JOURNAL OF MARITIME RESEARCH

Vol XX. No. II (2023) pp 77–88

ISSN: 1697-4840, www.jmr.unican.es

Modern development of ship wind systems within the new rating of Top-7 projects

V. Nastasenko[1,*], V. Protsenko[2], M. Babii[3]

ARTICLE INFO

Article history:
Received 23 Feb 2023;
in revised from 26 Mar 2023;
accepted 08 Apr 2023.

Keywords:
Decarbonization in the transport fleet, better sailing systems and ways of their development.

ABSTRACT

The problem of decarbonization of human activity is one of the most important in the conditions of the ever-increasing threat of global warming. It is solved differently in all areas of modern society, primarily in the fields of engineering and technology. The transport fleet could not be aloof from solving this problem, as it consumes about 6% of the total volume of oil fuel, and the share of greenhouse gases generated during its combustion in ship's internal combustion engines (ICE) is ≈ 3% of their total amount. Therefore, the International Maritime Organization (IMO) in Appendix VI of the Convention "MARPOL 73/78" introduced restrictions on emissions of harmful substances by sea transport. Among the main technical ways to reduce them, the IMO recommends the use of wind and solar energy. Since solar energy systems have small specific power, it is unable to replace ship's ICE. Sailing energy was the main energy on the weasels 150 years ago, so it is potentially able to replace ship diesel engines. A new revival of sailboats began in the 60s of the XX century. At the same time, it is important to choose the right ways and the best options for sailing systems, which allows you to avoid wasting time and money on the development of unproductive options. Therefore, the selection of the TOP-7 best options is an urgent and important task and constitutes the **main goal** of the work being performed. Its **scientific novelty** is the substantiation of the best options for modern ships sailing systems and ways of their evolution for the development of recommendations for their design and use. **Research methods** are based on the comparison of technical and economic indicators of the best ship wind systems of world. **Work results**. In 2019, Captain Paul Watson highlighted the TOP-7 projects of ship wind systems. In 2022, based on criticism of its shortcomings, a new TOP-7 rating was developed. Its further justification based on the development of new projects of ship wind systems in recent years is given in this work. **Conclusions.** Modern projects of ship wind systems and their development paths confirm the validity of the new TOP-7 rating, therefore it is recommended for further research and development of ship wind systems.

1. Introduction.

The problem of decarbonization of human activities (reduction of CO and CO_2 greenhouse gas emissions) is one of the main ones [1] in the face of the ever-increasing threat of global warming. It is solved in different ways in all spheres of society's life and activities, primarily in the fields of engineering and technology. Within the framework of this problem, the transport fleet could not be aloof from its solution, since it consumes about 6% of the total volume of oil fuel, and the share of greenhouse gases produced during their combustion is ≈ 3% of

[1]Doctor of Technical Sciences, Professor of the Department of Transport Technologies and Mechanical Engineering of Kherson State Maritime Academy, Ukraine.

[2]Doctor of Technical Sciences, Professor of the Department of Transport Technologies and Mechanical Engineering of Kherson State Maritime Academy, Ukraine.

[3]Ph.D., Associate Professor of the Department of Operation of Ship Power Plants of Kherson State Maritime Academy, Ukraine.

*Corresponding author: V. Nastasenko. E-mail Address: nastasenko2004@ukr.net.

their total amount. Therefore, the International Maritime Organization (IMO) in Annex VI of the MARPOL Convention 73/78 [2] introduced restrictions on emissions of harmful substances from the burning of traditional fuels on ships. For this purpose, the energy efficiency index (EEDI) was introduced in 2009 [3]. However, it only solves the problem of reduction of harmful emissions. The complete transition of the transport fleet to alternative energy is a difficult future step that still requires the solution of many scientific and technical problems. Among the main technical means of reducing CO and CO_2 emissions, the IMO recommends the use of wind and solar energy.

However, the specific power of solar batteries is very small compared to the power of ship's internal combustion engines, so they require large areas, which are not available on the ship. As a result, marine solar energy can only be an additional type of energy and is not considered in this paper.

Since only 150 years ago the transport fleet was mainly sailing, this indicates the possibility of wind energy being the main one on the ship. That is why it is given great attention in world shipbuilding. In this work, it is also given the main attention.

The relevance of the research is due to the fact that as a result of the war in Ukraine, the prices of traditional ship energy carriers - oil fuel and natural gas - have increased. This is an important incentive for the development of sailing systems. However, this situation is temporary and after the war prices will fall again. Therefore, the maximum possible amount of work should be performed in this period, which meets the modern requirements of the development of the transport fleet. However, this first requires a thorough analysis of known marine sailing systems.

Analysis of recent researches and publications. Selection of previously unsolved parts of the general problem, setting goals and objectives of the study. The analysis of literary and patent sources showed that since the beginning of the revival of the sailing fleet in the 60s of the 20th century, the transition to wind energy has not happened, which requires determining the reasons for this situation. At the same time, it is important to choose the right ways and the best options for the development of sailing systems, which will avoid wasting time and money on the development of unproductive options. Therefore, the selection of the TOP-7 best options for marine wind systems is an important technical and economic problem and is the **main goal** of the work being performed. Its **scientific novelty** is the substantiation of the best options for modern ship sailing systems and ways of their evolution for the development of recommendations for their design and use.

The **research methods** are based on a comparison of the technical and economic indicators of the analyzed ship wind systems, taking into account the best world achievements.

Analysis of the current stage of development of ship wind systems showed that all the leading maritime powers of the world (Japan, Great Britain, France, Germany, Sweden, Spain, China, etc.) are working on this problem. Much attention is paid to her in the company Sea Shepherd Ocean Action, in which Captain Paul Watson worked. In 2019, he highlighted the TOP-7 projects of ship wind systems [4], which he recognized as the best in world at that time (Table 1).

In Ukraine and in the geographical space of the former (until 1991) Soviet Union, the greatest achievements are associated with the work of the Kherson State Maritime Academy, where Professor V. Nastasenko received 12 patents for inventions of wind and hydro-wave ship power systems and has more than 60 scientific works in this field, including international level [5, 6, 7]. The accumulated experience of scientific and practical work since 2007 allowed us to criticize well-known projects of ship wind systems and develop our own new rating of the TOP-7 projects [6, 7], which is listed in Table 2.

Table 1: Basic TOP-7 projects of ship wind systems by Captain Watson.

Ranking	Project name	Project features
7	B9 Sail Cargo Ship	Sails with rotary masts, which are installed on the axis of the vessel and do not have rigging for their attachment to the hull, which simplifies their rotation and control.
6	Eco Marine Power Wind-Solar Ship	A large number of rigid rotary sails installed on both sides of the vessel's hull, which use wind and solar energy.
5	Sky Sails / Kite Ship	Flexible liftable sails are towing kites that are mounted on the bow of a vessel for its movement in the wind.
4	Flettner Rotor Ship	Vertical rotating cylinders that reproduce the Magnus effect as a ship's propulsion.
3	NYK ECO Ship 2030	Complex system of flexible lifting sails, solar panels and improvements of the smoothness of the hull, superstructures and all energy systems of the ship.
2	STX Eoseas	5… 6 masts more than 100 m high with flexible lifting and rotating sails.
1	E/S Orcelle	Rigid liftablesails with solar panels on their surface and hydrowave fins that convert the energy of the waves.

