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Additional Analysis of the Possibilities of Ship Wind Systems

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ABSTRACT

The problem of global warming is currently one of the most important for all humanity. One of the ways to solve it is to reduce emissions of greenhouse gases CO_2 and CO. The combustion of petroleum-based fuels is an important source of such emissions. Although the transport fleet accounts for less than 3% of such emissions per year, but when the fleet is transferred to other energy sources, this share will be 40% of the 7.4% annual emissions reduction required by the COP-21 decision. Thus, finding ways to replace petroleum fuels with environmentally friendly energy sources in the transport fleet is an important and urgent task.

One way to solve this problem is to switch to an environmentally friendly sailing fleet, which was the main one just 130 years ago. However, problems arose regarding the technical and economic possibilities of developing and implementing modern sailing ships. Their justification and selection of the best options is the main goal and constitutes the scientific novelty of the work performed. New results of the work. A correctly chosen strategy allows avoiding further mistakes as well as unproductive waste of time and technical and economic resources in the development of sailing systems. Conducted analysis Includes an of more than 40 of the most well-known variants of sailing ships. Conclusions. Based on the analysis of well-known projects, a concept of sailboat development has been developed to avoid unproductive waste of time and money on ineffective options.

1. Introduction.

One of the main threats to modern humanity is the threat of global warming of the Earth's climate. The consequence of this threat is the melting of the glaciers of the Northern Ocean and Antarctica, which contain 1.81% of fresh water from its total amount of 2.46%, since the basis of 97.54% of water on Earth is salt water of oceans and seas [1]. The fresh water from the glaciers dissolves in it and is lost forever, the level of the world ocean will rise, which will lead to flooding of many coastal areas.

From the increase in temperature, the desert zones will increase, flora and fauna will be oppressed. One of the causes of the threat to the climate is emissions of greenhouse gases CO and CO_2. Of these, 3% of the total annual emissions are emissions from traditional fuels used by the transport fleet [2]. Taking into account the need to reduce annual CO and CO_2 emissions by 7.4% [3], the transition of the transport fleet to alternative energy sources allows solving this problem by $3/7.4{\times}100\% \approx 41\%$.

The problem of decarbonization of transport fleet can be solved by reducing fuel consumption. For her solution International Maritime Organization (IMO) recommends used wind energy [4].

Since the 60s of the 20th centuries, in the face of the threat of exhaustion of traditional fuels, the revival of the sailing fleet began, but no significant progress was made, which indicates

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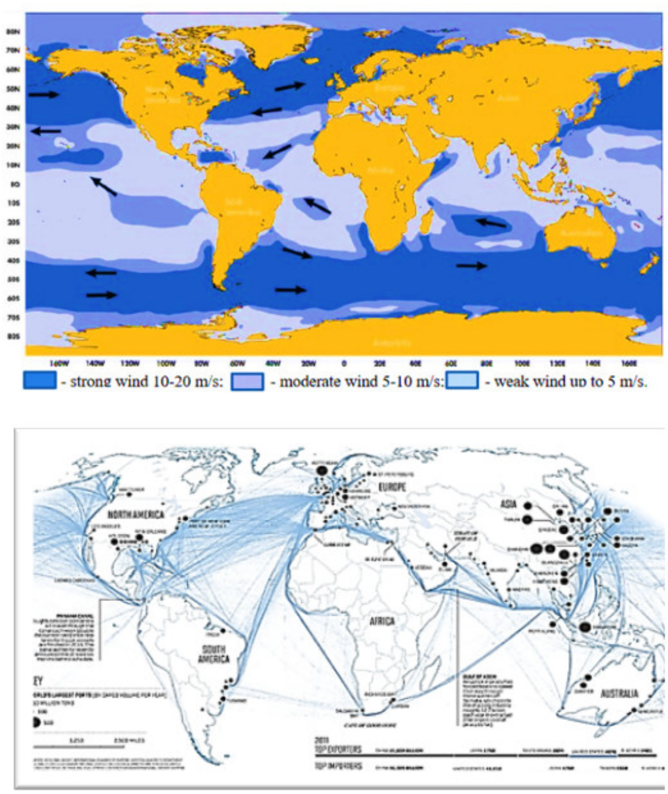
the difficulty of solving this problem. In such conditions, it is important to determine the best projects of ship sailing systems [5]. The correct choice of ship wind systems allows you to avoid spending money and resources on the development of unpromising projects, which is an important task for the development of ship alternative energy [6, 7].

2. Analysis of shipboard wind energy.

It is based on the works [6, 7] and the results presented at the Congress on Renewable Energy 2024 [8]. Their analysis showed that it sails are effective only in those areas where the average annual wind speed exceeds 10 m/s. Their area (highlighted in bright blue) and their connection with the main shipping routes are shown in Fig.1. [9, 10].

Figure 1: Stable wind currents in the world ocean.



Source: www.earth.nullschool.net.

Considering the intensity of vessel traffic, a complete transition to sailing systems in the transport fleet is possible for 1/3 of the routes and vessels. In all other cases, sails can be used only as additional systems that reduce fuel consumption by 30 – 35% [7]. Adequately to these indicators, it is possible to reduce CO and CO_2 emissions by the transport fleet only for 1% of 7.4%.

However, ship wind energy requires the creation of complex technical systems and does not work when the vessel is moored. An example of a modern sail is shown in Fig. 2 [11].

The Pyxis Ocean cargo ship in 2023 fitted with two enormous sails developed by British engineering outfit BAR Technologies.

Figure 2: Basic designs of modern sailing systems corporation Mitsubishi for transport vessels.

Source: Sails of Pyxis Ocean ship.

Figure 3: Lifting telescopic sails of the Wind Challenger company.

Source: www.mol.co.jp.

The dimensions of such a design are: height 37.5 m, main sail width 10 m and two side sails – width 5 m each. The sails are built in a similar way to wind turbines in order to withstand the high winds at sea. Swiss cargo trader Cargill has released the results of a six-month trial period of the vessel Pyxis Ocean, which was equipped with wind sails from BAR Technologies [11]. Cargill said that the MC Shipping Kamsarmax achieved performance in line with forecasts, which is equivalent to an average saving of 3 tons of fuel per day. According to estimates by BAR Technologies and Cargill, this corresponds to a reduction in emissions of 11.2 tons of CO_2 per day. The data was verified by a third party, namely DNV, which was hired to verify the fuel savings calculations [11]. With favorable wind strength and direction, these figures tripled.

Instead of rigid sails, the Wind Challenger company has developed telescopic lifting sails to pass under bridges. They also pivot in the direction of the wind (Fig. 3) [12, 13].

Figure 4: Systems for lowering and raising the masts of Neoliner sailing vessels.

Source: www.boatinternational.com.

This is a real project that is undergoing industrial testing.

Figure 5: Real ship wind systems with Fletcher rotors and their inclination.

