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Marine fuel from the past to the future

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Abstract

Currently, about 90% of world transport is via water, which means that maritime transport is a decisive factor in the development of civilization. In order for it to effectively continue and compete with other means of transport, it is necessary to use the cheapest marine fuels on ships. The demand for machines generating mechanical energy to propel ships resulted in their dynamic development and, simultaneously, forced the search for primary energy sources (fuels) that enable the production of the working medium. The era of coal and petroleum fuels began in the 19th and 20th centuries, respectively. Today, in the 21st century, we stand at a crossroads – what next? The transition fuel will likely be LNG and biofuels. Ammonia will also occupy a significant share of the fuel market, but the target fuel will be hydrogen. Based on historical and contemporary sources, this article discusses the changes in the use of marine fuels that have occurred since the 19th century.

Introduction

Coal, as a source of thermal energy, has been known to mankind for many centuries. The famous merchant and traveler Marco Polo in the 13th century, after his journeys to the Far East, wrote about black stones that were burning, but the Europeans of that time did not believe him. Due to the process of deforestation in Europe, hard coal began to be used increasingly more widely. The first industrial revolution at the turn of 18th and 19th centuries contributed to this, which required the use of coal to produce steam as a working medium.

At the end of the 19th century, people became interested in the possibilities of processing crude oil and obtaining kerosene, lubricating oils, and then diesel and gasoline from it. Refineries were built and started to specialize in the production of fuels. Due to the inconvenience of coal transport, and its lower calorific value compared to petroleum-derived fuels, the oil era began at the beginning of the 20th century and continues to this day.

The increase in the concentration of carbon dioxide in the atmosphere, observed since the 1980s and the observation that it may be related to climate change on Earth, made it necessary to look for alternative fuels that contain no or less carbon in the waste molecules. There was also an interest in biofuels as renewable fuels. The fuels that need reducing included coal, petroleum fuels, and even natural gas and propane-butane (fossil fuels).

As a ship fuel, the era of coal began around 1800 and ended around 1950. Whereas the era of petroleum fuels began around 1900, and continues to this day, but its decline is to be seen around 2050. This would mean that both eras would last about 150 years. Currently, there is another revolution in the energy market, including marine fuels, which will end in about 30 years, when oil resources are exhausted and the competition will be won by one or several fuels that will be better in terms of ecology (i.e., the impact on the natural environment). Illustrative changes in the use of marine fuels are shown in Figure 1.

The demand for energy is growing every year at the rate of 3–5%. In 2021, world energy consumption was estimated at $595.15 \cdot 10^{18}$ J (595.15 Exajoules) (BP, 2022). In 2021, about 370 million tons of marine fuel were used in maritime transport. This is about $14.8 \cdot 10^{18}$ J in absolute terms and about 2.5% of the world's energy consumption (IEA, 2021). To support the development of civilization, it is necessary to find energy sources that ensure further development. One of the basic conditions is the lowest possible price (Ship & Bunker, 2022). The repeatedly observed increase in energy costs (i.e., the fuel crises) caused an economic slowdown but, fortunately, it did not cause long-term collapses. Figure 1 presents an illustrative share of primary energy sources in maritime transport in the years 1800–2050.

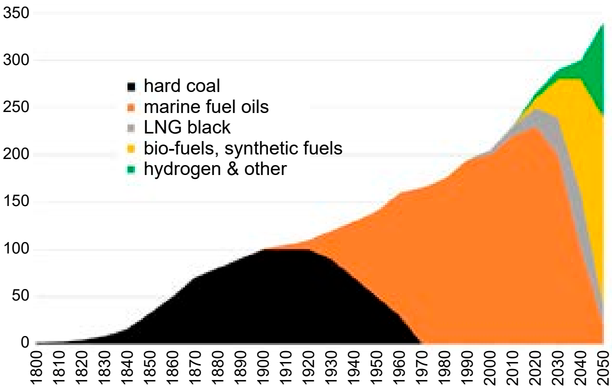

Figure 1. Illustrative share of primary energy sources in marine transport in the years 1800–2020 and forecasts for 2030–2050

