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# Applicability of Wind Assisted Propulsion System (WAPS) to the Smaller Ships in the Bay of Bengal

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*ABSTRACT*

The International Maritime Organization (IMO) introduced the Energy Efficiency Design Index (EEDI) to mitigate $CO_2$ emissions from the shipping industry. As this regulation applies to all sea-going vessels exceeding 400 Gross Tonnes and is becoming increasingly stringent, the demand for cost-effective and alternative propulsion solutions is rising. While renewable energy presents a promising option for reducing $CO_2$ emissions, its economic viability compared to fossil fuels remains a challenge. This study evaluates various wind-assisted propulsion systems (WAPS) based on performance and cost-effectiveness, identifying the most suitable option for small vessels operating in the Bay of Bengal. A mathematical model has been employed to assess net power output, revealing that the Flettner rotor is the most efficient and economical choice. Additionally, an analysis of optimal true wind angles and rotor rotational speeds has been conducted to determine the best operating conditions under local environmental factors. The findings indicate that increasing rotor speed enhances energy savings; however, beyond a certain threshold, the gains become marginal.



## 1. Introduction.

As a mandate to the Kyoto Protocol IMO adopted EEDI as a mandatory index for all sea-going ships over 400 GT in 2011 (MARPOL 2011). The updated IMO GHG Strategy sets a higher collective goal of achieving net-zero greenhouse gas (GHG) emissions from international shipping around 2050. It also includes a commitment to promoting the adoption of alternative zero and near-zero GHG fuels by 2030, along with defined milestone targets for 2030 and 2040 (MARPOL 2023). For this reason, the adopted index (EEDI) is getting stringent over time.

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Renewable energy is considered an everlasting energy source to work with. The most abundant renewable energy sources include sunlight, wind, and waves. The Wind Assisted Propulsion System (WAPS) is a technology that utilizes the energy of the wind to thrust a vessel forward assisting in the reduction of fuel consumption. Wind-assisted ship propulsion systems are innovative technologies designed to harness the power of the wind to help propel ships, reducing their reliance on traditional fossil fuel-based engines. These systems are primarily aimed at making shipping more sustainable and environmentally friendly.

Different types of WAPS currently exist today to assist ship propulsion systems. Among them, Sails, Flettner Rotos are Kites can harness wind energy to supplement or even replace traditional engine power, making shipping more sustainable, fuel-efficient, and environmentally friendly. However, not all types are equally and cost effectively efficient to all types of ships. In addition, adopting wind-assisted propulsion systems on smaller ships can be more challenging compared to larger vessels because of scale and space constraints, engineering challenges, operational efficiency, cost considerations, maintenance, market availability and regulatory hurdles in many cases.

The Bay of Bengal is an important commercial sea route from ancient times because of the strategic location, booming trade, and commerce of South and Southeast Asia, energy transportation, fisheries, and coastal tourism. The trade among the regional countries is increasing day by day which also reflects the increase of Gross Development Growth (GDP) of these regions for the last decade (Bank, n.d.). Different sized and types of ships plying over the bay. Therefore, a study on the applicability of WAPS on those vessels is required. This kind of study depends upon the zone because the energy intensity of renewable sources is not uniform.

An estimate in 2021 shows that wind energy shares 43.21% of total renewable energy of the world, which is closely second to solar energy that shares 48.28% of the total (REN21 2022). This proves wind being one of the potential renewable energy sources to be harnessed.

The study focuses on optimization and effective operation of the Wind Assisted Propulsion System for ships with lesser deadweight suitable for plying over the Bay of Bengal. Given the geographical and environmental conditions this study provides a significant insight over comprehending the influence of wind over this region to the extent of its variability which leverages a significant potential for advancement of sustainable shipping industry, trade and commerce and fuel-efficient transportation system. The scope of this study is multi- dimensional as it holds the in-depth insights on several aspects of aerodynamic, sustainability, naval architecture and fuel efficiency. The primary objective of this research is to implement an energy-efficient strategy to use renewable energy sources, like offshore wind energy to reduce fuel oil consumption and Greenhouse gas emission and to determine the feasibility of the system by calculation net power output of the system at each wind condition.

This study focuses on the vessels ranging from 2000 to 5000 DWT, though higher capacity vessels plying over the Bay of Bengal. The main reasons are,

(i) Bigger vessels can accommodate bigger-sized WAPS, and higher energy saving is possible for those cases. However, it would be very challenging to propose a cost-effective WAPS for smaller sea going short trip vessels.

(ii) Another reason of choosing the size vessel is, majority of Bangladeshi sea going ship owners owns 2000-5000 DWT sized vessels to continue trade in the Bay of Bengal region, especially with India and Myanmar. One of the aims of this study is to facilitate Bangladeshi ships owners to achieve the goal set by IMO.

### *1.1. Research Gap.*

The use of renewable energy to ships are not new, yet commercial viability and cost effectiveness is still not up to the mark. Since the intensity of renewable energy is not consistent, zonal analysis is required before implementation. Bay of Bengal lacks this kind of study when WAPS is considered for ships. One study evaluated the Sustainable solar energy potential on marine passenger ships of Bay of Bengal, however, the potentiality of WAPS has yet to be investigated.

The distribution patterns of marine wind resources play a crucial role in the energy-saving performance of sail-assisted ships. However, the absence of effective evaluation methods for enhancing wind energy utilization limits efficiency, leaving significant potential for further optimization (Ma et al. 2023).

