

Mariana, Panaitescu; Fanel-Viorel, Panaitescu; Mihail-Vlad, Vasilescu; Robert-Alexandru, Daineanu

Article

Energy balance for a hybrid naval propulsion system

Journal of Shipping and Trade (JST)

Provided in Cooperation with:

Shipping Research Centre (SRC), The Hong Kong Polytechnic University

Suggested Citation: Mariana, Panaitescu; Fanel-Viorel, Panaitescu; Mihail-Vlad, Vasilescu; Robert-Alexandru, Daineanu (2022) : Energy balance for a hybrid naval propulsion system, Journal of Shipping and Trade (JST), ISSN 2364-4575, SpringerOpen, London, Vol. 7, Iss. 1, pp. 1-20, <https://doi.org/10.1186/s41072-022-00114-9>

This Version is available at:

<https://hdl.handle.net/10419/298925>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.



<https://creativecommons.org/licenses/by/4.0/>

ORIGINAL ARTICLE

Open Access

Energy balance for a hybrid naval propulsion system



Panaitescu Mariana^{1*} , Panaitescu Fanel-Viorel¹, Vasilescu Mihail-Vlad² and Daineanu Robert-Alexandru²

*Correspondence:
panaitescumariana1@gmail.com

¹ Department of Engineering Sciences in Mechanics and Environment, Faculty of Electro-Mechanics, Constanta Maritime University, 104 Mircea cel Batran Street, 900663 ZC Constanța, Romania

² Doctoral School of Mechanical Engineering, Constanta Maritime University, 104 Mircea cel Batran Street, 900663 ZC Constanța, Romania

Abstract

Introduction: The purpose of this paper is to present an analysis on the energy balance of the hybrid energy system and the mooring scheme for a container ship, as well as the energy balance of the electricity generating systems, from unconventional sources. The methods applied to achieve the main objective consist of analytical calculations and simulations in the ANSYS Fluent program for various positions of the analyzed system, as follows: a) technical characteristics of the container ship; b) elements of the hybrid energy system, which uses unconventional energy; c) energy balance of electricity generating systems from unconventional sources; d) connecting conventional and unconventional power sources to the ship's main power bar.

Results: Finally of researches, the results obtained are: a) the volume, mass and ascending force of the FLETTNER balloon with helium, assimilated with an airship; b) positioning scheme of large vertical wind turbines installed in the bow of the container ship and in the stern of the container ship; c) the energy balance of electricity generating systems from unconventional sources; d) schemes for connecting conventional and unconventional energy sources to the ship.

Conclusions: The calculation of the energy balance of the two types of wind energy capture systems depending on the speed of the ship, in ideal wind conditions and depending on the number of vertical wind turbines running, which use wind energy. Of course, it will never be necessary to turn on all wind power equipment at full capacity. The FLETTNER balloon can generate more power and for this reason, we must to present the number and diameter of cables needed to transmit electricity. Through this research, following the installation of the elements of the hybrid diesel-electric power system with energy from conventional (fossil fuels) and unconventional energy sources (a FLETTNER balloon with helium and four large vertical wind turbines) placed on a ship container portability, both the manoeuvrability and the stability of the ship, do not change fundamentally.

Keywords: Energy, Hybrid, Ship, FLETTNER balloon, Wind, Turbine

Introduction

Capturing and using wind energy, which is much more suitable for modernizing existing ships. The equipment used is reliable, cheap and does not require the installation of new propulsion machines. But in the future, based on accessibility and lower prices of new technologies, we are convinced that it is possible to use other types of unconventional

energies efficiently. The use of wind energy, as a global energy surplus and the discharge of power of a conventional propulsion system, leads to a number of definite advantages:

- Reducing pollution as a result of the replacement of conventional energy, with unconventional energy captured from the marine environment, green energy.
- Unconventional energy captured from the ship's marine environment, solar or wind, saves some of the fossil fuels and lubricants consumed on board ships.
- Stimulating research and development of technologies for the capture of renewable, green, ecological energy, both for the sea and for land.
- Increasing operational safety through the existence of two relatively independent electricity generator systems, one in relation to the other.
- Reduction of pollution, noise and vibration caused by the diesel engine.
- Complying easily with the recently introduced requirements of international legislation regarding the amount of exhaust emissions into the atmosphere, in line with the strategic energy targets set worldwide.

20–25 years ago, at various conferences and congresses in the field of shipping, certain methods of propulsion were presented, different to those based on internal or nuclear combustion engines. These methods of generating electricity using unconventional energy sources, energy green, were considered as mere opinions, aberrations, or opinions about what a ship might look like in the distant future.

In 1999, the *Green Ship* concept was introduced. This work is part of the *Green Ship* concept, which analyses alternative methods of ship propulsion, along with shipbuilding (modified ship hull shapes, use of silicone-based paints), ship equipment (high-performance and less polluting equipment), engines propulsion and fuels (silent engines and bio fuels), unconventional energy sources.

This paper focuses on the effect of the FLETTNER balloon (raised to a certain height and connected to the container ship) and the large vertical wind turbines installed on the deck of the container ship. The system is hybrid because it can switch from a conventional power source to an unconventional, green power generator.

In the recent years, the interest in propelling ships by alternative and combined methods has grown significantly (Figs. 1, 2) (Grosan 2011).

Systems such as the Magnus effect-based FLETTNER rotor, studied over 40 years ago, were installed today on board merchant ships. The sails, used for hundreds of years for propulsion, have already been tested in combination with solar cell panels, the technological methods being the latest.

This research is considered timely and appropriate, given the alarming increase in ship-source pollution and the international maritime community's interest in finding alternative propulsion solutions.

The purpose of this paper is to present the overall energy balance of the hybrid system and the mooring scheme on a container ship. The main construction features of the ship, the elements of the hybrid system, the location of the FLETTNER balloon on a container ship as an alternative power source, with the calculations related to the anchoring elements, the minimum lift force, the minimum volume of the FLETTNER balloon—if full helium, or the minimum lift force required for the balloon to stay in the air when it is full

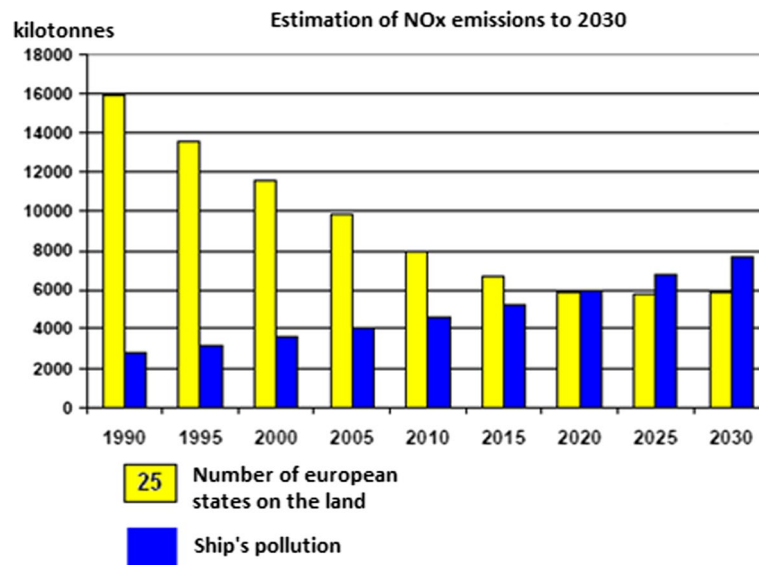


Fig. 1 An estimation of NOx emissions to 2030 (Grosan 2011)

