Harnessing wind energy on merchant ships: case study Flettner rotors onboard bulk carriers

Ibrahim S. Seddiek[1] · Nader R. Ammar[2,3]

Abstract
Shipping faces challenges of reducing the dependence on fossil fuels to align with the international regulations of ship emissions reduction. The maritime industry is in urgent need of searching about alternative energy sources for ships. This paper highlights the applicability of harnessing wind power for ships. Flettner rotors as a clean propulsion technology for commercial ships are introduced. As a case study, one of the bulk carrier ships operating between Damietta port in Egypt and Dunkirk port in France has been investigated. The results showed the high influence of the interaction between ship course and wind speed and direction on the net output power of Flettner rotors. The average net output power for each rotor will be 384 kW/h. Economically, the results reveal that the use of Flettner rotors will contribute to considerable savings, up to 22.28% of the annual ship's fuel consumption. The pay-back period of the proposed concept will be 6 years with a considerable value of levelized cost of energy. Environmentally, NO_x and CO_2 emissions will be reduced by 270.4 and 9272 ton/year with cost-effectiveness of \$1912 and \$55.8/ton, respectively, at annual interest rate of 10%.

Keywords Wind energy · Flettner rotor · IMO · Ship emission reduction · Cost-effectiveness

Introduction

More than 90% of the international trade is transported by ships (Jiang et al. 2018; Pasha et al. 2020). In year 2019, about 92,295 ships of 1.98 million deadweight shared in the maritime field activities, and more than 60,000 ships transported billions of tons of cargo worldwide (UNCTAD 2019). On the other hand, this growth contributed significantly to increasing the amount of emissions from ships. Annually, vessels emit large quantities of pollutants into the air, principally in the form of nitrogen oxide (NO_x), particulate matter (PM), and sulfur oxide (SO_x), which have been steadily expanding and affect human health (Ammar and Seddiek 2018, 2020; Seddiek 2016). Latest statistics revealed that maritime transport is responsible for producing 3% of the world's total greenhouse gas emissions, contributing to global warming and extreme weather effects (Abdelkhalek et al. 2014; Bouman et al. 2017; Sadek and Elgohary 2020; Seddiek 2017; UNCTAD 2019).

In continuous steps, the International Maritime Organization (IMO) seeks to reduce the adverse effect of ship emissions by issuing the relative regulations within Annex VI of Marine Pollution Convention 78 (Ammar 2018, 2019a; Ammar and Seddiek 2017; Halff et al. 2018; IMO 2018, 2019). In addition to the international legislations, IMO pursues to urge those interested in the shipping industry to reach zero emissions ship either through the use of alternative fuels or a clean source of energy onboard ships (Ammar 2019b; Joung et al. 2020; Scott et al. 2017). Regarding alternative fuels, all practical studies and researches proved that LNG can be considered an alternative and possible solution to replace conventional fuels in maritime shipping as it shows the lowest cost compared with the other alternative technologies

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(Elgohary et al. 2014; Mohseni et al. 2019). With reference to new power sources, many research studies have been examining the applicability of using fuel cells, solar panels, and wind turbines to be a source of energy onboard ships (Clodic et al. 2018; Ghenai et al. 2019; Welaya et al. 2011; Welaya et al. 2013) .

Wind energy can be considered as an attractive option for marine applications. It is a renewable source and can be used in combination with low carbon fuels (Crist 2009; Parker 2013; Traut et al. 2014). The focus of the current paper is to evaluate the potential for Flettner rotor-powered ships. The literature review addresses the use of Flettner rotors in marine applications from the viewpoints of practical applications and researches. It was shown by De Marco et al. (2016) that Anton Flettner, in 1920, was the first engineer who studied the effectiveness of using Flettner rotors as ship propulsion system. Buckau ship is considered the first ship that enrolled this system in 1924 as a retrofit ship. Two years later, M/V Barbara became the first new build ship equipped by Flettner rotors (Seifert 2012). After a long time, in year 2010, Enercon, a wind energy company, launched a Flettner-powered cargo ship named E-Ship 1. Recently, two 30-m-tall rotor sails have been installed on a Maersk Tankers vessel (Norsepower 2015). Arief et al. (2018), Lele and Rao (2017), Searcy (2017), Seifert (2012), Talluri et al. (2018), and Traut et al. (2014) analyzed and evaluated the potential for implementing Flettner rotor systems for different ship types. As a step toward studying the applicability of the use of Flettner rotors in marine application, the present paper aims to analyze the Flettner rotor performance and to study the effect of different parameters on the turbine's net output power. These parameters include the effect of wind characteristics, ship speed, lift coefficient, motor speed, and rotation coefficient. In addition, a bulk carrier ship is investigated as a case study. An economic and environmental analysis for the case study is performed to evaluate the economic feasibility of Flettner rotors, levelized cost of energy, and their effectiveness in reducing ship emissions.

Flettner rotors' principles and fundamentals

In order to study the technical, environmental, and economic effects of using Flettner rotors onboard ships, the theoretical operation of these systems should be firstly presented. The main principle for the operation of Flettner rotors is the Magnus effect as shown in Fig. 1a (Lele and Rao 2017; Pearson 2014). It was first described by Heinrich Gustav Magnus in 1953 (Lele and Rao 2017; Talluri et al. 2018). The Magnus effect correlates with the velocity and pressure of a moving fluid (Gupta et al. 2017; Kray et al. 2014; Pezzotti et al. 2020). As the pressure of a moving fluid decreases, its velocity will be increased and vice versa. When induced wind

current attacks a rotating cylinder, it retards the air on one direction and accelerates it on the opposite direction. High- and low-pressure regions will be formed around the rotating cylinder (Badalamenti and Prince 2008; Searcy 2017; Seifert 2012; Zdravkovich 1997). As a result of this pressure difference, lift and drag forces will be developed in the perpendicular and the parallel directions of the wind flow, respectively, as shown in Fig. 1b.

The produced lift and drag forces by the Magnus effect are a supporting mean for ship propulsion if a rotating cylinder is properly mounted onboard the ship. The rotation of the cylinder is controlled by an electric motor mounted onboard the ship. The power consumed by the motor and the thrust produced from the Flettner rotor will regulate the amount of the main engine power that can be replaced. The produced thrust can be calculated as the summation of the lift and drag forces in the ship direction (Ballini et al. 2017; Bentin et al. 2016; Bordogna et al. 2020; Bordogna et al. 2019; De Marco et al. 2016; Kray et al. 2012; Mittal and Kumar 2003; Traut et al. 2014).

Flettner rotor modeling

In this section, a simple technical, environmental, and economic modeling is presented. The modeling is divided in two subsections. The first section will present the technical model of the Flettner rotor. However, the second part illustrates the economic and environmental issues in case of using Flettner rotor onboard ships.