## 2. Methodology.

Principal aim of this research is to identify effective WAPS for the smaller ships plying on Bay of Bengal. To reach the aim, following methodology will be followed:

**Choosing the most suitable WAPS:** By comparing advantages and disadvantages of different available WAPS system and considering geographical constraints of Bay of Bengal as well as size of the ship, installation and operational cost and difficulties, amount of weight carried by each of the technologies and their operational efficiency from existing data, the most suitable WAPS will be chosen for analysis.

**Wind data collection:** Accurate wind speed, direction and frequency data will be collected from available sources. Since ships are flying through different locations of Bay of Bengal, wind data for all locations may not be available. In that case, appropriate theory/formula will be used that will convert available data to be used for different locations and heights as required according to the height of the selected technology.

**Power produced by WAPS:** Net power savings by the chosen WAPS will be calculated. A mathematical model has been constructed using a series of empirical formulas to determine the amount of power saved in terms of the given conditions. The outcome has been calculated for variable wind speed each month and the striking angle of the wind and for variable operational settings for the selected technology. The savings will vary monthly as the wind velocity and directions vary in this region season wise. Average savings per annum will be considered as the total power savings.

## 3. Comparison of Different Measures to Harness Wind Energy.

The choice of wind energy harnessing method depends on factors such as wind resource availability, location, scale, and intended application. Advances in technology and ongoing research continue to improve the efficiency and cost-effectiveness of various wind energy harnessing measures. Harnessing wind energy can be accomplished through various methods and technologies, each with its advantages and disadvantages.

There are several available wind-assisted propulsion systems, each with its own unique design and working principles. Following three ideas are emerging as the top designs for wind-assisted propulsion:

(i) Flettner Rotor.
(ii) Hard Sail.
(iii)Kite Sail.

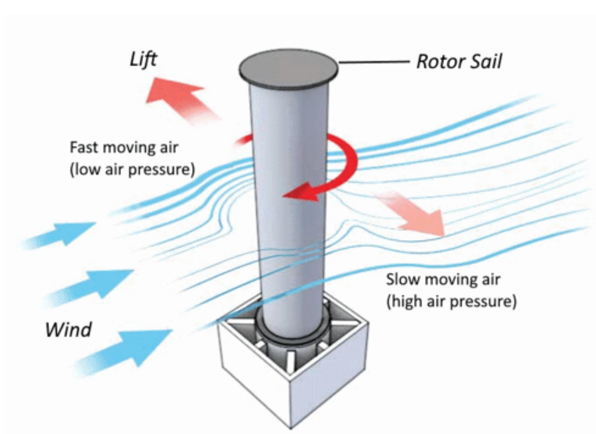
These three types will be discussed in the following subsections and a table of comparison will be prepared to find the most suitable option for this research.

### 3.1. Flettner Rotor.

Flettner rotors encompass vertical cylinders that revolve, harnessing the Magnus effect to generate upward force when wind flows over them. These rotors necessitate external mechanical input to produce lift and impelling force, with their maneuverability contingent on prevailing wind speed and orientation. When integrated into maritime contexts, these rotors engender thrust. Within nautical contexts, these specific rotor propulsion mechanisms are commonly referred to as Flettner rotors, named after the pioneering German inventor who initially installed such a apparatus aboard a vessel in the early 1920s. While Flettner rotors have the potential to curtail a ship's energy consumption, they are not suited for primary propulsion purposes.

The Rotors can be said to have several advantages. They are easy to install, operate and maintain. The Rotor sails come with five sizes of sail heights of 18, 24,28, 30 or 35 meters (Naida, n.d.). The Rotor sail basically works on the phenomena of the 'Magnus effect'. Magnus effect is a process of creating a lift force around a rotating body placed within a certain area of fluid flow which helps to curve the projectile of a spinning object. When the wind encounters the cylindrical shaped spinning Rotor, the air flow accelerates on one side and decelerates on the other. Due to the pressure differences a lift force is created which is perpendicular to the direction of the wind flow (Figure 1). As a result, the ship then tends to proceed toward the low-pressured zone where there is the least resistance, but the ship's hull resists this sidewise force, and a component of the force propels the vessel forward within the low-pressured zone ensuring the least resistance to overcome consuming lesser energy. The Rotor sails can be mounted on any part of the ship depending on design, route, cargo operation, lightweight distribution, etc. The height of the Rotors can also be adjusted by constructing it into several tiers or just by adding a hinge to allow the structure to bend and make it easy to pass through any bridge.

Figure 1: Magnus effect on Flettener Rotor (Patowary 2021).




Source: Authors.

### 3.2. Hard Sail Technology.

The shape of the rigid sail can be of several types like trapezoidal, square rig, or aerofoil shaped. The most efficient shape with the least surface area and production cost can be considered with an aerofoil shape. The aerofoils would generate a lift force to propel the ship forward. The sails are to be angled toward the direction of the wind so that there's a generation of a low-pressure area on one side and high pressure on the other side during faster wind flow causing the sail to capture the wind and propel the ship towards the low-pressured zone by implementing a drag force over the sail. When the flow of wind is perpendicular to the vessel, the vessel does not lose any speed. By setting the sail at an angle of 45 degrees with the direction of motion and with the direction of the wind, the resistance can be reduced, and greater velocity can be obtained heading forward. The basic physics of sails deals with the reduction of resistance along the flow to obtain higher speed. The Ocean bird, a Swedish ship-building technology has taken an innovative step to power even the largest ship using wind energy. The latest concept includes the design of a massive Car Carrier and Truck Carrier vessel, which is 200 meters long and 40 meters wide with a capacity of carrying up to 7000 cars, planned to install four to five colossal wind sails of the height of 80 meters which can be lowered down to 20 meters when needed, promises to reduce GHG emission by as much as 90% by using the wind propulsion system which can be said to be a huge success (Loz, n.d.). The team has built a 7-meter test model and has already been tested in the open sea and experienced the mentioned success and is on work to deliver the vessel by the end of 2024. Another massive favorable outcome has already been obtained by the ship called the SHOFU MARU (Mitsui O.S.K. Lines 2019). This ship uses a wind sail called the Wind Challenger which has been proved to be capable of saving fuel consumption by 5 to 8%, by saving about 25,000 liters of fuel (Loz, n.d.).