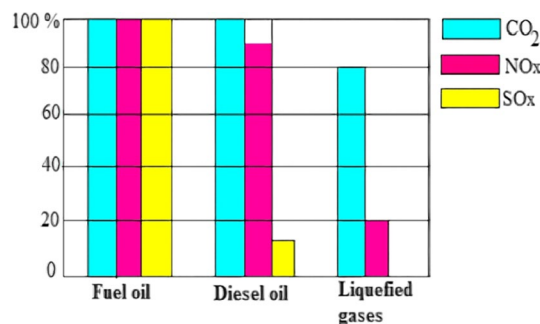


Fig. 2 Pollutant emissions from naval engines (Grosan 2011)

of hydrogen, electricity generators from the proposed unconventional sources. Also will be presented following points of interest:

- -positioning scheme and the necessary area for the positioning of the 4 large vertical wind turbines installed in the bow of the container ship;
- the technical characteristics of the large vertical wind turbine for a container ship. The ANSYS FLUENT 12.0 program was also used to simulate the velocity and force distributions on the FLETTNER balloon and on the studied wind turbines.

The components of a hybrid system used for power generation using unconventional sources

Ship particular information

For the study is used container ship with the following characteristics:

- Ship length (L); L = 168.56 m;

- Ship width (l); l = 29.4 m;
- Container ship capacity (TEU-twenty-foot equivalent unit); Capacity = 1638 TEU;
- Gross tonnage (GT); GT = 19,795 t;
- Displacement (D); D = 39449 t;
- 4 Diesel Generators, P = 2000 kW/for each.

Operational data before and after the studied cases

Technical operational data in Fig. 3 (Vasilescu and Dinu 2020):

Environmental policies to reduce the emissions are forcing the shipbuilding industry to decrease the consumption of fossil fuel by increasing the efficiency in maritime transport and for equipping the ships with renewable energy sources (Vasilescu 2019a; Ammar et al. 2021; Gabriela 2020; Milan 2018; Bergeson and Kent 1985; Craft et al. 2012).

Wind energy is a source of renewable energy, generated from wind power (Vasilescu 2019b; Adaramolo 2014; Bergeson and Kent 1985; Craft et al. 2012). It is free, plentiful and with high potential at sea (Ben-Hakoun et al. 2016). Wind power is the use of air flow through turbines to provide mechanical power, which has the role of rotating some generators and creating electricity.

The energy balance of the system is made for a ship speed of 15 knots (or 7.71 m/s) and a true wind speed of 5 m/s, for all true winds with angular values between 0° and 360°. As the true wind speed increases by 5 m/s, 10 m/s, 15 m/s, 20 m/s, the output power generated by the vertical wind turbines increases.

Vertical wind turbines are one of the various equipments needed to capture and harness wind energy (Adaramolo 2014).

A wind turbine is an equipment that transforms the kinetic energy of the wind into mechanical energy which is further transformed into electrical energy. In this paper

		Alternative power sources	Renewable energy sources							
			crossing	Crossing	maneuver		during merchandise operations	In port	in damage	on fire
					without propellant	with propellant				
without refrigerated contain	Generator capacity (kW)	2000	1600	1600	3690	1600	1600	150	150	
		RF X 1	SG X 1	SG X 1	SG X 1 + LG X 1	SG X 1	SG X 1	EG X 1	EG X 1	
	Total power (kW)	before particular cases	1032.8	1032.8	1344.4	3011.1	1132.2	893.3	108	97.6
		case 1	812.8	812.8	1034	2700.7	860.2	614.1		
		after C1&2	812.8	812.8	1034	2700.7	860.2	614.1		
	after C0&1&2	812.8	812.8	1034	1034	860.2	614.1			
generator load (%)	before particular cases	64.55	64.55	84.03	81.6	70.76	55.83	71.98	65.06	
with refrigerated containers (6kW* 650 pcs) (kW)	Generator capacity	7000	5780	5780	7870	570	5780			
		B x 1 + RF X 3	SG X 1 + LG X 2	SG X 1 + LG X 2	SG X 1 + LG X 3	SG X 1 + LG X 2	SG X 1 + LG X 2			
	total power (kW)	before particular cases	4993.4	4993.4	5305.1	6971.7	5092.9	4853.9		
		after CP1	4712.8	4712.8	4934	6600.7	4760.2	4521.3		
		after CP1&2	812.8	812.8	1034	2700.7	860.2	621.3		
after CP0&1&2		812.8	812.8	1034	1034	860.2	621.3			
generator power (kW)	before particular cases	86.39	86.39	91.78	88.59	88.11	83.98			

Fig. 3 Operational container ship data (Vasilescu and Dinu 2020)

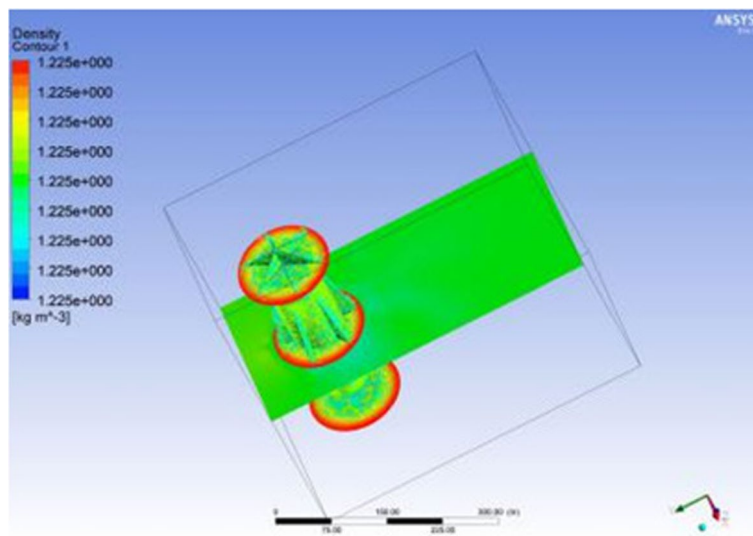


Fig. 4 Balloon density distribution in the XOY plane-wind speed 10 m/s and wind direction 0° (ANSYS Fluent 12.0 2009; Vasilescu and Dinu 2020)