Source: Authors.

Table 2: New TOP-7 projects of ship wind systems proposed of professor Nastasenko.

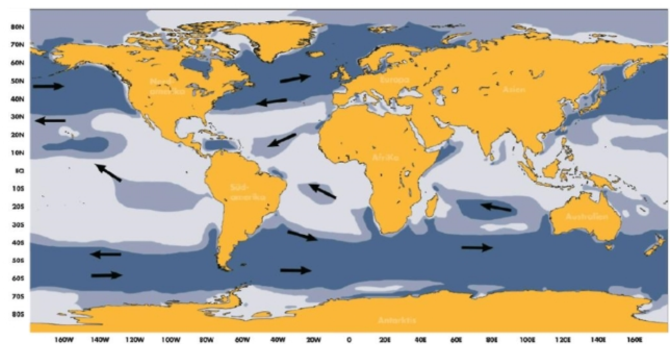
Ranking	Project name	Project features
1	2	3
7 (1)	E/S Orcelle (Sweden)	Rigid liftablesails with solar panels on their surface and hydrowave fins that convert the energy of the waves.
6 (5)	Sky Sails /Kite Ship (Germany)	Flexible liftable sails are towing kites that are mounted on the bow of a vessel for its movement in the wind.
5 (2)	STX Eoseas (France)	5… 6 masts more than 100 m high with flexible lifting and rotating sails
4 (7)	B9 Sail Cargo Ship (UK)	Sails with rotary masts, which are installed on the axis of the vessel and do not have rigging for their attachment to the hull, which simplifies their rotation and control.
3 (3)	NYK ECO Ship 2030 (Japan)	Complex system of flexible lifting sails, solar panels and improvements of the smoothness of the hull, superstructures and all energy systems of the ship.
2 (4)	Flettner Rotor Ship (Germany)	Vertical rotating cylinders that reproduce the Magnus effect as a ship's propulsion.
1 (6)	Eco Marine Power Wind-Solar Ship (Japan)	A large number of rigid rotary sails, which are installed on both sides of the vessel's hull and use wind and solar energy.

Source: Authors.

A feature of the works [5, 6, 7] is a critical analysis of known ship wind systems, which is given little attention in the works of other authors. Among them, the work [8] is interesting, but it analyzes only 4 of the 7 projects considered in [5, 6], namely: 1) B9 Sail Cargo Ship, 2) Sky Sails / Kite Ship, 3) Flettner Rotor Ship, 4) Eco Marine Power Wind-Solar Ship. In addition, the criticism of the negative indicators of these projects in [8] is not complete enough. In the paper [9], only one option is analyzed – Fletcher rotors and their shortcomings are rejected altogether.

In works [5 - 7] it is shown that the main problem of using ship wind systems is the speed of steady wind flows in the world ocean, which are shown in Fig. 1.

Figure 1: Steady annual directions of wind flows in the oceans.



strong wind 10 ... 20 m/s; – moderate wind 5 ... 10 m/s; – weak wind up to 5 m/s.

Source: Authors.

Since the modern average speed of ship delivery of goods is 7 ... 15 *m/s*, the tailwind in the seas and oceans very often does not catch up with the ship. However, the use of sailboats of the accompanying principle of action is advisable on routes where the average annual wind speed exceeds 10 m/s, namely in the so-called "roaring" 40's and "crazy" 50's latitudes. On the equator and tropical routes, where the average annual wind speed is only 5 m/s and very often there is a multi-month calm, the use of sails is unproductive; they become useless cargo that reduces the transport work of the ship.

Thus, the lower limit for the use of wind is an economic speed of cargo delivery of 10 *m/s*, and the upper limit is a wind speed of 17 m/s (on the Beaufort scale, this is the "fresh wind" at which the top sails on the masts are folded and put out of action, and at a wind speed of 21 m/s - this is a storm that ships are advised to avoid).

In addition to wind speed limitations, the second limitation is the sail capacity (total sail area) of the vessel. It should be such that, due to the thrust of the sails, it completely or partially compensates for the resistance of the vessel to the oncoming flow of water and air. Therefore, the large tonnage of ships (over 25,000 tons) requires a large number of sails and masts (over 7).

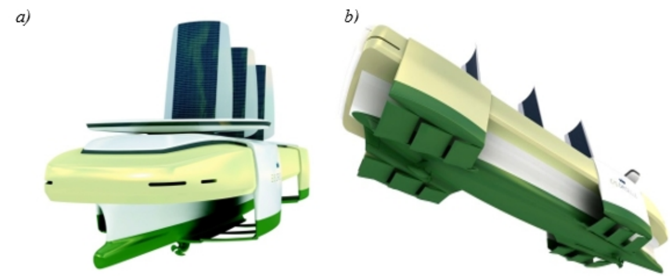
However, with the ship's own speed, which is developed by the diesel engine, it must be deducted from the useful wind speed, which reduces the effectiveness of the sails. When the wind speed is greater than the ship's own speed, the sails can: either increase its speed, or reduce the fuel consumption to achieve the required speed due to the additional thrust of the sails, or due to the internal thrust of the diesel engine, it is possible to reduce the area of the sails.

Another limitation is the need to train the rank and file crews of ships, which on average change every six months. This requires extensive development of the technical and economic base and training system, with simulators and PC programs, which must be developed now, since the use of sailboats and additional sailing systems on ships is a promising and inevitable process..

Presentation of the main material of the study. It should be taken into account that in works [4, 6], projects of sailing vessels up to 2019 were considered. Since they have developed in recent years, it is necessary to perform a new analysis of them, which is the main task of the current work. The analysis is carried out further in the order of increasing rating given in Table 2.

In the new TOP-7 [6], the 2025 ship project E/S Orcelle [10] was placed in the 7th place, which in the basic TOP-7 [4] took the 1st place because it had all 3 types of unconventional energy: 1) wind, 2) solar, 3) hydrowave (the latter was not available in other TOP-7 projects). The main elements of ship alternative energy of this project are shown in Fig. 2:

Figure 2: "E / S Orcelle 2025" ferry project (Sweden) with a system of rigid liftable sails with solar panels (a) and hydrowave fins (b).



Source: solarnavigator.net.