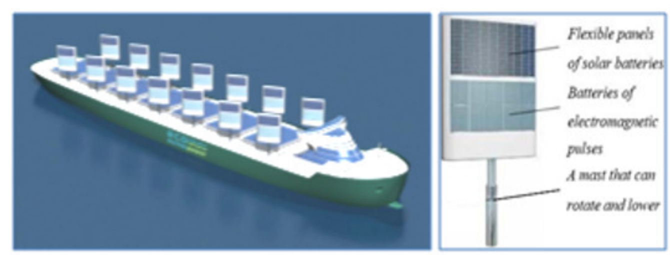
Source: www.offshore-energy.biz.

The Neoliner company has developed systems for raising and lowering masts with flexible sails that allow ships to pass under bridges (Fig. 4) [14, 15].

Actual ship designs with Fletcher rotors from the company «Norsepower Rotor Sail» have found wide application and their number is constantly increasing. Ships pass under bridges when the supporting columns are tilted. When loading and unloading the ship, the columns tilt (Fig. 5) [16].

A more complete analysis of ship wind systems was carried out in [7], its results are valid at the present time, and therefore will not be repeated. It shows that the two-row sail systems "Eco Marine Power Wind-Solar Ship-2025" of the company Eco Marine Power, (Fuluoka Japan) [17] are preferable, with the location of low rotating masts along the sides of the vessel. This increases the sail area, reduces the roll in strong winds and the pitching in gusts (Fig. 6), where this project is recognized as the best [6, 7].

Figure 6: Project of the dry cargo ship "Eco Marine Power Wind-Solar Ship-2025" with solar panels on rotating masts.



Source: www.offshore-energy.biz.

This project [17] is taken into account in the new concept of the STX Eoseas [18] vessel, in which the developers abandoned high masts [19] in favor of smaller ones located on the sides of the vessel, that tilted when passing under bridges (Fig. 7).

Figure 7: Initial and new projects STX Eoseas project with inclined sails mast along the sides of the vessel.

Source: www.stirlingdesign.fr.

The double row project is taken into account by the Wind

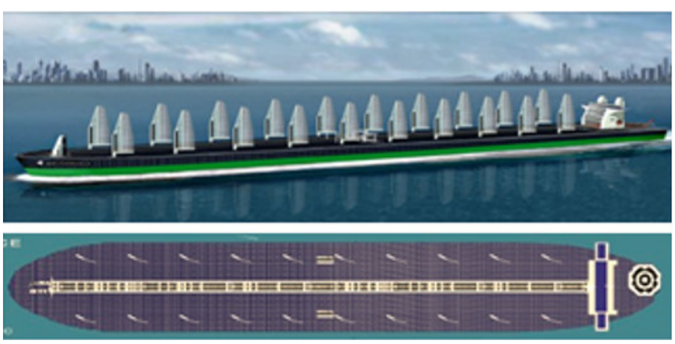
Challenger company in the designs of telescopic masts shown in Fig. 4 [13], and also by the Neoliner company in the designs of two paired inclined masts shown in Fig. 8 [20].

Figure 8: The improved sailing system of the Neoliner company and the passage of the vessel under the bridge.

Source: www.mol.co.jp.

Strictly adhering to the concept [17] are the developers of Sauter Carbon Offset Design (SCOD) Swiss Confederation, in 2011 have presented their Green vessel project Deliverance, it's DynaWing Solar Hybrid Supertanker that qualifies Post Panamax Vessel (Fig 9) [21].

Figure 9: The DynaWing Solar Hybrid tanker project that qualifies Post Panamax Vessel.



Source: www.charterworld.com.

However, the issues of strength, reliability and durability of these systems have not been fully resolved. The main goal of the work performed is the analysis of these problems. Development of recommendations based on this analysis is its scientific novelty. The research methodology consists of a technical and economic analysis of the advantages and disadvantages of the main sailing systems projects on the transport fleet and the selection of the best of them on the basis of the adopted scale of criteria. The main ones are: 1) completeness of achieving the final result; 2) minimal costs and simplicity for production and maintenance; 3) simplicity and reliability of the system.

3. New results of the work and their discussion.

The initial stage is the analysis of the strength of the mast systems. An important criterion for the strength of mast is the reduction of their height, which is provided by the scheme [17]. Additional advantages in this case are the reduction of the ship's roll and its pitch, as well as easier passage under bridges. The clarity of the disadvantages of high masts is shown in Fig. 10, where there is a clear roll of the yacht "Maltese Falcon" [22]. If it is permissible for a yacht, then for a transport vessel – the roll is undesirable. An example of this is the picturesque picture of the tea clipper "Thermopylae" competing in races with the famous clipper "Kitty Sark" (Fig. 10) [23].

Figure 10: Real tilt of the yacht "Maltese Falcon" and the roll of the tea clipper "Thermopylae", depicted by the artist.

Source: www.sailtraininginternational.org.

If high masts are unavoidable, as is the case in the design of yacht [24] (Fig, 11), then rear narrow mainsails are more appropriate, which allow better restoration of the air flow between closely spaced masts and are more effective in crosswinds.

Figure 11: The E-Volution Solar Hybrid Sailing yacht project, in which diesel engines are replaced by electric motors.

Source: www.charterworld.com.

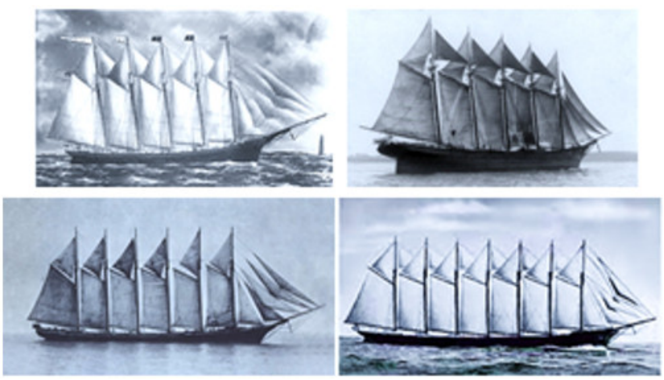
In this case, it is advisable to revise the design of the B-9 Sail Cargo Ship (Fig. 12) [25] to reduce the roll shown in Fig. 10 and better action in non-tailwind conditions.

This is confirmed by the fact that the schooners in the transport fleet were built with the largest tonnage and after the arrival of the steam fleet and were in operation the longest. At first, the number of masts on the schooners increased from 3 to 4. The first of 12 others, the 5-masted schooner "Governor Ames", was built in 1888. The first 6-masted schooner "George W. Wells" was built in 1900, but the 2nd schooner "Wyoming" is better known. The first and only 7-masted schooner "Thomas W. Lawson" was built in 1902 (Fig. 13) [26 – 29].

Figure 12: Development of the B-9 project based on the designs of the pleasure yacht Maltese Falcon.

Source: www.slate.com.

Figure 13: Real versions of 5, 6, 7 mast schooners of past centuries.



Source: www.en.wikipedia.org.

Figure 14: Sailing cruise ship ”ClubMed 2” (France).

Source: www.shipshub.com.