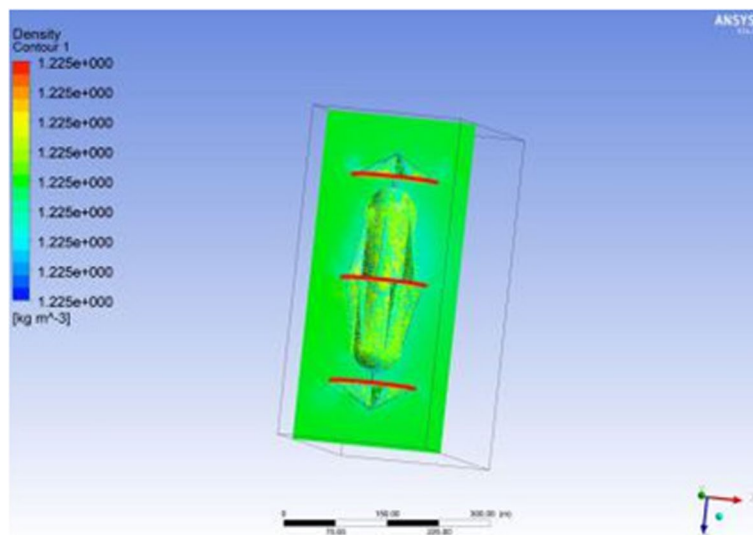


Fig. 5 Balloon density distribution in the XOZ plane-wind speed 10 m/s and wind direction 0° (ANSYS Fluent 12.0 2009; Vasilescu and Dinu 2020)

the geometry and the mesh of a large vertical wind turbine and the FLETTNER balloon were achieved with the help of the ANSYS FLUENT program. In addition we used the variation of the density distribution of the respective object on the plane along the flow direction, for two different planes: a horizontal plane parallel to the XOY and a vertical XOZ plane, for a wind speed of 10 m/s and a wind blowing in one direction (Figs. 4, 5) (ANSYS Fluent 12.0 2009; Vasilescu and Dinu 2020).

The wind turbine has a rotor with blades oriented on a vertical axis, which driven by the power of the wind drives an electric generator. The wind moves the turbine blades that drives the electric generator. The mechanical system also includes a

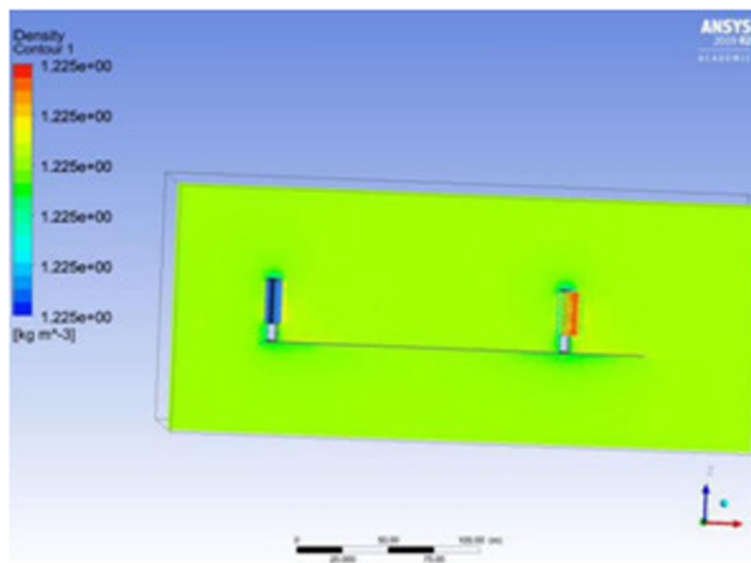


Fig. 6 Vertical wind turbine positioned on the main shaft of the ship (Vasilescu and Dinu 2020)

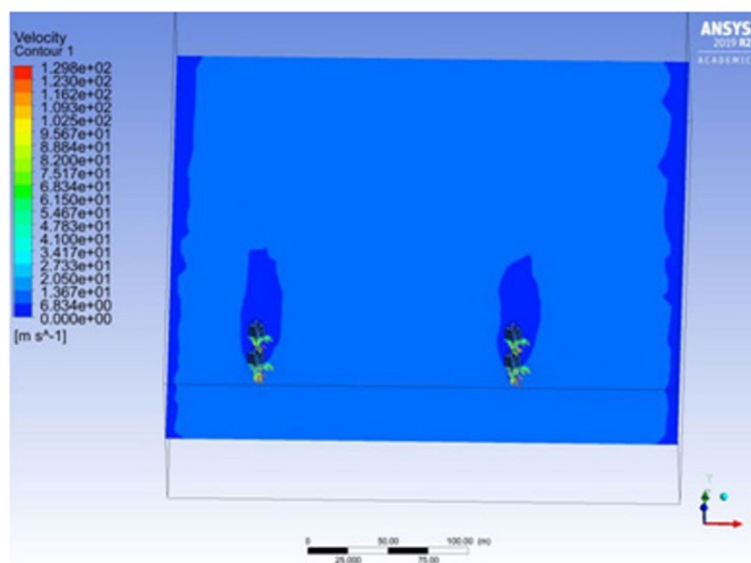


Fig. 7 Vertical wind turbine positioned on the main shaft of the ship (image projected in ANSYS Fluids, in the XY plane) (Vasilescu and Dinu 2020)

speed multiplier that directly drives the central axis of the electric generator (Fig. 6) (Vasilescu and Dinu 2020).

The main components of large vertical wind turbines are (Fig. 7) (Vasilescu and Dinu 2020):

- A control panel, which gives the commander full control over the operation and performance of the wind turbine (Fig. 8) (Vasilescu 2020);
- A fully automatic control system, which optimizes the feed force of the turbines;
- One current generator for each turbine.



Fig. 8 Control equipment (Vasilescu 2020)

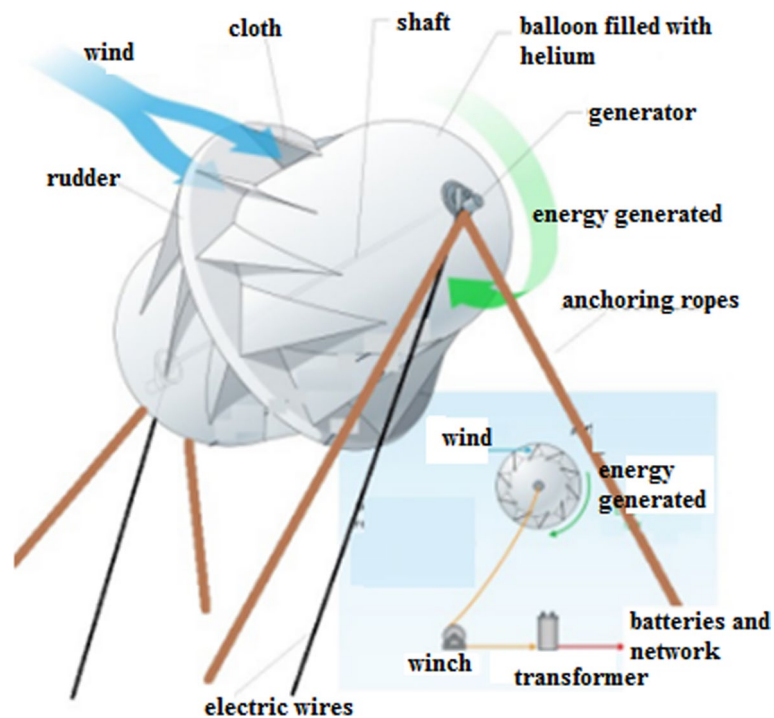


Fig. 9 FLETTNER balloon components (Vasilescu and Dinu 2020)

The *FLETTNER balloon* is a device that generates electricity at high altitude. It rotates around a horizontal axis in response to wind, efficiently generating clean, renewable electricity at a lower cost than all competing systems (Fig. 9) (Vasilescu and Dinu 2020).

The conclusion of the research is that the *FLETTNER balloon*, positioned at 300 m altitude can generate about 1000 kWh. Using the *FLETTNER balloon*, full of helium, we can capture winds from 183 to 305 m altitude, generating up to 1000 kWh. The *FLETTNER balloon* can generate electricity both at low wind speeds of 3 m/s but also at high speeds of 28 m/s.

