Using Flettner Rotors and Parafoil as Alternative Propulsion Systems for Bulk Carriers

Abstract

The global shipping industry is currently experiencing a tough time due to the sluggish market situation and the oversupply of tonnage. Also, more stringent regulations on exhaust emissions have generated a significant impact on the already delicate market. Leadership in costs is one of the classic strategies to succeed in a competitive environment. Fuel is one of the most important items in the budget to consider when moving cargo across the oceans. However, up to now, there are just a few ships equipped with wind-assisted technologies to reduce fuel expenditures. Positioned in an interdisciplinary framework, this study aims to increase knowledge and understanding about the utilisation of Flettner rotors and parafoil as alternative sources of power to propel merchant vessels. To achieve this purpose, this research draws on data, information, techniques and theories from a variety of sources in both public domain and private databases. Based on the existing knowledge and scholarship, and the primary data gathered by interviews and questionnaire survey, this paper intends to critically examine the feasibility and economic benefits derived from the use of two alternative propulsion systems.

Keywords: Shipping; Flettner rotor; Parafoil; Ship; Costs

1. Introduction

The international community is facing a dilemma since it seems that the human way of life is not sustainable (Anderson and Bows, 2012). Maintaining greenhouse gas emissions at low levels "for preventing dangerous anthropogenic interference with the climate system" was the specific goal set in the United Nations Framework Convention on Climate Change (UNFCCC, 2014). Reduction of Carbon emissions can be achieved either by constraining the demand, by the optimisation of the operations, or by the implementation of new technologic developments (Traut et al., 2014a). Considering that the control of the demand could produce some controversy and that the room for improvement by optimisation is limited, it seems that technology could be essential for the achievement of the objective (Traut et al., 2014a). Experts are continuously developing new systems to cut down emissions to the atmosphere in the generation of power for human consumption (Kang et al., 2011; Wang et al., 2017a, 2017b). Some of these innovative systems are designed to utilise renewable sources of energy to improve their efficiency (Wang et al., 2017a).

The release of noxious emissions is not only produced by power generation. In 2012, international seaborne transport was responsible for 2.2% of global CO_2 emissions (Smith et al., 2014). Although this percentage represented an improvement in comparison with 2007, the total amount of CO_2 discharged to the atmosphere by the sector was about two times the figure produced in 1990

(Anderson and Bows, 2012; Smith et al., 2014). As a consequence, the shipping industry is receiving pressure to control and reduce the noxious emissions (Adamopoulos, 2017; Anderson and Bows, 2012), and the scientific community designing and testing systems to build cleaner vessels (Luo and Wang, 2017; Pili et al., 2017; Traut et al., 2014a).

Simultaneously, the maritime sector has been living in difficult times after the global financial crisis in 2008, and most shipping companies are suffering tough financial issues (Tan, 2016). It is widely accepted that the difficulties were originated from the weakening of the seaborne trade which came together with the economic recession (Glave et al., 2014). In the meantime, the world fleet has been significantly developed since 2008 (Clarksons Research Services Ltd, 2017; UNCTAD, 2020), and it has caused a structural situation of oversupply (UNCTAD, 2019). This framework seems to have promoted strong price competition among the shipping companies (Hapag-Lloyd AG, 2016), and as a consequence, the freight rates have decreased significantly (Clarksons Research Services Ltd, 2017). This situation has produced a significant reduction in the financial results of the shipping companies which with their recently delivered vessels are forced to stay in the market (Sand, 2011). This effect has been felt especially in the bulk carrier sector, in which despite some fleeting recovery in 2017, companies are struggling to make profits (Lin, 2017).

The delicate situation of many shipping companies has generated significant interest focused on finding a possible solution from the analysis of the factors involved in this issue. The efficient operation of vessels requires previous identification and analysis of all the costs involved. Among these, fuel oil is of primary importance (Clarksons Research Services Ltd, 2017; Neylan, 2016). Consequently, controlling fuel consumption could be a key factor for the competitiveness of a shipping company.

While there is a significant field of knowledge mainly focused on emissions reductions and power savings (Traut et al., 2014a), the availability of literature specifically on the financial and strategic consequences of the application of low carbon systems in shipping companies is significantly limited. This article aims to evaluate the practicality of the utilisation of Flettner rotors and Parafoil as alternative sources of power to propel merchant vessels. It is positioned in an interdisciplinary framework that integrates relevant data, information, concepts, perspectives and theories drawn from economics, engineering and nautical studies.

This research is the first one that delivers its results measured in US dollars, placing the outcomes in the framework of a competitive market and analysing the strategic implications of investing in wind-assisted propulsion systems. There is no doubt that it will make a significant contribution to the existing knowledge to overcome some of the existing barriers which have impeded the utilisation of these technologies during the last decades (Rehmatulla et al., 2017). To achieve the aim of this research, a combination of qualitative and quantitative approaches is employed, and the following objectives are critically examined:

a) To identify alternative energy sources to fit in mid-sized cargo ships.

b) To examine the cost-effectiveness and financial feasibility of the use of these propulsion systems in a newly built 60,000DWT bulk carrier, based on the energy savings obtained.

c) To evaluate the prospect of utilising the identified systems in the maritime industry and the limitation of this study

2. Literature review

With the stricter emission control regulation set by the International Maritime Organisation (IMO) and the possible introduction of carbon emission taxation in the regions such as the US and EU. The application of renewable energy sources and technologies is therefore actively being researched in the marine propulsion sector. Bengtsson et al. (2011) investigated well-to-propeller fuel consumption and environmental impacts of four fossil fuels and two exhaust abatement techniques. Their analysis showed that these alternative fuels and technologies achieved a 78-90% reduction of acidification and eutrophication potentials compared to conventional fossil fuels. Hwang et al. (2020) applied Life Cycle Assessment (LCA) method to evaluate the lifetime environmental impacts of liquefied natural gas (LNG), methylglyoxal and hydrogen for a ferry operating in Republic Korea (ROK). Even though the application of fossil-based alternative fuels leads to lower emissions of SO_x , NO_x and particulate matter (PM), the authors indicated major challenges related to greenhouse gas (GHG) emissions. Gilbert et al. (2018) also indicated these problems and concluded that no widely available fuel exists currently to deliver on both motivations in reduction SO_x , NO_x ,PM and GHG emissions. Hydrogen and bio-derived fuels have the potential, if key barriers can be overcome. Recently, fuzzy logic and multi-criteria decision making (MDCM) methods have been adopted in the literature supporting the decision making to select the best emission control technology. Sahin and Yip (2017) developed an improved decision supporting method based on fuzzy analytic hierarchy process (FAHP) used to compare the performance of diesel propulsion systems and alternative propulsion technologies. The IG-FAHP method can provide more accurate and realistic results to better support the decision making in technology selection compared with conventional methods (Sahin et al., 2015).

Wind-assisted propulsion technology has been used as a viable solution to reduce the environmental footprint of the shipping sector. Over the past decade, there has been a number of studies on wind-assisted systems which emphasised the feasibility and potential of the technologies for fuel-saving and decarbonisation. For example, Traut et al. (2014b) developed a comparative analysis on wind kite and Flettner rotors. They proposed a performance model to simulating the potential contribution of these technologies in reducing fuel consumption. The results showed that Flettner rotors could provide more than half of the required engine power. To investigate the efficiency of Flettner rotors, Hirdaris and Cheng (2012) tested the Integrated Greenwave MK1 Rotor system on a Panamax Bulk Carrier. They concluded that Flettner rotors could provide major propulsive power required by the ship in light wind condition.

However, the debate on the effectiveness and efficiency of Flettner rotors mainly concentrated on the issue of fuel-saving in vessel operation. According to Bordogna et al. (2020), the performance of Flettner rotors is highly dependent on the ship type, geographical range and location, technical performance and weather conditions. Talluri et al. (2018) assessed the feasibility of using Flettner rotors on four typical Sea Lines. An up to 20% reduction in fuel consumption has been recognised for the ship with Flettner towers. The level of fuel-saving in the above research has been confirmed by a real ship case. The fuel consumption recorded of Enercon E-Ship 1 showed that up to 22.9% of fuel consumption has been saved by equipped with four 25 meters high rotors onboard (Schmidt, 2013). Searcy (2017) analysed the potential fuel saving of implementing Flettner rotors based on the data gathered from Fiji's domestic shipping. Saving between 10% and 15% have been recognised as the most likely reduction level of fuel consumption.

Interest in the application of kites to assist ship operating as early as the 1980s, with abundant research proving it is technically feasible. One of the earliest experiments were conducted by Loyd (1980), which investigated the ability of kites to produce energy. More recently, the literature provided numerous articles which focus on the technical issues in kite systems application, such as flight control (Fagiano et al., 2013), structure deformation (Breukels, 2011), and flight strategies optimisation (Dadd, 2013; Naaijen et al., 2006). The contribution from research Leloup et al. (2016) assessed the fuel-saving ability of a 320 m^2 kite for a 50,000 DWT tanker. They concluded that fuel saving of up to 15% at a wind velocity of 9.77 m/s and up to 50% under 15.68 m/s.

After an extensive literature review, it has been established that Parafoil and Flettner rotor were recognised as promising alternative technologies, given rising fuel costs and environmental pressures. Despite growing interest in the analysis of wind-assisted technologies, the existing studies were limited regarding the diversity in ship types, technical performance, geographical locations and sailing modes. This inspired this paper to investigate the holistic performance of Parafoil and Flettner Rotor systems. A comparative study was conducted from an environmental and economic point of view and illustrated in the case of a newly built 60,000DWT bulk carrier.

3. Research Method

To achieve the objectives of this study, a comparison of the fuel costs in three case studies has been carried out. The scenario utilised for the study considers a recently build dry bulk carrier with a standard fuel oil engine.

3.1 Performance assessment

A specific approach was adopted to compare the environmental and economic performance of wind-assisted propulsion systems, providing support in early-stage decision making. The approached was derived from a number of studies, such as Iannaccone et al. (2020), UNDOS (2019) and UNEP (2004). The authors used qualitative methods to assess the aspects and impacts of each case from a practicability point of view to improve its use for naval architects, researchers, government agencies and vessel operators. An indicator method was adopted for measuring the performance of the systems.

To make a fair comparison of the selected propulsion systems, the following approach was taken, as shown in *Figure 1*. First of all, the boundaries of the analysis, the ship type and alternative propulsion systems were defined. Subsequently, the indicators for evaluating different impact factors were determined, covering two main domains (environmental and economic) for sustainability assessment. A detailed description of the indicators was presented in 3.1.1 and 3.1.2. The models for investigating the environmental and economic benefits of the Flettner rotors system and Parafoil system were then developed based on the Techno-economic Environmental Risk Analysis (TERA) framework. Finally, emission reductions and cost savings after using the wind-assisted propulsion systems were assessed in the case study based on an ocean-going bulk carrier.