Apart from all these successes there are some notable disadvantages of rigid sail. The use of sails totally depends on wind conditions. There would be no use of the sails if there was no wind. To overcome this issue, it is necessary to obtain the wind condition data of the route and might need to improvise it. Also, rigid sails might not be a perfect solution for every route. Since wind is natural, no one can be sure of its availability. For these reasons the ship must carry the amount of fuel it would consume without the sails for which it would eat up some extra weight and would hamper cargo capacity (Atkinson, n.d.). Also, the installation cost and maintenance costs might be greater since the operating system includes some highly expensive modern equipment like a telescopic wind sensor and other such things.

### 3.3. Kite Sail.

The newest and one of the most unique ideas to utilize the wind to propel a ship is kite sail technology. A massive kite is to be hoisted from the forward of the ship to allow the kite to capture the wind along its direction and pull the vessel forward. It is almost like kiteboarding or kite surfing. The biggest benefit that can be obtained from a kite sail is that it is totally lightweight and needs no deck space to hold it. Besides it doesn't even need any power source to operate. Recently, a French startup company called the 'Airseas' tested a 2700 square foot parafoil kite called the 'Seawing' which was used to pull a cargo ship weighing up to 21,528 tons (Frangoul, n.d.). The company also claims that this technology can reduce fuel consumption and emission by up to 20%. This kite sail technology can easily be confirmed as the least expensive to install and operate and effective for cargo ships since they don't have much weight of their own. For the construction process of the kite sail, it is generally made of polyester fibers, which is a polymer derived from petroleum with an ester functional group. They are also much cheaper as they cost around 5.06 USD per kilogram which can be sail a lot cheaper than the material used for Rotors and hard sails (Frangoul, n.d.). Though kite sails have a lot of benefits, it must overcome some significant challenges. Kites can't be used the whole time during a voyage. It will be of no use when there is no wind. Again, if the wind suddenly drops, there's a chance to lose it. That's why the kite sails must be waterproof, rigid, and durable, and most importantly it must be airtight. To overcome these problems, the Seawing technology also promises the kites self-monitoring technology so that they can fold themselves up when there is no wind and can adjust themselves according to the weather and direction of the wind.

Figure 2: Rigid / Hard Sail (Mitsui O.S.K. Lines 2019).


Source: Authors.

Figure 3: Kite Sail (Mitsui O.S.K. Lines 2019).


Source: Authors.

### 3.4. Comparison of the Three Available Wind Energy Harnessing Measures and Choosing the Best Option.

The main objective of explaining Flettner Rotor, Rigid Sail and Kite Sail is to identify the best option for seagoing ships in the Bay of Bengal. Table 1 presents the comparison of these three options. The Flettner Rotor's utilization of Fiber Reinforced Plastic (FRP) material strikes a harmonious balance between strength and weight, granting it a significant advantage over the bulkier Rigid Sail and the lightweight Kite Sail. Furthermore, its production cost ranging from $400,000 to $950,000 positions it as a cost-effective choice compared to the considerably higher costs associated with Rigid Sail and Kite Sail.

In terms of both fuel savings and emission reduction, the Flettner Rotor unequivocally takes the lead. Its substantial 8% reduction in fuel consumption per voyage outperforms Rigid Sail's range of 5-8% or 25,000 liters. The Flettner Rotor also showcases an exceptional annual reduction of 3400 tons in GHG emissions, further solidifying its environmental superiority.

Table 1: Comparison of characteristics of Flettner Rotor, Rigid Sail and Kite Sail.

| **Item** | **Flettner Rotor** (Naida, n.d.) | **Rigid Sail** (Mitsui O.S.K. Lines 2019; Atkinson, n.d.) | **Kite Sail** (Frangoul, n.d.) |
|---|---|---|---|
| Material | FRP | FRP | Polyester Sheet Fabric |
| Weight (Approx) | 34 tons | 100 tons | 150 Kg |
| Production Cost (USD) | 400,000-950,000 | 1-1.5 million | 1.7-2.8 million |
| Amount of Saved Fuel | 8% per voyage | 5-8% per voyage or 25,000 liters | Up to 20% or Up to 10 tons, average 3 tons per day |
| Amount of GHG Emission Reduction | 3400 tons per year | 5-8 % per voyage | |
| Level of Operation and Maintenance | Easier | Medium | Complicated |

Source: Authors.

## 4. Data Collection, Calculation and Results.

The purpose of the calculation is to find the amount of energy added by Flettner Rotor to the ship. This added power as the saved energy required by the ship for a certain speed which can be converted as saved fuel.

To calculate added energy by Flettner Rotor, following data are required:

(i) Monthly wind speeds to the height of the rotor for the zone considered.

(ii) Average direction of wind, that is angle of attack.