Technical modeling

For a moving vessel with a speed of (V_s), the true wind speed and direction (V_t, γ) will affect the Flettner rotor performance. This is because the changes in true wind direction to a moving vessel will result in a change in apparent wind speed (V_a). Consequently, the apparent wind speed will affect Flettner rotor to generate the thrust in ship direction. Figure 2 illustrates the angles between ship and wind velocities as well as two coordinate systems. The (X_h, Y_h, Z_h) coordinate system is used for the vessel hull, while (X_f, Y_f, Z_f) is introduced for the course through the ocean.

The apparent wind speed (V_a) can be calculated as a function of the vessel speed (V_s) and the true wind speed (V_t), as expressed in Eq. (1), assuming very small drift angle. In addition, its direction can be determined using Eq. (2):

$$V_a = \sqrt{V_t^2 + V_s^2 - 2V_t V_s \cos\gamma} \tag{1}$$

$$\beta = \cos^{-1}\left(\frac{V_t^2 - V_a^2 - V_s^2}{-2V_a V_s}\right) \tag{2}$$

Fig. 1 Magnus effect (**a**) and schematic of the resulting lift and drag forces onboard a ship (**b**)

(a)　　　　　　　　　　　　　　　　　　(b)
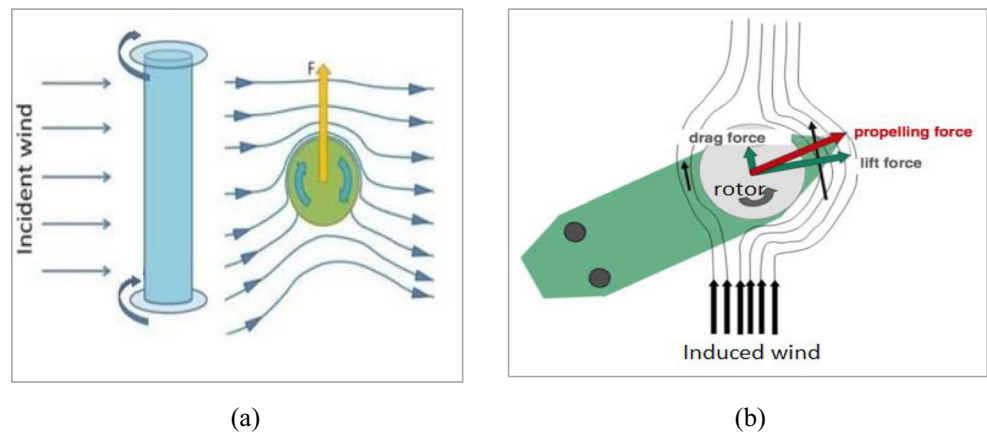
The rotational speed of the Flettner rotor has a great influence on the produced power. The rotors are assumed to be structurally connected to the ship hull. The rotation coefficient (C_{rot}) is the ratio between the rotor rotational speed (U_{rot}) and the apparent wind speed as expressed in Eq. (3):

$$U_{rot} = C_{rot} \times V_a \tag{3}$$

The flat plate boundary layer theory can be used to calculate the resistive force and the power required to overcome the skin friction of Flettner rotor system. Schlichting's formula can be used to calculate the skin friction coefficient as a function of Reynolds number. The power needed to turn the rotor (P_{con}) and to overcome the friction force can be calculated using Eq. (4). It can be noted that this is an approximate assessment and additional aspects, as bearing roughness can also influence the required power:

$$P_{con} = \left[\left(\frac{0.455}{(log(Re))^{2.58}} - \frac{1700}{Re} \right) \times \rho_a \times \frac{U_{rot}^2}{2} \times A_r \right] \times U_{rot} \tag{4}$$

where ρ_a is the air density, A_r is the surface area of the rotor, Re is the Reynolds number. Re can be calculated using Eq. (5):

$$Re = \frac{\rho_A . C_{rot} . V_a . L_{Re}}{\mu} \tag{5}$$

where L_{Re} is the characteristic length of rotor, and μ is the air dynamic viscosity.

To determine the effective power in ship direction (P_s) and then the net output power of the Flettner rotor (P_{net}), the lift and drag forces are resolved. P_s and P_{net} can be calculated considering the ship propulsion efficiency η as expressed in Eqs. 6 and 7 (Lele and Rao 2017):

$$P_s = (C_L \times sin\beta - C_D \times cos\beta) \times \left(\frac{\rho_A \times V_a^2}{2} \right) \times A \times V_s \tag{6}$$

$$P_{net} = (P_s - P_{con}) \times \eta \tag{7}$$

where C_L is the lift coefficient, C_D is the drag coefficient, and A is the maximum wind-projected area of the Flettner rotor.
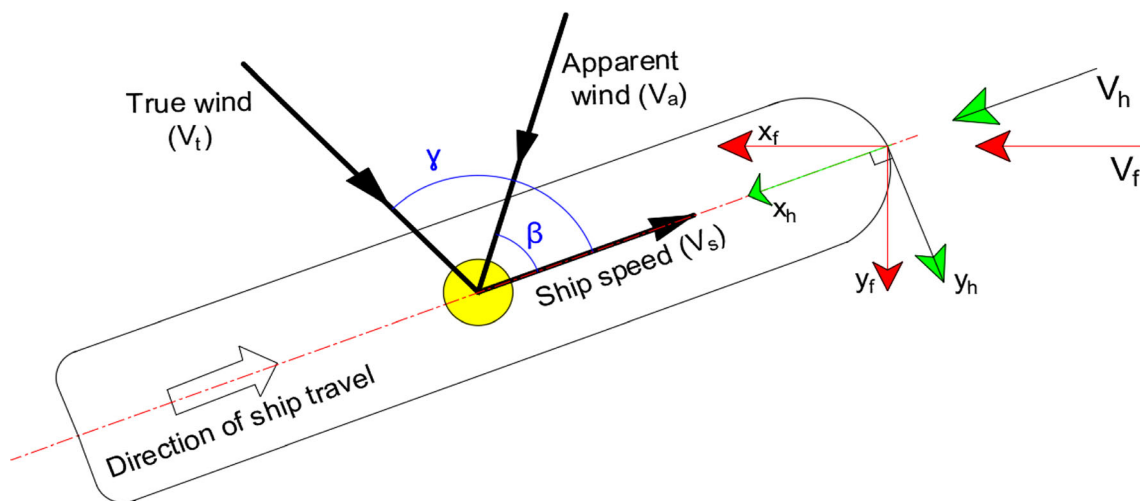

Fig. 2. Ship and wind velocity angles

The lift and drag coefficients for each Flettner rotor can be calculated based on the numerical modeling as expressed in Eqs. 8 and 9:

$$C_L = \sum_{i=1}^{4} \sum_{j=1}^{4} \sum_{k=1}^{3} a_{ijk} SR^i AR^j \left(\frac{d_e}{d}\right)^k \tag{8}$$

$$C_D = \sum_{i=1}^{4} \sum_{j=1}^{4} \sum_{k=1}^{3} b_{ijk} SR^i AR^j \left(\frac{d_e}{d}\right)^k \tag{9}$$

where SR and AR are the spin and the aspect ratio of Flettner rotor. (a_{ijk}) and (b_{ijk}) are coefficients related to the geometrical and functional operations of Flettner rotors. Their values based on the fit procedure for the numerical results, as presented in De Marco et al. (2016). de/d is the large end plate and Flettner rotor diameter ratio. Equations 8 and 9 are valid for the following ranges: $1.0 \leq de/d \leq 3.0$, $1.0 \leq SR \leq 3.0$, and $2.0 \leq AR \leq 8.0$.