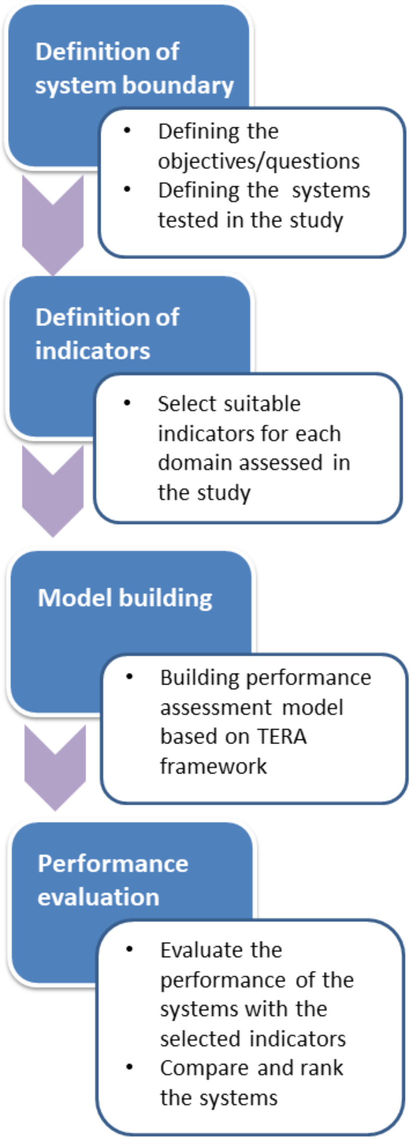


Figure 1: Flowchart of the methodology applied in this study

3.1.1 Environmental indicator

The environmental performance of the systems was determined by the indicator of the emissions quantity of a ship during the trip. The main air emissions resulting from shipping activities include carbon dioxide (CO_2), sulphur oxides (SO_x), nitrogen oxides (NO_x), particular matters (PM) and volatile organic compounds (VOCs). Emissions of CO_2 contribute significantly to the global warming effect, while emissions of NO_x, SO_x, PM and VOCs impact mainly on human health and the local ecosystem of port cities. The values of emissions generated during vessel trip mainly depend on the factors of engine power (P), load factor (L_e), running hours of ships (h) and the emissions factors of the fuel (E_f). The total emissions generated from ship operating (E_q) can be calculated based on the equation (1) proposed by Ammar (2019). At low engine load, emission values can be calculated using the method and coefficients given by ICF (2009).

$$E_q = P * L_e * E_f * h \qquad (1)$$

Where E_q is the total emission quantity of ship operation

L_e is load factor

E_f is the emission factor of the fuel

P is engine power in kW

h is the total working hours of ship

3.1.2 Economic indicator

The economic viability of the wind-assisted technologies was assessed using the indicator of the payback period (PP). The payback period in capital budgeting refers to the time required to recoup the funds expended in an investment or to reach the break-even point (the point at which total cost and total revenue are equal). It is defined through two main cost functions: investments and savings.

The investment function includes all the investments relevant to purchase and install wind-assisted systems. The saving function was defined as the overall costs differences between the ships with Flettner rotor or Parafoil systems and the baseline ship without wind-assisted system installation. An investment with a shorter payback period is considered to be better since the investor's initial outlay is at risk for a shorter period. The equation for calculating the payback period can be expressed as:

$$PP = \frac{Total\ investment}{net\ cash\ flow} \qquad (2)$$

3.1.3 Framework for performance evaluation

The core modules for system performance evaluation were designed based on the Techno-economic Environmental Risk Analysis (TERA) framework presented in Talluri et al. (2018), as shown in *Figure 2*. TERA is a framework that has been widely applied to the works of product design, asset management and multi-disciplinary optimisation. It has recently been successfully used to assess the performance of wind-assisted ship propulsion systems in Traut et al. (2014) and Talluri et al. (2018).

This study applied a TERA model framework to investigate the potential advantages of wind-assisted systems for the reduction of gaseous emissions and fuel consumption. The core modules enable the simulation of the performance of the diesel-mechanical propulsion systems, Flettner rotors and Parafoil kits under different routes, atmospheric/weather conditions and wind patterns. These modules were then integrated with the indicator method to evaluate the performance of the systems from environmental and economic perspectives.

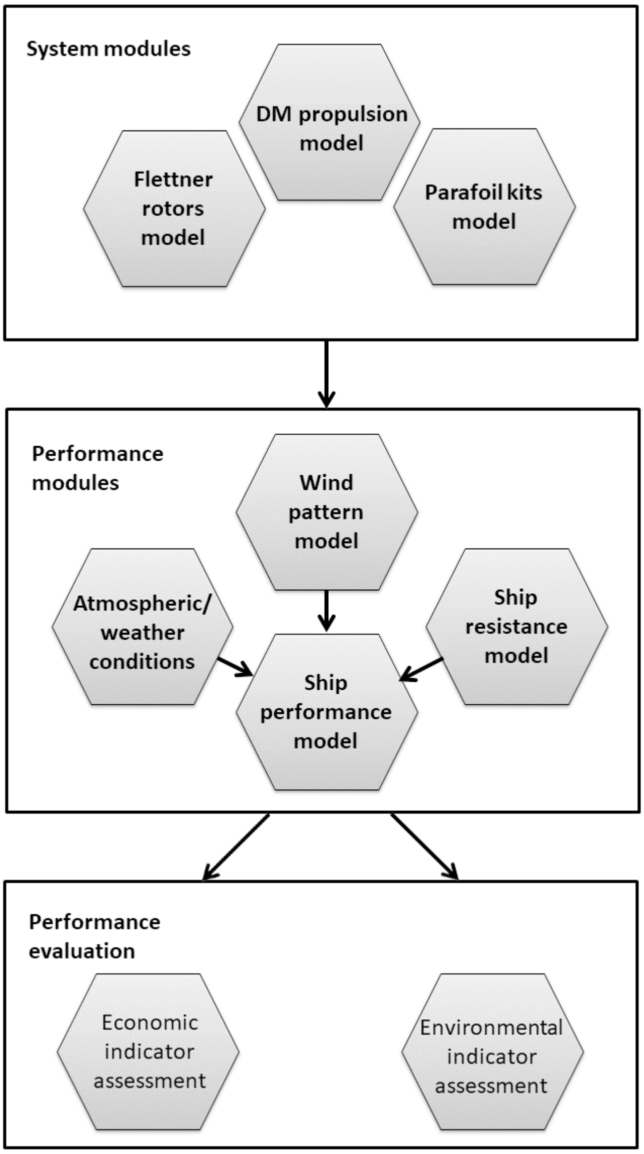


Figure 2: Schematic of the TERA framework in this study

3.2. Data collection

One of the first considerations in choosing this topic was the availability of data (Saunders and Lewis, 2012). The application of Flettner rotors and Parafoil systems in the marine industry was still in an early stage, there were no sufficient data in the published literature to complete the model building and conduct a detailed case study to evaluate the potential benefit of Flettner rotors and Parafoil systems. For this reason, the sources which were to provide primary data were contacted by email at an early stage of the process. A favourable answer was received from practically all of them. Due to the scope and nature of the subject matter at hand, purposive sampling was chosen as the most appropriate(Saunders et al., 2016). Research on the internet was undertaken to identify alternative propulsion systems. The sample of devices was reduced by three factors. Firstly, the pragmatic philosophy of this paper required that any technologies which have not been tested in real vessels were excluded. Secondly, the utilisation of wind as a totally clean source of power was assumed. Thirdly, due to the distances involved between ships, their operators, shipyards and the researchers, email was found to be the most appropriate means of data collection.

Information to simulate the gains regarding the efficiency of a ship fitted with alternative power sources was provided by companies that commercialise them. As a consequence, some degree of bias could be expected (Saunders et al., 2016). To compensate for this, a classification society and a naval architect were also interviewed to build a model to reach the original conclusions arrived at. Additionally, secondary data was gathered to set a real context for the case studies. Future simulations described took into consideration data such as the vessel's specifications, operational speed, and fuel consumption. This information was collected online from open access data published by Clarksons Research, the analysis of costs was provided by Drewry and the official websites of the engines' manufacturers. Statistical data related to wind patterns were collected from official sources including Admiralty UKHO publications.

The data obtained from interviews and questionnaire surveys were used to design Flettner rotors and Parafoil systems in the case study and assess the benefits of each system. This helped to achieve the aim of this study and enable readers to make their judgement about the merits and limitations of these alternative technologies.

4. Case Studies

The ship is set to sail from the Gibraltar Strait to the Panama Canal following an itinerary close to the great circle route. The fuel costs of this voyage, according to the specifications of the vessel, will be compared with the prediction of the fuel costs of the same ship fitted with different alternative propulsion systems. The exercise will be repeated for the opposite voyage, from the Panama Canal to the Gibraltar Strait, to reach more consistent conclusions.

4.1 Selected case ship and ship particular

Case Study 1: "Standard ship"

The first case study is going to consider a particular cargo ship equipped with a marine fuel oil (MFO) engine crossing the North Atlantic in a selected route and its return voyage. Weather conditions are not going taken into consideration. Motor vessel Xing Xi Hai, a 60,498 DWT bulker built-in 2017, was selected for this study. The ship's length between perpendiculars (LBP) is 193 meters. She can transit all the locks of the Panama Canal. Most importantly, the vessel is fitted with a MAN six-cylinder main engine type 6S50ME-B9.3, developing 7800kW at 99 rpm. Her fuel consumption is 25 tonnes per day at a speed of 13.50 knots. The specifications of the baseline bulk carrier are summarised in *Table 1*.

Table 1: The specifications of the baseline bulk carrier

Length between perpendiculars (m)	194.5
Capacity (DWT)	60,000
Velocity	14.4 kts
Fuel consumption (tonne/day)	25
Power delivered by the engine (KW)	6468.36
Engine load (%)	82.93
Resistance	645.67 kN

Case Study 2: Flettner rotors

In this case, the ship selected is going to be the same but with Flettner rotors on the deck. Flettner rotors or rotating sails are the first low carbon alternative propulsion technology we evaluate in this project. Experiments have been carried out to analyse their performance at critical and supercritical Reynolds numbers (Bordogna et al., 2019). However, information about the fuel savings produced by the installation of these devices in marine propulsion units is not always clear, and ranges from 7% to 20% (Norsepower Oy Ltd, 2017; Schuler, 2017). Agent-based models and simulations have yielded results that vary in quantum, thus beseeching further research on the subject (Karslen et al., 2019). To obtain more precise data, we interviewed personnel from a large manufacturer of these rotating sails. One of the main pieces of information received was the performance (depending on wind conditions) of a rotating sail of 24m x 4m when the vessel sails at 14.5 knots (*Figure 3*). Besides, a written questionnaire was answered by a senior manager from the sales and marketing department at "Norsepower", a Scandinavian company involved in marketing and installing FR on ships. Data collected in the survey suggests that a good option would be to install three rotating sails on a single vessel to optimise fuel consumption and installation expenditure.