Materials and methods

This article uses available historical literature on the energy sources available at that time and the development of engines producing mechanical energy. With the development of industry and transport, there has been a significant increase in energy demand. This has resulted in the search for new and more efficient energy sources, resulting in the use of fuels derived from crude oil and natural gas. The progressive development of heat engines with ever greater efficiency and available power was also indicated. The turn of the 19th and 20th centuries marked the beginning of the rapid development of electricity sources (thanks to the inventions of Edison and Tesla) and the advent of the electricity era. The dynamic development of new designs of heat engines went hand-in-hand with the growing demand for primary energy sources. Attempts were made to use nuclear energy for peaceful purposes (i.e., nuclear power plants), which occurred in the 1950s. On the basis of the changes taking place, which are reflected in the bibliography and the author's professional experience, an assessment of the changes is made and an attempt is made to propose what the future would bring. The considerations in this article mainly concern marine fuels and there may be differences in the case of analyzes concerning all energy sources used worldwide. There is a specificity of sea transport that requires meeting additional requirements. For fuels, it is now a requirement to have as little greenhouse gas emissions as possible after the combustion process, mainly carbon dioxide and nitrogen oxides. For this purpose, the CO_2 equivalent emission factor is determined.

Results

Requirements for marine fuels

One of the basic requirements for marine fuels is their availability. This means that fuel should be available in practically every port at a price similar to the average in other ports. This allows for the ordering, buying, and storing of enough fuel to reach the next port without having to build up supplies (additional storage costs, greater draft, increased resistance to sail, and increased fuel consumption). This enables the ship to have an enlarged cargo section. Despite the certain (required) autonomy of sailing, the amount of fuel on the ship is limited as much as possible. The second important requirement is the high calorific value of the fuel per unit of mass. This allows for the limiting of space (volume) for fuel reserves. Table 1 compares selected fuel parameters in the 19th century, while Table 2 provides those available in the 20th century.

In use at the time was a lower quality boiler fuel, but the unification of the marine power plant as mono-fuel (unifuel) in the 1980s and 1990s meant that the same fuel was used to drive main, auxiliary engines and supply the boilers.

The lack of a distribution network, or the possibility of bunkering in the ports of other potential marine fuels (liquefied natural gas – LNG, liquid petroleum gas – LPG, methanol, ethanol, and other biofuels), significantly limits the availability of these fuels, which slows down the process of switching to new, more ecological fuels (Chevron, 2022).

Table 1. Comparison of selected parameters of solid fuels

Parameter	Fuel		
	Dry wood (chips)	Lignite	Hard coal
Bulk density [kg/m^3]	300–600	700–900	800–950[1]
Lower calorific value [MJ/kg]	14–16	5.9–23.9[2]	22–28
Preferred mode of transport	Conveyor belt	Conveyor belt	Conveyor belt or crane grapple

[1] Real density 1200–1400 kg/m^3, silicates and carbonates as a coal contamination 2600–2800 kg/m^3.

[2] Adsorbs water, hygroscopic.

Table 2. Comparison of selected parameters of liquid marine fuels in 20th century

Parameter	Fuel		
	Marine gas oil	Marine diesel oil	Heavy fuel oil
Density at 15°C [kg/m^3]	820–850c	830–890	870–1050
Lower calorific value [MJ/kg]	42–43	41–42	39–41
Mode of bunkering	Pumping through pipelines, bunkers, road and rail cisterns	Pumping through pipelines, bunkers, road and rail cisterns	Pumping through pipelines, bunkers
Temperature of bunkering	Ambient, above −10°C	Ambient, around 20°C	Around 50°C

The type of marine fuel used is significantly influenced by legal regulations related to environmental protection and the emission of harmful substances into the atmosphere in the exhaust gases, but the most important will be the price of the primary energy unit due to the significant share of fuel costs in the ship's operation. Changes in fuel prices (energy carriers) in the world markets have an impact on the shipping market. The fuel crisis of 1973–1974, and the significant increase in crude oil prices, caused far-reaching changes in ship propulsion, forcing the use of engines with higher efficiency and lower specific fuel consumption. Basically, from this period, one can point to a sharp withdrawal from the use of steam turbines in marine propulsion.

The unit price of energy contained in future marine fuels will have a decisive influence on the ship owners' decision to switch to a given fuel. At the moment, this is a great unknown that places shipowners in a difficult position to make decisions affecting economic results (MOL, 2022). Changing the type of fuel used on a ship to another type is always associated with serious costs of rebuilding the ship's fuel system and adapting the engines to a different type of fuel. It also requires additional training of ship crews.