In modern designs of transport vessels, oblique sails have been chosen by the Neoliner company (Fig. 4, 8) and others [30, 31]. The sailing vessel ”ClubMed 2” of the French tourist company ClubMed (1992) is also a 5-masted schooner and the largest modern sailing vessel in the world. Its length is 194 m, height - 80 m, displacement is about 15,000 tons, number of passengers 386, crew 214 people, speed up to 15 knots (Fig. 14) [32].

The company has a sister ship to this vessel, the cruise ship “ClubMed 1”, “Wind Surf”, and three 4-masted ships “Wind Spirit” and “Wind Star”, with a capacity of 148 passengers and 84 crew members.

The main advantage of schooners compared to ships and barks is a simpler sail rig, which reduces the labor intensity of their operation and maintenance. This helps to reduce the number of crew and the cost of its maintenance, which is an important goal of ship owners. For example, the crew of the schooner ”Thomas W. Lawson” was reduced to 16 people, which was excessive in the absence of automation at that time and led to the loss of the ship on Friday, December 13, 1907 due to loss of sail control in a storm.

However, in any case, the crew of schooners is incomparably smaller than the crews needed to manage the sails of barks, as shown by the example of the bark ”Nippon Maru” built in 1927 in Japan (Fig. 15) [33]. On the military battleships of the 19th century there were crews of 800 - 1200 people, which is unacceptable for the transport fleet, especially the modern one.

On the new bark ”Nippon Maru II”, built in 1984, devices are installed that automatically ensure the furling and setting of all sails [34], which has sharply reduced the number of the crew.

Figure 15: ”Swallows on the masts” - setting sails on the 1927 bark ”Nippon Maru”.

Source: www.shipshub.com.

Since the ships and barks of the 20th century required large crews, they gave way to less labor-intensive (in maintenance) ships with mechanical drive, and the Suez and Panama Canals, where sails could not be used, completed the transition of the transport fleet to steam engines, and then to diesel engines. Therefore, since the 2nd third of the 20th century, sailing ships were mainly used as auxiliary and training vessels, and with the development of tourism – as cruise ships. Some of them have become museums. Currently, training sailing ships are used in 30 countries of the world on all continents and there are many ships – new construction. Each of the famous sailing ships deserves attention, but this requires separate work. Therefore, only a number of examples are selected, which are: 1) the largest operating training 4-masted bark ”Sedov” (Russia), built in Weimar Germany in 1921 under the name ”Magdalene Vinnen” [35]. It has a length with bowsprit of 117.5 m, displacement of 7,320 t, sail area of 4,192 m^2. 2) 4-masted barks ”Nippon Maru” (1927) and ”Nippon Maru II” (1984), (Japan), they have a length of 110.09 m, sail area of 2,760 m^2 [34]. 3) 3-masted ”Frigate ARA Libertad” (Argentina), built in 1963, length with bowsprit 103.75 m; displacement: 3,765 t, sail area – 2,646 m^2 [36]. 4) bark ”INS Tarangini” (India), built in 1997, length 54 m, sail area – 1,035 m^2 [37] (Fig. 16).

Figure 16: Examples of sailing ships – training vessels of some countries of the world.

Source: www.korabley.net.

Ukraine also has its own training sailing ship – the 3-masted frigate Druzhba – the first of 5 identical sailing ships built in the Polish People’s Republic in 1986–1990 by order of the USSR for the country’s naval institutions, based on the prototype – the frigate Dar Młodzieży (1981). Its length is 108.8 m, displacement is 2946 t, and sail area is 3015 m^2 (Fig. 17) [38].

However, the transfer of the vessel from the Ministry of the Marine Fleet to the penniless Ministry of Education of Ukraine made it impossible to maintain it, so in 1992 the vessel was converted into a cruise yacht in the Italian port of Messina. The number of places for cadets was reduced from 130 to 30. Since the beginning of the 21st century, the vessel has been moored in the Odessa port, where junior cadets of the National University ”Odessa Maritime Academy” periodically undergo practical training [38].

Figure 17: Sailing training ship ”Druzhba” of the Odessa Maritime Academy.

Source: www.uk.wikipedia.org.

The need to ”moonlight” training vessels to cover the costs of their maintenance is a common problem for all countries in the world.

The Kherson Maritime College (now a state academy) also received its own training vessel in 1951 - ”Tovarishch”, this is the barque ”Gorkh Fock” built in 1933 (Germany), its length is 82 meters, the sail area is 2000 m^2 (Fig. 18) [39].

Figure 18: Bark ”Tovarishch” - a training vessel of the Kherson Maritime School from 1951 to 1999.

Source: www.kavun.city.

The vessel participated in many regattas and was their winner and prize-winner many times. About 15 thousand cadets underwent practical training on it. After the vessel was transferred from the Ministry of Fisheries to the Ministry of Education, problems with its maintenance began. In 1995, the vessel was removed from the regatta due to problems with the condition of the hull and rigging. It was sent for repairs to England. However, the Ministry of Education did not have $ 3 million for repairs. In addition, the validity of the ship's documents expired, and the bark remained under arrest in the port of England. The feeble attempts of Ukrainian President L. Kuchma and Prime Minister V. Yushchenko to find the necessary funds were unsuccessful. No sponsors were found either. And in 1999 the ship was sold for the price of scrap metal – for $ 500 thousand, which is the price of a luxury car, which corrupt officials began to drive. The ship was bought by the city authorities of Stralsund and put into storage as a museum, since in 1948 in Germany the Gorch Fock II had already been built and sailors were trained on it [40]. However, it would have been a noble act for the German authorities and the city to hand over the ship after the war as aid to the exhausted and destroyed Ukraine and to Kherson, a hero city of the war.

The development of automation eliminates the problem of setting, removing and controlling sails, which led to the construction in 1999 of the 5-masted cruise bark "Royal Clipper" for the Swedish company Star Clippers Ltd. The length of the vessel is 134.8 m, the displacement is 4425 tons, the sail area is 5040 m^2, the number of passengers is 225, the crew is 106 people. The vessel has 42 sails and masts of different heights [41]. In the new vessel "Flying Clipper" of 2017 – 4 unified masts 50 m high, the length of the vessel increased to 162 m, the sail area increased to 6377 m^2 with a reduction in their number to 35 sails, the number of passengers and crew members increased, respectively, to 300 and 150 people (Fig. 19) [42].