The purpose of the study is to use two engines: one diesel from MAN and one electric (Vasilescu 2020; Milan 2018; Demadi et al. 2010).

The high-power diesel engine will be able to operate during the use of diesel generators. Also, a large vertical wind turbine, the FLETTNER balloon, and the electric motor will have as main source of unconventional power generators, respectively FLETTNER rotors installed on the ship's deck, the FLETTNER balloon and diesel generators as a secondary source.

The two engines will not work at the same time; their operation will be done in shifts by using an automatic system with the role of switching the propulsion from the diesel engine to the electric one.

The diesel generator system, the large vertical wind turbines and the FLETTNER balloon, will be controlled by an automatic computerized system. During crossings when unconventional energy sources are turned on, we will use the electric motor. The main electricity generators will be: the large wind turbines and the FLETTNER balloon. In case the energy produced by the latter is not enough, diesel generators will enter the shift, at minimum power, to cover the energy deficit existing. By using diesel generators when needed at minimum power, we reduce fuel consumption to a minimum, thus reducing pollution and costs. In Fig. 10 (Vasilescu 2020) we noted with G1, G2, G3, G4 the diesel generators, with B—the FLETTNER balloon and with RF1, RF2, RF3, RF4 the large vertical wind turbines.

The hybrid system will provide the necessary energy without polluting (Vasilescu 2020; Adaramolo 2014; Ben-Hakoun et al. 2016).

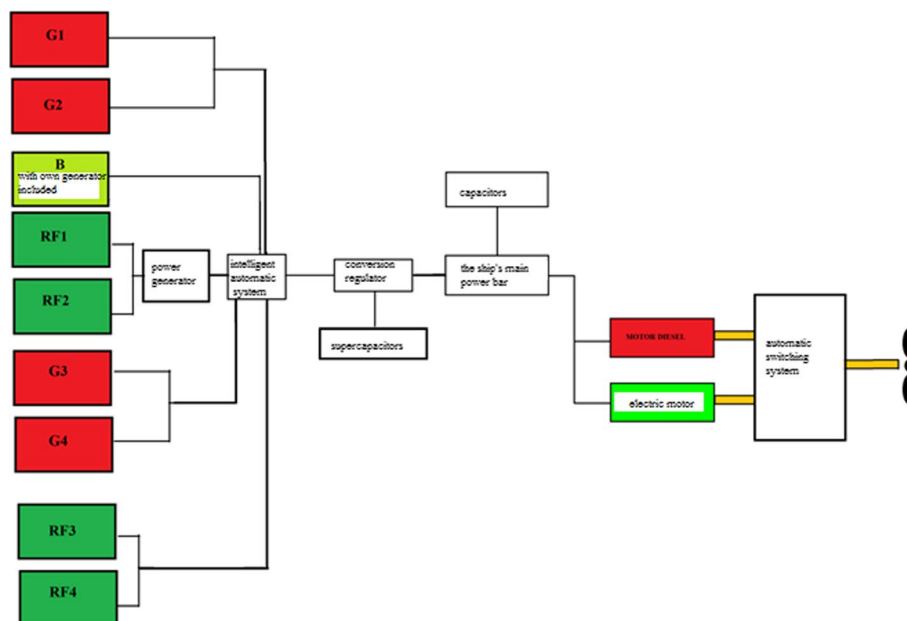


Fig. 10 Hybrid propulsion system-connection diagram to an automatic computerized generator control system (Vasilescu 2020)

Energy balance of the hybrid energy system and mooring scheme for a container vessel

Elements of the hybrid energy system, which uses unconventional energy

On the container-containers with the above characteristics, we will consider two directions of study:

- direction 1—a FLETTNER rotor with helium (Adaramolo 2014);
- direction 2—two-four large vertical wind turbines on the main deck of the ship (Vasilescu and Dinu 2020).

The placement of the FLETTNER balloon with helium on a container ship as an alternative power source

The FLETTNER helium balloon, positioned at an altitude of 300 m above the container ship, will generate approximately 1000 kWh (Vasilescu 2019b).

To calculate the volume, the mass and the ascending force of the FLETTNER helium balloon, we tie it to an airship.

The technical characteristics of the balloon are (Vasilescu 2020):

$L_B = 245 \text{ m}$; $V_b = 200000 \text{ m}^3$; $m_b = 5000 \text{ kg} = 5t$; $\rho_A = 1.29 \text{ kg/m}^3$; $g = 9.8 \text{ m/s}^2$; $P = 1000 \text{ kW}$; $U = 690 \text{ V} = 0.9 \text{ kV}$.

The forces were calculated in the ANSYS FLUENT 12.0 program and we obtained the values of different directions and speeds of wind (Fig. 11) (Vasilescu 2020):

$$F_a = \rho_A V_b g = 1.29 \times 200000 \times 9.8 = 2528400 \text{ N} = 2528.4 \text{ kN}; \tag{1}$$

where L_B =length of balloon; V_b =volume of balloon; m_b =weight of balloon; ρ_A =density of air; g =gravitational acceleration; P =rotor power; U =the voltage of the generated electric current; F_a =the rising force of the balloon.

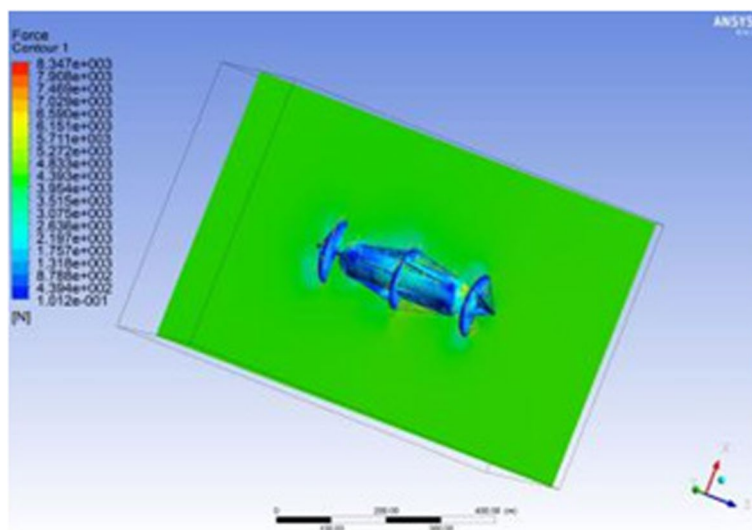


Fig. 11 Balloon force distribution in the XOZ plane for 10 m/s and direction 30°

- Calculation of the intensity of the electric current through the power cable

$$P = \sqrt{3}UI \cos \varphi \quad (2)$$

where $\cos \varphi \cong 1$,

$$I = \frac{P}{\sqrt{3}U} = \frac{1000 \text{ kW}}{\sqrt{3} \times 0.69 \text{ kW}} = 837.7 \text{ A} \quad (3)$$

Using the tables of the electric cable manufacturers (Demadi et al. 2010), it results that for an current of 838 A, are necessary two three-phase cable systems, with a minimum section of 300. For safety will consider 6 single-phase CYY (-F) cables with an upper section of 1×400 . This type of cable has an outer diameter of 38 mm, a copper mass of 4000 kg/km and a total mass of 4030 kg/km.