Factors that determined the transition to other fuels

Hard coal as a ship fuel has a number of disadvantages. The main problem is its transport to the port, loading it into a bunker on the ship and then moving it to be manually delivered to the furnace of the steam boiler. It is troublesome and requires a lot of work, including manual work. It has a calorific value of 22–28 MJ/kg, which is about 60% of the value for marine fuels derived from crude oil processing. Coal dust creates a risk of spatial explosion. Such events occurred most often in boiler furnaces, but fires in bunkers also occurred (the coals are prone to spontaneous combustion). Liquid fuels do not have most of these mentioned disadvantages. They can be transported by pipelines that ensure tightness. Fuel transport processes can be automated. They require much less work. Despite the significant complication of liquid fuel systems, appropriate requirements were developed to ensure the safety of transport operations, their cleaning, and delivery to engines. The transformation from solid to liquid fuel took place in a short time. Attempts at the gasification of coal and the production of liquid fuels were established during World War II but were not further developed after its end. Despite much greater coal resources than crude oil resources, the processes of producing liquid or gaseous fuels from coal are not going to change this trend. There remains the problem of what to do with the carbon monoxide and dioxide produced in the process.

Typical liquid marine fuels in the 20th century were marine gas oil (MGO), marine diesel oil (MDO), and heavy fuel oil (HFO), which have a high calorific value of 39–43 MJ/kg with a relatively high density in the range of 820–1050 kg/m^3 (Table 2). They are stored in atmospheric tanks with venting pipes connected to the atmosphere. In the storage tanks, only the HFO is heated to a temperature of about 50°C in order to pump this fuel between the tanks.

The regulations adopted by the IMO are intended to significantly reduce carbon dioxide emissions from maritime transport (IMO, 2018a; IMO, 2018b; IMO, 2019). The goal is to reduce carbon equivalent emissions by 55% by 2050 (*Fit for 55*). This means that the consumption of petroleum-derived fuels should decrease by at least 85% by this year. Since around 2000, it has been preferable to switch to liquefied natural gas as a marine fuel. This option is used by gas carriers for LNG transport, as they use gas (boil-off gas, BOG) as fuel, which has evaporated in the cargo space. Thanks to this, the ship does not need to have a system for re-liquefying gas, which, due to the increase in pressure in the cargo tanks, had to be redirected from the tank for further processing (heating and compression) to be used as fuel. For the largest gas carriers, installations for condensing surplus are built, which cannot be used in energy devices of the ship power plant.

LNG appears to be a transition fuel. In the process of its combustion, the emission of carbon dioxide is about 30% lower, but due to possible leaks from fuel systems and the occurrence of periodic misfires in the engine cylinder (e.g., when changing the engine load), methane gas leaks into the atmosphere. A leakage (slip) of about 1.5% of methane reduces the environmental benefit of using LNG as a fuel (Herdzik, 2018). It is impossible to achieve the goal set by IMO (*Fit for 55*). On the other hand, it should be emphasized that the use of methane obtained from biological processes, i.e., biomethane, is recognized as an ecological fuel, the actual CO_2 emission of which is not included in the emission to be reduced. Chemical synthesis of methane was attempted using carbon dioxide captured from flue gases from other industrial processes, known as synthetic methane. An assessment of how to treat the final CO_2 emissions to the atmosphere from the combustion of synthetic methane remains an issue for further discussion.

Potential marine fuels that could replace the currently used petroleum fuels are being sought (Herdzik, 2021). Especially biofuels such as methanol, ethanol, and fatty acid methyl esters (FAME) are considered. The main barriers to their use will be their availability on the marine fuel market and then their price. Potential fuels that do not contain elemental carbon in the molecule are also considered. Research on the use of ammonia has been undertaken, which confirmed the possibility of its use under certain conditions, but it is technically possible. There remains the problem of green synthetic ammonia production technologies that currently do not meet the conditions to compete with petroleum fuels when analyzing the ecological effects of well-to-wake. Once the technical feasibility of using ammonia as a marine fuel has been verified, it will be used as a transition fuel with a market share of

Table 3. Selected parameters of the current and potential marine fuels and their availability