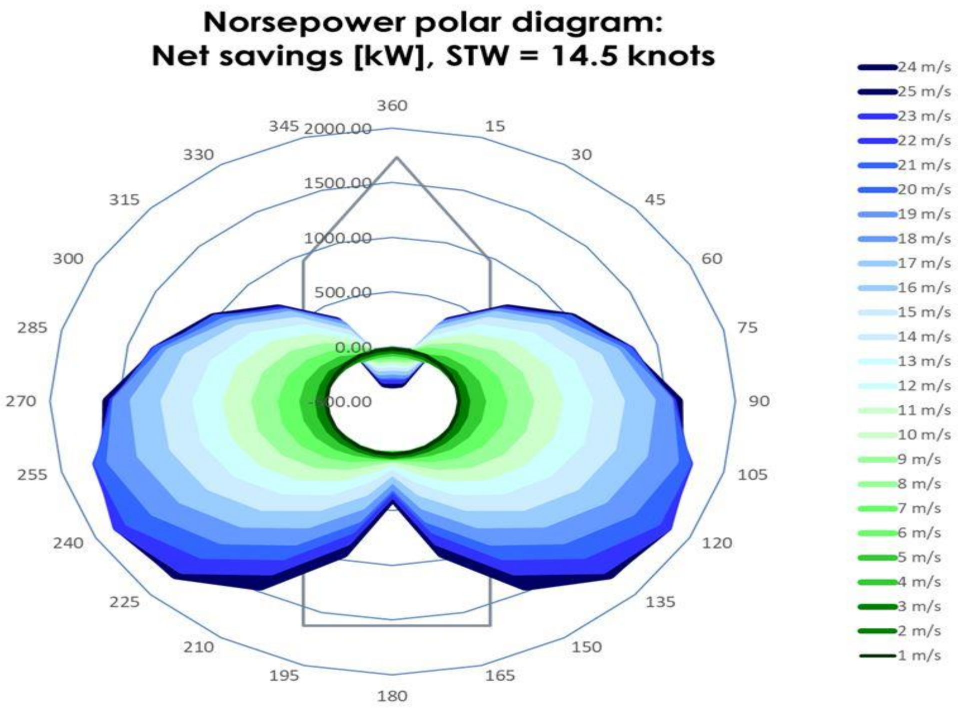


Figure 3: Flettner rotor polar diagram. Source: Norsepower.

The performance of the rotating sails depending on the wind conditions was converted into a numeric table detailing the direct relationship between the wind speed in m/s, the true wind angle and the propulsion power created by the Flettner. This propulsion power will be directly reduced from the engine power, and consequently, the g/kWh will also be modified.

The operation of the Flettner rotors demands control of the rotation speed, which is automatically adjusted according to the necessities. Therefore, the power demand for spinning the columns is variable and supplied by the low voltage system on board (Norsepower Oy Ltd, 2017). According to the manufacturers, the maximum power demand would be less than 90 kW (Kornei, 2017). Consequently, it will be considered irrelevant for this study.

An example of the application of this process is as follows:

- In January, the wind symbol for area 2 (*Table 2*) indicates that there is a 19% chance to blow Northerly winds at an average force 4 Beaufort (National Imagery and Mapping Agency-Department of Commerce, 2002).
- Force 4 is equivalent to 7 m/s (Met Office, 2017).
- The course over the ground of the vessel in this area should be 264°, considering that it is bound to the Panama Canal.
- This means that the ship is receiving the wind at 96° on her starboard side.

Case Study 3: Parafoil

For the last case, the ship selected is going to be the same as in the second instance but with a Parafoil fitted on the foredeck. The information needed to undertake this part of the project was obtained from the internet (Skysails GmbH, 2017) and also from written questionnaires sent to the Marketing and Business Development department at "Skysails GmbH", a well-known European manufacturer and installer of parafoils on conventional oceangoing cargo ships, of which "Beluga Skysails" is one such ship. The results are summarised in *Figure 4* and show the favourable performance of the Parafoil depending on wind conditions when the ship is sailing at 10 knots.

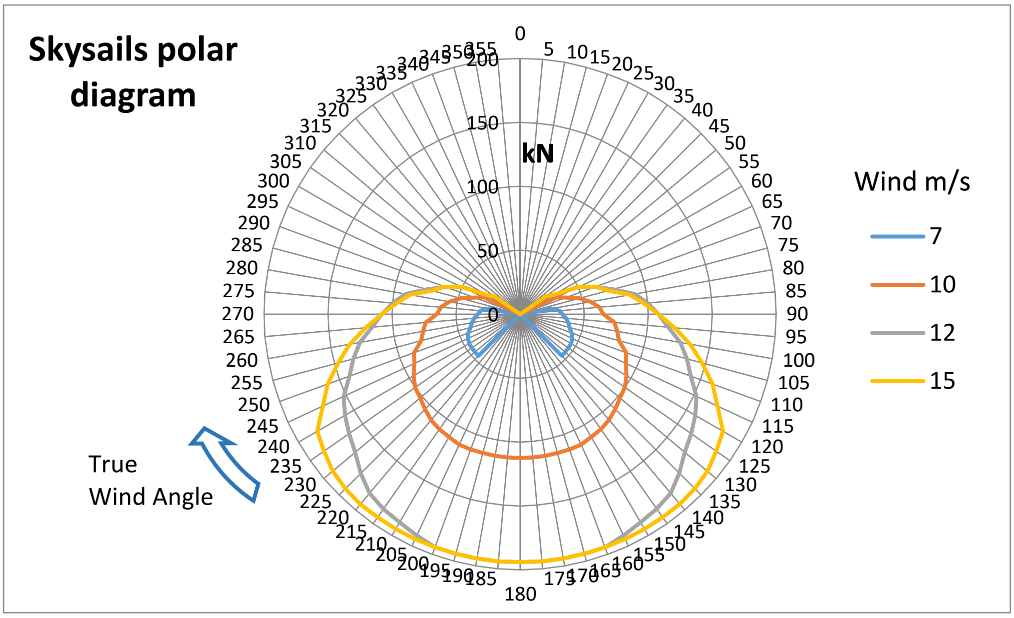


Figure 4: Parafoil polar diagram SOG=knots (Skysails GmbH, 2017)

It is relevant that the information obtained about the performance of the Parafoil is expressed in kN of force for a ship sailing at 10 knots, differently from the performance of the Flettner rotors, which was in kW of power for a vessel travelling at 14.5 knots. This makes the process of comparison significantly longer since the engine specifications do not associate force and power, and also because the apparent wind sailing at 14.5 knots is different than the apparent wind sailing at 10 knots. As a result, it is necessary to introduce two intermediate steps. The first to estimate the Skysails polar diagram when the ship is sailing at 14.5 knots, and the second to convert kilonewtons into kilowatts.

Additionally, the change in the wind due to height must be considered. The Parafoil has been designed to fly at a height of 100-150 meters above the sea surface (Skysails GmbH, 2017). At that height, the wind is usually stronger, as it is less affected by the friction of the sea (Suisse Eole, 2017). Though there is no single accurate method to estimate the increase of wind speed due to the lack of friction at heights, Suisse Eole (2017) uses a logarithmic wind profile as a solution. Therefore, we use the same and the wind force has been increased accordingly.

An example of the calculation of the fuel and emission savings derived from the utilisation of the Parafoil is the following:

- As has been stated previously, in weather area number 2, there is a 19% chance to sail with Northerly wind. In this case, the wind force on the surface is 4 Beaufort, or 7 m/s (Met Office, 2017).

When the wind force on open land is 4 Beaufort, at the height of 100 meters it will be estimated at 8.13 m/s, and at a height of 150 meters, it will be 8.38 m/s (Suisse Eole, 2017).

- The course to steer to go to the Panama Canal from Gibraltar Strait in area number 2 is 264°, which means that the wind is received at 96° from the bow.
- The next step has been to calculate the apparent wind angle (AWA) and apparent wind speed (AWS) when the ship is sailing at 14.5 knots at a course over the ground of 264º when the wind blows 96º from the bow. This has been made through a vectorial sum.
- As the performance of the Parafoil has been obtained when the ship is sailing at a speed of 10 knots, the AWA and AWS for this speed have been calculated to obtain the benefits of this device according to apparent wind conditions.
- Matching apparent wind conditions have been found whether the vessel is sailing at 10 or 14.5 knots. From this matching apparent wind conditions, it has been assumed that the towing forces would be equivalent, however, some of the apparent wind conditions for sailing speed = 14.5knots have not met an equivalency. Graphical interpolation has been used to fill in the gaps as is seen in *Figure 5*.

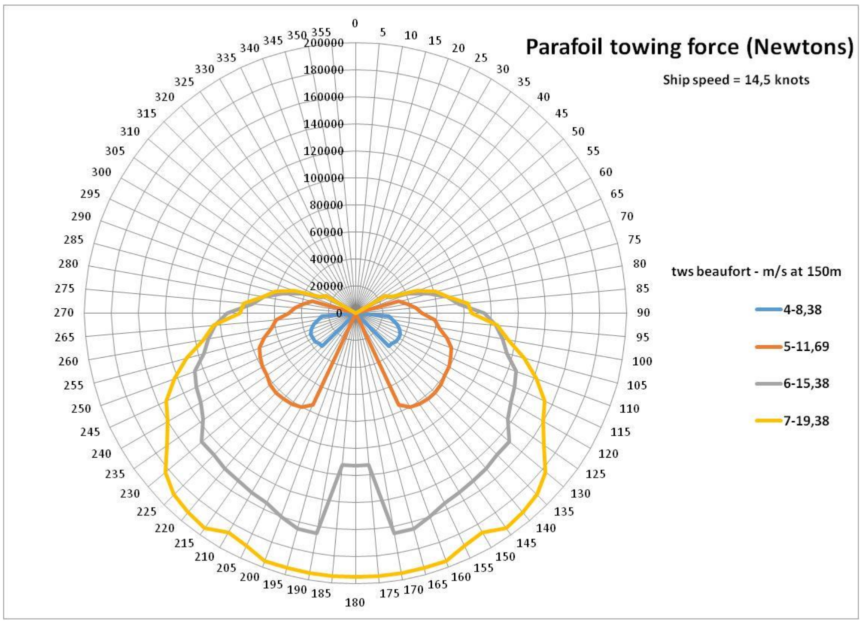


Figure 5: Parafoil polar diagram SOG=14.5 knots

4.2 Route

The proposed route for the research was a cross Atlantic voyage from Gibraltar Strait to the Panama Canal. Although weather routing tools can be used to optimise its fuel consumption, with savings of 2%-4% claimed for standard ships and an extra 14%-17% for ships with wind-assisted propulsion systems (Bentin et al., 2016), it was necessary to assume some simplifications and recreate the route which could be chosen by any ship's master following the great circle passage joining these two points. Nevertheless, the characteristics of this itinerary could produce some bias, considering that the prevailing winds in the area are more established from the North and East quadrants (National Imagery and Mapping Agency- Department of Commerce, 2002). Furthermore, winds in the Atlantic, like in many sea areas of the world, vary daily, as well as with seasons, and the time of the day. The same ship on an identical route could face different wind conditions a day later in the same positions. The angle of encounter between the ship, its windage area presented and hence the nett efficiency could also vary. To minimise some of these effects, the return trip from the Panama Canal to the Gibraltar Strait is also included with the objective to provide more balanced results.