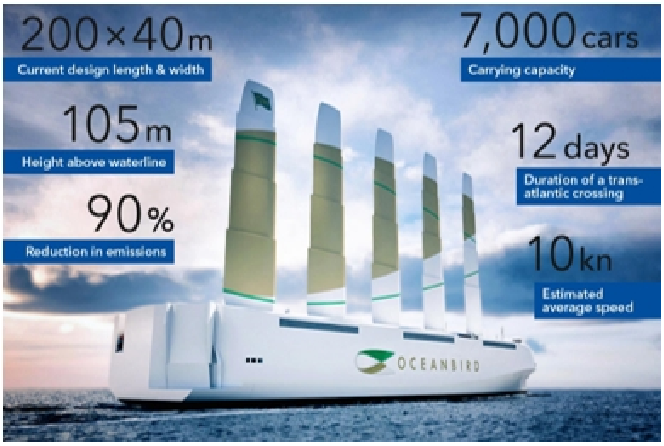
However, the project [10] ended its existence. In the new project of the ship [11], there are no hydro-wave platforms-fins, since their efficiency is < 25% due to the large number of transformations of the oscillating movement of the fins into the rotation of the rotor shaft of the electric generator. The fins and their hinges are overgrown with flora and fauna of the seas and oceans, so their oscillation becomes difficult, which reduces the efficiency to 0. In addition, the platforms carry the threat of damage to the ship's hull when it runs aground, which can lead to the sinking of the ship. Instead of lifting sails, retractable telescopic ones are made, which turn in the direction of the wind. There are no solar panels on the sails, as they significantly increase the price of the project, but do not always have appropriate lighting angles when turning the sails downwind. The general appearance and main parameters of the new vessel are shown in Fig. 3.

However, the new project [11], relative to the previous most innovative project [10] with all 3 types of alternative energy, turned into a pragmatic ordinary project, not worthy of the 1st place in the TOP-7. Therefore, his 7th place in the new TOP-7 is fair.

It should be noted that the work [12] states that not using free solar energy is a waste. Therefore, it is recommended to review the new project of the vessel [11] and return to the project of 2000 [13], which is shown in Fig. 4.

It provided for the installation of solar panels on the roof of the ferry. It is appropriate for the area of the new ferry 200 x 40 = 8000 m^2, as it gives a peak daily power of electrical energy

Figure 3: New project of a vessel based on the E/S Orcelle ferry.



Source: dnv.com.

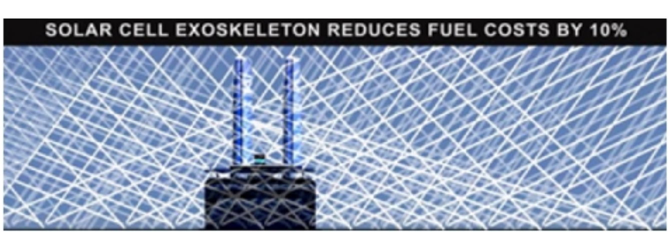
Figure 4: Initial design of the E/S Orcelle ferry.

Source: solarnavigator.net.

of 1400 *kW/h* and an average daily power of 240 *kW/h*, which is enough for the lighting of the ship or for the operation of its other systems.

However, it is impractical to place solar panels on the sides of the ship, since their specific efficiency is only 25% of the action of the batteries on the roof, even when using 10% of the energy of the sun's rays reflecting waves (Fig. 5).

Figure 5: Scheme of the action of the sun's rays on the waves and the ship's hull [11].



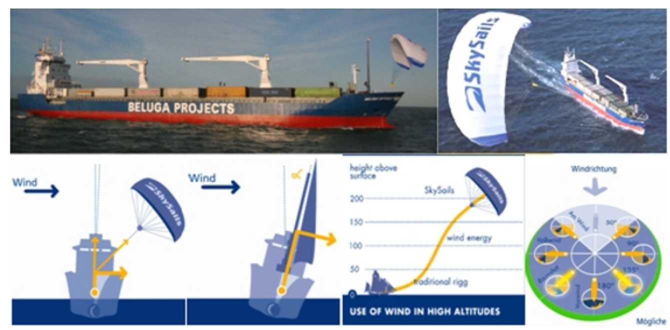
Source: dnv.com.

Taking into account the area of the 2 side surfaces of the vessel 2 x 1000 = 2000 m^2, and when only 10% of the reflected solar energy acts on the non-illuminated side, the annual average daily power of electricity will be 20...30 *kW/h*, which is unprofitable for solar batteries with such a large area .

It is also recommended to return to the installation of rotary sails on the sides of the ship's hull, which increases their number and sailability and reduces the roll and sway of the ship under the action of wind and its gusts.

In the old TOP-7, the Sky Sails/Kite Ship system [14] was in 5th place thanks to its main advantages: the ability to transport cargo on the ship's deck; absence of roll; of greater force and speed of the wind at a height where there is no friction between air and water; of simple removal of the sails from action in strong wind, or in its absence (Fig. 6).

Figure 6: SkySails system with flexible lifting sails – kites (Germany) and conditions of use of wind at high altitude.



Source: Authors.

In the new TOP-7, the Sky Sails / Kite Ship sail system was moved to the 6th place as unpromising. However, it is being revived in the "Airseas" project [15] and a number of other firms. The new systems have a mobile module for mechanisms, which is easily mounted on the ship (Fig. 7), and also have a sail with an area of 1000 m^2 (at Sky Sails, the areas of the sails were 160, 320 and 640 m^2):

Figure 7: "Airseas" sail system with an autonomous mechanism module for installation on a ship.

Source: Airseas.

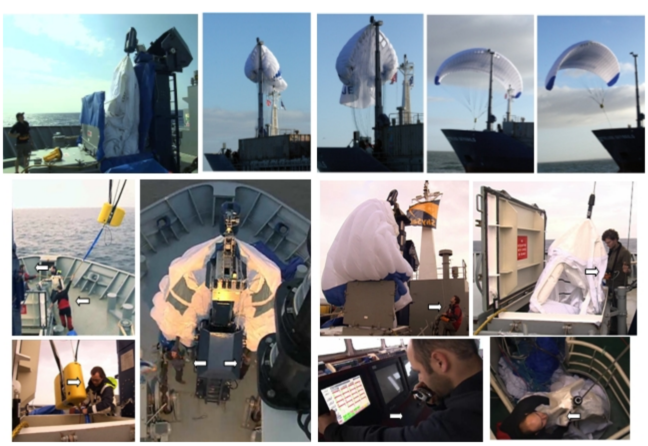
However, it is not clear how the developers of "Airseas" eliminated the main shortcomings of the Sky Sails system:

1. The possibility of falling into the water and drowning the sail during its ascent and descent, as a result of unexpected gusts and vortices of the wind (if you remember your childhood, the launch and descent of a kite was not always successful). When a sail worth more than $1 million falls, it fills with water and it is impossible to raise it,

which is dangerous for the movement of the ship. Therefore, the sail has to be cut down and thrown into the sea.

2. The relative complexity of launching, lowering and bunkering the sail, carried out in 4 stages (Fig. 8), which are controlled by 3 people, namely: a) raising the mast, which further pulls the sail out of the bunker, its inflation, and release into flight (when lowering sail actions are performed in reverse order); b) grabbing the sail control module (a yellow container that does not allow shocks) and carefully lowering it into the bunker (one person gives it, and the second person in the bunker receives it); c) pulling the sail to the mast after its descent, blowing air from it (two people) and folding it; d) lowering the sail into the bunker (one person serves it, the second person in the bunker receives it). Those who have packed a parachute know that with careless packing, the webs of the dome and the slings can get mixed up and problems will arise with the opening of the parachute. All these operations are complicated when the bow part of the ship sways with waves, and the sails with gusts of wind. At the same time, the danger of performing work for the specified 3 persons increases [16]. A fourth person controls the flight and descent of the sail from the wheelhouse.