The effect of the interaction between Flettner rotors on the flow field includes potential and viscous parts. The viscous section impact appears as wake and turbulence produced by flow separation and vortices. The circulation induced changes in the apparent wind speed and direction for each Flettner rotor. The analytical solution for the potential flow effects in the x-y plane for a group of Flettner rotors is presented by Garzón and Figueroa (2017). The two components of the induced flow for each Flettner rotor in the X and Y directions, V_x and V_y, can be calculated using Eqs. 10 and 11, respectively (Tillig and Ringsberg 2020):

$$V_x = \frac{V_{ind.} \cdot r}{\sqrt{x^2 + y^2}} \cos\left(\arctan\left(\frac{y}{x}\right)\right) \tag{10}$$

$$V_y = \frac{V_{ind.} \cdot r}{\sqrt{x^2 + y^2}} \sin\left(\arctan\left(\frac{y}{x}\right)\right) \tag{11}$$

where r is the Flettner rotor radius, and $V_{ind.}$ is the induced velocity at each Flettner rotor. $V_{ind.}$ can be calculated as a function of the rotor circulation Ω. The circulation can be calculated using known lift coefficients (C_L) using Kutta-Joukowsky formula or from model tests (Abbot and Von Doenhoff 1959; Bordogna et al. 2020). The relation between $V_{ind.}$, Ω, and, C_L is given in Eqs. 12 and 13 (Houghton et al. 2017; Swanson 1961):

$$\Omega = 2 \pi r V_{ind.} \tag{12}$$

$$C_L = (1 - R_c) \left(\frac{\Omega}{rV_a}\right) + \frac{R_c \sin(\gamma)}{2\pi} \left(\frac{\Omega}{rV_a}\right)^2 \tag{13}$$

where, R_c presents the ratio between the Flettner rotor radius (r) and the distance to the external vortex and (γ) is the vortex direction. The values of R_c and γ according to model tests are 0.25 and 210°, respectively, in the range of $1.0 \leq SR \leq 4.0$.

Environmental and economic modeling

To evaluate the environmental benefits in case of using Flettner rotors, the annual ship fuel saving (AFS_{FR}) is calculated using Eq. 14. It depends on the saved propulsion power during the trip (P_{FR}) in kW, specific fuel consumption of the main diesel engine (SFC_{ME}) in kg/kWh, the sailing hours per year (H), and number of Flettner rotors (N_{FR}).

$$AFS_{FR} = \sum_{i=1}^{i=n} N_{FR} \times P_{FR} \times SFCF_{ME} \times H \tag{14}$$

The annual reduction in emissions due to using Flettner rotors (AER_{FRS}) can be calculated using Eq. 15 (Ammar 2018; Ammar and Seddiek 2017, 2018, 2020):

$$AER_{FR} = \sum_{i=1}^{i=n} N_{FR} \cdot P_{FR} . F_e \cdot H \tag{15}$$

where F_e is the emission factors for the engine in g/kWh. These factors for slow speed marine diesel engine operated with heavy fuel oil are 18.1, 10.29, 1.4, 620.62, 0.6, and 1.42 g/kWh corresponding to NO_x, SO_x, CO, CO_2, HC, and PM emissions, respectively (IMO 2018, 2019).

From an economic point of view, the annual Flettner turbines cost (AFTC) will depend mainly on the initial, installation, operation, and maintenance cost and could be estimated as shown in Eq. (16):

$$AFTC = \frac{(1+i)^n}{(1+i)^n - 1} \left[N_{FR} \times CC + \sum_{y=1}^{y=u} C_y D_y \right]$$
$$+ \left[P_{con} . SFC_{AE} \times F_c \times 10^{-3} + C_{O\&M} \right] \times N_{FR}$$
$$\times H \tag{16}$$

where i is interest rate, n is the expected ship's working year after installation of turbines, CC is the initial cost of one rotor in USD per unit, $C_y D_y$ is the installation cost of one rotor in USD, P_{cos} is the power consumed for Flettner rotor in kW for one rotor, SFC_{AE} is diesel generator–specific fuel consumption in kg per kW, F_c is fuel cost in USD per ton, and $C_{O\&M}$ is the maintenance and operation cost in USD per hour. On the other hand, the optimistic effect of Flettner turbines appears in the form of annual saving cost (AFTSC), which may be determined as follows:

$$AFTSC = P_{FR} \times N_{FR} \times SFC_{ME} \times F_c \times (1 \pm p)^n \times H \times 10^{-3} \tag{17}$$

where, p is the expected increasing or reducing percent of fuel cost. Moreover, it preferred to estimate the levelized cost

of energy (LCOE) as an indication of importance of applying the proposed concept realistically. This parameter is widely used, and it was presented by the International Renewable Energy Agency (IRENA), which formulated it to be expressed as follows (Aldersey-Williams and Rubert 2019):

$$LCOE = \frac{\sum_{t=1}^{x} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{x} \frac{E_t}{(1+r)^t}} \qquad (18)$$

where x is the number of years of the investment period, t is one of the years during period x, I_t is capital expenditures costs (CAPEX) in year (t), M_t is operation and maintenance expenses costs (OPEX) in year (t), F_t is the fuel cost in year (t). E_t is the number of Megawatt hours generated by the Flettner rotors during year t, and r is the discount rate.

It is important to combine the environmental benefits that can be achieved through the application of Flettner turbines technique onboard ships and the costs involved in this application. To calculate the cost-effectiveness (CE_{em}) in dollars per ton, the annual costs of the project are divided by the annual quantity of emission reduced as a result of this proposal, as follows (Ammar 2019b; Ammar and Seddiek 2017, 2018):

$$CE_{em} = \frac{(ACV - ASV)}{ER_q} \qquad (19)$$

where ACV is the annual cost value of the proposed Flettner rotors ($/year), ASV is the annual fuel saving ($/year), and ER_q is the annual emission reduction for each species of exhaust gases in ton/year.