(iii) Design and dimension of Flettner rotor.

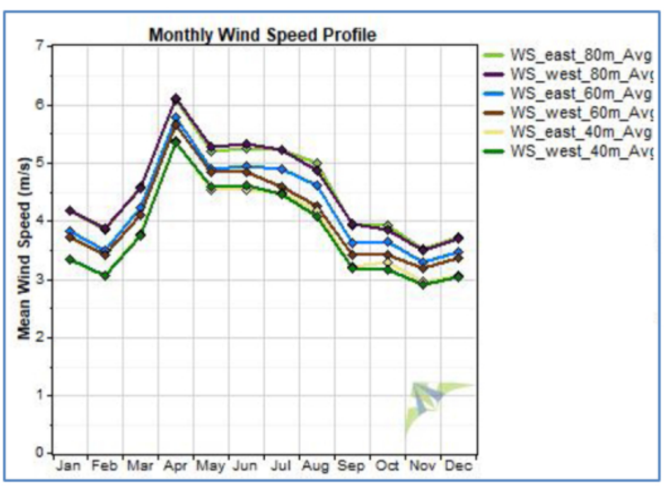
The calculation needs reliable wind speed and directional data. The following section will discuss data collection and applicability of those data.

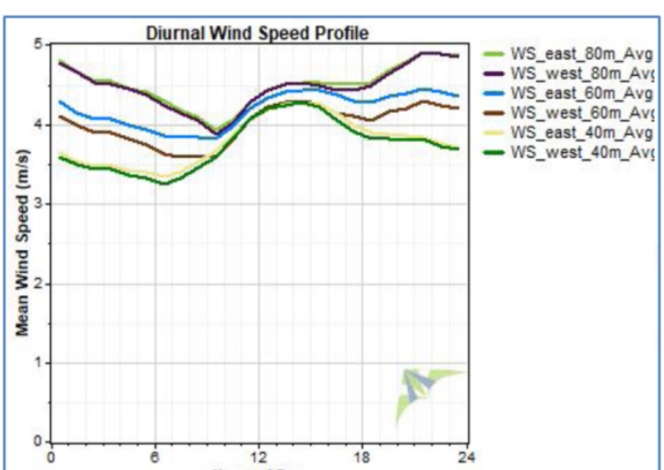
### *4.1. Data Collection.*

#### *4.1.1. Wind Data.*

USAID Bangladesh and the U.S. Department of Energy's National Renewable Energy Laboratory partnered with the Government of Bangladesh to develop a national wind resource assessment (Jacobson et al. 2018). They have collected wind data (Speed and Direction) from different locations of Bangladesh and some of those are near offshore regions. These data points are 40-meter, 60 meter and 80 meters from the sea level (Figure 4). In addition, data collection points are near shore, not from the sea route. Therefore, these data need to be converted to be applicable in this research. The conversion process has been discussed in the calculation section.

Figure 4: Wind speed, direction, and duration of wind in Mongla (Jacobson et al. 2018).




Source: Authors.

Wind data used in this research are at height 40, 60 and 80 meters from sea level. The rotor height is 18 meter and ship depths vary from 6 to 8 meters for the ships dead weight ranging 3000 to 5000 tonnes. Therefore, wind speed at 24-26 meters height is required. For this reason, the calculation process had to start with an approximate solution. The commonly used technique is to estimate speeds at higher altitudes and extrapolate the readings obtained and build-up the site's wind speed profile.

Various theoretical models are available for determining wind speed profiles, with the Monin-Obukhov method being the most commonly used to represent wind speed at different heights through a log-linear profile. However, its complexity makes it less practical for general engineering applications. As a result, studies often rely on simpler expressions that, while not entirely precise from a theoretical standpoint, can still provide sufficiently accurate results (Johnson 2017).

Another formula, known as the logarithmic wind profile law and which is widely used across Europe (Association, n.d.). However, that law may not be appropriate to use in different weather conditions as wind speed variation strongly depends upon the atmospheric pressure and temperature.

The most used of these simpler expressions is the Hellmann exponential law that correlates the wind speed readings at two different heights (Bauelos-Ruedas, Angeles-Camacho, and Sebastin 2011). In 1947 Frost (Sisterson et al. 1983) proved that Hellman coefficient with a value of $\alpha = 1/7$ described good atmospheric wind profiles for heights ranging from 1.5 and 122 metres during almost neutral conditions (adiabatic).

As per the Hellman exponential law

$$\frac{V}{V_o} = \left(\left\{\frac{H}{H_o}\right)\right\}^{\alpha} \tag{1}$$

Where, V is the speed at height H, Vo is the speed to the height Ho and $\alpha$ is the Hellman exponent.

Using this equation, wind speed of 40-meter height has been converted to 25 meters. The value of the exponent obtained using existing data at 40, 60 and 80 meters. Average exponent value for 80 to 60 meters, 80 to 40 meters and 60 to 40 meters was considered which is 0.248. Details are presented in the following table.

Table 2: Hellman exponent values for different heights.

| H (m) | $V_H$ (m/s) | Ho (m) | Vo (m/s) | α |
|---|---|---|---|---|
| 80 | 4.494 | 60 | 4.186 | 0.2467 |
| 80 | 4.494 | 40 | 3.783 | 0.2484 |
| 60 | 4.186 | 40 | 3.783 | 0.2495 |

Source: Authors.