For a cable length of 300 m = 0.3 km the total mass of a cable is.

$$m_c = 4030 \times 0.3 = 1209 \text{ kg} = 1.209t.$$

The total mass of electrical cables that the FLETTNER helium balloon must support is.

$$m_{ct} = 6 \times m_c = 6 \times 1.209t = 7.254t.$$

- Technical data for anchoring system of the FLETTNER balloon with helium

4 anchor ropes, made of polypropylene fiber and polyester, are needed to anchor the balloon. From the practical applications (Adaramolo 2014; Craft et al. 2012) the following dimensions are chosen according to the needs of the study for the anchoring parameters: $d = 80$ mm; $m_p = 0.31$ m/kg; $F_R = 1225$ kN = 1225000 N, where d -diameter at the rope; m_p : rope weight; F_R : strength of the rope.

The advantages of melting polypropylene and polyester fiber ropes are:

- do not absorb water;
- have high heat resistance;
- have great flexibility over time;
- are easy to handle.

Calculation of the mass of a rope of 300 m:

$$m_{p300} = 300 \text{ m} \times m_p = 300 \text{ m} \times 0.31 \text{ m/kg} = 93 \text{ kg} \quad (4)$$

Calculation of the mass of the 4 ropes:

$$m_{pt} = m_{p300} \times 4 = 93 \text{ kg} \times 4 = 372 \text{ kg} = 0.372t \quad (5)$$

Calculation of the resistance forces of the 4 ropes:

$$F_{RT} = 4 \times F_R = 4 \times 1225 \text{ kN} = 4900 \text{ kN} \quad (6)$$

Comparison of the ascending force F_a with the total resistance force of the F_{RT} ropes:

$$F_a = 2528.4 \text{ kN}; F_{RT} = 4900 \text{ kN}.$$

It can be seen that $F_{RT} > F_a$ so the ropes resist in the process of anchoring the balloon. From the previous calculations it can be seen that the FLETTNER rotor with helium must support a mass of 12,626 t.

$$m = m_{ct} + m_{pt} + m_b = 7.254 + 0.372 + 5 = 12.626 \text{ t} \tag{7}$$

Calculation of the minimum lift force F'_a required for the balloon to be suspended in the air (Fig. 12) (Vasilescu 2019b):

$$\sum F_y = F'_a - G_{He} - G_B - G_{cp} \tag{8}$$

where G_{He} helium weight force; G_B balloon weight force; G_{cp} weight force for cables and ropes.

If

$$\sum F_y = 0 \tag{9}$$

$$0 = F'_a - G_{He} - G_B - G_{cp} \tag{10}$$

$$F'_a = G_{He} + G_B + G_{cp} = m_{He}g + m_b g + m_{cp}g \tag{11}$$

$$m_{He} = \rho_{He} V_B = 0.179 \times 200000 = 35800 \text{ kg} \tag{12}$$

$$F'_a = 35800 \times 9.8 + 5000 \times 9.8 + 7626 \times 9.8 = 474.574.8 \text{ N} = 474.5748 \text{ kN}$$

From the above calculations we can see that the minimum ascending force required $F'_a = 474.5748 \text{ kN}$, it is much lower than the ascending force, $F_a = 2528.4 \text{ kN}$, which the balloon can lift (Fig. 13) (Vasilescu 2020).

Calculation of the minimum volume of the FLETTNER balloon: if it is full of helium:

$$F'_a = 35800 \times 9.8 + 5000 \times 9.8 + 7626 \times 9.8 = 474574.8 \text{ N} = 474.5748 \text{ kN}$$

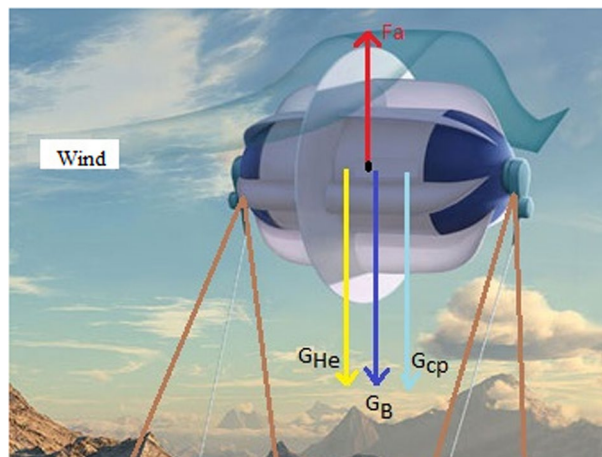


Fig. 12 The forces that appear and influence the rise of the rotor (Vasilescu 2019b)

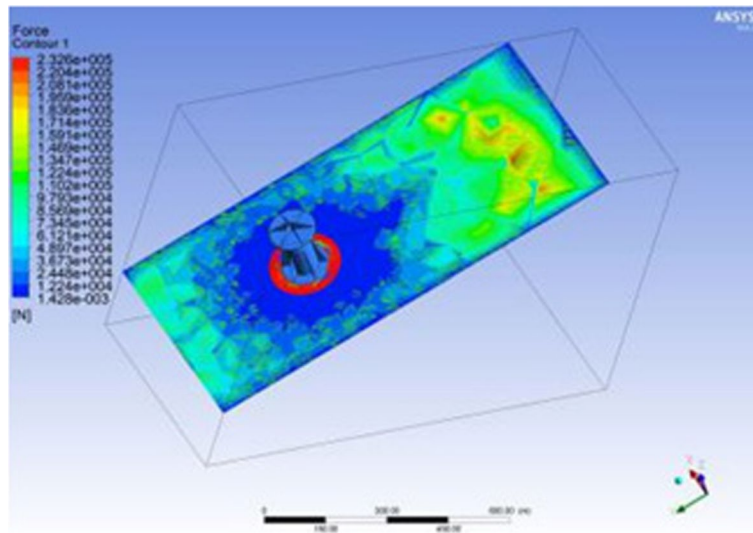


Fig. 13 Distribution of force in the XOY plane of a wind speed of 10 m/s and a wind direction of 30° (Vasilescu 2020)

$$F_a = \rho_A V_B g \tag{13}$$

$$F'_a = \rho_A V_{BHe} g \tag{14}$$

$$474574.8 = 1.29 \times V_{BHe} \times 9.8 \tag{15}$$

$$V_{BHe} = \frac{474574.8}{9.8 \times 1.29} = \frac{474574.8}{12.642} = 37539.5349 \text{ m}^3 \cong 37540 \text{ m}^3.$$

The minimum volume of the balloon full of helium is 37540 m³ for the FLETTNER balloon to be buoyant.

Calculation of the minimum lift force F_a required for the balloon to stay in the air when it is full of hydrogen:

$$\sum F_y = F''_a - G_H - G_B - G_{cp} \tag{16}$$

where G_H hydrogen weight; G_B balloon weight; G_{cp} weight cables and ropes.

If

$$\sum F_y = 0 \tag{17}$$

$$0 = F''_a - G_H - G_B - G_{cp} \tag{18}$$

$$F''_a = G_H + G_B + G_{cp} = m_H g + m_b g + m_{cp} g \tag{19}$$

$$F''_a = m_H g + m_b g + m_{cp} g \tag{20}$$

$$m_H = \rho_H V_B = 0.0899 \times 200000 = 17980 \text{ kg} \quad (21)$$

$$F''_a = 17980 \times 9.8 + 5000 \times 9.8 + 7626 \times 9.8 = 299938.8 \text{ N} = 299.9388 \text{ kN}$$

From the above calculations we can see that the minimum required ascending force of the balloon full of hydrogen F''_a is much lower than the ascending force F_a .