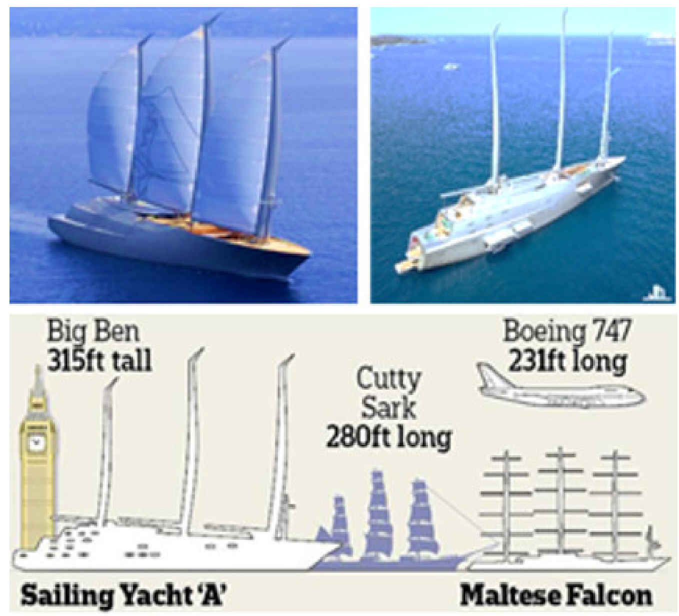
Figure 19: Cruise barks "Royal Clipper" and "Flying Clipper" of Star Clippers Ltd.

Source: www.korabley.net.

The new bark is second in size only to the schooner "ClubMed 2". Automation has simplified the operation of all cruise vessels, but servicing such a large number of automatic devices requires the allocation of a group of specially trained crew members. With their number of 84, 214 [32] and 106, 150 people [42], such allocation is possible, but for transport vessels, where the crews are reduced to 16 – 20 people and ship owners are trying to reduce them further, there is no additional service personnel, and adding new duties to crew members is difficult, since they already have other additional duties. The use of such masts and sails on the transport fleet is impractical, considering also that they will interfere with the loading and unloading processes.

The highest masts (about 90 m) have the yacht "A", built in Germany in 2017 for the Russian billionaire Melnichenko, the designer of the yacht is Philippe Starck. The entire sailing rig of the vessel was created by the US company Doyle Sails: the sails with an area of 3747 m^2 are set, removed and controlled automatically (Fig. 20) [43].

Figure 20: Yacht "A" and comparison of its dimensions and height of masts.



Source: www.wikipedia.org.

The advantage of this system is that there are only 3 masts and sails, which simplifies their operation and maintenance. With a displacement of 12,700 tons, the vessel can be used as a transport vessel, but this option is questionable due to the high cost of the vessel, its masts and sails, the height of which limits their access to the ports of the Baltic Sea. However, as a cruise vessel, it can be successfully used and compete with other spectacular and romantic cruise ships, such as the Royal Clipper (Fig. 19). Both of these types of vessels can remain monuments to the beauty and romance of the sailing fleet, although more practical and economical for cruises are small (for 8-20 passengers) combined sailing and solar yachts. Although the variety of entertainment is inferior to large vessels, but they provide access to swimming and fishing in the sea. There are many such yachts, an example is the yachts-catamarans ZEN company (Zero Emision Nautic Ltd Incorporated, Malta), NASA developer, which rises and lowers automatically (Fig. 21) [44].

It is necessary to take into account the statement of Admiral Drake that the higher the masts, the better, because the wind speed at a height is higher than at the water surface, since there is no braking of it. But these advantages constitute an addition of only a few percent, which for pirates and racing yachts could be decisive. But when operating a transport fleet, a slight increase in thrust can be compensated by additional installation

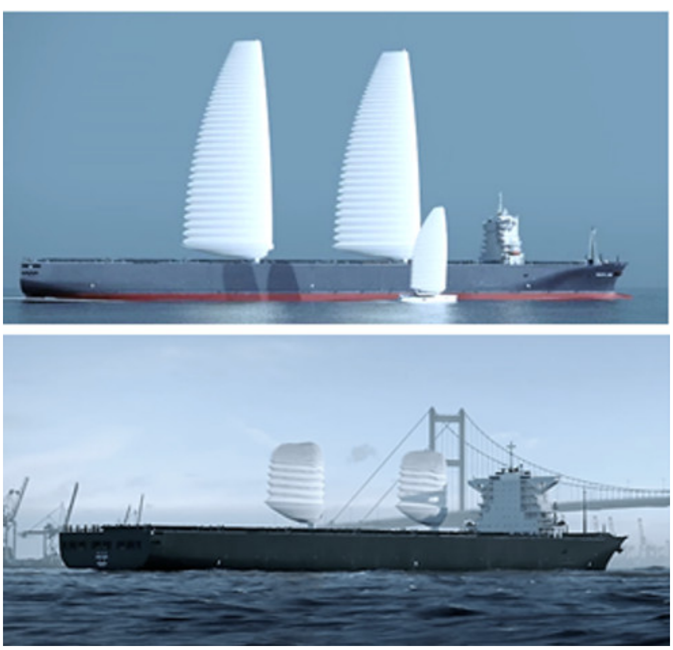
Figure 21: Hybrid catamaran yacht with automatic flexible mast sail and solar panels.

Source: www.itboat.com.

of low masts. The developers of the STX Eoseas project refused high masts (105 m), in favor of lower ones, located along the sides of the vessel (Fig. 7).

The gigantism of masts and sails can be justified if they do not complicate their operation and maintenance, for example, in the project of inflatable systems, which are mobile when unfolding and folding when passing under bridges and when a storm is approaching (Fig. 22) [45].

Figure 22: The system of inflatable sails in working condition and when passing under bridges.



Source: www.flotilia.com.

Although inflatable sails are simpler and cheaper than mast sails, they require ventilation systems and energy costs to inflate. They must also be periodically switched on to maintain the sails in working order during the voyage, since air diffuses through the sail material. To effectively deflate the sails, a reverse of the pressurization system is required, leading to suction, which also leads to additional energy consumption. Therefore, more accurate economic calculations are required for these systems.

The problem of reversal is solved in aircraft turbines, but these are expensive technical systems for turning their blades. A simpler one is a reversible fluid coupling, installed between the electric motor and the supercharging fan system. However, all these systems lead to higher prices and a decrease in their reliability, and most importantly - to the need for their constant supervision and maintenance, which is an additional burden for crew members.

It should also be taken into account that in order to use such sails in various wind conditions, additional training of crews is required, for which it is necessary to create training systems and simulators, which leads to additional time and investment. Then certification and IMO permits are required, which will be given only after a thorough study of the safety of the system. This is an additional expenditure of time and resources.

Tall masts require solutions to their strength problems, but there are fewer problems for control organizations. In the "Maltese Falcon" yacht project [22], which has received practical implementation, the diameter of the masts at the base is > 1 m, and the masts of yacht "A" have even more impressive dimensions (barge length for their transportation 66 m), which not only increases the complexity and cost of their manufacture, but also the weight, even with the use of reducing weight of highly durable materials such as Kevlar (Fig. 23) [43].

Figure 23: Masts of the yacht "Maltese Falcon" and yacht "A".

Source: www.wikipedia.org.

A simpler solution to the problem of mast strength was proposed in the schooner "ClubMed 2" by implementing 2 perpendicular cable guy wires behind the masts (Fig. 24) [32], however, this option has not yet received further widespread development.