Case study

Wadi Alkarm (IMO: 9460760) is a bulk carrier ship that was built in 2011. The ship is registered in Alexandria port with registry number of 3633 under the Egyptian flag. The principal dimensions of the ship length, breadth, and draft are 229 m, 32 m, and 14.46 m, respectively. The dead weight of the ship is 80,533 MT with a total gross tonnage of 43,736 MT. The transported cargo includes coal, iron, ore, and grain with Suez Canal gross and net tonnages of 45,016 MT and 40,414 MT, respectively. The main technical data for the case study can be summarized in Table 1 (FleetMon 2020; Marine Traffic 2020).

M/V Wadi-Alkaram sails in a route from Damietta port in Egypt to Dunkirk port in France. Figure 3 shows the ship directions that changed at Tunisia, Algeria, Morocco, Spain, and Portugal. With average speed of 13 knots, the ship takes about 13 to 15 days for one route.

Table 1 Main technical data for the case study ship

Vessel name	Wadi Alkarm
IMO number	9460760
Length	229 m
Breadth	32 m
Draft	14.46 m
Gross tonnage	43,736 MT
Service speed, knots	13.5
Main engine type	MAN B&W
Number of cylinders	7S50MC-C(MK VII)
NCR (continuous running)	13,545 BHP X 123 RPM
Diesel generators	3 × 625 kW at 1200 RPM
Number of trips per year	10

Figure 4 illustrates the proposed locations of four Flettner rotors on the ship's main deck. The rotors will be distributed along the ship length, specifically at port and starboard of hatches number 2 and 4. The rotors will be installed in the way that lets free moving for crew to carry out the necessary operations and maintenance activities on the main deck, and it will not hinder the loading and unloading of the cargo. In terms of the possibility of installation, the bulk carrier ships are considered one of the most suitable ships for installing this type of turbines, as there are no winches on the surface where the goods are loading and unloaded, whether by external winches or by belts.

The selected Flettner rotor model to be installed onboard the case study is the Norsepower rotor (Norsepower 2018). The rotors are installed onboard the ship on foundation with a bolt connection and height of 2.5 m. The rotor height and diameter are 24 m and 4 m, respectively. The total weight of the rotor including the foundation is 34 tons. The supported tower for the rotor is a cylindrical steel structure. The variable rotor speed changes from 0 to 225 rpm with 90 kW electric motor drive. The operational wind speed range for the rotor starts from 0 to 25 m/s with a survival wind speed of 70 m/s and a maximum continuous thrust of 175 kN.

The following assumptions are made for simplicity regarding ship route, ship stability, and wind speed and direction. The investigated ship is assumed to travel on a fixed route at constant speed from Damietta port to Dunkirk port. The installation of the Flettner rotors will not have an effective impact on ship stability and displacement. The initial calculations for the Flettner rotor technical results are performed at ship speed of 13.5 knots, during cruise in the open sea, over true wind angles from 0° to 360°. Both ship drift angle and bearing friction are neglected. The ship propulsion system efficiency is assumed to be 60% (Lele and Rao 2017; Tillig and Ringsberg 2020; Traut et al. 2014). The values for the air density and dynamic viscosity are assumed 1.225 kg/m^3 and
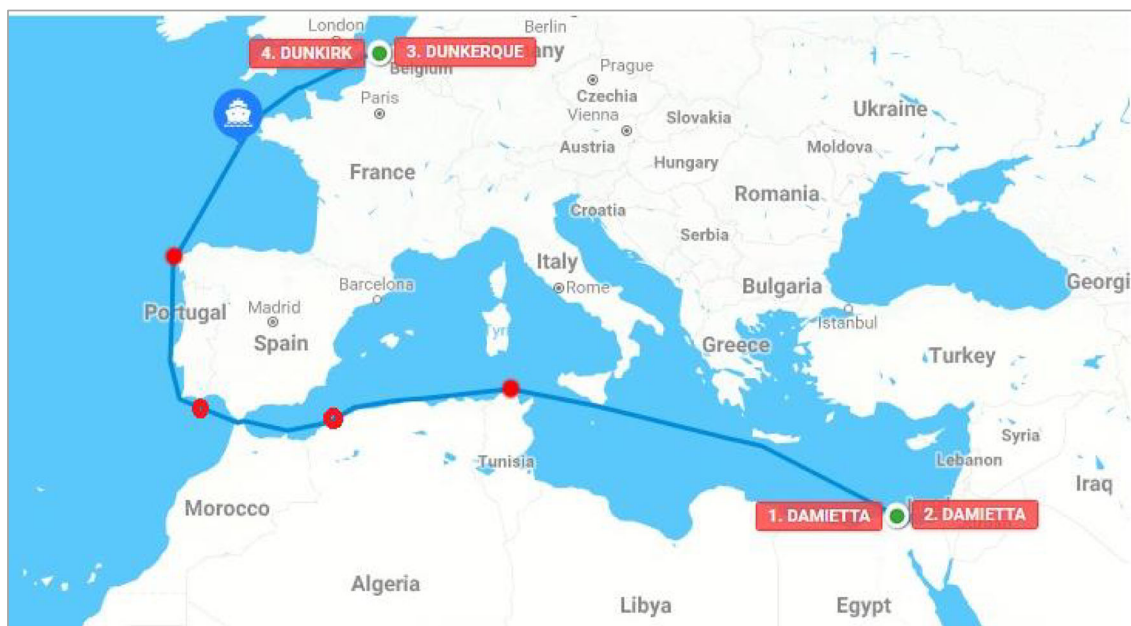
Fig. 3 Ship's route and passing points

1.789×10^{-5} N-m/s^2, respectively (Cimbala and Çengel 2013; Nakayama and Boucher 1998a). Schlichting's equation is used for calculating friction coefficient (Munson et al. 2012; Nakayama and Boucher 1998b). The data for wind speed and direction were based on the meteoblue climate statistics (Meteoblue 2020).

Results and discussion

In this section, the technical, environmental, and economic results for using Flettner rotor onboard the selected case study are presented. The results imply the effect of wind speed variation, ship's speed, lift coefficient, motor speed, and rotation coefficient on the net output power of Flettner rotors. In

addition, the environmental and economic effects of using Flettner rotor onboard the case study are discussed.