Parameter	Type of fuel				
	Heavy fuel oil HFO	Methanol	Fatty acid methyl esters FAME	LNG black/bio/synthetic	Ammonia
Lower calorific value [MJ/kg]	39–41	20–23	43	48–52	18.6
Density at 15°C [kg/m^3]	900–1050[1]	794	765	442–470[2]	638.6[3]
Physical state at 15°C	Liquid[1] (liquid fuel)	Liquid (liquid biofuel)	Liquid (liquid biofuel)	Liquid[2] (gas fuel)	Liquid[3] (gas fuel)
Distribution network	Exists, available, checked	Network does not exist, infrastructure development	Network does not exist, infrastructure development possible, limited capacity to cover the demand	Only in selected ports, bunkering procedures according to the IGF code	Does not exist, unavailable, no bunkering procedures
Type of fuel storage tank on a vessel	Atmospheric tank, connection to the atmosphere with a vent pipe	Atmospheric tank, protected by the pressure-vacuum valves	Atmospheric tank, connection to the atmosphere with a vent pipe	Atmospheric tank, protected by pressure-vacuum valves or a pressure tank with a safety relief valve	Atmospheric tank, protected by pressure-vacuum valves or a pressure tank with a safety relief valve

[1] at temperature 50°C.
[2] at temperature −161.5°C, should be below the critical temperature of −82.45°C.
[3] at temperature −33.4°C, it may be a liquid up to a critical temperature of +132.41°C.

around 20% for marine fuels, but its importance will decrease after switching to hydrogen fuel using fuel cells. The combustion of fuels in heat engines is accompanied and will be accompanied by the emission of harmful substances into the atmosphere, mainly in the form of nitrogen oxides. Therefore, fuel cells seem to be the solution we are waiting for. Selected parameters of the current and potential marine fuels are shown in Table 3.

Hydrogen, which appears to be the ultimate marine fuel, is not essentially a primary fuel. It can be produced by many processes. Its generation can be justified by the use of excess electricity production from renewable sources (wind farms, photovoltaics, sea currents, and sea waves) as a way to store energy. Due to the limited efficiency of heat engines, it seems advisable to use it in fuel cells. The development of technologies for hydrogen generation, its storage, and high-efficiency reprocessing into electricity justifies the hope of its dissemination, also as a marine fuel.

It is necessary to replace petroleum fuels with another source of primary energy. The following are mentioned here: hydrogen, and nuclear energy, and, in the transitional period, bio-methanol, bio-ethanol, bio-diesel, synthetic fuels, FAME, SVO, etc.

Development of marine engines in a nutshell

It was steam engines that replaced the work of human muscles and wind and contributed to revolutionary changes and the emergence of industry. The beginnings of the construction of a steam piston engine date back to the beginning of the 17th century (Sommerset's water-commanding engine – in 1628), just like the steam turbine (Giovanni Branca's steam turbine – in 1629), but their popularization took place about two hundred years later. The primary energy source for these engines was thermal energy from splitting wood, charcoal, peat, and, later, hard coal.

The idea of using steam to propel ships and the construction of the first working piston steam engine is attributed to Denis Papin (1688), although this idea was not realized then. The main reason was the lack of interest by the London Royal Society in 1708 (Urbański, 1997). Steam engines, which were originally used to drive pumps, spinning machines, and locomotives, had to be used to drive ships. The first ship with steam propulsion was put into operation in 1807. Her name was *Clermont*. A paddle-wheel steamship was used to carry passengers on the Hudson River between New York City and Albany.

The 19th and early 20th centuries were the era of hard coal as an energy source for the production of steam. The very dynamic development of the piston steam engine continued throughout the 19th century. In 1889, the *Puritan* ferry was built with a 5500 kW twin-piston top-rocker steam engine capable of delivering a ship speed of 21 knots. The height of this engine was 21.64 m. At the beginning of the 20th century, most ships were still powered by a reciprocating steam engine. Classic examples are White Star Line's *Titanic* (sank 1912), *Britannic* (sank 1916) and *Olympic* (she sailed as a passenger liner on the North Atlantic route between 1911–1935). In the late 19th century, in 1884, after Charles Parsons patented a multi-stage reactive steam turbine to drive a generator, she began the era of ship turbine propulsion. In 1889, he built a small vessel called *Turbinia* (30 m long, 2.75 m wide, and 0.91 m deep) with a turbine drive, which developed a speed of 19.75 knots. After improving the propulsion system, on the occasion of the diamond jubilee of Queen Victoria of the British Empire, in 1897 in Spithead, *Turbinia* reached a speed of 34.5 knots. This year is considered to be the beginning of the use of turbine propulsion for ships, especially warships. Cunard Line ordered direct turbine-powered vessels (RMS *Lusitania* and RMS *Mauretania*, launched in 1906, and RMS *Aquitania*, launched in 1913), which were to reach speeds of about 27 knots. They fought for the so-called The Blue Ribbon of the Atlantic, losing in 1929 to the German passenger ship Bremen. The power of RMS Mauritania's steam turbines was 54 MW, in which 990 tons of hard coal were used daily. The engine department crew consisted of 366 people (Urbański, 1997). The inconvenience associated with the use of hard coal as a fuel on board ships caused the slow shift away from this fuel in favor of petroleum diesel fuels. This allowed for a significant reduction in the space occupied by spare fuel, the possibility of automatic feeding of the boilers with fuel supplied by fuel pumps, and a reduction in the number of crew members.