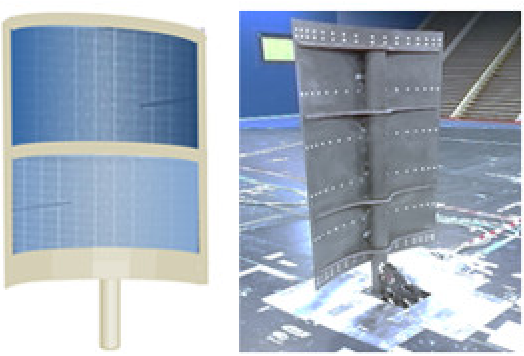
Therefore, instead of huge and expensive sails, a more appropriate scheme is to install small, simple and cheap rigid side-turning sails along the sides of the vessel, similar to the "Eco marinepower" project (Fig. 6) [17], which have a coating of so-

Figure 24: Masts with lateral reinforcing guy wires on the schooner «ClubMed 2».

Source: www.shipshub.com.

lar panels on the outer front and on the concave rear surfaces (Fig. 25). [46].

Figure 25: Model of a rigid rotary sail with surfaces for solar panels.



Source: www.researchgate.net.

The use of rigid sails was associated with the oil crisis of the 1970s. At first these were simple turning sails (Fig. 25) without solar panels. The first to be equipped were tankers with a displacement of 10-15 thousand tons, since their speed is acceptable for the wind speed (Fig. 1), 5 vessels underwent real testing on Japan-Australia voyages. An example is the tanker "Shin Aitoku Maru" built in 1980 (Japan) [47]. Sails could not replace the main engines, but provided 10 to 30% fuel savings in favorable wind conditions. Another example is the bulk carrier Aqua City of Aqua City Maritime, 1980, (Japan) with more complex aerodynamic sails of the aircraft wing type [48]. They worked in a wider range of wind directions, but also became ineffective after the fall in oil prices. The Japanese dry cargo ship "Usuki Pioneer" with a length of 162.5 meters was equipped with another type of wind-powered dynamic sails [49]. The vessel operated successfully from 1985 to 1995, transporting timber and grain. However, in 1995, the vessel's sail center was dismantled due to high maintenance costs and the need for frequent repairs [49]. The third type of sail is the ASPS, with 3 sails on a single rotating base [50], developed by the Winship consortium (UK). All these 4 projects are presented in Fig. 26.

Figure 26: Main projects of ships with rigid sails of the 80-90s of the 20th century.

Source: www.sail-friend.ru.

The decline in oil prices, maintenance problems and the need for periodic repairs of complex sails have led to a decline in interest in this area among ship owners. However, the need to reduce CO and CO_2 emissions has led to its revival in the 21st century, as confirmed by the projects presented in Figs. 2 – 12.

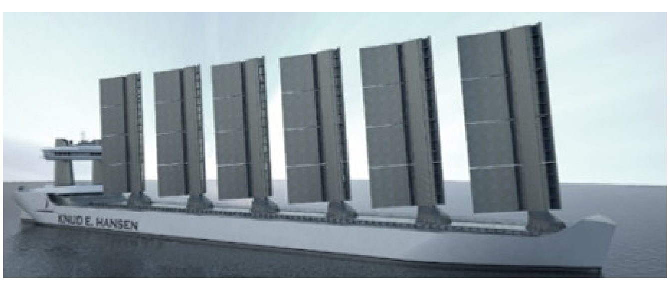
Figure 27: Winship consortium sailing ship projects for the 21st century.

Source: www.windshiptechnology.com.

In the project [50], when passing between the surfaces of 3 sails, the air flows are compressed and their speed increases, which, according to Bernoulli's law, leads to a decrease in the pressure between them and the external air pressure pushes the vessel. Therefore, such a system operates at a minimum cross-wind speed, which is very important in areas of minimal winds in the world's oceans (Fig. 1). At the same time, unlike rotor columns [16], they do not require mechanisms and a constant drive for their rotation, which not only eliminates fuel costs for these movements, but also increases the reliability of the system, due to its simplification. When the masts are arranged with ribs along the axis of the vessel's movement and the direction of the wind, its stability increases even in a storm. The Winship consortium's projects continue to develop [51], new options are shown in Fig. 27.

The projects of rigid sail systems of the 90s of the 20th centuries were not used, therefore in the 21st century the development of rigid sails was connected with the creation of 2-3-section structures that catch and change the wind direction. Their example is shown in Fig. 2 and in the project of the unmanned vessel of the company KNUD E. HANSEN (Germany, Holland), used on fixed routes in the zone of wind speed > 10 m/s [52]. The vessel has 5 masts and 5 rigid rotary sails of 2 sections, a length of 150 m, a width of 20 m, a displacement of about 15 thousand tons. (Fig. 28).

Figure 28: Prospective projects of a sailing cargo vessel - drone KNUD E. HANSEN company.



Source: www.knudehansen.com.

However, it is more expedient to develop this project with an onboard scheme for installing masts of reduced height, similar to the project [17]. Optimization of the number, height and area of sails will increase the displacement of these vessels from 15 to 25 thousand tons, which will bring them into the most massive and economical group of vessels of the transport fleet. Reducing the complexity of manufacturing and servicing sails from only 1 section increases their viability. However, an even more preferable option is the transition to catamaran vessels with rows of low sails on each hull.

In the 21st century, there has been a tendency to complicate sails, as shown in projects [11] and [46]. They are similar in many ways, which allows for a general analysis to be conducted for them, based on an assessment of the complexity and reliability of the systems, as well as the labor intensity of their maintenance. The initial for the analysis was the design of a sail of 3 sections. The mechanisms for turning of his main session and side flashes are shown in Fig. 2. However, their disadvantage, and the control system for them, is that they are exposed to the effects of the external marine environment. Systems for tilting the masts when entering a port are also used (Fig. 29), which can be similar to the tilting systems of the rotor columns shown in Fig. 5. However, with a small height of the masts and sails, these systems will not be needed, which is an important simplification.

Figure 29: Pedestals with mechanisms on board the vessel for stowing sails on its deck and a variant of doubling the masts by installing them on both sides of the vessel.

Source: www.researchgate.net.

For the Pyxis Ocean cargo ship, it is possible to install similar sails on the second side of the vessel, following the example of [53], which doubles the achieved thrust and fuel economy figures [11].

However, it should be noted that the complexity of manufacturing and servicing such sails increases, and their reliability decreases, especially taking into account the duration of their operation. For example, for an aircraft, 1000 flight hours are accumulated over 4-6 months of operation with daily supervision and maintenance of the aircraft, and for a ship, 1000 hours is the duration of only one 6-week voyage, without daily inspection and maintenance of the sail, due to small crews, whose members have other responsibilities. It is also necessary to take into account the impact of the aggressive marine environment on gears and automation, so the transition to such a system requires more in-depth research in this area. If the real increase in the indicators of complex sails does not exceed the amount from sails of a less complex design, but of their greater number, then the advantages are fewer complex systems, namely concave sails, which during a storm turn with their edge in the direction of the wind.