As a result, the route utilised can be considered as a semblance sample to navigation in many other sea areas of the world. With this premise, the research will be deemed more useful, more consistent with the pragmatic philosophy of this study and fits better with the standard operations of existing shipping lines.

In consideration of the above, the coordinates of the extremes of the itinerary are:

Gibraltar Strait: 36° 0,00'N - 6° 0.00'W

Panama Canal: 9° 26,00'N - 79° 54,00'W

It is necessary to include an intermediate waypoint to cross the Lesser Antilles in:

Sombrero Island Pass: 18° 40,00'N - 63° 30,00'W

Imray North Atlantic Ocean Passage Chart 100 was used to draw the great circle route utilised in this project (Imray Laurie Noire & Wilson Ltd, 2012).

4.2.1 Weather analysis

This study required additional analysis of the weather conditions during the passage, as wind-dependent technologies were going to be assessed. *Figure 6* is an example of a pilot chart with a detail of the prevailing wind conditions and their frequencies in different areas. It has been retrieved from an official source.

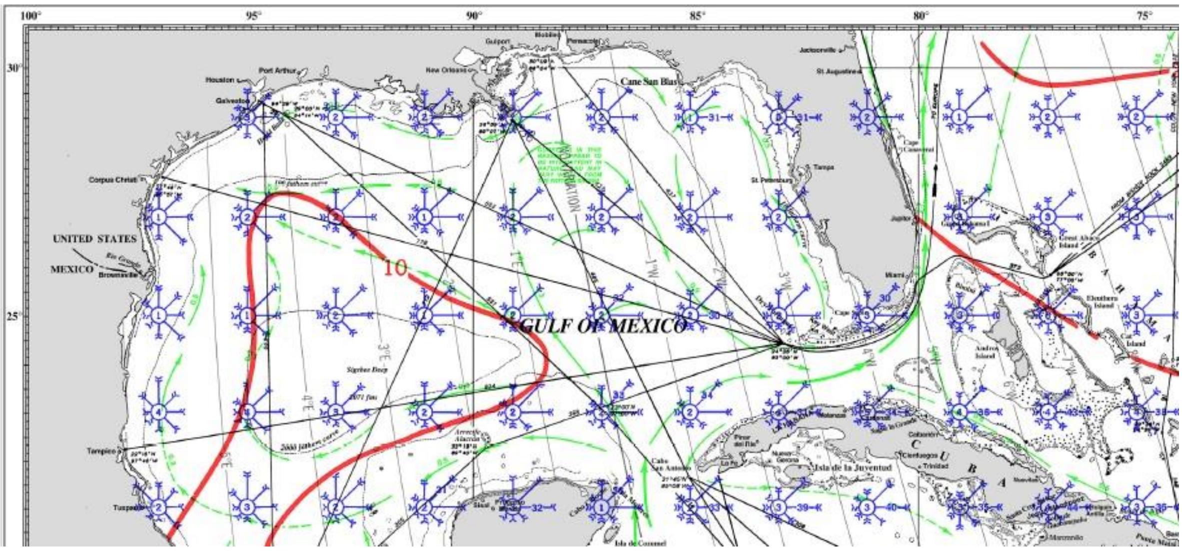


Figure 6: Sample of prevailing weather conditions (National Geospatial-Intelligence Agency, 2017)

The detail in *Figure 6* shows a series of symbols. These symbols represent the average wind conditions in the surrounding stretch of water. An example of one of these symbols is shown in *Figure 7*, and the interpretation is as follows:

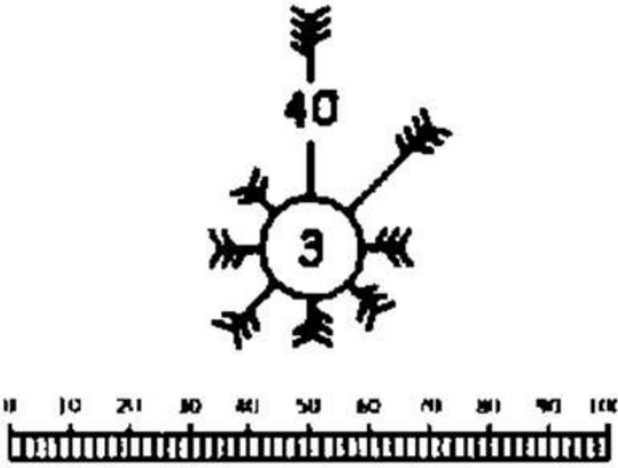


Figure 7: Sample of wind pattern for an area (National Imagery and Mapping Agency-Department of Commerce, 2002)

- In 40% of the days the wind comes from the North with an average intensity of 7 on the Beaufort scale (Bs 7)
- 19% of the days North-easterly winds with an average intensity of Bs 7
- 6% of the days Easterly winds with an average intensity of Bs 5
- 5% of the days South-easterly winds with an average intensity of Bs 5
- 5% of the days Southerly winds with an average intensity of Bs 5
- 9% of the days South-westerly winds with an average intensity of Bs 5

- 8% of the days Westerly winds with an average intensity of Bs 5
- 5% of the days North-westerly winds with an average intensity of Bs 4
- 3% of the days calm airs

The measurement of the symbols was carried out manually, by enlarging the scale of the charts and printing each of them on four DIN-A3 papers.

The Beaufort wind force scale (*Table 2)* was developed by the UK Royal Navy member Sir Francis Beaufort in 1805, and its use is widely spread by official sources (Met Office, 2017). Each degree of force, indicates an interval of mean speeds of wind during 10 minutes at the height of 10 meters (Royal Meteorological Society, 2017), meaning that stronger gusts are expected.

Table 2: Beaufort scale (Agencia Estatal de Meteología, 2020)

Beaufort wind scale	Wind speed		Wind descriptive terms
	knots	m/s	
0	1	0-0.2	Calm
1	1-3	0.3-1.5	Light air
2	4-6	1.6-3.3	Light breeze
3	7-10	3.4-5.4	Gentle breeze
4	11-16	5.5-7.9	Moderate breeze
5	17-21	8-10.7	Fresh breeze
6	22-27	10.8-13.8	Strong breeze
7	28-33	13.9-17.1	Near gale
8	34-40	17.2-20.7	Gale
9	41-47	20.8-24.4	Severe gale
10	48-55	24.5-28.4	Storm
11	56-63	28.5-32.6	Violent storm
12	64+	32.6+	Hurricane

For the case studies contained in this work, the degrees of force from the Beaufort scale appearing in the first column of *Table 1* are going to be converted to the values of mean wind speed in m/s. The purpose of this conversion is to adapt the data to the information received from the representatives of the Flettner rotors and Parafoil companies.

The weather information for the route has been retrieved from the *North Atlantic Ocean* section of the *Atlas of Pilot Charts*, published by the United States Government (National Imagery and Mapping Agency- Department of Commerce, 2002). This publication contains a detail of the prevailing wind and current conditions in the planned route.

Climate conditions are given for each square area of five degrees of latitude per five degrees of longitude. The areas in which our pre-set itineraries run have been identified and are detailed in *Table 3*. There is also a chart for each month of the year, describing the evolution of the wind patterns throughout the year (National Imagery and Mapping Agency- Department of Commerce, 2002).

Table 3: Weather study areas

Weather Area	NW corner lat	NW corner long	NE corner lat	NE corner long	SE corner lat	SE corner long	SW corner lat	SW corner long
-	-	-	-	-	-	-	-	-
1	40N	10W	portuguese coast		Moroccan coast		35N	10W
2	40N	15W	40N	10W	35N	10W	35N	15W
3	40N	20W	40N	15W	35N	15W	35N	20W
5	35N	25W	35N	20W	30N	20W	30N	25W
6	35N	30W	35N	25W	30N	25W	30N	25W
7	35N	35W	35N	30W	30N	30W	30N	35W
8	35N	40W	35N	35W	30N	35W	30N	40W
9	35N	45W	40N	45W	30N	40W	30N	45W
10	30N	45W	30N	40W	25N	40W	25N	45W
11	30N	50W	30N	45W	25N	45W	25N	50W
12	30N	55W	30N	50W	25N	50W	25N	55W
13	25N	55W	25N	50W	20N	50W	20N	55W
14	25N	60W	25N	55W	20N	55W	20N	60W
15	25N	65W	25N	60W	20N	60W	20N	65W
16	20N	65W	20N	60W	15N	60W	15N	65W
17	20N	70W	20N	65W	15N	65W	15N	70W
19	15N	75W	15N	70W	COLOMBIAN COAST			
20	15N	80W	15N	75W	COLOMBIAN COAST		10N	80W
21	10N	80W	COLOMBIAN COAST				PANAMANIAN COAST	

The symbols of each of the nineteen areas of the case study itinerary for each of the twelve months of the year have been measured and converted into percentages of prevalence. Then, the waypoints in which the route intersects with the borders of the areas have been listed to calculate the nautical miles and the hours the vessel would sail in such wind conditions. Considering this, each weather condition has been weighted according to its effect. The waypoints are detailed in *Table 4.*

Table 4: Waypoints List

Waypoint	Position		Waypoint	Position
1	36°N 6°W		12	25°N 53°30'W
2	35° 50'N 10°W		13	24°10'N 55°W
3	35° 30'N 15°W		14	21°30N 60°W
4	35°N 20°W		15	20°N 61°30'W
5	34°20'N 25°W		16	18°40'N 63°30'W
6	33°20'N 30°W		17	17°20'N 65°W
7	32°N 35°W		18	15°N 70°W
8	30°30'N 40°W		19	12°30'N 75°W
9	30°N 41°20'W		20	10°N 79°W
10	28°40'N 45°W		21	9°26'N 79°54'W
11	26°30'N 50°W			

Consequently, the courses over the ground to be followed by the vessel have been calculated by joining the waypoints obtained in the previous step. This information has also determined the position of the ship concerning the wind direction. This is a relevant part of the work because both alternative sources of energy not only act differently depending on the wind speed but also depending on the incidence angle of the wind (Norsepower Oy Ltd, 2017; Skysails GmbH, 2017). The effects of the stream and the wind on the course of the ship have been considered as not significant for this purpose.