Technical and environmental results

It is important to include the aerodynamic interaction effects among different Flettner rotors when studying their performance onboard a ship. The potential part of this interaction is dominating as the apparent wind speeds and directions are changed according to the induced circulation (Tillig and Ringsberg 2020). The apparent wind speed and direction at each rotor is highly affected by the position and the circulation of the other rotors. Therefore, the lift and drag coefficients, as well as the optimum rpm, should be calculated according to the characteristics of the experienced wind speed and

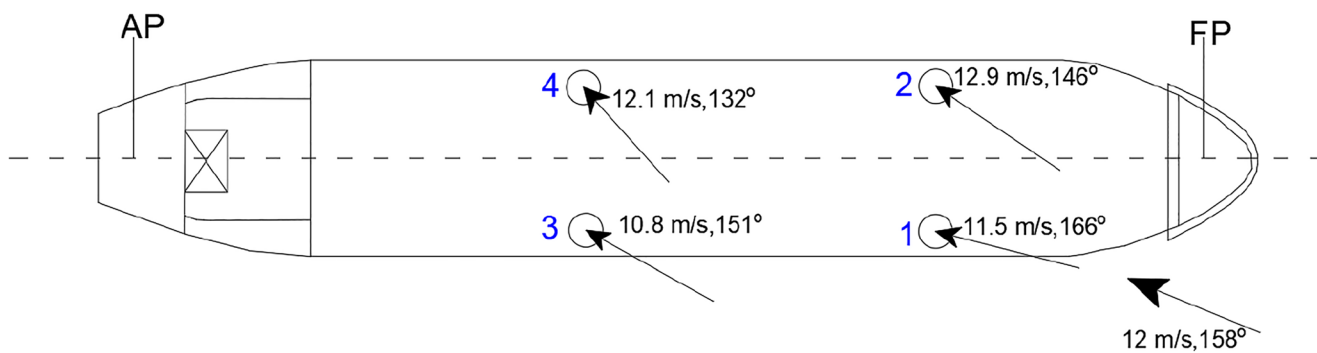**Fig. 4** Flettner rotors locations onboard the case study
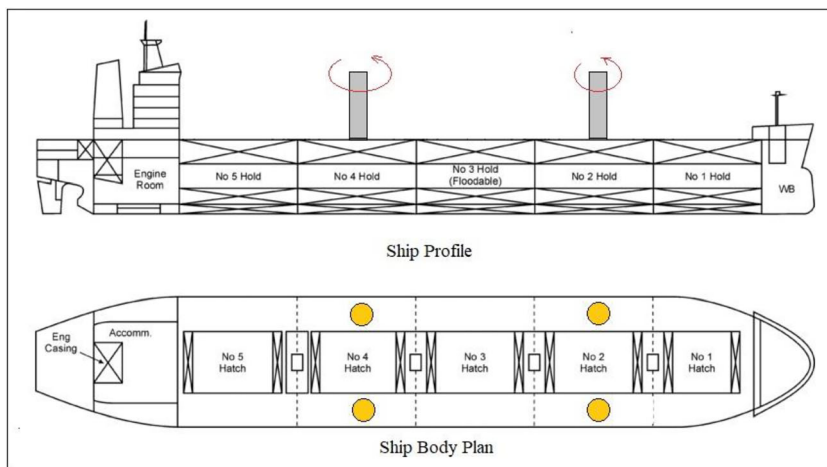
Fig. 5 The apparent wind speeds and directions for the four rotors at ship speed of 13.5 knots, V_t=6.5 m/s, and γ=225°

directions. The wind speeds and angles agree with these practices by sail boats at various locations in a fleet (Bethwaite 2013). The optimum rpm for each rotor is calculated according to wind speed, wind direction, and the induced velocity at each rotor, and the preferred spin ratio ranges from 1.0 to 3.0 for marine applications (De Marco et al. 2016). To show the interaction effects of the installed four Flettner rotors, the induced flow field for the case study, at V_s = 13.5 knots and V_t = 6.5 m/s, is illustrated in Fig. 5. The induced flow is calculated using MATLAB program, according to Eqs. 10–13, at true wind angle of 225° (V_a = 12m/s, β = 158°). The longitudinal and transverse distances between rotors are 65 m and 25 m, respectively. In addition, the apparent wind speeds and directions at each rotor are shown in Fig. 5, considering the different interaction among the four rotors.

Among the important parameters that define Flettner rotor performance are the lift and drag coefficients which can be calculated using Eqs. 8 and 9. They determine the lift and drag forces generated and consequently the system effective forces in ship direction and perpendicular to it. Figure 6 shows the effective forces in ship direction for the four Flettner rotors, organized according to Fig. 5, considering the aerodynamic effects with and without interaction. The effective force values are calculated at optimum rpm for each rotor whose diameter

and height are 4 m and 24 m, respectively. These dimensions are consistent with the ship taken into consideration. The calculations are performed at ship speed of 13.5 knots, according to the wind characteristics of the route for the case study. The aim of these considerations is a rough evaluation of the potentiality of the Flettner rotors as a marine propulsion device. It can be noticed that the forward Flettner rotors 1 and 2 benefit from the interaction, while the aft rotors 3 and 4 suffer from it. In addition, the side force produced from each Flettner rotor is augmented as a result of flow interactions.

The net output power of each Flettner rotor with and without aerodynamic interaction, organized according to Fig. 5, can be presented in a polar plot as shown in Fig. 7. It explains the variation rotor's net power output because of change of the true wind speed from 5 to 25 m/s. The other variables including lift and drag coefficients change for each rotor according to its circulation and spin ratio. It can be noticed that the rotor power consumption is increased as the wind velocity increases. The net output is positive as the thrust generated is higher than the resistive force. The net output power depends on the wind characteristics and ship speed. Figure 7 a and b show the effect of reducing ship speed from 13.5 knots to 10 knots on the net output power at different wind characteristics. The results are identical for the positive and negative angles

Fig. 6 Effective force in ship direction from the four Flettner rotors with and without interaction at ship speed of 13.5 knots
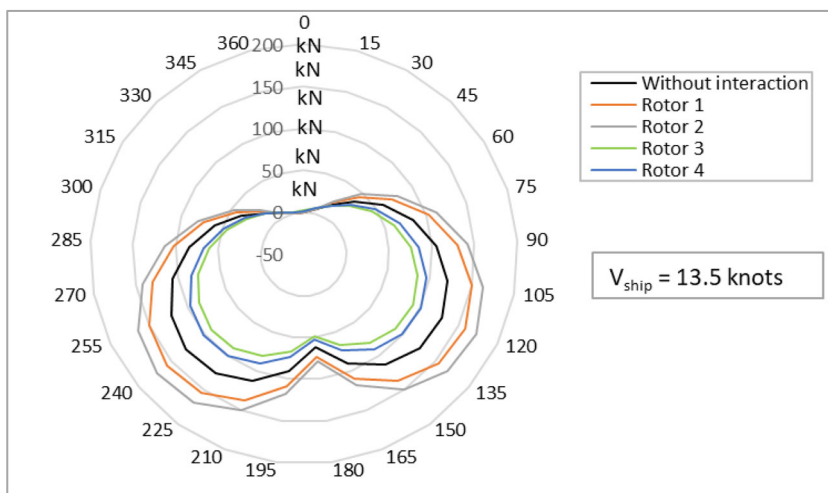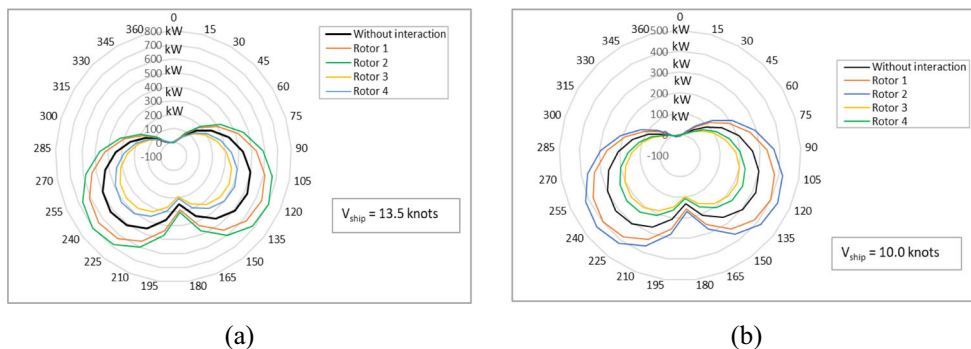
Fig. 7 Flettner rotor net power variation with true wind characteristics and ship speeds of 13.5 knots (**a**) and 10 knots (**b**)