The possibility of supplying piston engines with diesel fuel made it possible to use them for propelling ships. It is assumed that the first application occurred in 1903 on a Russian river ship, the *Vandal* tanker. The first sea-going vessel (mv *Romagna*) was built in 1910, fitted with two Sulzer diesel engines delivering 280 kW at 250 rpm. In 1920 (ten years later), there were about 2 thousand ships powered by diesel engines (Urbański, 1997).

The main barrier to the popularization of piston engines for the propulsion of ships was their limitation of the power necessary to obtain a satisfactory ship speed. The use of propulsion systems with multiple diesel engines significantly complicated the design of the ship's engine room. It was not until the 1960s that they began to displace the use of steam turbines on smaller ships. In these years, the piston steam engine ceased to be used in the propulsion of newly built ships due to its dimensions and, above all, too low efficiency. Marine steam turbines used in main propulsion became less used after 1974 due to drastic increases in the price of marine fuel. Having less efficiency, they were doomed to niche applications. The era of the dominance of marine diesel engines began and continues to this day. A significant improvement in the efficiency of these engines has been achieved by using, inter alia, deep waste heat utilization systems.

Ship gas turbines are used in the propulsion of ships, for which the size of the power plant is a significant limitation, with high power demand. A niche application is super-fast catamarans with speeds of 30–50 knots and some passenger ships that sail in the waters around Antarctica or the waters around the North Pole, such as Alaska. They emit much less harmful substances into the atmosphere. Unfortunately, they consume more fuel (they are less efficient) by 20–25%, which in the case of traditional fuels results in a greater emission of carbon dioxide. In these cases, the possibility of using more ecological fuels should be considered. The share of gas turbines in ship propulsion is already visible and will increase. However, the use of steam turbines is disappearing (Figure 2).

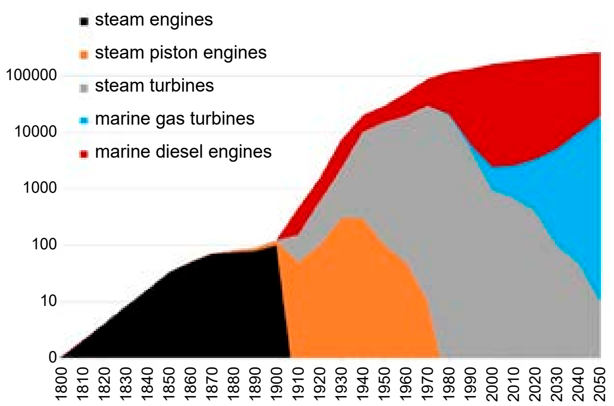

Figure 2. Illustration of the distribution of main propulsion marine engines depending on the type of heat engine. (Attention. The numbers on the ordinate are on a logarithmic scale)

The restrictions on the emissions of harmful substances into the atmosphere from marine diesel engines, required after 2000, forced us to take measures to meet them. The emission of nitrogen oxides has been reduced several times as a result of the use of exhaust gas recirculation systems and/or exhaust gas reduction systems. This made it difficult to further improve the efficiency of these engines (Morsy El-Gohary, 2013; Chybowski & Kazienko, 2020). The reduction of sulfur oxide emissions became possible after introducing the obligation to use low-sulfur fuels. After 2020, requirements have entered into limiting carbon dioxide emissions and, generally, the limits of CO_2 emissions in terms of the transport effect. Despite undertaking various activities related to reducing the hull resistance and increasing the overall efficiency of the propulsion, etc., the intended goals have not been achieved. The prospect of switching to fuels with less or no carbon in the molecule remains (Herdzik, 2022; IRENA, 2022a). Biofuels are also an alternative (IRENA, 2022b; McGill, Remley & Winther, 2013).