Calculation of the minimum volume of the FLETTNER Balloon: if it is full of hydrogen:

$$F''_a = 299.9388 \text{ kN} = 299938.8 \text{ N}$$

$$F_a = \rho_A V_{BG} \quad (22)$$

$$F''_a = \rho_A V_{BH} g \quad (23)$$

$$299938.8 = 1.29 \times V_{BH} \times 9.8 \quad (24)$$

$$V_{BH} = \frac{299938.8}{1.29 \times 9.8} = \frac{299938.8}{12.642} = 23725.5814 \text{ m}^3 \cong 23726 \text{ m}^3$$

The minimum volume of the balloon full of hydrogen is 23726 m^3 for the FLETTNER balloon to be buoyant.

Calculation of the dimensions of the FLETTNER flask if it is full of helium or hydrogen from the initial volume:

$$V_B = 200000 \text{ m}^3; V_{bHe} = 37540 \text{ m}^3; V_{bH} = 23726 \text{ m}^3;$$

$$\frac{V_B}{V_{BHe}} = \frac{200000}{37540} = 5.327 \cong 5$$

$$\frac{V_B}{V_{BH}} = \frac{200000}{23726} = 8.429 \cong 8$$

$$L_B = 245 \text{ m};$$

$$A_B = \frac{\pi D^2}{4} = \frac{3.14 \times 25^2}{4} = 490.625 \text{ m}^2; \quad (25)$$

$$L_{BH} = \frac{245}{5} = 49 \text{ m};$$

$$V_{BHe} = 37540 \cong 40000 \text{ m}^3;$$

$$A_{BHe} = \frac{490.625}{5} = 98.125 \text{ m}^2;$$

$$D_{BHe} = \sqrt{\frac{4A_{BHe}}{\pi}} = \sqrt{\frac{4 \times 98.125}{3.14}} = 11.18 \text{ m}; \quad (26)$$

$$L_{BH} = \frac{245}{8} = 30.625 \cong 31 \text{ m}; \quad V_{BH} = 23726 \cong 25000 \text{ m}^3;$$

$$A_{BH} = \frac{490.625}{8} = 61.328 \text{ m}^2;$$

$$D_{BH} = \sqrt{\frac{4A_{BH}}{\pi}} = \sqrt{\frac{4 \times 61.328}{3.14}} = 8.83 \text{ m}. \quad (27)$$

Placement of four large vertical wind turbines on a container ship as an alternative power source

For the placement of large vertical wind turbines on a container ship we will have to sacrifice two bays, more precisely, two turbines will be placed in the first bay of the bow, port/starboard, and two other turbines at the stern of the ship port/starboard.

The foundation of each turbine has a diameter of 4 m. Taking into consideration that around the foundation has to be an access path and a space for connection and subsequent maintenance, we will consider that the area needed to place a foundation is $S_R = 25 \text{ m}^2$ (where S_R -the area required for the foundation of a turbine). It will be build a 10 m high metal foundation to benefit from stronger winds, with an area of 25 on which the 24 m high turbine will be positioned (Fig. 14) (Vasilescu 2020).

From the above diagram it can be seen that the 2 turbines located in the bow of the ship, will occupy the spaces of 2 containers each, a 45-foot container with dimensions $L = 13.76 \text{ m}$; $l = 2.5 \text{ m}$ and $H = 2.58 \text{ m}$. The space between the 2 turbines located at the bow of the ship, on its width, will be left free, for good wind circulation:

$$S_1 = 19.4 \times 5 = 97 \text{ m}^2.$$

The space behind the rotors to the stern of the ship will also be left free (Fig. 15) (Vasilescu 2020):

$$S_2 = (14 - 5) \times 29.4 = 9 \times 29.4 = 264.6 \text{ m}^2.$$

The turbine is made of fibreglass reinforced plastic/carbon fibre reinforced polymer (Table 1) (Craft et al. 2012; Demadi et al. 2010). This material is light and durable material. The weight of a rotor together with the foundation is about 40 t.

From the table above (Table 2) (Vasilescu 2019b), it can be seen that at a ship speed of 19 Nod and a wind of 10 m/s, a single large vertical wind turbine can generate 500 kWh, and for a wind of 22 m/s, it can generates 2000 kWh.

Following the installation of the 4 turbines, at a ship speed of 19 Nod and a wind of 10 m/s it will be possible to generate approximately 2000 kWh, and for a wind of 22 m/s, approximately 8000 kWh.

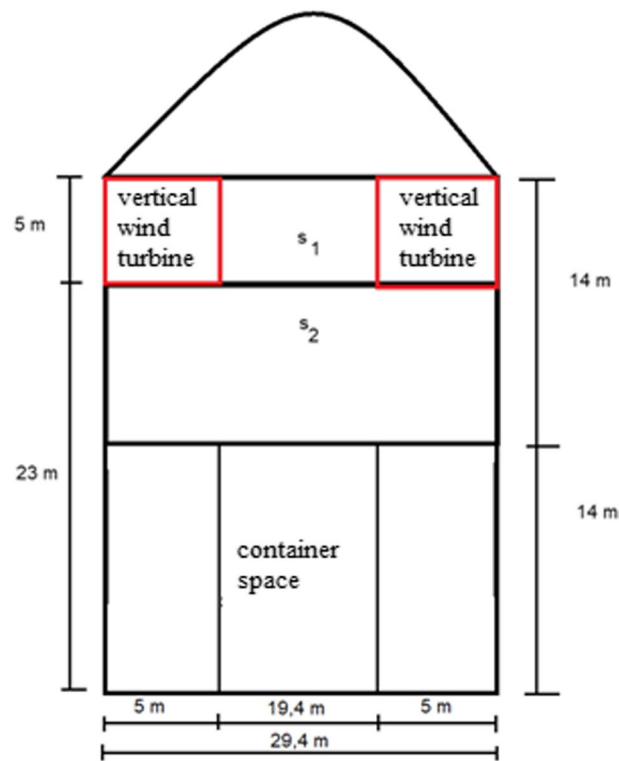


Fig. 14 Positioning scheme of 2 of the 4 large vertical wind turbines installed in the bow of the container ship (Vasilescu 2020)

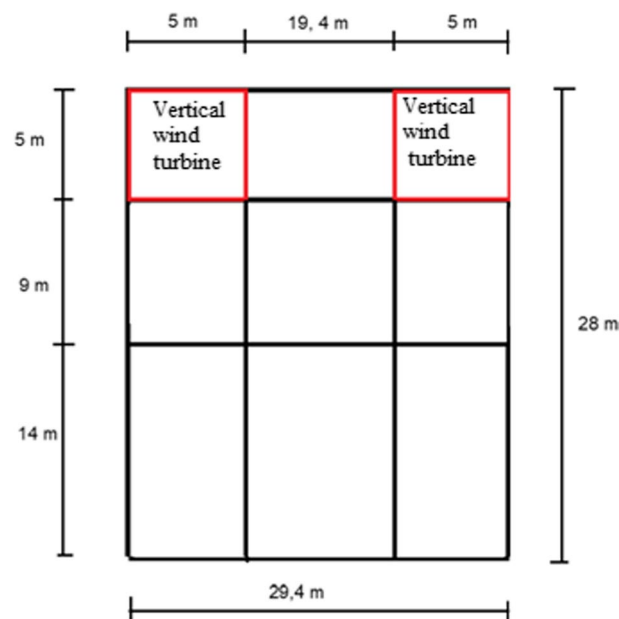


Fig. 15 Positioning scheme of 2 of the 4 large vertical wind turbines in the stern of the container ship (Vasilescu 2020)