(a)   (b)

because of the symmetric characteristics of the net output power. The highest values of the net out power for the selected Flettner rotor can be obtained at true wind speeds higher than 22 m/s over ranges of wind angles from 105 to 135 degrees and from 225 to 255 degrees. The maximum net output power, shown in Fig. 7, is reduced from 704 to 437.5 kW at true wind directions of 120° and 240° when the ship speed is reduced from 13.5 to 10 knots.

The speed of the rotor determines the required power for its operation which affects the net output power of the Flettner rotor. Figure 8 shows the effect of coefficient of Flettner rotor rotation, organized according to Fig. 5, on the net output power for the four rotors considering the aerodynamic interaction among them. The figure is drawn at an average rpm of 80 for the four rotors considering wind speed, wind direction, the induced velocity at each rotor, and different spin ratio for each rotor. As the coefficient of rotation increases, the net output power will be reduced due to the increased power required for rotor rotation. In contrast, the net output power is increased at low rotational coefficient values.

To evaluate the environmental benefits of the Flettner rotors, the annul fuel saving is calculated based on the saved propulsion power. Using wind data available in the meteoblue climate data (Meteoblue 2020), the total annual fuel saving, from the four rotors, can be calculated as shown in Fig. 9. It shows the annual fuel saving based on the ship route and wind

characteristics all over the year. The highest annual fuel saving, from Fig. 9, is 3528 ton/year achieved in January. On the other hand, the lowest annual fuel saving will be 223 ton corresponding to October wind characteristic data. The average net output power for the ship route all over the year based on wind speed, direction, and ship course is 1537 kW with an average annual fuel saving of 1693 ton/year for the used four rotors. Finally, using four Flettner rotors will lead to saving in ship fuel consumptions by 22.28%.

From the calculated values of the annual fuel saving due to using Flettner rotors, the annual emission reduction can be estimated. Figure 10 shows the values of the reduced NO_x, SO_x, CO, CO_2, and HC at true wind angles from 0° to 360° and ship speed of 13.5 knots. These values are calculated for the four Flettner rotors, according to the wind characteristics of the route for the case study. The highest emission reduction can be achieved at true wind angles of 120° and 240°. This is due to the increased rotor's lift force and the net output power. In contrast, the lowest reduction values will be at wind angles of 0° and 360°.

The actual amount of reduced emissions due to using the Flettner rotor onboard the selected case study, based on the ship route from Damietta to Dunkirk ports, is shown in Fig. 11. The higher the value of emission reduction, the more environmental benefits will be gained. The highest annual emission reduction rate is 9272 ton/year for reducing CO_2

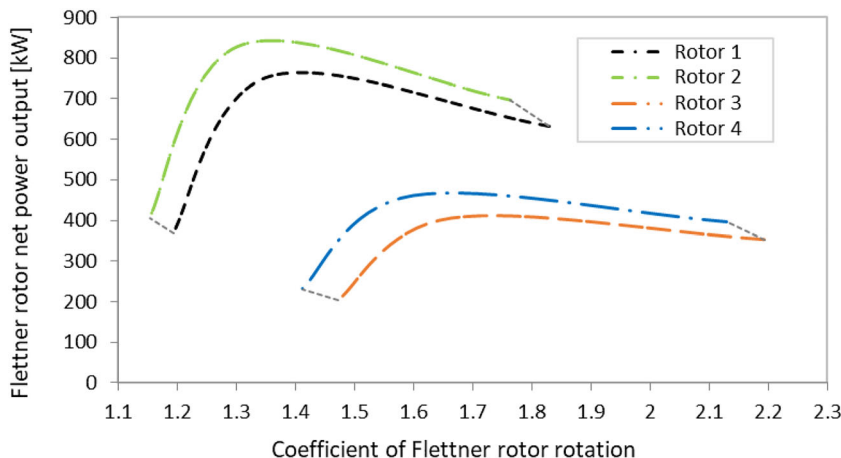**Fig. 8** Coefficient of rotation effect on the Flettner rotors net power

Fig. 9 Average annual fuel saving based on ship route and true wind speed and direction
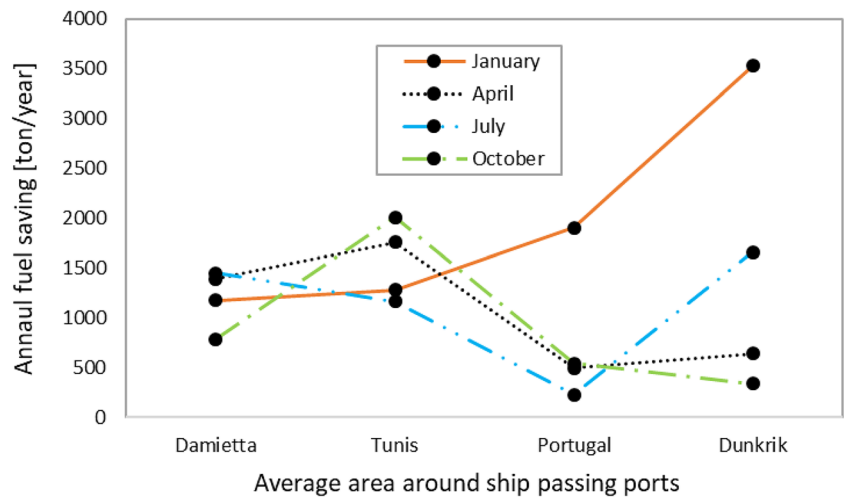