Figure 8: The main operations of raising, lowering, bunkering and controlling the sail by 4 persons performing these works.



Source: Authors.

Since it is unprofitable to keep a special crew on board to perform these works, they will have to be performed by full-time crew members, which will increase their current workload with the corresponding need to negotiate labor relations. Only on pleasure yachts is this work a romantic pastime.

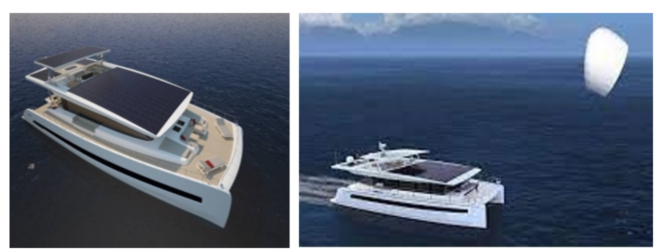
If the 1st drawback can be eliminated by meticulous training of crew members, which requires the creation of an appropriate training base, and this is significant time and money, then the 2nd drawback can only be solved by complex automation. And this is again additional time and money. Therefore, one should wish success in solving these problems, since the final result is positive - it is a reduction of harmful emissions into the Earth's atmosphere, especially for slow-moving vessels. However, the more automation outside the ship's premises, the faster it will break.

For example, these are the four-wheel-drive yachts powered by solar energy that have their own speed of 7 ... 7.5 knots. The sail enables the "Planet Solar Turanor" catamaran to move at a speed of up to 10 knots (Fig. 9) [17]. This gave the catamaran a "second life", as the $12 million price tag significantly reduced demand for it. Using the thrust of one's own engines allows reducing the sail area, which can also be implemented for other vessels. Similar systems of sails were also received by other solar-powered catamarans (Fig. 10) [18], which confirms the perspective of combining these two developments.

Figure 9: Combination of the "Planet Solar Turanor" yacht (Germany) with a SkySails type sail.

Source: vadebarcos.net & Skysails.

Figure 10: Catamaran "Chloe" (Holland) powered by solar batteries with a SkySails type sail.



Source: Authors.

Despite the growth in demand, the shortcomings of this system - its use for slow-moving vessels of small displacement - leave it in 6th place in the new TOP-7.

The innovative STX Eoseas project with an arc-shaped sail in the lower part of the mast, which increases the vessel's thrust (Fig. 11) [19], was moved from the 2nd to the 5th place in the TOP-7 [6].

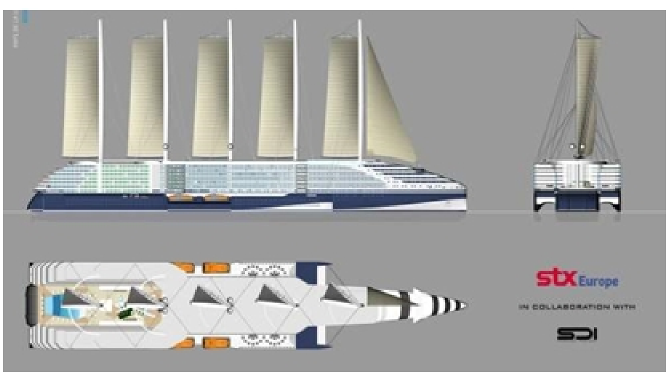
In another variant, the construction of masts and sails have simpler straight shapes, similar to schooner sails (Fig. 12) [20]. Roll and pitch is reduced by a trimaran-type hull with a width of 60 m. However, the general dependence of the ship's motion on the wind speed remains.

Also, there remains the problem of tilting high masts (over 100 *m*) for passage under bridges. However, there is a possible solution to this problem, which is proposed in the project of the yacht "Glory" (Fig. 13) [21]. Her masts can tilt and turn. But for this, it is necessary to solve the problems of the use

Figure 11: Mast sails in the "Eoseas" passenger ship project of STX Europe (France).

Source: SDI.

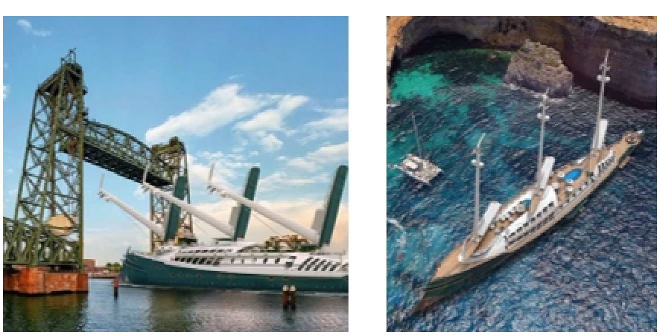
Figure 12: Project of the ship "Eoseas" with sails of a simple straight shape - schooner type sails.



Source: ship-technology.com.

of patents, because for them, either the payment of royalties is required, or we have to wait until their expiration.

Figure 13: Concept: 170-meter sailing superyacht "Glory".



Source: robbreport.com.sg.

Turning and tilting masts and sails inside the ship's residential superstructures (Fig. 14) [22] is technically difficult and will most likely be prohibited by the Maritime Register. Therefore, it is necessary to search for new innovative solutions.

Figure 14: Concept: Installation of masts inside the superstructures of the Eoseas vessel.

Source: ship-technology.com.

Under these conditions, the concept of building a ship has changed. The new project received sails that can tilt (Fig. 15) [23], which improved their ability to pass under bridges. However, the location of the sails on the roof of superstructures leads to its shifting, due to the moment from the action of opposing forces - wind and water resistance on the submerged hull of the ship, which is an important drawback.

Figure 15: A new concept for placing lifting sails on the roof of ship superstructures.

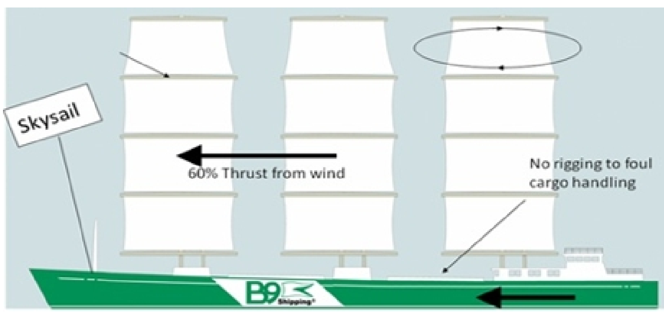
Source: intermedia.eus.

Thus, the STX Eoseas high-mast project exhausted itself, as did the E/S Orcelle project, and was therefore rejected by the developers themselves in favor of another project [23]. However, thanks to his other innovations (hull, engines, propellers) [24], in the new TOP-7 rating, he was left in 5th place,

Since the lateral installation of sails already refers to the option of Eco Marine Power Wind-Solar Ship [25], therefore this option of STX Eoseas is considered in the ongoing work below.

In the new TOP-7, the B9 Sail Cargo Ship project (Fig. 16) [26] moved from the 7th place to the 4th place and overtook the STX Eoseas project, since its masts and sails are simpler and more efficient, and the use of traction from its own ICE reduces the area of sails, or makes it possible to reduce fuel consumption. However, like previous projects, he it depends on the wind speed in the world ocean and on the route.