Using the obtained value for the Hellman's exponent along the route over the Bay of Bengal, the obtained wind data has been converted to the wind speed for required height according to the Flettner Rotor's parameter. Since the height of the

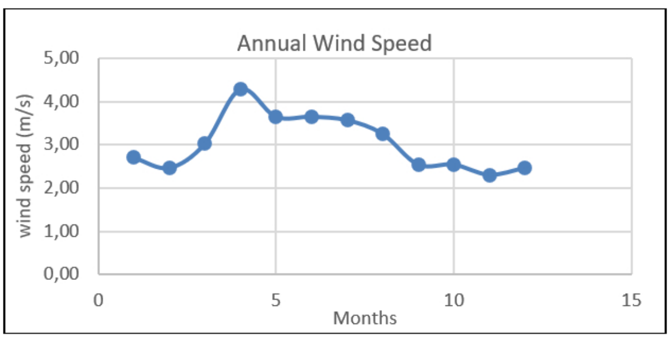
Flettner Rotor is 18 m, the wind speeds are converted to 10, 15 and 25 meters to develop a wind profile with the varying height and the average profile value has been taken for the calculation of net power output. The obtained annual wind data has been mentioned in the following table.

Table 3: Annual wind speed data.

| Annual Wind Speed at Height (m/s) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec |
| 2.70 | 2.46 | 3.02 | 4.29 | 3.65 | 3.65 | 3.57 | 3.26 | 2.54 | 2.54 | 2.30 | 2.46 |

Source: Authors.

Figure 5: Annual wind speed data.




Source: Authors.

### 4.1.2. *Flettner Rotor Consideration.*

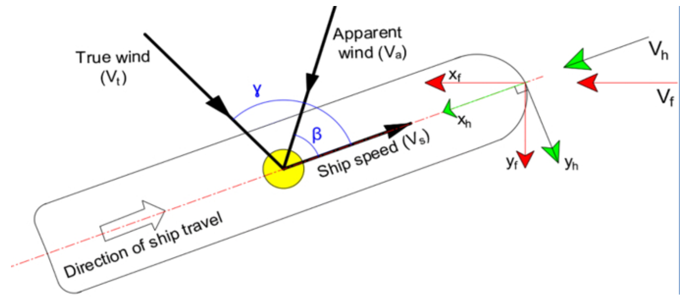
Since this research focused on the applicability of WAPS on the ships of Bay of Bengal, the most suitable and available Flettner Rotor that can be used has been considered.

For a ship of Deadweight 2,000 tons to 5,000 tons, from all the existing Rotor dimensions (Naida, n.d.) the smallest one has been considered for such a handysize bulk carrier since it is seen that the larger Rotors are generally used for capsizing ships of 70,000 to 100,000 DWT. A bigger Rotor implemented on a smaller ship can hamper stability due to its heavy weight. Selected Flettner Rotor dimensions are presented in table 4.

## 4.2. *Calculation.*

The calculation procedure starts with the determination of apparent wind velocity acting on the Rotor, which is basically the vector sum of the true velocity of wind and the ship's velocity. It can directly be calculated by deducting the speed of the ship from wind speed but can also be calculated by the following equation. This also derives a similar result. Figure 6 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.

Figure 6: Ship and wind velocity angles (Seddiek and Ammar 2021).




Source: Authors.

The apparent wind velocity depends on the true wind velocity $V_t$ and the velocity of the ship $V_s$. The value of true wind speed and ship velocity are known for this calculation.

Apparent Wind Velocity,

$$V_a = \sqrt{V_t^2 + V_s^2 - 2V_tV_s cos\,(\gamma)} \quad (2)$$

And the Resultant angle has been calculated using the cosine law of triangular velocity,

$$\beta = \cos^{-1}\left(\frac{V_t^2 - V_a^2 - V_s^2}{-2V_aV_s}\right) \quad (3)$$

The rotation coefficient is to be known for further calculations, which is the ratio of the rotational speed of the Rotor and the obtained Apparent velocity. This term has been introduced to establish a relation between the apparent velocity Va and rotational speed of the rotor Urot.

$$Rotation\ Coefficient, C_{rot} = \frac{U_{rot}}{V_a} \quad (4)$$

The flat plate boundary layer theory can be applied to determine the resistive force and the power required to overcome the skin friction in a Flettner rotor system. The skin friction coefficient, as a function of the Reynolds number, can be evaluated using Schlichting's formula. The power required to rotate the rotor ($P_{con}$) and counteract the frictional force can be calculated using Eq. (5). However, it is important to acknowledge that this is an approximate estimation, as additional factors, such as bearing roughness, may also influence the total power requirement.

$$P_{con} = \left[\left(\frac{0.455}{(\log{(Re)}\,)^{2.58}} - \frac{1700}{Re}\right) * \rho_a * \frac{U_{rot}^2}{2} * A_r\right] * U_{rot} \quad (5)$$

where $\rho_a$ 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):

$$Reynold's\ number, R_e = \frac{\rho_a C_{rot} V_a L_{Re}}{\mu} \quad (6)$$

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

To calculate the effective power in the ship's direction (Ps) and the net output power of the Flettner rotor ($P_{net}$), the lift and drag forces are analyzed. Ps and $P_{net}$ are determined by factoring in the ship's propulsion efficiency ($\eta$), as defined in Equations 7 and 8. (Lele and Rao 2017):

$$P_s = (C_L{*}sin\beta - C_D{*}cos\beta) * \left(\frac{\rho_A{*}V_a^2}{2}\right) {*}A{*}V_s \tag{7}$$

$$P_{net} = \{(P\}_s - P_{con}) {*}\eta \tag{8}$$

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. Drag coefficient ($C_D$) and lift coefficient ($C_L$) depends on the shape and dimension of the acting equipment, wind flow condition and its velocity, and the dynamic feature of the equipment. The coefficients are based on the results in (Da-Qing, Leer-Andersen, and Allenström 2012) but corrected to better match the full-scale measurements, presented below.