The development of marine engines resulted in an increase in their power and, at the same time, in their thermal efficiency (Table 4). This was one of the reasons for the changes taking place, the abandonment of the construction of steam piston engines, and a significant reduction in the use of steam turbines. This enabled an ability to reduce the total fuel consumption (primary energy) and increased the economics of sea transport.

The possible applications of electric propulsion for ships using electricity stored on board or generated in fuel cells are being considered. Despite the potential for such possibilities, there are significant limits to their maximum power and energy reserve to ensure the required autonomy of the ship. As a result, such solutions were applied to small vessels engaged in short-distance ferry navigation (e.g., in the Norwegian fjords).

The efficiency of the energy system for the marine diesel engine in deep waste heat utilization systems reaches the value of 60%. A similar result is obtained in cogeneration systems with a gas turbine and a utilization steam turbine. In the second case, due to the quality requirements of turbine fuels, which are more expensive, the total fuel costs are higher. The possibilities of increasing the efficiency of heat engines are limited by the efficiency of the Carnot theoretical cycle, properly applying the theoretical cycle of Clausius-Rankine and Brayton-Joule, and through additional actions aimed at the Carnot cycle.

It was only after the introduction of the MARPOL Convention, and especially Annex VI, that more attention was paid to the protection of the environment, especially the atmosphere. The most

Table 4. Thermal efficiencies of thermodynamic cycles of marine engines

Type of marine engine	Steam piston engines	Steam turbines before and after 1920	Diesel engines before 1940	Modern marine diesel engines (four stroke and two stroke)	Gas turbines (simple and combined cycle)	Combined systems: COGAS/ CODOG
Thermal efficiency [%]	5–15	10–15/20–31	15–20	44–52	36–42/38–45	50–60

hazardous one was carbon dioxide, which is a product of the combustion of hydrocarbons contained in petroleum fuels. In connection with the introduced limits of greenhouse gas emissions, the use of other fuels or energy sources began to be considered. The use of photovoltaic cells, Flettner rotors, and kites makes it possible to reduce the demand for energy from fuels but their share is within the range of 1–5%, which allows a temporary meeting of the requirements related to the carbon intensity indicator (CII) regulations.

Increasing the efficiency of mechanical and electrical energy production is possible thanks to the use of fuel cells. They are devices of the future. Obtaining power up to 1 MW is too small a value to compete with the current main propulsion power of ships. Reaching the 10–100 MW range will allow entry into this market and substantially eliminate heat engines. The problem remains as to which energy source is used to power fuel cells, how to accumulate an adequate supply of primary energy on a ship and, above all, the availability and unit price of primary energy. Solving these problems will significantly revolutionize ship propulsion systems (Concave, 2017; Turbomachinery International, 2022).

Conclusions

From the 19th century to the present day, two eras of marine fuels can be seen. Initially, there were about 150 years of the hard coal era, which has been slowly replaced by petroleum fuels since the beginning of the 20th century. This latter era is also likely to last approximately 150 years. The depletion of crude oil resources, and above all the increase in environmental protection requirements, which requires reducing the negative impact of maritime transport, has caused an increasing interest in alternative fuels. Natural gas extracted from deposits, like LPG gas fuels, can only be transition fuels. Recognizing that carbon dioxide emissions from biofuels are not counted as actual CO_2 emissions, they may slowly replace current petroleum fuels. The production of synthetic fuels depends on the development of technologies that must be energy-saving, environmentally friendly and, above all, based on the capture of carbon dioxide from other combustion processes or the atmosphere. Production technology will continue to be developed and ammonia will be used more widely as a marine fuel over the next thirty years. I believe, however, that there will be a shift away from the use of ammonia in favor of hydrogen. The main goal is to move away from carbon-based fuels in favor of using hydrogen. The transitional era of the use of many marine fuels is already underway and will continue until the transition to hydrogen technologies. The transitional period is 2000–2050. After 2050, the era of hydrogen as a marine fuel should begin. How long will it last? It is not known, but technical and technological progress will continue, and it is difficult today to indicate what awaits us in 50–100 years. Due to the coming regulations limiting the emission of GHG into the atmosphere, and also from sea transport, there will be significant changes in the fuels used as a source of primary energy on ships. This process is expected to accelerate significantly in 2023 (e.g., in a Singapore port, it will soon (i.e., this year) be possible to bunker ammonia as a fuel for ships).

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