Figure 16: The concept of the B9 Sail Cargo Sailing Ship (UK).



Source: newatlas.com.

In the new version, the B9 Sail Cargo Ship received additional inserts in the lower part of the masts (Fig. 17) [27], which increased their height and allowed the deck to be used for cargo transportation.

The ship received innovative swivel masts with concave rayls, which increases the thrust of the sails, which are currently being tested on yachts (Fig. 18) [28]. However, the inclination of the masts for passage under bridges is not yet available, but in the future it will be easier to implement than in the STX Eoseas project.

Figure 17: An improved version of the masts of the B9 Sail Cargo Sailing Ship project by DykstrA.

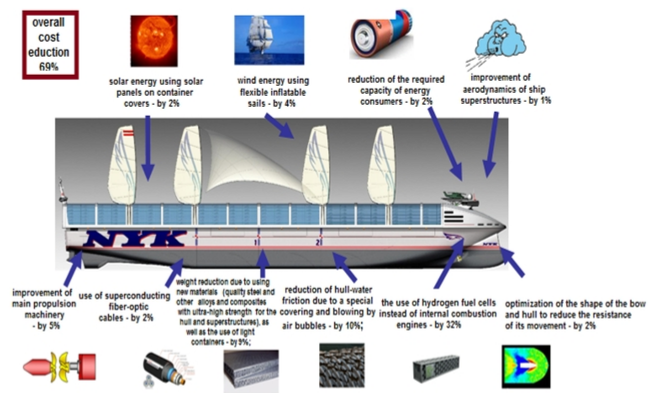
Source: thenationalnews.com.

The NYK ECO Ship 2030 project (Fig. 19) [29] remained in 3rd place in the new TOP-7. It has more innovations than project STX Eoseas [24], so it is ahead of it. The project [29] did not receive significant changes, as it already used known advanced technologies.

Figure 18: Rotating masts and sails with a concave shape of rails.

Source: shutterstock.com & doylesails.com.

Figure 19: Main ways to reduce energy and fuel costs in the NYK Super Eco Ship 2030.



Source: Authors.

However, the use of removable lids for closing containers with solar panels on them (Fig. 20) [29] significantly increases the cost of the vessel and complicates its operation, and most importantly - increases the risk of damage to the lids (they are gradually removed and installed one on top of the other on the vessel deck, since there is usually no place for them at the pier).

Figure 20: Lids for closing the containers with solar batteries of the NYK ECO Ship 2030.

Source: seanews.com.tr.

Therefore, there are few chances for the introduction of this type of solar batteries. Other innovative elements are gradually introduced, as they are real in production and operation. For example, the NYK ECO Ship 2030 project has inflatable lifting sails. This direction was developed in the projects of the Michelin concern (Fig. 21) [30] and is now being tested on ships and yachts.

Figure 21: Inflatable mastless sails of the Michelin concern and their descent for passing under bridges.

Source: en.futuroprossimo.it & axios.com & Alain Wicht.

The Flettner Rotor Ship project [31] in the new TOP-7 moved from 4th place to 2nd. This is one of the best projects, the demand for which is increasing nowadays, because it works at crosswind speeds from 3 m/s. An increasing number of ships are equipped with rotor columns of the Norsepower concern of various capacities in the number of 1 to 6 per ship and more (Fig. 22).

In a new version, this project received columns that bend when passing under bridges [32]. Columns can also tilt so as not to interfere with the processes of loading and unloading the vessel (Fig. 22).

Figure 22: Modern ships with Glacier rotary column.

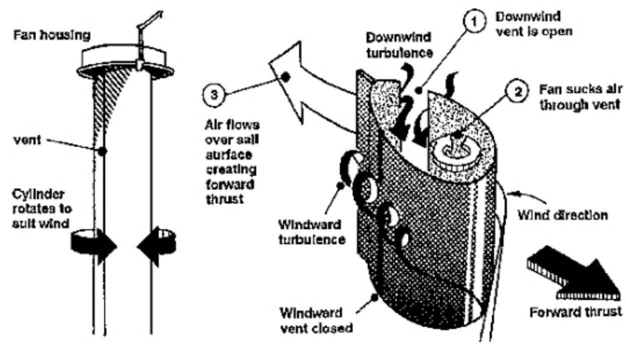
Source: Various authors.

However, Fletcher rotors compete with Cousteau turbosails, the scheme of which is shown in fig. 24 [33]. They are hollow cylinders with a special pump that creates a vacuum on one side of the turbosail, pumping air through a slot into its middle. External air begins to flow around the turbosail at different speeds and according to Bernoulli's law, the vessel moves in a direction perpendicular to the air pressure.

Figure 23: Rotor columns that can tilt so as not to interfere with the operation of the vessel.

Source: Various authors.

Figure 24: Schematic diagram of Cousteau turbosail.



Source: tecnologia-maritima.blogspot.com.

Advantages - the turbosail is only turned relative to the direction of the wind and does not rotate further. It allows the ship to move in any direction of the wind, when the power of the pump is sufficient for this. However, this system has not yet become widespread, only the yacht "Alcyone" (Fig. 25) [34] and a few single project ships were equipped with them.

Figure 25: Alcyone yacht with a Cousteau turbosail.

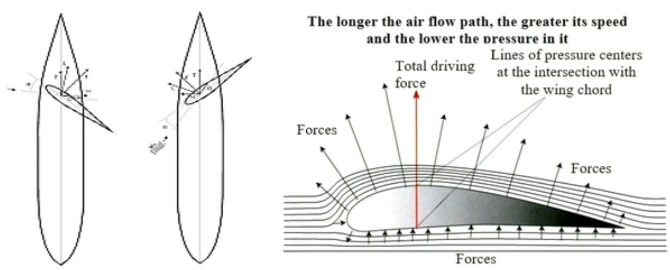
Source: tecnologia-maritima.blogspot.com.

The reason for this may be a banal misunderstanding of the principle of action: *how can a stationary column move a ship*? This used to be the case with Fletcher rotors, but Norsepower's efforts have changed that. However, there is no such investor for Cousteau turbosails, Norsepower does not need competitors. Therefore, it is necessary to correct such a situation by everyone who can do it, with the support of marine and environmental organizations. As a possible option, the project is accepted and further developed by the Norsepower company in parallel with the Fletcher rotors.

It should be taken into account that the design of a vessel with rotary columns (Fig. 22) does not correspond to the general marine aesthetics of modern sailboats. They should have an eye-pleasing white color or the blue color of sea water. It is not possible to decorate the columns, for example, with pictures or advertising, because their flickering when the rotors rotate can cause epileptic attacks in those who see them. A turbosail that does not rotate can have drawings or beautiful advertising and be more aesthetic in appearance.

A substitute for unaesthetic Fletcher rotors and turbosails are wind-dynamic sails of the type of a vertical set wing of an airplane [35]. It creates a driving force due to the different fluidity of the sides, according to Bernoulli's laws (Fig. 26). Advantages – no additional movements in the system are required. This system is tested on airplanes, which facilitates its development and implementation.