$$\begin{aligned} C_L &= -0.0046\,SR^5 + 0.1145\,SR^4 - 0.9817\,SR^3 \\ &\quad +3.1309\,SR^2 - 0.1039\,SR \end{aligned} \tag{9}$$

$$\begin{aligned} C_D &= -0.0017\,SR^5 + 0.0464\,SR^4 - 0.4424\,SR^3 \\ &\quad +1.7243\,SR^2 - 1.641\,SR + 0.6375 \end{aligned} \tag{10}$$

Where, SR is the spin ratio of the rotating motion of the Flettner Rotor which is determined by equation 11 below,

$$SR = \frac{U_{rot}\ (D/2)}{V_a} \tag{11}$$

Where, D is the diameter of the Flettner Rotor.

### 4.2.1. Sample Calculation.

Table 4: Rotor design, wind, and air data.

| | | | |
|---|---|---|---|
| Rotor Height | h | 18 | m |
| Rotor Diameter | $D_{cyl}$ | 3 | m |
| Surface Area of Rotor | $A_r$ | 176.71 | $m^2$ |
| Rotor Cylinder Volume | V | 127.23 | $m^3$ |
| Characteristic Length | $L_{RE}$ | 18 | m |
| Max Projected Area | A | 54 | $m^2$ |
| Thom Disk Diameter | $D_{disk}$ | 4 | m |
| Dynamic Viscosity of Air (at 30 deg C) | μ | 1.87E-05 | |
| Ship propulsion efficiency | *H* | 0.6 | |
| Ship Speed | $V_s$ | 5.14 | m/s |
| True wind direction | Γ | 40 | deg |
| True wind direction | Γ | 0.7 | rad |
| Cylinder rpm | | 500 | rpm |
| Rotational Speed of Rotor | $U_{rot}$ | 8.33 | rps |
| Air Density (at 30 deg C) | $\rho_a$ | 1.17 | $kg/m^3$ |

Source: Authors.

Table 5: Calculation of net power added by the rotor for at $40^0$ true wind direction.

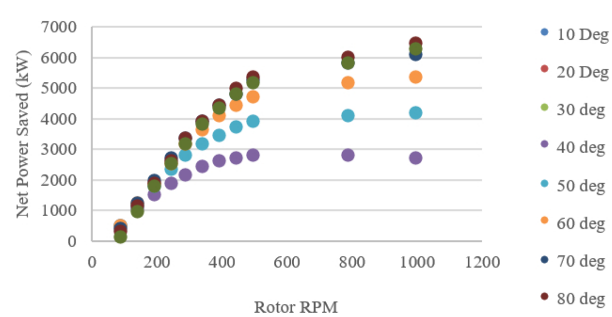
| Month | True Wind Speed ($V_t$) (m/s) | Apparent Wind Velocity ($V_a$) (m/s) | Resultant Angle ($\beta$) (°) | Lift Coefficient ($C_L$) (–) | Drag Coefficient ($C_D$) (–) | Effective Power ($P_s$) (kW) | Power Consumed by Rotor ($P_{rotor}$) (kW) | Net Added Power by Rotor ($P_{net}$) (kW) |
|---|---|---|---|---|---|---|---|---|
| January | 2.30 | 3.69 | 0.41 | 10.44 | 3.02 | 3113.22 | 40.82 | 1843.44 |
| February | 2.10 | 3.79 | 0.36 | 10.26 | 2.94 | 2091.63 | 40.82 | 1230.49 |
| March | 2.57 | 3.58 | 0.48 | 10.65 | 3.11 | 4463.74 | 40.82 | 2653.75 |
| April | 3.65 | 3.32 | 0.79 | 11.13 | 3.33 | 9827.68 | 40.82 | 5872.12 |
| May | 3.11 | 3.41 | 0.63 | 10.97 | 3.25 | 7136.15 | 40.82 | 4257.20 |
| June | 3.11 | 3.41 | 0.63 | 10.97 | 3.25 | 7136.15 | 40.82 | 4257.20 |
| July | 3.04 | 3.43 | 0.61 | 10.93 | 3.24 | 6802.86 | 40.82 | 4057.23 |
| August | 2.77 | 3.51 | 0.53 | 10.79 | 3.17 | 5468.84 | 40.82 | 3256.81 |
| September | 2.16 | 3.75 | 0.38 | 10.32 | 2.97 | 2432.97 | 40.82 | 1435.29 |
| October | 2.16 | 3.75 | 0.38 | 10.32 | 2.97 | 2432.97 | 40.82 | 1435.29 |
| November | 1.96 | 3.85 | 0.33 | 10.12 | 2.88 | 1406.71 | 40.82 | 819.53 |
| December | 2.10 | 3.79 | 0.36 | 10.26 | 2.94 | 2091.63 | 40.82 | 1230.49 |
| **Average annual net added power by rotor (kW)** | | | | | | | | **2695.74** |

Source: Authors.