Table 1 Technical data sheet of the large vertical wind turbine adapted for a container ship (Craft et al. 2012; Demadi et al. 2010)

Model	Dimensions
Vertical wind turbine	
Height × diameter (m)	24 × 4
Material	Fibreglass reinforced plastic/ carbon fibre reinforced polymer
Rotor speed (rpm)	0–225; variable
Structure	
Tower	Cylindrical-steel
Foundation height (m)	10
Rotor and foundation weight (t)	40
Components	
Electric motor	90 kW, 50/60 Hz IE4,IP55
Environmental conditions	
Operating Temperature (°C)	(+ 50)... (– 30)
Wind speed required for operation (m/s)	0–25
Resistance to wind force (m/s)	70

Table 2 Energy generated by the large vertical wind turbine (Vasilescu 2020)

Ship speed: 19 Nod	Ship speed: 19 Nod	Ship speed: 19 Nod
Real wind power (m/s)	True wind direction(°)	Generated energy (kWh)
10	60–130; 230–300	500
22	105–135; 225–255	2000

Table 3 Energy performance E (kWh) of electricity generator systems from unconventional sources (Vasilescu 2020)

Device	Energy performance E (kWh) Wind speed: 10 m/s	Energy performance E (kWh) Wind speed: 22 m/s
FLETTNER helium balloon		1000
4 Large vertical wind turbines	2000	8000

Energy balance of electricity generator systems from unconventional sources

The energy balance of electricity generator systems from unconventional sources (Vasilescu and Dinu 2020; Vasilescu 2020; Adaramolo 2014; Ammar et al. 2021) is presented in Table 3 (Vasilescu 2019b):

The two systems (Fig. 16) can generate together an energy between $E = 2000$ kWh and $E' = 8000$ kWh. During the voyages, the ship uses only one generator, of $E = 2000$ kWh.

Due to the international law, the ship will use fossil fuel propulsion near ports (Ben-Hakoun et al. 2016).

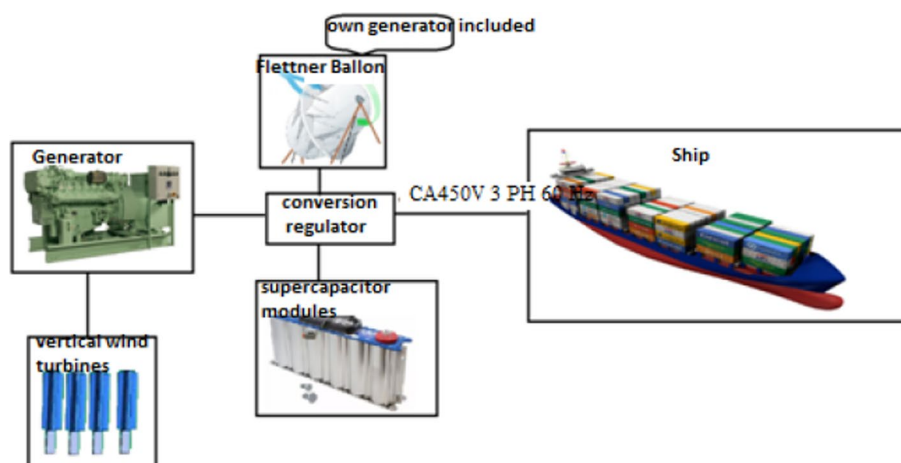


Fig. 16 Scheme for connecting the hybrid energy system to a container ship (Bergeson and Kent 1985; Craft et al. 2012)

Discussions and evaluation of the results

The connection of conventional and unconventional power sources to the main power bar of the ship will be realized as follows:

On the port side it will be installed:

- Generator 1 (G1—CA450V 3 PH 60 Hz 2000 KVA)
- Generator 2 (G2—CA450V 3 PH 60 Hz 2612.5 KVA)
- FLETTNER balloon (B—CA450V 3 PH 60 Hz 1000 KVA)
- Vertical wind turbine 1 (FR1—CA450V 3 PH 60 Hz 2000 KVA)
- Vertical wind turbine 2 (FR2—CA450V 3 PH 60 Hz 2000 KVA)

On the starboard side it will be installed:

- Generator 3 (G3—CA450V 3 PH 60 Hz 2612.5 KVA)
- Generator 4 (G4—CA450V 3 PH 60 Hz 2612.5 KVA)
- Vertical wind turbine 3 (FR3—CA450V 3 PH 60 Hz 2000 KVA)
- Vertical wind turbine 4 (FR4—CA450V 3 PH 60 Hz 2000 KVA).

The four vertical wind turbines installed on the main deck of the ship and the FLETTNER balloon with helium, generate a direct current. In order to be able to connect these unconventional power sources, the current is brought to the main power bar of the ship at 450 V AC and 60 Hz. For this, 5 current inverters were used: one of 690/450 V 1500kVA for the FLETTNER balloon and four of 690/450 V 2500 kVA for each of the four turbines vertical windmills.

If the FLETTNER helium balloon is installed on the ship and *the wind blows across the ship, port or starboard*, it will slow the ship by 0.12% of the ship's towing power. Being of such low value, it can be considered negligible in relation to the traction force of the ship.

The wind speed and the force of friction of the air with the FLETTNER balloon with helium, coupled, do not influence the manoeuvre of the ship.

If the wind blows perpendicular to the length of the FLETTNER balloon with helium that means from the stern or bow of the ship it does not affect the manoeuvrability of the ship, because the rotor will rotate faster, will generate more electricity, but will not move the balloon. The stabilizers will help the balloon maintain its position.

Factors that may affect the safety of the ship during the march, as a result of the installation of vertical wind turbines:

- increasing the moment of inclination due to lateral forces;
- increasing the running period;
- possible occurrence of strong vibrations.

The Simulation (Vasilescu 2020) has shown that the static angle of inclination of the container ship with large vertical wind turbines installed on its deck does not exceed the normal roll angle of the ship and can be considered negligible being smaller of 1%. This means that the installation of large vertical wind turbines on the deck of a container ship will not affect the manoeuvrability of the ship.

Conclusions

Through this research, following the installation of the elements of the hybrid diesel-electric power system with energy from conventional (fossil fuels) and unconventional energy sources (a FLETTNER balloon with helium and 4 large vertical wind turbines) on a ship container, the manoeuvrability and the stability of the ship do not change fundamentally. In terms of stability, cross-sectional stability has diminished (4,3184 < 4,3200). The longitudinal stability of the ship, due to the location of unconventional energy sources, has improved (27,281 < 227,518).

There are no major differences in the manoeuvrability of the ship compared to the ship without the hybrid power system installed.