Figure 26: Wind-dynamic sails of the lateral principle of action and the scheme of their operation.



Source: Authors.

The evolution of the system is the ASPS hybrid power plant with 3 sails on a single rotary base (Fig. 27) [36], which was developed by the Winship consortium. These sailing designs should be considered promising, but they are patented, and it is very difficult to circumvent the operating principles used in the patents. Therefore, it is necessary to either pay additional royalties for the use of patents, or wait for their expiration. Thus, a greater demand for these projects should be expected from the end of the 30s of the XX(t century. At the same time, unaesthetic rotors can be completely replaced by sails that are more familiar to marine aesthetics and design. However, for such a transition, full-scale research should be conducted.

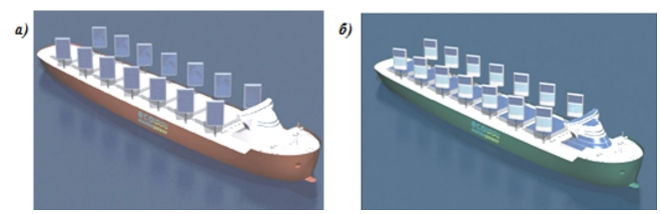
Figure 27: The ASPS hybrid sail propulsion system developed by the Winship consortium.

Source: dnv.com.

In the new TOP-7 [6], the Eco Marine Power Wind-Solar Ship 2050 project (Fig. 28) [25] was moved from 6th to 1st place, as the most promising. Its main advantages:

1) placement of swivel sails on the sides of the ship's hull, which reduces its roll from the action of the wind and swaying during its gusts; 2) reducing the height of the sails, which facilitates the passage of the vessel under the bridges and reduces the load on the masts and their attachment points; 3) doubling the number of sails and sailability; 4) the possibility of turning the sails according to the wind; 5) equipping the sails on both sides with solar batteries, including those that operate at night from infrared rays; 6) covering the surface of superstructures and even hatches for closing holds with solar cells.

Figure 28: Project of a 2025 drycargo ship "Eco marinepower" (Japan) with rotary side sails and solar panels on them (a) and with solar panels on the hatch covers and vessel superstructures (b).



Source: ecomarinepower.com.

On this basis, the new STX Eoseas project (Fig. 15) was developed, in which the sails on the roof of the superstructures tilt, which improved the ability of the vessel to pass under the bridges. The next project (Fig. 29) [37] also received Fletcher rotors, which are not clear how and where to tilt.

But the aesthetics of the vessel with rotors on the roof of the superstructures deteriorated, although the designers hid them among the sails. This shortcoming can be avoided if you use wind-dynamic sails (Fig. 26), which can be a harbinger of the death of rotors, which are unaesthetic in the design of ships. In addition, when using wind-dynamic sails, rotors are unnecessary, since the effect of their action is the same. Therefore, the use of Fletcher rotors in the new STX Eoseas project is either a tribute to fashion or excessive respect for the authority and success of the Norsepower company, or banal ignorance of wind-dynamic sail systems.

Figure 29: Development of the STX Eoseas project based on the Eco Marine Power project.

Source: Oliver Design - Ecoship.

The Eco Marine Power Wind-Solar Ship project is very promising if the displacement of the sail attachment points relative to the submerged hull of the ship is avoided. Therefore, almost all modern designs of sailboats, in addition to axial installation of sails, include lateral installation (Fig. 30) [38]. The passage of the NEOLINER sailboat under the bridges is shown in Fig. 31.

Figure 30: Projects of NEOLINER sailboats with axial and lateral installation of sails.

Source: marineindustrynews.co.uk & offshore-energy.biz.

Figure 31: Development of the STX Eoseas project based on the Eco Marine Power project.

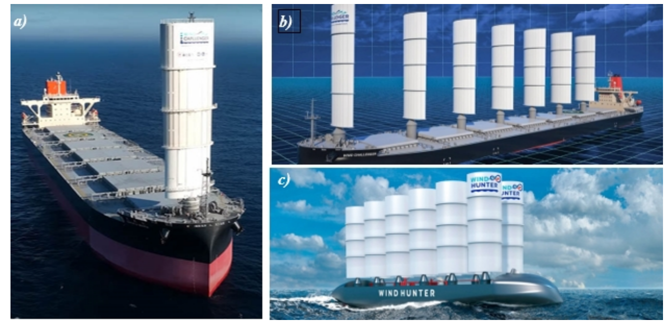
Source: Mauric.

Other examples of projects of telescopic ship lifting sails in different versions: a), b) axial [39], c) lateral [40] installation, shown in Fig. 32: At the same time, it is more expedient for the load of the system to perform lifting blocks of sails in the opposite direction, with a decrease in their area from bottom to top. But it can be an enforcement action to circumvent another patent.

The widespread use of sail installations on board ships confirms the correctness of the nomination of the Eco Marine Power Wind-Solar Ship project to the 1st place in the new TOP-7 [6].

All new options for sails are tested in modern yacht designs, which is a reasonable way and creates real prospects for choosing the best options. At the same time, preliminary tests are carried out on models, including computer's, so their development is necessary. The effective development of wind ship energy requires the cooperation of all leading firms, both designers and manufacturers, which include DNV (Norway), Norsepower (Finland), Vallenius (Sweden), NYK (Japan), Eoseas (France) and others.

Figure 32: Real ship and projects of ships with axial and lateral installation of telescopic lifting sails.



Source: mascontainer.com & mol.co.jp & worldenergytrade.com.

Thus, all modern ship wind systems development projects confirm the validity of the new TOP-7 listed in Table 2.

Conclusions.

1. Modern sailing ship systems are limited in use by wind speed, and the development of new systems has not removed these limitations.

2. The most effective use of sailing vessels of the accompanying principle of action on fixed routes in areas with an average annual wind speed > 10 m/s ("roaring" 40s and "crazy" 50s of latitude) with a limitation of the maximum wind speed to 17 m/s with.

3. In tropical, subtropical and equatorial zones, where the average annual wind speed is 5 m/s, mast sailing systems of the accompanying principle of action are ineffective and become useless cargo that reduces the transport work of the ship.

3. The development of new ship wind systems confirmed the accuracy of the new TOP-7 rating of the best projects proposed by Professor Nastasenko.

4. In the new rating, the E/S Orcelle (Sweden) project, which occupied the 1st place in the basic rating of Captain Paul Watson, was moved to the 7th place, the fidelity of this option is confirmed by the fact that this project ended its existence by the decision of its manufacturers and continues to develop another way.

5. In the new rating, the Sky Sails/Kite Ship project (Germany) moved from 5th to 6th place, the fidelity of this option is confirmed by the fact that it is effective only in limited cases - for slow-moving vessels of small displacement.

6. In the new rating, the STX Eoseas (France) project moved from 2nd to 5th place, the fidelity of this option is confirmed by the fact that it does not solve the problem of lowering very high masts to pass under bridges, but in new versions of ships preference is given to the lateral installation of lifting masts and sails of a smaller height.

7. In the new rating, the B9 Sail Cargo Ship (UK) project moved from 7th to 4th place, the fidelity of this option is confirmed by the fact that the designs of its masts and sails are promising, but the problem of their lowering for passing under bridges, not resolved.

