million (according to the price list for bulk carriers in force according to the date of access) [44]. By analogs to existing means of transport and far-reaching simplification, it can be assumed that the construction of such a hydrogen-powered vessel may cost the shipowner about \$60 million. The estimated total cost during the 10-year operation of the vessel, depending on the chosen solution, is presented in Table 4. From

**Table 4.** Comparison of costs during the ten-year operation of the vessel

Type of fuel used to propel the ship	Estimated cost [mln \$]	CO <sub>2</sub> emissions [t]
Conventional drive (low-sulfur fuel)	66	261746
Alternative propulsion (hydrogen)	30	226512
Alternative drive (conversion)	30	-

the data in the table, it can be deduced that if the ship is 15 years old and has 10 years left to scrap, the cost of operation is similar. This is because the cost of conventional fuel along with CO<sub>2</sub> emission fees will be similar to the cost of rebuilding and then operating a hydrogen-powered ship. One must also take into account that the cost of conversion is an estimate, in addition to the fact that over the next few years the price of diesel fuel will increase and hydrogen will decrease, as cheaper methods of producing it develop. Despite hydrogen being produced primarily from natural gas, CO<sub>2</sub> emissions are still 14% lower than those from burning fossil fuels. Of course, developing non-fossil fuel methods of hydrogen production will make these emissions even lower. To fully assess the sensibility of converting a ship to alternative propulsion, it is also necessary to consider the depreciation costs of both a conventionally propelled ship and a ship with a new propulsion system. As for conventional propulsion, the basic depreciation rate for floating fleets is 7% per year [45], while there is no depreciation data for marine vessels, as it is only in the development stage.

As can be inferred from the above analysis, this conversion is not too challenging or problematic from a technical point of view. Certainly, the adaptation of a several-year-old bulk carrier to a hydrogen fuel cell system requires a great deal of work and numerous structural changes. In addition, and very importantly from the point of view of the function performed by the ship, it will be necessary to arrange one hold for containers with stored hydrogen. With the ship's lifespan averaging about 20–25 years, it is currently unknown whether this conversion will be economically justified, as this depends mainly on fuel prices. Environmentally, the conversion makes sense, because even for hydrogen derived from natural gas, CO<sub>2</sub> emissions will be lower. In general, a ship of this size and purpose should be designed with a hydrogen system in mind at the very beginning of its design. Otherwise, the cost of adaptation and the amount of work unfortunately, but may be commensurate with the revenue the ship can generate.

The ship-owner should decide which of the emission reduction methods presented in the article is the optimal solution. The choice of one of them should be influenced by, among others: the route covered by that vessel, environmental conditions, the ability to adjust the structure, the

age of the ship, and in the case of hydrogen fuel, the availability of fuel. In addition to the main advantage which is to reduce the emission of toxic compounds to the atmosphere, ship conversion has some disadvantages, mainly of a financial nature, that ship-owners should take into account.

## CONCLUSIONS

The purpose of the above work was to analyze the feasibility of using a hydrogen fuel cell to propel a Panamax-type bulk carrier sailing in the ECA special control zone. The proposed solutions have considerable energy and environmental potential, which in the not-so-distant future may find wide application in both the marine and industrial sectors.

ECA zones already have strict rules regarding the combustion of heavy fuels, and these rules will become increasingly stringent in the future. The installation of hydrogen on ships in the future may become an everyday occurrence due to its environmental as well as economic aspects.

Adapting a bulk carrier that is several years old to a hydrogen fuel cell system requires an enormous amount of work, numerous structural changes, and the arrangement of one cargo hold for containers with stored hydrogen. Given that the ship's lifespan averages about 20÷25 years, this procedure may not be economically justified. Ideally, a ship of this size and purpose should be equipped with a hydrogen system from the beginning of construction. Otherwise, the cost of adaptation and the amount of work unfortunately may prove to be disproportionate to the revenue the ship can generate.

The cost of operating the vessel will be similar, as the purchase price of conventional fuel plus CO<sub>2</sub> emission fees will be similar to the cost of converting and then operating a hydrogen-powered vessel.

Based on current trends, it can be concluded that in the long run, the operation of a hydrogen-powered ship will be lower than that for a conventionally powered ship, as the price of diesel fuel and CO<sub>2</sub>-related allowances will increase in the coming years, while hydrogen will decrease especially with the development of cheaper methods of producing it.

Considering that hydrogen is currently produced primarily from natural gas, CO<sub>2</sub> emissions are still 14% lower compared to those resulting from burning fossil fuel. Of course, developing non-fossil fuel methods of hydrogen production

will make these emissions even lower. Despite the aforementioned disadvantages of converting to hydrogen propulsion on a seagoing vessel, hydrogen technology is becoming increasingly popular and attractive. The environmental benefits of this conceptual design are crucial for the entire industry, which is why all major maritime companies are intensively developing their offerings because they see the potential that exists in hydrogen.

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