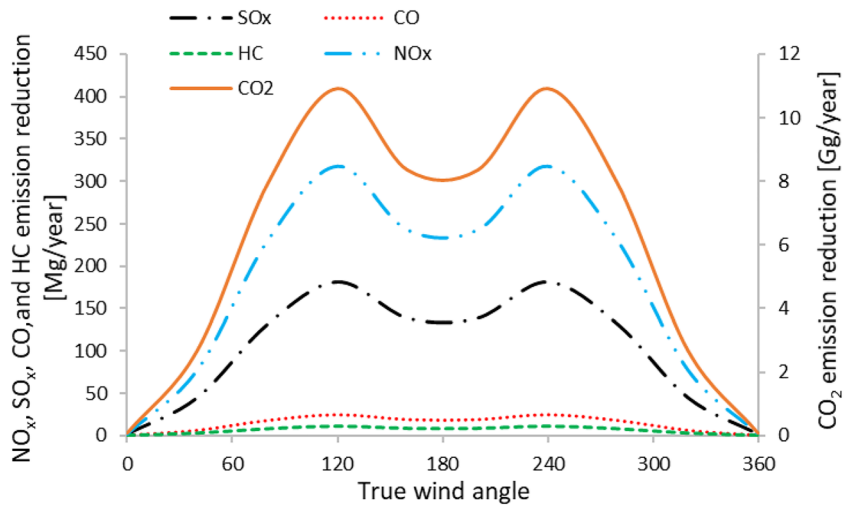**Fig. 10** Emission reduction due to using Flettner rotor model at different wind angles
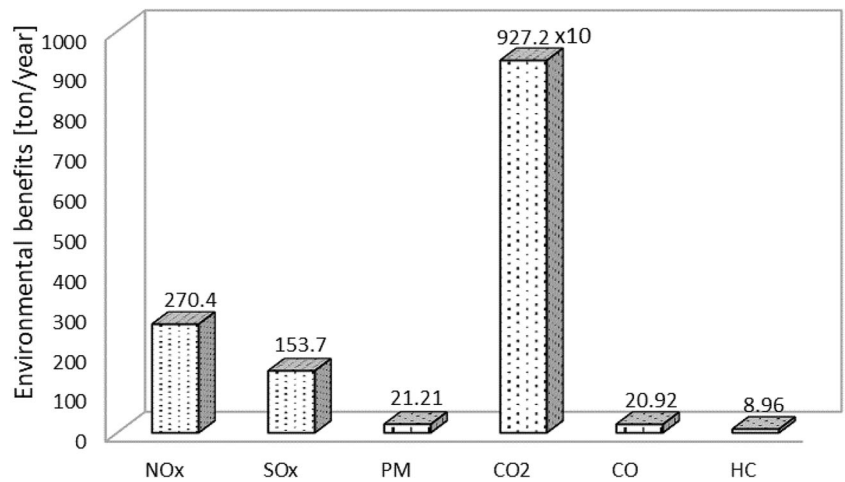

Fig. 11 Environmental benefits due to using four Flettner rotor models onboard the case study at ship speed of 13.5 knots

emissions. This is because of the high percent of carbon in the used heavy fuel oil used. The second-high reduced emission species is the NO_x emissions due to the high nitrogen percent in the air during burning of marine fuel in the diesel engine of the ship.

Economic results

Using the data collected about M/V Wadi Alkarm regarding sailing periods, and fuel prices, Fig.12a presents various scenarios for the annual CAPEX cost in case of applying the proposed system onboard the ship. Cases I, II, and III show the variation of the annual Flettner turbine cost (AFTC) with the expected ship's working years, after installation of the rotors onboard, at different interest values. The number of working years plays a role in reaching the minimum value of annual capital cost. The AFTC value for the present study will be about

$399,978, $517,212, and $650,463 per year, assuming annual interest rates of 5%, 10%, and 15%, respectively.

Moreover, Fig. 12b presents the value of ship's annual saving cost due to installation of Flettner turbines onboard, which is achieved because of reducing the annual ship's fuel consumption, at different scenarios of fuel price trends. The figure implies the possibility of achieving variable annual saving cost, which could reach to $1.30 and $3.29 million by the end of the determined project's lifetime, at 5% and 10% increment percentages, respectively. However, this value would account only $175,000 if the fuel price showed a dramatic annual decrease by 5%. On the other side, Fig. 13 presents the net saving value (NSV) at different economic scenarios for the proposed concept. Case (b) presents NSV for the selected case study at the current fuel price, case (a) presents NSV with an expectation of fuel price increment by 10%; however, case (c) presents NSV with an expectation of fuel price reduction by 5%.

Fig. 12 **a** Flettner rotors annual capital cos. **b** Ship's annual saving cost
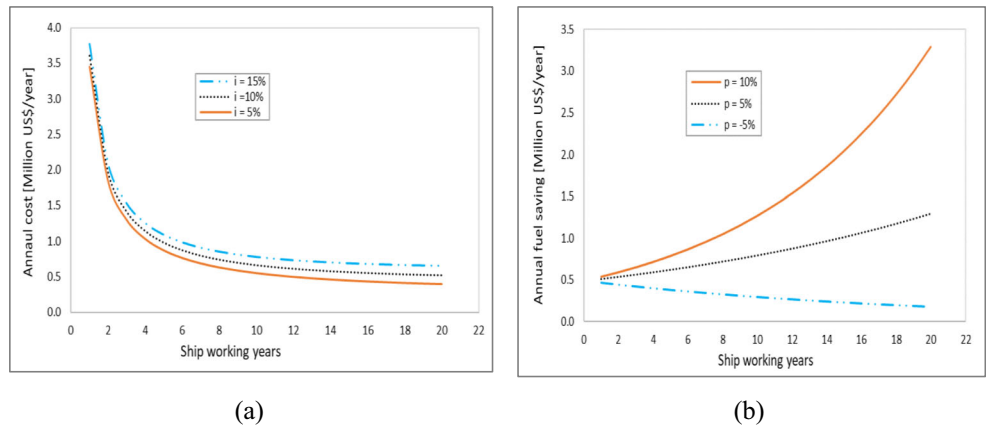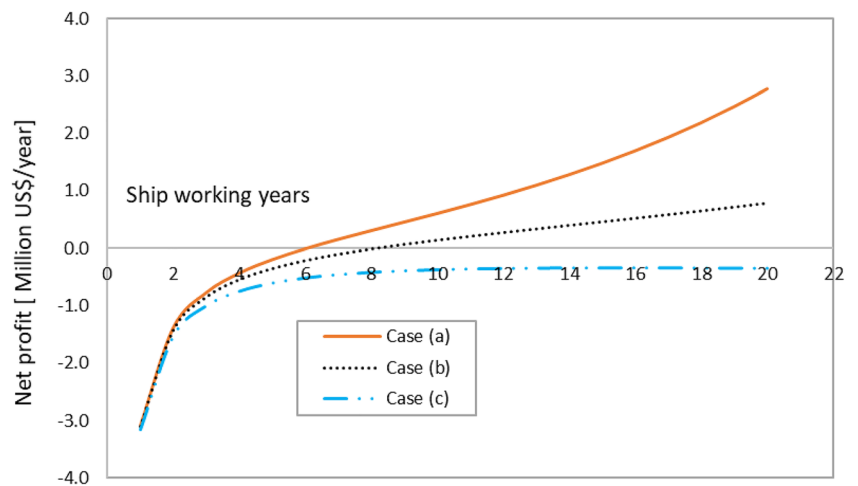

(a)

(b)

Fig. 13 Ship's net saving value and payback period

From Fig. 13, the proposed concept will be able to support the ship's operating costs after 6 and 8 working years for case (a) and case (b), respectively. On the other hand, with the condition of case (c), the project will be economically useless regardless of the ship's age. With reference to LCOE, Fig. 14 shows the tendency of this value at different conditions. Case I presents the value of LCOE for the case study with $0.05/kWh after 8 years of operation. Case II presents the effect of occurrence of an evolution in the turbine industry, which in turn will affect the cost of manufacturing and the accompanying reduction in the annual cost of the project. The current cost for one of the proposed Flettner rotors is $750,000 (GL-MEEP 2019). It can be noticed that a reduction in Flettner turbine cost by one third will lead to a reduction in LCOE by 30%.