Overall, this represents a significant simplification of reality. The winds considered are only from eight different directions and the intensities reduced to only 13 possible speeds. This gives only 97 possible wind patterns, while theoretically, there are infinite possibilities. Additionally, the courses are never straight. The route followed by a ship on a great circle itinerary is constantly changing, adopting the shape of a curve. Nevertheless, this interpretation will be appropriate considering the use made of it by governmental institutions, the practice adopted on ships by navigating officers (National Geospatial-Intelligence Agency, 2017) and the little degree of detail obtained for the performances of the alternative sources of energy.

4.3 **Environmental impact, merits and limitations:**

4.3.1 “Standard diesel-mechanical propulsion ship”

The environmental aspects and impacts of conventional MFO powered engines have been well documented in numerous journals as well as in the IMO GHG reports. Marine propulsion engines are typically fuelled by MFO which results in high levels of sulphur oxides (SOx) in the emissions as well as CO2. Marine generators and other equipment emit NOx which can have long-reaching harmful impacts on the environment. MFO is generally the lowest grade of oil, left after the distillation process and thus far cheaper than the higher grades of oil used in other transportation. While its use enables cheaper fuel to be used for international trade, thus providing economies of scale to ocean shipping, its environmental impact can be deleterious, especially to air quality.

Based on daily consumptions reported by *Xing Xi Hai* we find that the vessel burns an average of 25 tonnes of heavy fuel oil (HFO) per day (Clarksons Research Services Ltd, 2017). Consequently, it will be necessary to calculate the power delivered and the load in the MAN 6S50ME-B9.5 engine equivalent to this fuel consumption. We also compute exhaust emissions corresponding to this SFOC through linear interpolation (shown in bold in *Table 5).*

Table 5: Extract of the engine specifications with interpolated values

Load %SMCR	Power kW	Speed r/min	SFOC g/kWh	Fuel Tonnes/Hour	Fuel Tonnes/day	Exhaust gas kg/s
100	7800	99	165.5	1.2909	30.9816	16.4
95	7410	97.3	164.3	1.217463	29.219112	15.7
90	7020	95.6	163.5	1.14777	27.54648	14.9
85	6630	93.8	161.6	1.071408	25.713792	14.6
82.93	**6468.36**	**93.01**	**161.02**	**1.04**	**25.00**	**14.43**
80	6240	91.9	160.2	0.999648	23.991552	14.2

4.3.2 Flettner rotors

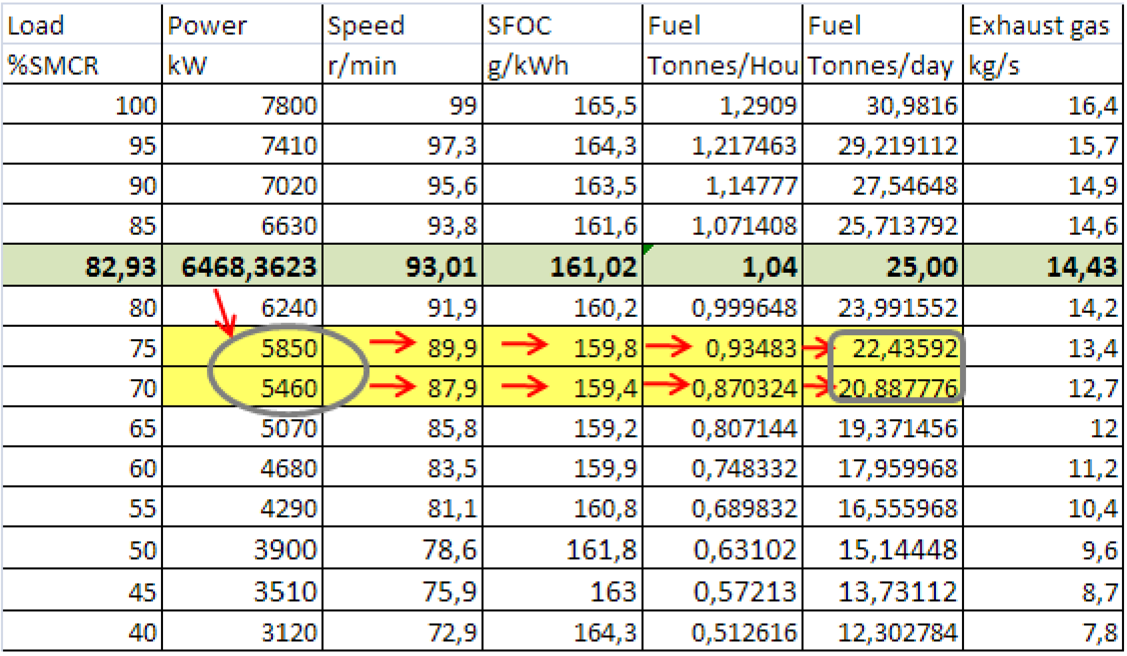
Table 6 is a detail of the polar table created from the information received from Norsepower. Under the wind speed of 7m/s, received at 94 from the bow makes the Flettner rotors produce power between 847,65 kW and 846,41 kW, which after interpolating gives a figure of 863,35 kW.

Table 6: Flettner rotors performance table in kW

		Wind speed m/s							
		1	2	3	4	5	6	**7**	8
True Wind Angle	0	-22,41	-28,03	-34,27	-41,13	-48,63	-56,75	-65,49	-74,86
	15	-66,74	-83,00	-101,09	-120,99	-142,70	-166,23	-191,58	-218,74
	30	-65,25	-79,86	-96,10	-113,99	-133,52	8,79	37,85	77,31
	45	-62,90	-74,93	-88,34	32,90	98,49	185,99	292,74	416,80
	60	-59,88	-68,64	34,68	124,27	246,69	396,89	572,45	771,94
	75	-56,41	1,49	78,64	204,08	365,14	557,66	780,84	1032,81
	90	-52,75	10,74	105,24	246,03	422,22	631,90	874,65	1147,81
	105	-49,16	12,69	106,71	242,09	410,04	611,30	846,41	1108,20
	120	-45,86	6,57	84,76	197,47	337,65	512,30	716,21	940,20

This power can be reduced from engine power. *Table 7* shows the new power requirement for the engine, and consequently the new SFOC for a constant ship speed. The new average specific fuel consumption in area 2 during the 19% of the days blowing Northerly winds, will be a value somewhere between 159.4 and 159.8 g/kWh. These values are equivalent to 20,88 and 22,43 tonnes per day. Considering a daily standard fuel consumption of 25 tonnes, this represents an average reduction of about 14,15% of fuel in this area, when Northerly winds are blowing. Linear interpolation has been the technique used to find all intermediate values. Each fuel-saving related to a weather condition has been weighted according to its prevalence in the area. This process was repeated for each of the eight different wind conditions in each of the 19 weather areas of the route, and for each of the 12 months of the year.

Table 7: Example of the application of the power reduction derived from the Flettner rotors



Load %SMCR	Power kW	Speed r/min	SFOC g/kWh	Fuel Tonnes/Hou	Fuel Tonnes/day	Exhaust gas kg/s
100	7800	99	165,5	1,2909	30,9816	16,4
95	7410	97,3	164,3	1,217463	29,219112	15,7
90	7020	95,6	163,5	1,14777	27,54648	14,9
85	6630	93,8	161,6	1,071408	25,713792	14,6
82,93	**6468,3623**	**93,01**	**161,02**	**1,04**	**25,00**	**14,43**
80	6240	91,9	160,2	0,999648	23,991552	14,2
75	5850	89,9	159,8	0,93483	22,43592	13,4
70	5460	87,9	159,4	0,870324	20,887776	12,7
65	5070	85,8	159,2	0,807144	19,371456	12
60	4680	83,5	159,9	0,748332	17,959968	11,2
55	4290	81,1	160,8	0,689832	16,555968	10,4
50	3900	78,6	161,8	0,63102	15,14448	9,6
45	3510	75,9	163	0,57213	13,73112	8,7
40	3120	72,9	164,3	0,512616	12,302784	7,8

During their usage at sea, Flettner rotors result in zero carbon emissions and do not consume any fuel. Thus, their carbon footprint, SOx and NOx emissions, and GHGs are zero. However, they do produce noise in the air, albeit much lower than a conventional main engine. When connected with the propeller, they do produce underwater noise, thus disturbing marine fauna. The harmful effects of propeller noise on right whales have been demonstrated in the North Atlantic, resulting in speed restrictions for ships approaching certain parts of the United States and Canada during certain times of the year. Flettner rotors connected with propellers have similar detrimental effects.

Drag on the Flettner rotors can vary, and their performance is questionable when faced with adverse winds and in strong wind conditions. It is normal for ships on ocean passages to experience winds of 20-50 knots, often in directions that are not conducive for them to proceed on their intended course. This is addressed in conventional ships using set and drift, and with powerful engines. For example, it is normal for a 199m long 63,600 dwt bulk carrier with a MAN B&W 5S 60 ME main engine to have an engine power output of 8,300 kW @ 91 rpm SMCR and 6,640 kW @ 84.5 rpm. CSR (80% SMCR) resulting in a normal sea speed of 14.3 knots and lower or higher speeds depending on wind direction and speed. Flettner rotors have a far lower power output, thus making them questionable as a complete replacement for the conventional fuel-powered main engine for conventional large ocean-going cargo ships including bulk carriers and tankers. Current experiments have only resulted in augmenting existing main engine power, and not replacing them entirely, hence their real environmental impact might be limited to that associated with e few tonnes of fuel saved.