### 4.3. Results and Discussion.

For conducting the study, the power output of the Flettner Rotor has been calculated by considering several key factors which can directly influence the performance. The sample calculation presented in section 4.2.1 has been implemented for wind angles starting from 100 to 1800. Initially, a calculation has been conducted to determine the optimum operational condition for the Rotor by analyzing the net power output for each applied RPM since the rotational speed is the basic operational parameter of the Flettner Rotor that is to be controlled according to the prevailing environmental condition.

Figure 7: Net power saved by the rotor for different rpm.

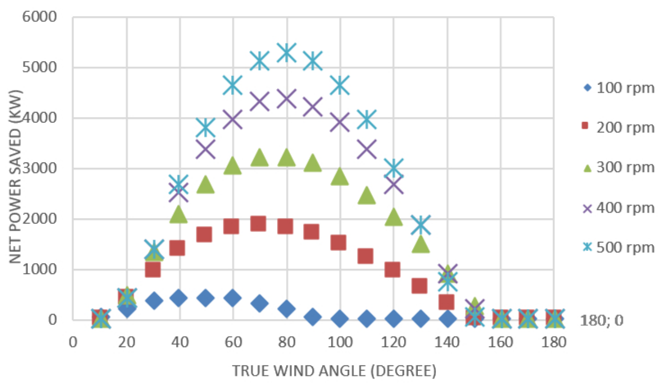



Source: Authors.

From figure 7, it is clear that the net output of the Rotor doesn't change much after 500 RPM as the curve almost stabilizes into a straighter constant term which indicated that an optimum operational outcome to be observed within the range of 100 to 500 RPM. For this reason, a calculation up to 500 RPM has been conducted further.

The Rotor RPM has been taken ranging from 100 to 500 RPM at an interval of 100 RPM which is a primary dependent variable since the RPM in reality is to be adjusted according to the wind speed available and the angle of Attack of the striking wind. Considering all these operational conditions, the calculation has been conducted utilizing the mathematical model as mentioned in section 4.2.1 to determine net outcome according to variable wind speed and wind angle. One sample has been mentioned below [Figure 8] to illustrate the effect on efficiency as per rotational speed and angle of attack.

Figure 8: Net power saved by the rotor at different wind angle and rotor rpm.




Source: Authors.

From figure 8, the results illustrated that the net power output observed to be the optimal with the rotational speed with 500 RPM yielding the highest output particularly at higher wind speed and moderate angle of attack since the power consumption by the rotor drastically increases with the increase of rotational speed, net delivered power starts to decline.

At lower rotational speed like 100 RPM, from figure 8, the net output was significantly observed to be lower across all the angles of attacks and wind speeds. As the RPM was increased a noticeable rise has been observed in net output. Thus, the higher rotational speed facilitates a more substantial Magnus effect which generates higher lift and power.

The optimum net output was achieved within a specific range of angle of attacks wearing between 50 degrees and 90 degrees, particularly at higher RPM and wind speeds which parallelly satisfies the principle of Magnus effect.

To determine the most optimum operational condition for the Flettner Rotor, further calculations were conducted beyond 500 RPM to observe the net power outcome as per applied condition.

## Conclusions.

The study aimed to assess the feasibility and advantages of Wind Assisted Propulsion Systems (WAPS), with a specific focus on Flettner Rotors, for small vessels operating in the Bay of Bengal. Several key achievements and limitations emerged from this study. One significant achievement of this study is the recognition of the Flettner Rotor as a promising wind-assisted propulsion technology for small vessels. Its operational simplicity, efficiency, and cost-effectiveness make it a practical choice for enhancing sustainability in maritime transportation. The calculation of potential net power savings using the Flettner Rotor signifies another significant achievement. Through extensive analyses, the study examined the impact of various wind conditions and rotor speeds on power savings. These findings underscore the importance of optimizing rotor RPM to maximize power savings effectively.

This study provides a comprehensive analysis of the Flettner rotor's performance under varying wind and operational conditions. By examining the effects of wind speed, angle of attack, and rotational speed several insights are obtained. It was found that optimal power output is achieved at 500 RPM within an angle of attack range of 50–100 degrees, with a lift-to-drag ratio balancing aerodynamic performance. This range represents an ideal operational condition to maximize power generation and efficiency

Most of the existing researches were focused on larger vessels with bigger Flettner rotors equipped on them, operating at a higher wind speed. In contrast, this study is based on smaller Flettner Rotors, implemented on smaller vessels, plying over a shorter route and lower wind speed. Despite of having so much constraints, achieving even nearly 10% efficiency can be considered as a reliable technology to have a greater operational potential at a less favorable environment.

Nevertheless, it is essential to acknowledge certain limitations and drawbacks in this research. One limitation is the reliance on wind data collected from near-shore locations in Bangladesh, which may not fully represent open sea wind conditions. Future studies should incorporate a more precise wind dataset specific to Bay of Bengal shipping routes. Additionally, the study assumed a uniform distribution of wind speeds throughout the year, overlooking potential seasonal and regional variations. Accounting for these variations in future research would enhance the study's realism. Furthermore, the study predominantly focused on a single size of the Flettner Rotor suitable for smaller ships. Future research should explore optimizing rotor size and design for various ship types and sizes, considering factors such as stability, cargo capacity, and specific wind conditions. Looking ahead, future research endeavors should encompass the exploration of the most efficient rotor size and design, comprehensive analyses of annual fuel savings, evaluations of the long-term cost-effectiveness of wind-assisted propulsion systems, and Energy Efficiency Design Index (EEDI) calculations to gauge compliance with evolving IMO regulations.

## Declaration of Competing Interests.

The authors declare that they have no competing interests.