From the above calculations, it results that unconventional energy systems can be used to cover the minimum energy requirement, $E = 2000$ kWh, decreasing pollution and fuel consumption. Due to international law, the ship will use fossil fuel propulsion near ports (Ben-Hakoun et al. 2016).

It is considered that the installation of this hybrid energy system on a container ship is beneficial in terms of reducing fossil fuel consumption, reducing greenhouse gas emissions and is safe in terms of safe navigation.

This research paper paves the way for future research and development perspectives in the related field, green energy sources, hybrid power supply systems, from unconventional sources (wind energy) and conventional sources (fossil fuels).

It is considered that the research presented in this paper can be continued in terms of increasing the storage capacity of electricity produced by the FLETTNER balloon and vertical wind turbines.

The extension of the research can be done in terms of electricity production with the help of the FLETTNER balloon at altitudes higher than 300 m.

Studies may also be extended to the design and construction of ships specially equipped with a mixed propulsion system, in particular the shape of the hull, the shape of the ship's bulb and the friction reduction systems of the ship with water.

Another research possibility can be the installation of FLETTNER rotors that use the Magnus effect on the main deck of the ship, instead of the large vertical wind turbines.

The operation of on-board wind turbines involves research and finding optimal solutions for the practical application of the results obtained in order to reduce fuel consumption, the amount of gas emitted by ship engines and finally to reduce the degree of air pollution..

The shape of the FLETTNER balloon, but also of the ship, is an interesting research topic, CFD studies will be validated on models (with the passage of results in nature through similarity) or on prototypes.

Abbreviations

B	The FLETTNER balloon
D	Displacement
d	Diameter at the rope
F _a	The rising force of the balloon
F' _a	The minimum lift force
FR	Strength of the rope
FRT	The total resistance force
g	Gravitational acceleration
G1, G2, G3, G4	The diesel generators
GT	Gross tonnage
GHe	Helium weight force
GB	Balloon weight force
G _{cp}	Weight force for cables and ropes
GH	Hydrogen weight
GB	Balloon weight
G _{cp}	Weight cables and ropes
l	Ship width
L	Ship length
L _b	Length of balloon
m _b	The mass/weight of FLETTNER Ballon
m _c	The total mass of a cable
m _{ct}	The total mass of electrical cables
m _p	Rope weight
NO _x	Oxides of nitrogen
P	Total power
RF1, RF2, RF3, RF4	The large vertical wind turbines
S _R	The area needed to place a foundation of a turbine
TEU	Twenty-foot equivalent unit
U	The voltage of the generated electric current
V _b	The volume of FLETTNER Ballon
ρ _a	Density of air

Acknowledgements

Not applicable.

Author contributions

The individual contributions of authors to the manuscript: PM-performed 25% of content and analyzed actual status of renewable energies for modernizing existing ships and the use of wind energy, as a global energy surplus and the discharge of power of a conventional propulsion system (performed chapter Introduction, partial chapter 4.Discussions and evaluation of the results and partial chapter 5.Conclusions). PFV-performed 25% of content:chapter 2-The components of a hybrid system used for power generation using unconventional sources, partial chapter 4—Discussions and evaluation of the results and partial chapter 5-Conclusions. VMV—performed 45% of content; chapter 3—Energy balance of the hybrid energy system and mooring scheme for a container vessel, partial chapter 4—Discussions and evaluation of the results and partial chapter 5-Conclusions. DRA-performed 5% of content; chapter 6-List of abbreviations and chapter 7-References. All authors read and approved the final manuscript.

Author Information

Panaiteșcu Mariana professor in Engineering Sciences in Mechanics and Environment. Skills in: renewable energies-wind turbine; Ph.D in Hydraulics and Fluids Mechanics; Doctoral thesis in fluid flow on surfaces with variable geometry with technical applicability/wind turbines. All data for wind turbines processed by ANSYS Fluent were simulated by her Panaiteșcu Fanel-Viorel professor in Engineering Sciences in Mechanics and Environment. Skills in renewable energies-wind energy, solar energy; applications on renewable energy sources on the environment and climate; Ph.D. Engineer in Mechanical engineering; Doctoral thesis – Optimization of flows on curvilinear slopes. All data for the elements of the hybrid energy system, which uses unconventional energy, were calculated by him.

Vasilescu Mihail-Vlad assoc.expert in Doctoral School of Mechanical Engineering, deck officer; subject of his doctoral thesis is about design and operation of container vessels to improve energy efficiency. All data from ship were collected by him. All data for the energy balance of electricity generating systems from unconventional sources have been calculated by him.

Daineanu Robert-Alexandru student in Doctoral School of Mechanical Engineering; in his doctoral thesis make researches on optimizing the operation of container vessels. All data about technical characteristics of ship were collected by him.

Funding

Not applicable.

Availability of data and materials

Data sharing is "Not applicable" to this article as no datasets were generated or analyzed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Received: 9 December 2021 Accepted: 8 June 2022

Published online: 30 June 2022

References

- Adaramolo M (2014) Wind turbine technology—principle and design. Apple Academic Press, Toronto
- Ammar A, Azam A, Yanen W, Zhang Z, Ning L, Changyuan J, Mushtaq RT, Rehman M, Gueye T, Shahid MB, Wajid BA (2021) Additively manufactured nano-mechanical energy harvesting systems: advancements, potential applications, challenges and future perspectives. *Nano Convergence* 8:37
- ANSYS Fluent 12.0 (2009) Theory Guide. <http://www.afs.enea.it/project/neptunium/docs/fluent>. Accessed 20 Feb 2022.
- Ben-Hakoun E, Shechter M, Hayuth Y (2016) Economic evaluation of the environmental impact of shipping from the perspective of CO₂ emissions. *J Ship Trade* 1:15
- Bergeson L, Kent G (1985) Sail assist developments 1979–1985. *J Wind Eng Ind Aerodyn* 19:45–114
- Craft TJ, Iacovides H, Johnson N, Lauder BE (2012) Back to the future: FLETTNER-Thom rotors for maritime propulsion. Bagel House, London, pp 1–10
- Demadi A, Gao Y, Ehsani M (2010) Modern electric, hybrid electric, and fuel cell vehicles—fundamentals, theory, and design. CRC Press Taylor & Francis Group (2nd edn) Boca Raton
- Gabriela A (2020) Environmentally sound management of ship wastes: challenges and opportunities for European ports. *J Ship Trade* 5:12
- Grosan VN (2011) Research on sailing propulsion of commercial ships—the influence of unconventional propulsion systems on nautical qualities. Doctoral thesis, Constanta Maritime University, Romania
- Milan J (2018) Multidimensional examination of the performances of a liner shipping network: trunk line/route operated by conventional (Panamas Max) and mega (ULC—ultra large container) ships. *J Ship Trade* 3:13
- Vasilescu MV (2019a) FLETTNER rotor with helium. *J Mar Technol Environ* 11:71–74
- Vasilescu MV (2019b) FLETTNER rotor. *J Mar Technol Environ* 11:75–82
- Vasilescu MV, Dinu D (2020) Wind energy capturing devices with possible implementation on container ships. *J Mar Technol Environ* 11:49–54
- Vasilescu MV (2020) Research on the design and operation of container vessels to improve energy efficiency. Doctoral Thesis, Constanta Maritime University, Romania

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.