The impact of the manufacturing of these units, their blades and dynamos, and transporting them can be appreciably large. They are manufactured in specific countries, either in Northern Europe or in Far East

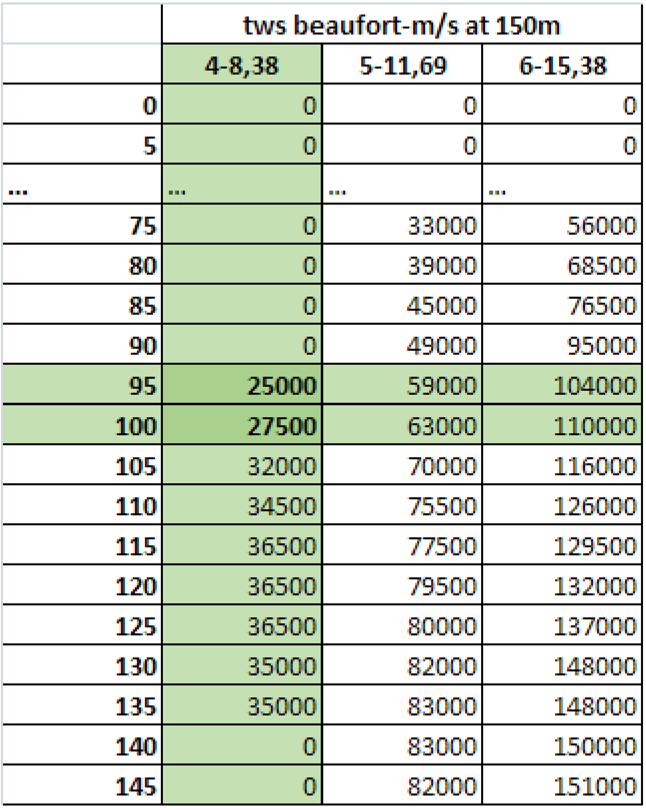
Asia due to intellectual property monopolies and components have to be shipped over larger distances, as compared to conventional marine engines whose manufacturing is more ubiquitous. Servicing Flettner rotors often requires highly specialised technicians, and most Flettner rotors installations come with contractual stipulations that necessitate the manufacturer's technician, often located in Northern Europe to only be deployed for any regular servicing (typically annually) or for any troubleshooting. Hence the added flights to transport these peeple need to be added when assessing the impact of their LCA, considering that once installed, main engines are typically left to continue functioning *in situ* for 20-35 years due to the extensive rework that would be necessitated to make any change in their installation. If Flettner rotors do not replace the conventional MFO powered marine engine entirely, the impacts of the conventional engine that they work with in tandem will continue to exist, thus minimising any perceived environmental benefits.

4.3.3. Parafoil

The benefits derived from the use of the Parafoil were the second item investigated during this project. As mentioned above, this kite depends on the wind to produce a towing force which reduces the load on the main engine and thus saves fuel. This towing force can be converted into a reduction of the load on the engine or an increase of the ship speed. As happened with the Flettner rotors, the study focused on maintaining the speed constant and reducing the load on the engine, rather than replacing conventional marine fuel oil engines completely.

The performance of the Parafoil has been summarised in T*able 8.* This table is used to find that the towing force delivered by the kite in such weather conditions is a value between 25000 and 27500 N.

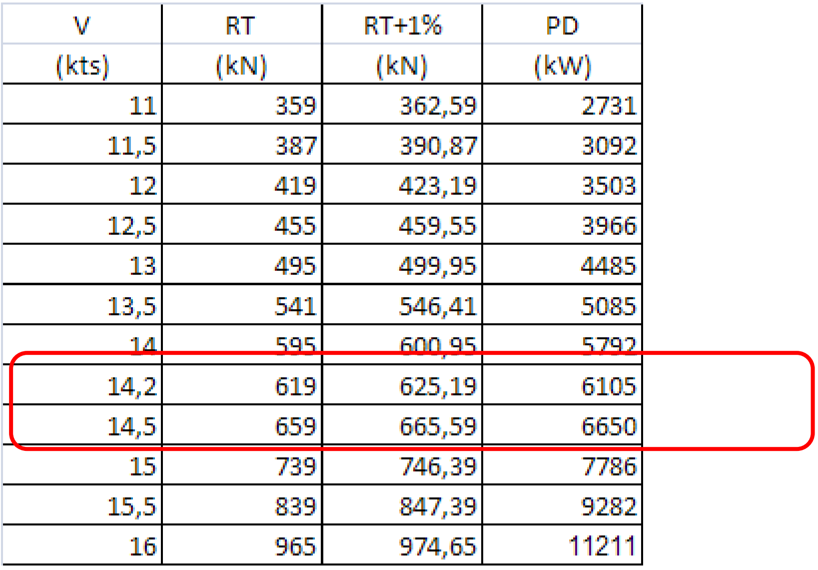
Table 8: Parafoil performance in N (Skysails GmbH, 2017)



	tws beaufort-m/s at 150m		
	4-8,38	5-11,69	6-15,38
0	0	0	0
5	0	0	0
...	...	...	...
75	0	33000	56000
80	0	39000	68500
85	0	45000	76500
90	0	49000	95000
95	**25000**	59000	104000
100	**27500**	63000	110000
105	32000	70000	116000
110	34500	75500	126000
115	36500	77500	129500
120	36500	79500	132000
125	36500	80000	137000
130	35000	82000	148000
135	35000	83000	148000
140	0	83000	150000
145	0	82000	151000

Linear interpolation has been used to find the intermediate values corresponding to 96° of true wind angle. The force obtained from the Parafoil is 25.5 kN. With this information, the force needed to keep the ship at a constant speed of 14.5 knots, instead of 659 kN are only 626.63 kN, which means 6124.36 kW from the engine as shown in *Table 9* All intermediate figures have been obtained by linear interpolation.

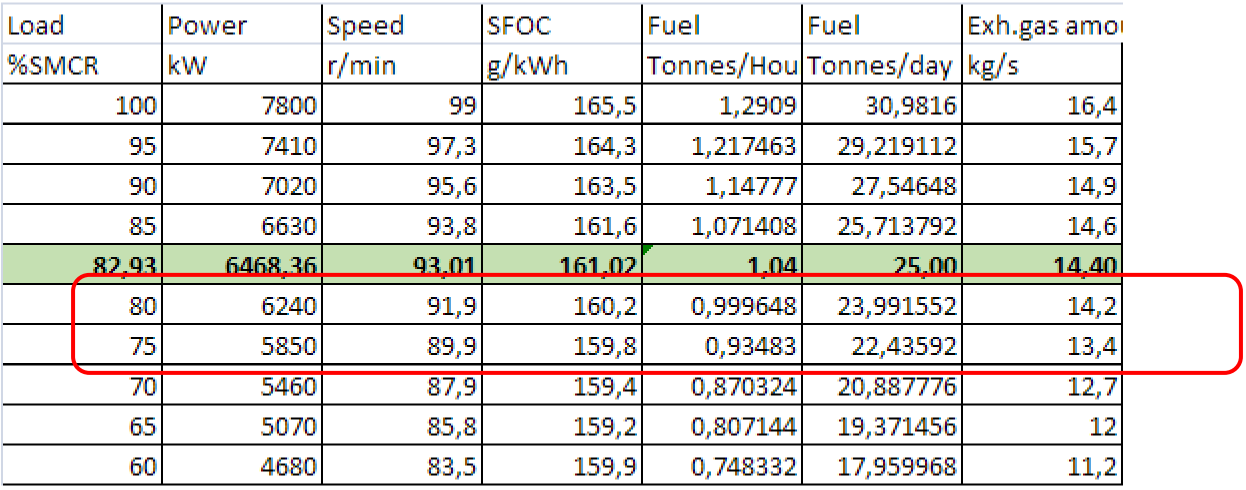
Table 9: Obtaining the kW required when there is a kN input from the kite



V (kts)	RT (kN)	RT+1% (kN)	PD (kW)
11	359	362,59	2731
11,5	387	390,87	3092
12	419	423,19	3503
12,5	455	459,55	3966
13	495	499,95	4485
13,5	541	546,41	5085
14	595	600,95	5792
14,2	619	625,19	6105
14,5	659	665,59	6650
15	739	746,39	7786
15,5	839	847,39	9282
16	965	974,65	11211

Once the power required has been calculated, the process would be the same as the one used for the Flettner rotors. It is necessary to work with the engine specifications table, as is shown in *Table 10.* The amount of fuel necessary in 24 hours to sail at a speed of 14.5 knots would be 23.5 tonnes. This means a reduction of approximately 5.8% of the fuel and 3 % of exhaust emissions.

Table 10: Example of the calculation of the new SFOC and exhaust emissions



Load %SMCR	Power kW	Speed r/min	SFOC g/kWh	Fuel Tonnes/Hou	Fuel Tonnes/day	Exh.gas amo kg/s
100	7800	99	165,5	1,2909	30,9816	16,4
95	7410	97,3	164,3	1,217463	29,219112	15,7
90	7020	95,6	163,5	1,14777	27,54648	14,9
85	6630	93,8	161,6	1,071408	25,713792	14,6
82,93	**6468,36**	**93,01**	**161,02**	**1,04**	**25,00**	**14,40**
80	6240	91,9	160,2	0,999648	23,991552	14,2
75	5850	89,9	159,8	0,93483	22,43592	13,4
70	5460	87,9	159,4	0,870324	20,887776	12,7
65	5070	85,8	159,2	0,807144	19,371456	12
60	4680	83,5	159,9	0,748332	17,959968	11,2

Each fuel and emissions savings have been weighted according to the prevalence of the wind condition in the area. The same entire process has been repeated for each of the eight different wind conditions in each of the 19 weather areas of the route, and for each of the 12 months of the year.

The implementation of the global sulphur cap means a reduction from 3.5% m/m to 0.5% m/m (IMO, 2016). This is more than 88% and by far more than the reductions obtained from the use of the Flettner rotors and Parafoil. Additionally, as the sulphur cap is expressed in percentage of the mass in the exhaust emissions (IMO, 2017), it is not clear if any equipment reducing the exhaust emissions per se or by improving the energy efficiency of an internal combustion engine, namely organic rankine cycle technologies (Pili et al., 2017) would be accepted. Therefore, it seems that the use of devices that "clean" but not reduce the exhaust gases, the installation of gas-oil turbines (Armellini et al., 2018) or the utilisation of low sulphur fuels are the only solutions to reach this parameter.

Another issue related to the environment is the emissions of GHG. It is not clear the system that will be in place to reduce and control CO_2 emissions. In any case, nor the parafoil or the Flettner rotors by themselves are the solutions to reach the target reduction established by 2050, The solvent-based carbon capture systems are presented by scholars as solutions to install onboard vessels with a remarkable cleaning potential (Luo and Wang, 2017).