However, case III presents the effect of decreasing the annual ship's sailing days, which may have occurred due to the impact of a slowdown in the growth of the global economy.

The figure shows that an accordance of decreasing the ship sailing period by 20% will increase the value of LCOE by 26%. This implies that applying the renewable energy onboard ships is sensible by the surrounding international events just as it is happening now with COVID-19.

Figure 15 shows the cost-effectiveness in case of applying Flettner turbines for the selected ship. Depending on the current prices of marine fuel oils, the used heavy fuel oil price onboard the selected ship is $300/ton (Bunkerworld 2020). Consequently, the cost-effectiveness values for NO_x and CO_2 emissions are 1912 and $55.78/ton, respectively, at an annual interest rate of 10%.

The Flettner rotor cost-effectiveness values agree with the same values that could be achieved from other technologies for the identical target (Ammar 2018; Ammar and Seddiek 2017). These results can be considered as a reasonable outcome in the way of applying more attractive renewable energy sources onboard ships.

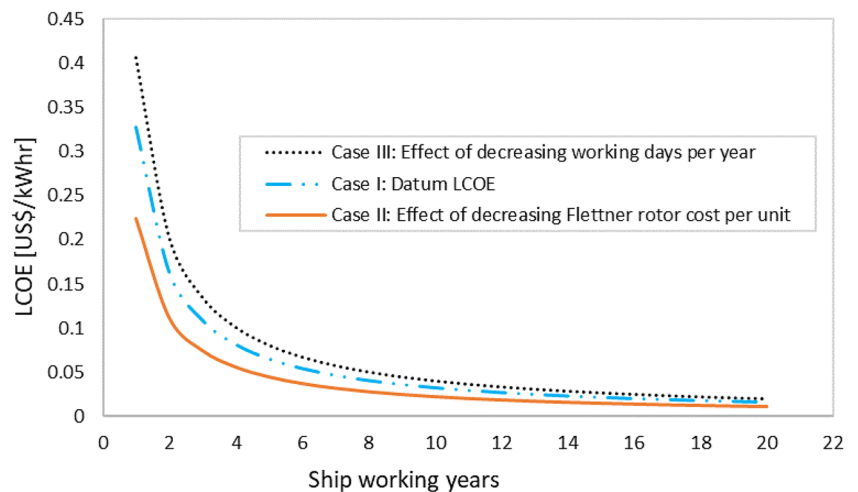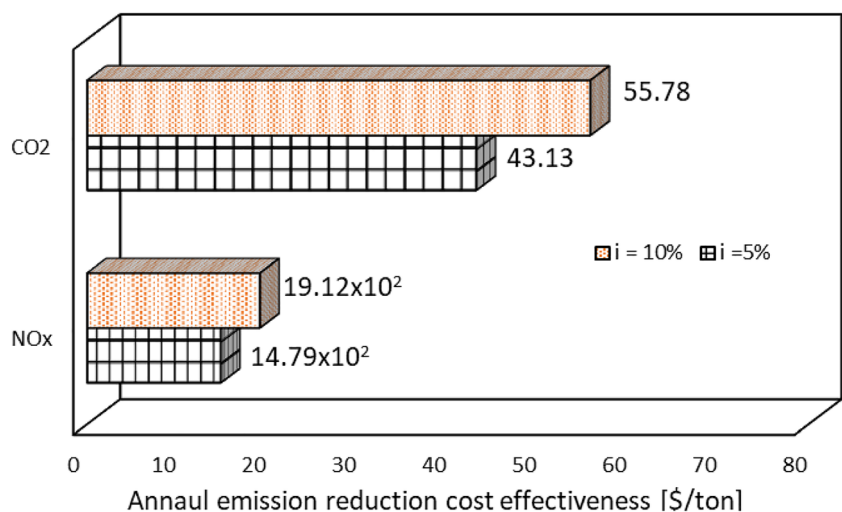Fig. 14 Levelized cost of energy vs ship's working years at different scenarios

Fig. 15 Annual emission-reduction cost-effectiveness for Flettner rotors

Conclusions

Zero-emission ships are the future target of the international maritime organization. With emphasis on wind power source, a literature review of the previous and current Flettner rotors powered ships in addition to the published researches is introduced. A simple model including the main technical features and the environmental and economic aspects is presented. The main conclusions can be summarized as follows:

- From a technical point of view, ship course and wind speed and directions are the main factors that affect the net output power from the Flettner rotors. Based on the selected case study, ship route, and Flettner model, the average net output power for each rotor will be 384 kW/h.
- From an environmental point of view, the optimum wind angles, for the selected rotor model, corresponding to the highest emission reduction percentages are 120° and 240°. For the case study, using the Flettner rotors onboard the ship will reduce the fuel consumption by 22.28 %. In addition, the NO_x and CO_2 emissions will be reduced by 270.4 and 9272 ton/year with cost-effectiveness of $1912 and $55.8/ton, respectively, at annual interest rate of 10%.
- From the economic viewpoint, various scenarios are taken to assist factors that affect this technology, to expect the annual capital cost, and to determine the payback period. The annual cost of the proposed concept will be $399,978, $517,212, and $650,463 per year at interest rate values of 5%, 10%, and 15% respectively. The selected rotors will be able to support the ship's economy after six working years. Moreover, a considerable levelized cost of energy value is achieved.
- Finally, fossil fuel is becoming scarce, and future international legislations concerning with the maritime environment will push and accelerate the process of shifting to the renewable and the green power systems for shipping.

Author contribution Ibrahim S. Seddiek: data curation, writing—original draft preparation, methodology, visualization, investigation, writing—reviewing and editing. Nader R. Ammar: conceptualization, methodology, software, visualization, investigation, writing—reviewing and editing.

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

Declarations

Ethical approval   Not applicable

Consent to participate   Not applicable

Consent to publish   Not applicable

Competing interests   The authors declare that they have no competing interests.

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