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## References.

Association, Danish Wind Industry. n.d. "Wind Energy Reference Manual." Accessed September 14, 2023. http://drøm-større.dk/wp-content/wind/miller/windpower web/en/stat/units-.htm.

Atkinson, G. n.d. “Rigid Sails for Modern Ships – It’s Unlikely to Be All Plain Sailing - Splash247.” Accessed September 14, 2023. https://splash247.com/rigid-sails-for-modern-ships-its-unlikely-to-be-all-plain-sailing/.

Bank, World. n.d. “GDP Growth (Annual %) - South Asia | Data.” Accessed September 14, 2023. https://data.worldbank.-org/indicator/NY.GDP.MKTP.KD.ZG?locations=8S.

Bauelos-Ruedas, Francisco, Csar Angeles-Camacho, and Sebastin. 2011. “Methodologies Used in the Extrapolation of Wind Speed Data at Different Heights and Its Impact in the Wind Energy Resource Assessment in a Region.” Wind Farm - Technical Regulations, Potential Estimation and Siting Assessment, June. https://doi.org/10.5772/20669.

Da-Qing, L., Michael Leer-Andersen, and Björn Allenström. 2012. “Performance and Vortex Formation of Flettner Rotors at High Reynolds Numbers.” In Proceedings of 29th Symposium on Naval Hydrodynamics.

Frangoul, A. n.d. “How Kites Can Save the Planet – or the Shipping Industry.” Accessed September 14, 2023. https://www-.cnbc.com/2015/09/14/how-kites-can-save-the-planet–or-the-shipping-industry.html.

IEA. n.d. “CO2 Emissions from International Shipping in the Net Zero Scenario, 2000-2030 – Charts – Data & Statistics - IEA.” Accessed September 14, 2023. https://www.iea.org/data-and-statistics/charts/co2-emissions-from-international-shipping-in-the-net-zero-scenario-2000-2030-2.

Jacobson, Mark, Caroline Draxl, Tony Jimenez, Barbara O Neill, Jared A Lee, Francois Vandenberghe, and Sue Ellen Haupt. 2018. “Assessing the Wind Energy Potential in Bangladesh Enabling Wind Energy Development with Data Products.”

Jasper Faber. 2020. “Fourth IMO GHG Study 2020.” International Maritime Organization.

Johnson, Gary L. 2017. “Wind Energy Systems.” Proceedings of the IEEE 105 (11): 2116–31. https://doi.org/10.1109/J-PROC.2017.2695485.

Lele, Akshay, and K. V.S. Rao. 2017. “Net Power Generated by Flettner Rotor for Different Values of Wind Speed and Ship Speed.” Proceedings of IEEE International Conference on Circuit, Power and Computing Technologies, ICCPCT 2017, October. https://doi.org/10.1109/ICCPCT.2017.8074170.

Loz, Blain. n.d. “Oceanbird’s Huge 80-Meter Sails Reduce Cargo Shipping Emissions by 90%.” Accessed September 14, 2023. https://newatlas.com/marine/oceanbird-wallenius-wing-sail-cargo-ship/.

Ma, Ranqi, Zhongyi Wang, Kai Wang, Haoyang Zhao, Baoshen Jiang, Yize Liu, Hui Xing, and Lianzhong Huang. 2023. “Evaluation Method for Energy Saving of Sail-Assisted Ship Based on Wind Resource Analysis of Typical Route.” Journal of Marine Science and Engineering 11 (4): 789. https://doi.org/-10.3390/JMSE11040789/S1.

MARPOL. 2011. “Resolution MEPC.203(62).” Vol. 9. http://ctic-cita.es/fileadmin/redactores/Explora/Tecnica_valoriz-_ANICE.pdf.

MARPOL. 2023. “Resolution MEPC.377(80).” Vol. 4.

Mitsui O.S.K. Lines, Ltd.. (2019). 2019. “‘Wind Challenger’ Design Acquires Preliminary Approval - Realizing Japan’s 1st Large Cargo Ship with ‘Sail’, Aiming at Reduction of GHGs - | Mitsui O.S.K. Lines.” 2019. https://www.mol.co.jp/-en/pr/2019/19065.html.

Naida, H. P. n.d. “Norsepower: 5 Tiltable Rotor Sails Installed on Vale-Chartered Ore Carrier - Offshore Energy.” Accessed September 14, 2023. https://www.offshore-energy.biz/-norsepower-5-tiltable-rotor-sails-installed-on-vale-chartered-ore-carrier/.

Patowary, K. 2021. “Flettner Rotor: Sailing Ships Without Sails.” Amusing Planet. 2021. https://www.amusingplanet.com-/2021/02/flettner-rotor-sailing-ships-without.html.

REN21. 2022. “Renewables 2022 Global Status Report.” Global Status Report for Buildings and Construction: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector. https://www.ren21.net/gsr-2022/.

Seddiek, Ibrahim S., and Nader R. Ammar. 2021. “Harnessing Wind Energy on Merchant Ships: Case Study Flettner Rotors Onboard Bulk Carriers.” Environmental Science and Pollution Research 28 (25): 32695–707. https://doi.org/10.1007-/S11356-021-12791-3/FIGURES/15.

Sisterson, D. L., B. B. Hicks, R. L. Coulter, and M. L. Wesely. 1983. “Difficulties in Using Power Laws for Wind Energy Assessment.” Solar Energy 31 (2): 201–4. https://doi.org/10.10-16/0038-092X(83)90082-8.