8. In the new rating, the NYK ECO Ship container ship project (Japan) remained in 3rd place, the fidelity of this option is confirmed by the fact that most of its innovations continued to develop, but the implementation of solar cells on the lids that close the containers is a doubtful option, because it complicates loading and unloading operations and leads to the risk of damage to the lids.

9. In the new rating, Flettner Rotor Ship (Germany), moved from 4th to 2nd place, the fidelity of this option is confirmed by the fact that it is effective in areas with wind speeds of 3 m/s and above, but it is competed by the Cousteau turbosail, which does not need to be rotated. But both of these options can be superseded by a wind-dynamic sail, which operates on the principle of distributing forces on the wing of an airplane. At the same time, unsightly rotors can be completely replaced by sails that are more familiar for marine aesthetics and design.

10. In the new rating, the Eco Marine Power Wind-Solar Ship project (Japan) moved from 6th to 1st place, the validity of this option is confirmed by the fact that the installation of sails on the sides of the ship's hull reduces its roll and sway under the influence of the wind and its gusts, as well as doubles the number of sails and sailability, so almost all modern ship designs are performed in 2 versions - with axial and side sail installations.

11. All options for installing sails on the roof of superstructures must take into account the moment of action of opposing forces from wind and water resistance on the submerged hull of the vessel, which increases the requirements for strength and reliability of their attachment points.

12. In the development of new projects and their research, it is proposed to take into account the new TOP-7 ship wind systems, which allows you to avoid unnecessary spending of time and resources on the development of non-productive options.

Acknowledgements.

The authors of the work express their sincere thanks to Captain Paul Watson for the great and important work he did to determine the TOP-7 best projects of ship wind systems, which marked promising ways of their development and became a push for other developments.

The work was performed on the basis of the authors' own works [5, 6, 7, 12, 16], as well as materials and photos of open access, therefore permissions for their use are not required.

References.

COP 21, from 30 November to 11 December 2015, in Paris, France [Electronic resource] Mode of access: https://unfccc.int-/event/cop-21.

Annex VI of the Convention «MARPOL 73/78[Electronic resource] Mode of access : https://docs.cntd.ru/document/499-014496.

MEPC.245(66) – 2014 Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index (EEDI) for New Ships,

Paul Watson. Top 7 Green Ship Concepts Using Wind Energy /Sea Shepherd Ocean ACTION Reports. [Electronic resource] Mode of access : https://www.marineinsight.com/green-shipping/top-7-green-ship-concepts-using-wind-energy/

Nastasenko V. A. Sudovaya al'ternativnaya energetika i realii yeye primeneniya v sovremennykh usloviyakh [Ship alternative energy and the realities of its application in modern conditions] / V. A. Nastasenko // East European Scientific Journal Wschodnioeuropejskie Czasopismo Naukowe (Warszawa Polska). – 2016. – ? 3 (7). – ?. 36–47. (In Russian)

Valentyn Nastasenko, Vyacheslav Svyrydo, Artem Andreev. (2022) New top-7 vessels wind projects and analysis of their practical possibilities for the transport fleet. / Journal of Maritime Research. Vol 19. No. 3 (2022) pp 30–38 Barcelona, Spain ISSN: 1697-4040, https://www.jmr.unican.es/index.php/-jmr/issue/view/67

Valentyn Nastasenko. Ship Alternative Energy, Problems and Prospects for its Implementation / RENEWABLEMEET20-23 International Meet on Renewable and Sustainable Energy March 13-15, 2023 | Rome, Italy, p, 86-87. [Electronic resource] – Mode of access : https://www.albedomeetings.com/-cms/pdfs/RENEWABLEMEET2023_abstract_book.pdf

Yunlong Wang, Xin Zhang, Shaochuan Lin and other. Analysis on the Development of Wind-assisted Ship Propulsion Technology and Contribution to Emission Reduction International Conference on Envi-ronmental Engineering and Energy doi:10-.1088/1755-1315/966/1/012012. 1. https://iopscience.iop.org/-article/10.1088/1755-1315/966/1/012012/pdf

Greg Troutwein (2018) Blowin 'in Wind: Pyat' zabluzhdeniy o vetrovom dvizhenii na korablyakh [Five misconceptions about wind motion on ships.] [Electronic resource] – Mode of access : https://ru.marinelink.com/news/blowin-wind-%D0%BF%D1%8F%D1%82%D1%8C-%D0%B7%D0%B0%-D0%B1%D0%BB%D1%83%D0%B6%D0%B4%D0%B5%D0-%BD%D0%B8%D0%B9-%D0%B2%D0%B5%D1%82%D1%-80%D0%BE%D0%B2%D0%BE%D0%BC-%D0%B4%D0%-B2%D0%B8%D0%B6%D0%B5%D0%BD%D0%B8%D0%B8-261689_

E/S Orcelle 2025 [Electronic resource] – Mode of access https://www.outube.com/watch.v=wAIAC4vU4lM

Oceanbird of the Wallenius company. [Electronic resource] – Mode of access : https://www.dnv.com/expert-story/maritime-impact/ Oceanbird-ro-ro-Embarking-on-a-new-era-of-wind-propulsion.html

Nastasenko V.A. Sravnitel'nyy tekhniko-ekonomicheskiy analiz ekspluatatsii sudovykh parusnykh i vetryanykh elektrogeneratornykh system [Comparative technical and economic analysis of the operation of ship sailing and wind power generating systems] / Rozvytok metodiv upravlinnya ta hospodaryuvannya na transporti: Zb. nauk. prats'. – Vyp. 4(65). – Odesa : ONMU. 2018 – s. 73-96. DOI https://doi.org/10.31375/2226-1915-2018-4-73-96 (In Russian).

Oceanbird of the Wallenius company**.** [Electronic resource] – Mode of access : https://www.dnv.com/expert-story/maritime-impact/ Oceanbird-ro-ro-Embarking-on-a-new-era-of-wind-propulsion.html.

SkySails system [Electronic resource] – Mode of access:

https://skysails-group.com/pdf-assets/SkySailsMarine_Brochure-_EN.pdf.

Airseas [Electronic resource] – Mode of access: https://www.-google.com/search?client=avast-a-1&q=airseas+kites&oq=Air-seas&aqs=avast.3.69i57j0l7.30185549j0j15&ie=UTF-8

Nastasenko V.O., Yevdokymova V.A. Sudnova al'ternatyvna enerhetyka ta osoblyvosti okhorony pratsi i bezpeky yiyi ekspluatatsiyi [Ship alternative energy and features of labor protection and safety of its operation] // Visnyk Khersons'koho natsional'noho tekhnichnoho universytetu – Kherson. KHNTU. 2014. Vyp. 1(48). –S. 77-82. (In Ukraine)

PARTNERS - SkySails : Towing a vessel with a kite [Electronic resource] – Mode of access : https://www.google.com/-search?client=avast-a-1&q=Sky+Sails+%2F+Kite+Ship&oq=-Sky+Sails+%2F+Kite+Ship&aqs=avast..69i64.6j0j1&ie=UTF-8#fpstate=ive&vld=cid:e4eae4f1,vid:zYDz08OYW6g

Catamaran "Chloe" (Holland) on solar batteries [Electronic resource] – Mode of access : https://www.google.com.ua/search-?sxsrf=AJOqlzVenu1i_8i0XW1qpzy_yiuv0l1flg:16787405006-42&q=%D0%BA%D0%B0%D1%82%D0%B0%D0%BC%D-0%B0%D1%80%D0%B0%D0%BD+%D0%BD%D0%B0+%-D1%81%D0%BE%D0%BB%D0%BD%D0%B5%D1%87%D-0%BD%D1%8B%D1%85+%D0%B1%D 0%B0%D1%82%D-0%B0%D1%80%D0%B5%D1%8F%D1%85&tbm=isch&source=univ&fir=N1IjDSXiEkYi.