When achieving the same options for the vessel's thrust when using sails of complex designs and sails of simple design by increasing their number, the use of more complex options can only be explained by the desire of the manufacturers of these sails to gain profit, to the detriment of the shipowners' benefit. However, the final conclusion still requires its own research. It should be taken into account that the complication of sail maintenance is an inevitable fact, but it should be minimal and carried out at port stops by crew members assigned for this purpose with additional payment for their work, and the reliability of the systems should exclude the possibility of their breakdown during the entire voyage of the vessel. Sails should be very simple, and their periodic repair and replacement should be carried out after a critical number of hours have been worked out, like aircraft engines, but this leads to additional costs for shipowners.

The telescopic lifting sails in Fig. 4 are also complex systems that require additional maintenance. In this case, the reverse version of folding sections, proposed in the "E/S Orcelle-2030" project (Fig. 30) is more preferable [54].

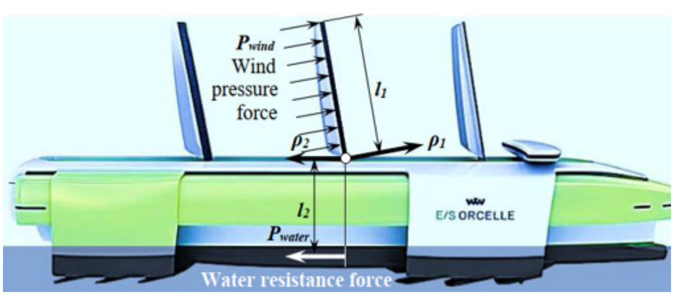
Figure 30: Basic variants of telescopic lifting sails.

Source: www.navalium.com.

The second important factor is the strength and reliability of the sail systems, since it has been strictly proven that reliability decreases with their complexity, and according to "Parkinson's laws", everything that can break will break someday. Therefore, all projects for placing sails on the roofs of ships do not meet these criteria (Fig. 7).

A generalized example of these problems is the project of the ship "E/S ORCELLE" [55], criticism of which is given in [6, 7]. In addition to the impossibility of turning the sails to increase their efficiency when the direction of the wind and the Sun changes, the different directions of the forces of action from the wind and of resistance of the hull to the water flow are critical (Fig. 31); on other masts, the scheme of action of the forces is the same.

Figure 31: Diagram of the action of wind (P_{wind}) and water (P_{water}) forces on a sail installed on the top deck of the ship.

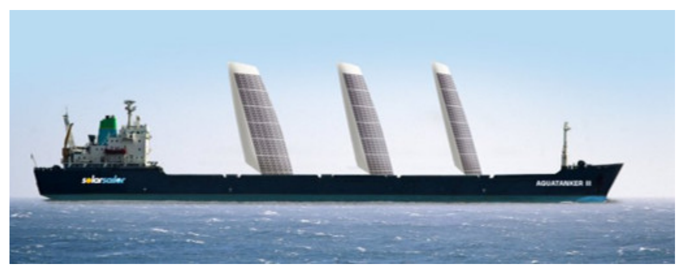


Source: www.yumpu.com.

The wind forces P_{wind} on the lever arm l_1 create a torque that leads to stresses ρ_1 at the sail attachment points, and the water resistance forces P_{water} on the lever arm l_2 create a torque that leads to opposite stresses ρ_2 at the same points. Their combination causes a shift in the place where the sail is attached and deformation of the surface on the top deck of the ship, and the higher the ship, the larger the shoulders l_1 and l_2, and the shift intensifies. If the issues of roof strength can be resolved, then the loads are transferred to the walls of the superstructures, and an increase in their thickness leads to an increase in the mass and cost of the ship, or only the cost, if a stronger metal is used. It is also necessary to remember about metal fatigue, which is aggravated by the variable magnitude of loads at different speeds and gusts of wind.

Despite the criticism of the rigid inclined masts of the E/S Orcelle project in [6, 7], new irrational projects using them continue to appear, in particular the Solarsailor project (Australia) [56]. The tanker, measuring 400 m by 31 m, is designed to transport large volumes of drinking water and has lifting sails with solar panels on them, which repeat all the shortcomings of the E/S Orcelle project [6, 7], therefore, this project is not recommended for further development (Fig. 32).

Figure 32: Project SolarSailor Aquatanker with rigid fixed sails.



Source: www.thefutureofthings.com.

Similar shifts occur when installing lifting sails on the top deck of the ship in the new STX Eoseas vessel designs (Fig. 7), and also when installing rotor columns in a similar way in the M/S Viking Grace cruise ferry design by Norsepower Oy Ltd. (Fig. 33) [57], since the columns create thrust by attaching them to the base on the high roof. This design is also not recommended for further development.

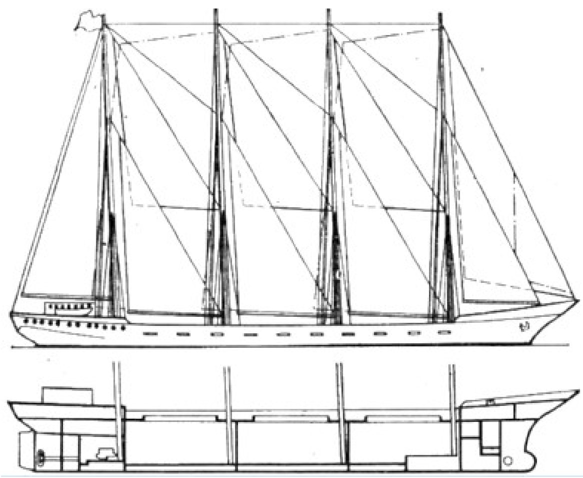
Figure 33: Rotor column on the roof of the M/S Viking Grace cruise ferry.

Source: www.ru.marinelink.com.

Shifts also occur when installing rotors on the ship's deck

(Fig. 5), but this is not so noticeable, since the additional traction of the columns is 10-15%, which is within the strength reserves of the deck, and the shoulder of forces to the hull submerged in water is not much greater - 10 - 15 m, compared to 30-50 meters in the STX Eoseas projects. But metal fatigue will still occur. It should be taken into account that the problem of "shift" was absent in classic sailing ships, since the root of the mast rested on the keel beam of the ship's hull (Fig. 34) [58].

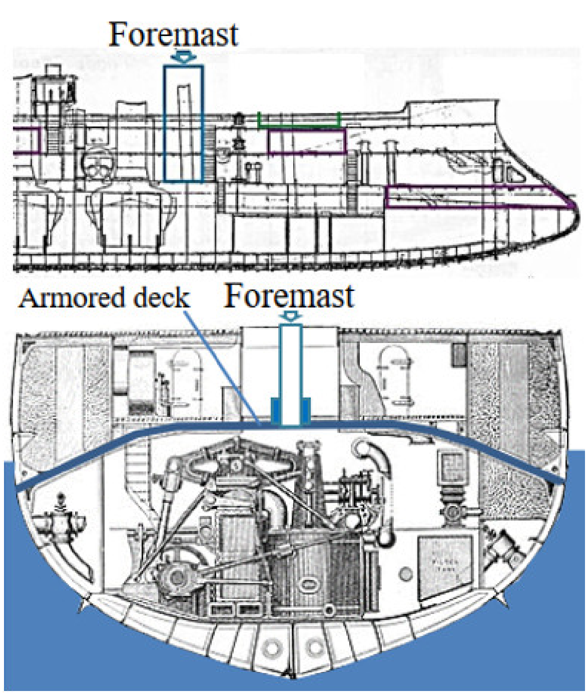
Figure 34: Installation of masts on the schooner "Condor".