4.4. Economic impact

4.4.1. Bunker prices

This paper aims to reach a figure which can be illustrative for determining the benefits of the use of alternative sources of energy. Fuel oil prices can be volatile and hence are subject to changes depending on the date, geographical location and the type of fuel.

The selection of a "go and return" trip was made to take into consideration a broad range of weather conditions that could make this work useful to a wide spectrum of readers. Consequently, the fuel oil price to determine the results of the standard ship in the proposed case studies should achieve the same objective.

The fuel type 380 cst has been selected to calculate a fixed figure for the fuel oil prices. Also, different worldwide markets have been taken into consideration, 20 specifically. Then, the average of all these markets has been calculated, from August 30, 2017 to August 30, 2019. The result has been 417.50 US$/tonne (Ship and Bunker, 2020).

Bunker costs are part of the voyage costs. It will be relevant to know who will support bunker expenses. Depending on the type of agreement between the shipowner and the customer, one or the other will be charged for this concept (Stopford, 2009).

4.4.2. Operating costs

Operating costs are defined as the expenses involved in the operation of ships. These expenses are supported by the shipowner in the cases of time and voyage charter. All the components of the operating costs of a ship are gathered and explained in the annual report Ship-Operating Costs published by

Drewry Maritime Research (Neylan, 2016). *Table 11* is a summary of the information extracted for a vessel similar to the one used in the simulation.

Table11: Supramax operating costs (Neylan, 2016)

Drewry's operational costs 2016/2017 Dry Bulk Carriers					
DWT	50-55,000				
Sector	Supramax				
Global fleet-No.	1,955				
Global fleet- DWT	114,222,368				
Avg. Age-years	4,9				
Youngest vessel - years	<1				
Oldest vessel-years	34.7				
Avg. Scrap age (2016)	29.5				
Avg. Size-DWT	58,426				
	US$/day				
Operating cost by vessel age	Newbuilt	5 years old	10 years old	15 years old	20 years old
Manning	1970	1970	1970	2070	1770
Insurance	370	350	350	340	310
Stores	140	210	300	300	300
Spares	40	210	300	360	380
Lubricating Oils	390	410	420	430	440
Repair and maintenance	240	320	350	360	370
Dry Docking	0	490	660	820	1150
Management and admin	850	870	910	910	920
Total	**4000**	4830	5260	5590	5640

(Source: Neylan 2016)

The daily operating costs of a vessel are different depending very much on the age of the ship. The newer the ship, normally the lower the costs. *Table 11* shows how this can be a consequence of the fatigue of the vessel and its components. Except for the insurance and the crew, the rest of the elements of the operating costs increase with the age of the ship (Neylan, 2016). The total operating costs for a newly built Supramax bulk carrier are estimated to be around 4000$/day.

4.4.3. Earnings

Shipowners obtain their incomes in many different ways. They can sell slots in their holds for each voyage, or even the whole ship. In this case, the price is paid by tonne loaded. This way of business is commonly known as the voyage charter. In a time charter, shipowners can also rent the vessel keeping the operation of the ship and supporting the operational risks, but it would be the charterer who would pay the operational costs. In this case, the freight rates are expressed in US$ per day. The last common way of obtaining earnings it would be to transfer to the customer all the operational and market risks. This way of arrangement where the ship-owner only finances the vessel and obtains in exchange a fixed compensation is called bareboat charter (Stopford, 2009).

Among the freight rates for the voyage charter, there are variations depending on the cargo handled and the length of the itinerary. As the prices are expressed in US$/tonne, it will be interesting for further calculations to harmonise them and express them in US$/day. Seven routes undertaken by a Supramax bulk carrier have been selected from Clarkson's database (Clarksons Research Services Ltd, 2017) to calculate a representative voyage charter rate. The details can be found in *Table 12*. The routes have been chosen to cover many of the oceanic navigation areas.

Table 12. Supramax voyage charter freight rates (Clarksons Research Services Ltd, 2017)

Date	**US Gulf-Japan 50000t Grain (HSS)**	**Richards Bay - Visakhapatnam 50000t Coal**	**Richards Bay-Pipavav 50000t Coal**	**Samarinda-Paradip 50000t Coal**	**Samarinda-Pipavav 50000t Coal**	**Texas-ARA 50000t Petcoke**	**Texas-India 50000t Petcoke**
	$/Tonne	**$/Tonne**	**$/Tonne**	**$/Tonne**	**$/Tonne**	**$/Tonne**	**$/Tonne**
2014	44.79	16.95	16.61	11.27	13.28	16.43	38.69
2015	30.07	10.73	10.26	7.31	8.38	11.9	26.53
2016	28.17	8.47	8.04	5.97	6.7	11	23.24
2017	36.52	12.05	11.58	7.35	8.31	12.71	31.21

The information enclosed in this table has been converted into US$/day. For this purpose, the length of the voyages has been calculated for the service speed of 14.4 knots. The distances between the ports have been retrieved from the online voyage planner SeaRoutes (SeaRoutes.com, 2017). *Table 13* is an extract of the new values translated to US$/day.

Table 13: Supramax voyage charter rates expressed in US$/day

Date	**US Gulf-Japan 50000t Grain (HSS)**	**Richards Bay - Visakhapatnam 50000t Coal**		**Average**
	$/day	**$/day**		**$/day**
2014	83552.26	68111.87	→	69194.11
2015	56099.12	43109.56	→	45479.53
2016	52550.4	34059.91	→	38657.13

2017	68131.14	48435.45	→	**50407.63**

As a consequence, the outcome of this process is an average freight rate of 50.407,63 US$/day in the year 2017.

The most accessible information about time charter rates is for one, three or five years. *Table 14* details these prices for a vessel with a size similar to the one chosen in this study.

Table 14. Time charter rates (Clarksons Research Services Ltd, 2017)

	1 Year Time charter Rate 58000 dwt Bulk carrier	**3 Year Time charter Rate 58000 dwt Bulk carrier**	**5 Year Time charter Rate 58000 dwt Bulk carrier**
Date	**$/Day**	**$/Day**	**$/Day**
2014	10952	10923	10910
2015	8106	8462	8712
2016	6495	6972	7660
2017	9279	**9625**	10022

It is noticeable that in 2015, 2016 and 2017 the prices for longer contracts are higher than for one year. However, in 2014 the effect was the opposite (Clarksons Research Services Ltd, 2017). There is reason to believe that these different behaviours of the market are related to the risk and the perception of the future. In 2014 the stakeholders were underpricing the long-time contracts due to the increase of risk of a decline of the rates for the future, as it resulted to happen. In the following years, the freight rates have already been very low, and therefore the forecasts for the future have been different. Based on the low market, the long-time contracts for the future have been comparatively higher than before (Clarksons Research Services Ltd, 2017).

Once again, the choice for the calculations will be influenced by the aim of neutralising these effects and find a solution that can be more serviceable. Thus, the current three-year time charter freight rate seems to have these attributes.

5. Key findings

As stated previously, the experiment consists of running three case studies. Two of them using one of the alternative sources of power previously identified.

5.1. Case study 1 - Standard ship

This case study is the framework against which the alternative propulsion systems are going to measure their benefits. As it has been explained before, the background is a vessel sailing in a circular route linking the Gibraltar Strait and the Panama Canal. The itinerary length is about 8600 nautical miles with different weather conditions (SeaRoutes.com, 2017). The weather patterns in the area indicate moderate to light winds, mainly from the NE (North East) quadrant (National Imagery and Mapping Agency-Department of Commerce, 2002).

The model ship used for the experiment is a Supramax bulk carrier fitted with a MAN 6S50ME-B9.5 engine. The cruising speed is 14.4 knots at a load of 82.9%. The fuel consumption under these circumstances is 25 tonnes per day. This is a new generation vessel, with an efficient fuel configuration. At a speed of 0.1 knots less than the average, it achieves a 7.4% fuel savings concerning her peer group of vessels (Clarksons Research Services Ltd, 2017). This information has to be taken into consideration since it could represent a bias. The model ship spends 24.9 days to go over the complete route without any stops. Consequently, it burns 622.5 tonnes of fuel oil. The standardised cost of the fuel for the entire voyage is 259,893 US$.

5.2. Case study 2 - Vessel equipped with three Flettner rotors

In this case, it has been considered the installation of three rotating sails on the deck of the standard ship. The Flettner rotors develop all their potential when the wind blows close to the beam of the vessel. Whenever this angle is modified, the performance drops reaching negative values when the wind comes from the bow (Norsepower Oy Ltd, 2017). However, this technology has proved to be quite versatile in different weather conditions, producing significant savings in both the go and return voyages.

The result of this case study is an estimated reduction of fuel burned by 4.75% in the route towards Panama and 3.23% of savings in the return trip. The average for the full itinerary is about 4%, meaning almost 25 tonnes of fuel saved and 10,370 US$ in 24.9 days. Considering an average of 300 days a year of navigation (Stopford, 2009), the yearly amount of savings would be 124,939 US$. If the total price for installing this equipment is 2,156,220 US$, the investment could be recovered in 17.25 years.

It is noticeable that in the less advantageous weather conditions, the Flettner rotors constituted a brake due to the friction with the air, producing an increase in fuel requirements. Nevertheless, in the most favourable wind, the maximum performance of the Flettner rotors produced savings higher than 25% of fuel, which is equivalent to 0.26 tonnes/hour and 2652 US$/day.

These results for this voyage are in line with the savings announced by one of the companies commercialising Flettner rotors (Norsepower Oy Ltd, 2017). Besides, there is a reduction of harmful particles sent out to the atmosphere of about 2.59%.

5.3. Case study 3 - Vessel equipped with a Parafoil

The last part of the project considers the same ship used in case study number 1, but with a Parafoil installed on her bow. The use of the Parafoil is optimum when the wind comes close to the transom of the vessel, and the intensity is force 6 Beaufort (Skysails GmbH, 2017). Nonetheless, the efficiency drops considerably as the wind moves forward.

The result of modelling the trip with the weather patterns of the Atlas of Pilot Charts and the Parafoil polar is a theoretical reduction of fuel consumption in the westward voyage of 1.35% in comparison with the standard ship, while the savings in the eastbound passage are below 1%. Altogether, it is an average of 1.065% on the round trip. This means about 6,62 tonnes of fuel saved and 2,767 US$ after 24.9 days. In other words, 0.26 tonnes of fuel per day.

Additionally, this device never produces increases in fuel consumption because it can be stored when the weather conditions are adverse.

The results are not in line with the numbers announced by the Skysails representative in the survey. This can be as a result of the long and complex process to make this study from the scarce data provided, because of the market focused perspective of Skysails, or due to a mix of both. The environmental gain of using the Parafoil in the studied routes is not noticeable as the reduction is less than 1%.