EOSEAS Green Cruise Ship Concep [Electronic resource] – Mode of access : https://www.stirlingdesign.fr/presses/conferences/stirling_design_green_ship_copenhagen.pdf.

STX Europe [Electronic resource] – Mode of access : https-://www.google.com/search?tbs=sbi:AMhZZivHA3bGcsLVJM-rtcsNMcZov2CYxtFCqfEmhcE6_1bBW45XOR1-zTduiyedeH-IjsBi89yWzwy5viSUvwrucK3HrpoB_1lw0bR-B86EHE6KM8-zI4Gk8fdz4YBIwaHAOtdejwTmmbusqpUpXsfy5VHJa4lKz2-a8TCw#imgrc=DKJaCT1zeZUTTM.

Concept: 170m sailing superyacht Glory [Electronic resource] – Mode of access: https:// interparus.com/concept-superyacht-glory/.

[Electronic resource] – Mode of access: https://www.google-.com/search?tbs=sbi:AMhZZivHA3bGcsLVJMrtcsNMcZov2C-YxtFCqfEmhcE6_1bBW45XOR1-zTduiyedeHIjsBi89yWzwy5-viSUvwrucK3HrpoB_1lw0bR-B86EHE6KM8zI4Gk8fdz4YBI-waHAOtdejwTmmbusqpUpXsfy5VHJa4lKz2a8TCw#imgrc=0-DYfz-iXfKJazM&imgdii=8p074o2yaOstJM.

Ecoship Review [Electronic resource] – Mode of access https-://crociereuk.wordpress.com/2015/01/17/eco-cruise-ship-concept-from-peace-boat/.

EOSEAS STX Europe. New Vision of Cruise Ship [Electronic resource] – Mode of access: https://www.youtube.com/-watch?v=ImawfvSsEmk.

Eco Marine Power Wind-Solar Ship [Electronic resource] – Mode of access: http://www.ecomarinepower.com/en/energysail.

The concept of the B9 Sail Cargo Sailing Ship [Electronic resource] Mode of access: https://slate.com/technology/2012/06/-wind-powered-cargo-ships-b9-s-radical-clean-energy-innovation-.html.

WASP (Ecoliner) / Sailing cargo ship [Electronic resource] Mode of access: https://www.dykstra-na.nl/designs/wasp-ecoliner/#.

Maltese Falcon / 87 m^3 mast Dynarig [Electronic resource] Mode of access: https://www.dykstra-na.nl/designs/maltese-falcon/#.

NYK Super Eco Ship 2030 [Electronic resource] – Mode of access: http://www.nyk.com/english/release/31/NE_090422.html.

Wisamo – giant inflatable wing sails from Michelin [Electronic resource] – Mode of access : https://www.flotilia.com/ru/-wisamo-gigantskie-naduvnye-parusa-krylya-ot-michelin-4334

Flettner Rotor Ship [Electronic resource] – Mode of access: https://www.google.com.ua/search?q=Fletcher%20Rotor%20Ship-&tbm=isch&hl=ru&hl=ru&tbs=rimg:CUfvZpeTdsVpYYXpt0G-_1x83Z&sa=X&ved=0CBwQuIIBahcKEwiQ0vKn97DsAhUAA-AAAHQAAAAAQEQ&biw=1263&bih=610

Norsepower Oy Ltd [Electronic resource] – Mode of access : https://www.offshore-energy.biz/norsepower-worlds-1st-tiltable-rotor-sails-installed-on-sea-cargo-roro/

Cousteau turbofan and its principle of operation [Electronic resource] – Mode of access: https://www.google.com/search?q=-%D1%82%D1%83%D1%80%D0%B1%D0%BE%D0%BF%D0-%B0%D1%80%D1%83%D1%81+%D0%BA%D1%83%D1%81-%D1%82%D0%BE&client=avast-a-1&sxsrf=AJOqlzVD4MS2O-PStI-iCtWyWtOaxHPp4iQ:1679146387020&tbm=isch&source=-iu&ictx=1&vet=1&fir=cqYwlYF_hOlGpM%252CeS1MntEXPkb-b4M%252C_%253B-IMsXm4ZI6eYYM%252CwQcbCfOsz6rnC-M%252C_%253BcSdk_aL-shYEMM%252CVDr4G5WrvZ-FFM-%252C_%253BPG0pZXnM5fiIPM%252Cohu9Agb14K_4QM%2-52C_&usg=AI4_-kQ_ggEnNrKfTM87uGFZLxYhg4ewkg&sa=X-&ved=2ahUKEwjX9bHfy-X9AhUpiP0HHfKvCcMQ_h16BAhc-EAE#imgrc=PG0pZXnM5fiIPM

Hydrographic vessel "ALCYONE" which was invented by Cousteau [Electronic resource] – Mode of access: http://shipregistr.-kiev.ua/gidrografichne-sudno-alcyone-yake-vinajshov-kusto/ (In Ukraine)

Soft wing sail [Electronic resource] – Mode of access: https://-www.google.com/search?q=35+soft+wing+sail+design&sxsrf=-AJOqlzXbYWJnN00DPpS8QeUXEoUgp3Yokg%3A167953707-6989&source=hp&ei=tLMbZLycOo777_UPlpmziA8&iflsig=AK-50M_UAAAAAZBvBxPbNGAntT_8QTIqHCaLhxn6lS9Kp&oq-=35.%09Soft+wing+sail+&gs_lcp=Cgdnd3Mtd2l6EAEYAzIFC-CEQoAEyBQghEKABMggIIRAWEB4QHTIICCEQFhAeEB1Q-AFgAYM2rAWgAcAB4AIABogGIAaIBkgEDMC4xmAEAoAE-CoAEB&sclient=gws-wiz.

Winship. Carbon neutral ship [Electronic resource] – Mode of access: https://windshiptechnology.com/.

Liner: concept Ecoship Review [Electronic resource] – Mode of access: https://crociereuk.wordpress.com/2015/01/17/eco-cruise-ship-concept-from-peace-boat/

NEOLINE SOLUTION https://www.neoline.eu/en/the-neoline-solution/

WIND CHALLENGER forward to future, the wind of our backs | Blue action mol MOL 001 https://www.mol.co.jp/en/bam-/001/.

WIND HUNTER Shape the future with wind and hydrogen | Blue action MOL 004 https://www.mol.co.jp/en/bam/004/.