Source: www.sailngstamps.ru.

On armored deck cruisers and destroyers, the root of the mast rested against a strong armored deck, which was connected to the ship's hull - in its underwater part (Fig. 35) [59].

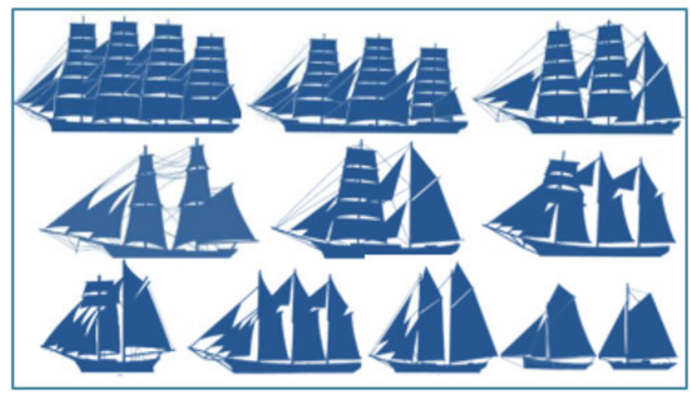
Figure 35: Installation of a mast with a stop against the armored deck of a warship.



Source: Shershov A. P.

It should be noted that in the latest designs of sailing vessels of the early 20th century, the masts were installed with a deviation from the vertical axis at an angle of 7 – 10^o, which, due to the deviation of wind forces, provided a slight "pulling" of the vessel's hull out of the water (especially for vessels of small displacement) and reduced its resistance during movement. Similar functions are performed by the vessel's bowsprit and all oblique sails in front of the vessel's masts, the diagrams of which are shown in Fig. 36 [60].

Figure 36: Oblique sails on the bowsprit and between the masts of the main types of vessels.



Source: www.shipshub.com.

The draft of the wind on the oblique masts and sails actually reduces the volume of the vessel in the water. However, on modern sailing ships, the tilt of the mast complicates its rotation and the operation of the sail, and the use of a bowsprit complicates the maneuvering of the vessel in the port (the schooner Condor does not have a bowsprit, Fig. 34). Therefore, the pulling of the vessel's bow out of the water can be provided by an additional sail system "SkySils" [61], or AIR [62], since the company "Airseas" has brought it to automatic use. However, it is limited by the size of the sails (up to 1000 m^2), and the additional weight of the sail launching and lowering system on the bow of the vessel sinks it (Fig. 37).

An analysis of the experimental version of installing a lifting sail on the bow of a vessel (Fig. 3, 30) showed that the effect of wind forces on it leads to the bow being flooded, so the effect of these tests is not the best. It is better to install the foremast further away from the bow of the vessel.

It should be noted that, apart from the systems with rotor columns of the company "Norsepower Rotor Sail" on the transport fleet and sailboats of cruise ships, none of the analyzed projects has been implemented on a large scale, which indicates insufficient attention to this problem. At the same time, each developer of sailing systems promotes its own version, there are no comparative tests with other projects. A single center is needed for this, but its creation is not even being discussed yet. The work performed fills the gap.

Figure 37: Airseas sail system with an autonomous module of mechanisms for raising and lowering his on the vessel.

Source: www.skysails-group.com.

Conclusions.

1. With an average speed of cargo delivery in the transport fleet of 14 – 20 knots, ship sailing systems are not able to completely replace the main engine except in areas where the wind speed exceeds 10 m/s, however, the real effect of their use allows saving from 10 to 30% of fuel, with adequate reduction of greenhouse gas emissions CO and CO_2.

2. The main limiting factor for the introduction of sails in the transport fleet is the increased labor intensity of their maintenance, which leads to an additional burden on crew members, the number of which on modern vessels has been reduced to a minimum.

3. The modern tendency to complicate the design of sails for the sake of a small increase in their efficiency is questionable, since it leads to the need for more time and an increase in the time and cost of their maintenance and repairs.

4. Increasing the height of the sails requires the need to lower and raise them when passing under bridges, which leads to additional complications in their designs and costs for their maintenance, therefore, low sail systems of simple designs are more appropriate, however, gigantism is acceptable for inflatable sail systems that quickly change height.

5. When achieving the same thrust in sail systems of complex designs and in sail systems of simple designs by increasing their number, the use of more complex options is impractical.

6. The sails should be positioned on both sides of the vessel, which doubles their thrust.

7. Complication of sail maintenance is an inevitable fact of their use, but it should be minimal and carried out on the ship's berths in the port by crew members assigned for this purpose with additional payment for their work, therefore the reliability of the sail systems should exclude the possibility of their breakdown during the entire voyage.

8. Sail systems should be kept simple and periodically repaired and replaced after a critical number of hours, similar to aircraft engines.

9. All sailing systems lead to additional costs for ship owners, which may pay off over a long period of operation, but their use is beneficial for the whole society, as it leads to a reduction in fuel consumption and greenhouse gas emissions.

10. It is necessary to overcome the psychology of the unprofitability of ship sailing systems, and ship owners need to compensate for additional costs through subsidies, such as payments for "green" energy, or tax reductions.

Conflict of interest.

The work was carried out by the authors on their own initiative, based on their own works [6, 7, 8] and open literary sources that do not require permission to use them. There is no conflict of interest.

References.

[1] My Water Shop. (s. f.). ¿Cuánta agua hay en la Tierra? https://mywatershop.com.ua/blog/skilki-vodi-na-zemli/.

[2] United Nations Framework Convention on Climate Change (UNFCCC). (2015). COP21 Paris Conference. https://unfccc.int/event-/cop-21.

[3] hNezavisimaya Gazeta. (2021, octubre 11). Methanol (archivo web). https://web.archive.org/web/20211024161949/https://www.ng.-ru/ng_energiya/2021-10-11/13_8274_methanol.html.

[4] International Maritime Organization (IMO). (2014). MEPC.-245(66): Attained Energy Efficiency Design Index (EEDI). https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.245(66).pdf.

[5] Watson, P. (s. f.). Top 7 green ship concepts using wind energy. Marine Insight. https://www.marineinsight.com/green-shipping/top-7-green-ship-concepts-using-wind-energy/.

[6] Nastasenko, V., Svyrydov, V., & Andreev, A. (2022). New top-7 vessels wind projects and analysis of their practical possibilities for the transport fleet. Journal of Maritime Research, 19(3), 30-38. https://www.jmr.unican.es/index.php/jmr/issue/view/67.

[7] Nastasenko, V., Protsenko, V., & Babii, M. (2023). Modern development of ship wind systems within the new rating of Top-7 projects. Journal of Maritime Research, 20(2), 77-88. https://www.-jmr.unican.es/index.php/jmr/article/view/716.

[8] Nastasenko, V. (2024). Analysis of the possibilities of ship wind systems. In Proceedings of AICRE-2024 (p. 58). https://eertc.-com/wp-content/uploads/2024/09/Proceeding-of-Annual-International-Congress-on-Renewable-Energy-3-5-Sep.-2024.pdf.

[9] Earth Nullschool. (s. f.). Wind flows in the world's oceans. https://earth.nullschool.net.

[10] World Economic Forum. (2024). World?s busiest ocean shipping routes. https://www.weforum.org/stories/2024/02/worlds-busiest-ocean-shipping-routes-trade/.

[11] YouTube. (s. f.). Sails of Pyxis Ocean ship [Vídeo]. https://-www.youtube.com/watch?v=KCD0eNyTc5U.

[12] Mitsui O.S.K. Lines (MOL). (s. f.). Wind Challenger project. https://www.mol.co.jp/en/bam/001/.

[13] Mitsui O.S.K. Lines (MOL). (s. f.). Wind Hunter project. https://www.mol.co.jp/en/bam/004.

[14] Facebook. (2022). Neoline project image. https://www.face-book.com/photo/?fbid=421492969980459.

[15] Boat International. (s. f.). Glory yacht concept unveiled. https://www.boatinternational.com/yachts/news/glory-yacht-concept-unveiled.

[16] Offshore Energy. (s. f.). Norsepower rotor sail installation. https://www.offshore-energy.biz/norsepower-worlds-1st-tiltable-rotor-sails-installed-on-sea-cargo-roro/.

[17] Eco Marine Power. (s. f.). EnergySail system. http://www.eco-marinepower.com/en/energysail.

[18] Crociere UK. (2015). Eco cruise ship concept from Peace Boat. https://crociereuk.wordpress.com/2015/01/17/eco-cruise-ship--concept-from-peace-boat.

[19] Stirling Design. (s. f.). EOSEAS green cruise ship concept [PDF]. https://www.stirlingdesign.fr/presses/conferences/stirling_design_green_ship_copenha.

[20] Facebook. (s. f.). Neoline project. https://www.facebook.com-/photo/?fbid=421492969980459.

[21] CharterWorld. (s. f.). Emax Deliverance motor yacht concept. https://www.charterworld.com/news/emax-deliverance-motor-yacht.

[22] MySkillsConnect. (s. f.). Modern sailing ships. https://myskillsconnect.com/vodnyj-transport/41858-sovremennye-parusnye-suda--59-foto.html.

[23] Wikipedia. (s. f.). Thermopylae (clipper). https://en.wikipedia.org/wiki/Thermopylae_(clipper).

[24] CharterWorld. (s. f.). Emax solar hybrid schooner. https://www.charterworld.com/news/66m-emax-evolution-solar-hybrid-schooner.

[25] Slate. (2012). Wind-powered cargo ships. https://slate.com/technology/2012/06/wind-powered-cargo-ships-b9-s-radical-clean-energy-innovation.html.

[26] Wikipedia. (s. f.). Governor Ames. https://en.wikipedia.org/-wiki/Governor_Ames.

[27] Village Craftsmen. (s. f.). George W. Wells wreck. https://www.villagecraftsmen.com/wreck-george-w-wells-september-3-1913/.

[28] Wikipedia. (s. f.). Wyoming (schooner). https://en.wikipedia.org/wiki/Wyoming_(schooner).

[29] Wikipedia. (s. f.). Thomas W. Lawson (ship). https://en.wikipedia.org/wiki/Thomas_W._Lawson_(ship).

[30] Yacht Russia. (2023). Cargo ships speed analysis. https://www.yachtrussia.com/news/2023/05/20/20230520-bystree-chem-obychnye-gruzovye-suda.html.

[31] Shipshub. (s. f.). Wind ships article. https://shipshub.com/ru-/article/1460-2.html.

[32] Shipshub. (s. f.). Wind ship technologies. https://shipshub.-com/ru/article/1448-2.html.

[33] Nippon Maru Foundation. (s. f.). https://www.nippon-maru.-or.jp/english/.

[34] Shipshub. (s. f.). Nippon Maru II. https://shipshub.com/ru/-article/1544-2.html.

[35] Korabley. (s. f.). Sedov. https://korabley.net/publ/194.html.

[36] Wikipedia. (s. f.). ARA Libertad. https://ru.wikipedia.org/wiki/ARA_Libertad.

[37] Korabley. (s. f.). INS Tarangini. https://korabley.net/publ/17-43.html.

[38] Shutterstock. (s. f.). Druzhba training ship. https://www.shutterstock.com.

[39] Google. (s. f.). Bark Tovarishch images. https://www.google-.com.

[40] Zakharov, A. (2010). Tovarishch, kotoryy my poteryali. http://-mycity.kherson.ua/avtory-ag/zaharov1/tovar-poter.html.

[41] Korabley. (s. f.). Royal Clipper. https://korabley.net/publ/145-.html.

[42] Korabley. (s. f.). Star Clippers. https://korabley.net/publ/1871-.html.

[43] MarineTraffic. (s. f.). https://www.marinetraffic.com.

[44] ItBoat. (s. f.). ZEN Yacht. https://itboat.com.

[45] Flotilia. (s. f.). Wisamo sails. https://www.flotilia.com.

[46] ResearchGate. (s. f.). Aerodynamics of wind-assisted ships. https://www.researchgate.net.

[47] MarineTraffic. (s. f.). Shin Aitoku Maru. https://www.marinetraffic.com.

[48] Dry cargo ship Aqua City Maritime : http://sail-friend.ru/index-.php?topic=260.0.

[49] Dry cargo ship Usuki Pioneer : .http://sail-friend.ru/index.php-?topic=260.0 https://seaspout.wordpress.com/tag/sail/.

[50] Hybrid sailing power plant ASPS : http://sail-friend.ru/index.-php?topic=260.0.

[51] Windship Technology. (s. f.). https://windshiptechnology-.com.

[52] CKnud E. Hansen. (s. f.). https://www.knudehansen.com.

[53] El Periódico de la Energía. (s. f.). https://elperiodicodelaenergia.com

[54] Navalium. (s. f.). https://navalium.com.

[55] Yumpu. (s. f.). E/S Orcelle project. https://www.yumpu.com.

[56] The Future of Things. (s. f.). SolarSailor. https://thefutureofthings.com.

[57] CFTS. (2018). https://cfts.org.ua.

[58] Sailing Stamps. (s. f.). Schooner Condor. https://sailngstamps-.ru.

[59] Shershov, A. P. (1994). History of military shipbuilding. Poligon.

[60] Shipshub. (s. f.). Classification of sailboats. https://shipshub-.com.

[61] SkySails. (s. f.). Marine brochure. https://skysails-group.com.

[62] Ouest-France. (s. f.). Airseas tests. https://agence-api.ouest-france.fr.