Overall, both devices produced fuel savings and exhaust emissions, being significantly more efficient in the three-rotors configuration. It is also noticeable that the Parafoil resulted to be more sensitive to the wind angle and force and performed well in a narrower weather spectrum. The study of these cases highlighted the potential of the combination of weather routing tools with any of the wind-assisted technologies presented in this research.

5.4. Financial metrics

An essential part of this project was the assessment of the economic feasibility of the installation of these wind-assisted technologies, and the determination of their contribution as part of a solution in a market with long-term overcapacity.

From an economic point of view, the installation of Flettner rotors seems to be a very recommendable and profitable option. Maybe this is the reason why one of the most renowned shipping lines has chosen two rotating sails to fit in one of its tankers as a project to measure and test the fuel savings derived from the use of the wind (Schuler, 2017).

Additionally, it is noteworthy that the benefits of both devices will vary proportionally with the bunker prices. Whenever the fuel becomes more expensive, more profitable will become both types of equipment.

The retrofit on a ship of an alternative source of power cannot be treated in this paper since all the calculations for case study one has been made considering a newly designed hull and engine, with higher performances. Nevertheless, taking into consideration that the fuel consumption of an old vessel should be higher, the author deems that the figures for fuel savings should be even higher for old ships.

It is general knowledge that shipowners frequently spend considerable amounts of money to obtain legal advice for obtaining savings in aspects such as crew and safety. Consequently, they very often flag out their ships in open registries adding some administrative expenses to the balance sheet of the company. An interesting issue for further research would be to assess the net savings obtained as a consequence of these policies and compare them with the net savings produced by the Flettner rotors or the Parafoil.

5.5. Strategic focus

Once it seems clear that the installation of at least one of these devices is economically feasible, there is an important question to answer. Why there are only a few vessels equipped with Flettner rotors? It is an important issue, especially considering that this is not a new technology. Rehmatulla et al. (2017) describe a number of main barriers to the utilisation of wind technologies in shipping. Amongst them, the limited access to capital and its costs could be properly addressed with this paper. However, the purpose of this project is not only testing the economic extent of the matter. It is also important to evaluate if it could be part of a solution for a company competing for a share of a market with overcapacity. The answer to the previous question could be related to the strategic dimension of the shipping companies and also serve for this project.

One of the reasons why wind technologies have not been used for the moment is because the shipowner frequently is not who supports the cost of the fuel. From the three ways of obtaining incomes, only in the voyage charter model, the shipowner has to pay the bunker expenses.

As seen in *Table 15*, the incomes of operating a Supramax bulk carrier by a shipowner whose business is principally voyage charter could average above 50,000 US$ per day (Clarksons Research Services Ltd, 2017). The operating costs of this ship would be around 4,000 US$ a day (Neylan, 2016). The daily fuel costs of the standard ship of the case study one were 7.873 US$. Altogether means that the shipowner has a margin of about 38,000 US$ per day to pay the rest of the voyage expenses such as ports or stevedores, and the rest are benefits. The savings produced by the Flettner rotors of 416.4 US$ represent less than 1% of the freight rate. Maybe this percentage is not noticeable enough, and only it is perceived as important in seasons of a strong recession. It is also important to mention that it seems logical that in a period of strong oversupply, the voyage charters are strongly reduced, and the ships probably stay many days without obtaining earnings. Thus, the substantial margins obtained are probably used to support the idle periods.

Table 15: Main findings - Summary

	Standard Ship	**Parafoil**	**Flettners**
Fuel Costs - US$/day	10437	10325	10021
Average fuel savings respect the standard - US$/day	n/a	111.1	416.4
Average fuel savings respect the standard - %	n/a	1.06%	3.9%
Fuel savings westbound route - %	n/a	1.35%	4.75%

Maximum fuel savings -%	n/a	17.34%	25.39%
Fuel savings eastbound route -%	n/a	0.78%	3.26%
Cost of the equipment tested - US$	n/a	2,428,143	2,156,220
Pay off period - years	n/a	75	17.26
Operation Costs - US$/day	4,000	4,000	4,000

Alternatively, for shipowners operating based on the time charter, fuel costs may not represent an issue since charterers are who pay for this item. However, a deeper analysis of this situation could be interesting.

A time charterer pays an average of 9,625 US$ per day. If this operator could choose a vessel to charter, probably would prefer one with a specific fuel consumption 4% lower than its competitors. This option could save 416.4 US$ every day in fuel, about 4.3% of the freight rate. Here is where the Flettner rotors become important. This charterer could become a leader in costs in his sector. Besides, could claim the *eco-friendliness* of his choices, obtaining some level of differentiation.

All these points have been described as strategies followed by successful companies in highly competitive environments (Palepu et al., 2016; Porter, 1998). Consequently, the first impression could be that the charterer would be the absolute beneficiary of the shipowner’s investment.

The shipowner would indeed have a competitive advantage against its competitors being the first choice for the charterers. It would be due to differentiation. The experts state that differentiation lets companies increase their prices (Palepu et al., 2016; Porter, 1998). If this shipowner reduces its freight rates by 170 US$, he will be sharing the benefits of fuel efficiency with the charterer. This will make it easier to charter the vessel being cheaper than the average, and the shipowner can recover the investment in the life cycle of the vessel. This could be a practical appliance of what is described as "split incentives", which is presented as another barrier to the use of wind-assisted vessels (Rehmatulla et al., 2017). This is the point where the Flettner rotors could become not only economically positive but also important strategically for a shipowner operating on a time charter basis.

6. Conclusion

The shipping industry has had a problem with the structural excess of capacity caused by a reduction of demand. Instead of adjusting to the new situation, shipowners have found themselves trapped in the market with recently delivered ships and orders placed for new tonnage still to be delivered. Therefore, the problem has worsened over the years. The result of this situation has been an increase in competition with the consequent decrease in the freight rates.

It is important to control the volume of expenses of the company to achieve leadership in costs. In seaborne transport, the amount of money dedicate to cover fuel consumption is more significant than any other section in the shipping companies' accounts. Thus, controlling the amount of fuel utilised could be key to succeed in this competitive framework. Additionally, if this extent is achieved by the utilisation of innovative and eco-friendly technologies, also differentiation could come implicitly. The Flettner rotors and the Parafoil are two alternatives to install onboard which use the wind to propel the vessel. These technologies have been in the market for years, more specifically, the Flettner rotors were first introduced about a century ago.

A simple method to evaluate the feasibility of these alternative propulsion systems has been to set a specific framework to compare the performances of these alternatives sources of power with a standard ship. The first consideration has been to create a framework that could apply to the largest number of situations possible. With this purpose, the ship selected is a modern standard Supramax bulk carrier, sailing in a circular route linking Gibraltar and Panama.

The results of the study are summarised in *Table 15*. They give evidence of the benefits of both alternative sources of power. However, the Flettner rotors solution has proved to be financially feasible. The research also disclosed the better versatility of the rotating sails in all weather conditions.

However, this analysis has to be considered with caution. The experiment represents our interpretation of real-world data. The freight rates, bunker prices, weather conditions and even the route are simplifications done to have an achievable project. Most of the simplifications of the model have been made bearing in mind prudence, which would most probably produce any variations of the forecasted savings upwards, however, the power consumption of the Flettner rotors electric engines have been neglected. This constitutes the main limitation of the study. Even considering the limitations, the outcomes of the project give evidence enough to reach the following conclusions:

First, rotating sails have proven to generate savings enough during the life of the vessel to make an investor not only to recover the initial outlay but also to make profits. Furthermore, ranks them among the possible strategic solutions to compete in an oversupplied market. Additionally, for a ship built to sail in a wide range of weather conditions, the Flettner rotors are a safer and more preferable option. Moreover, the frequent divergence between the allocation of the role of shipowner (investor) and the person who bears the fuel costs (beneficiary of the savings), makes necessary a share of the benefits. Thus, in some of the situations tested, only the Flettner rotors generate savings enough to constitute a strategic solution that allows the shipowner to repay the investment and the charterer to be a leader in costs.

In addition, although none of the technologies seems to be enough to reach the future sulphur cap or the CO_2 reduction target, they contribute to reducing noxious emissions and could be combined with other solutions.

List of references

Adamopoulos, A., 2017. Regulation - Brussels wants "more action, fewer letters" on emissions - Lloyd's list [WWW Document]. URL https://www.lloydslist.com/ll/sector/regulation/article547085.ece (accessed 1.12.17).

Agencia Estatal de Meteología, 2020. Escalas de Viento y Oleaje [WWW Document]. URL https://www.aemet.es/documentos/es/conocermas/maritima/escalas_de_viento_y_oleaje.pdf

Ammar, N.R., 2019. An environmental and economic analysis of methanol fuel for a cellular container ship. Transportation Research Part D: Transport and Environment 69, 66–76.

Anderson, K., Bows, A., 2012. Executing a Scharnow turn: reconciling shipping emissions with international commitments on climate change. Carbon Management 3, 615–628. https://doi.org/10.4155/cmt.12.63

Armellini, A., Daniotti, S., Pinamonti, P., Reini, M., 2018. Analysis of alternative energy production systems for a large cruise ship to meet new IMO regulations. Part A: GTs as prime movers. Applied Energy 211, 306–317. https://doi.org/10.1016/j.apenergy.2017.11.057

Bengtsson, S., Andersson, K., Fridell, E., 2011. A comparative life cycle assessment of marine fuels: liquefied natural gas and three other fossil fuels. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment 225, 97–110. https://doi.org/10.1177/1475090211402136

Bentin, M., Zastrau, D., Schlaak, M., Freye, D., Elsner, R., Kotzur, S., 2016. A New Routing Optimization Tool-influence of Wind and Waves on Fuel Consumption of Ships with and without Wind Assisted Ship Propulsion Systems. Transportation Research Procedia 14, 153–162. https://doi.org/10.1016/j.trpro.2016.05.051

Bordogna, G., Muggiasca, S., Giappino, S., Belloli, M., Keuning, J.A., Huijsmans, R.H.M., 2020. The effects of the aerodynamic interaction on the performance of two Flettner rotors. Journal of Wind Engineering and Industrial Aerodynamics 196, 104024. https://doi.org/10.1016/j.jweia.2019.104024

Bordogna, G., Muggiasca, S., Giappino, S., Belloli, M., Keuning, J.A., Huijsmans, R.H.M., van 't Veer, A.P., 2019. Experiments on a Flettner rotor at critical and supercritical Reynolds numbers. Journal of Wind Engineering and Industrial Aerodynamics 188, 19–29. https://doi.org/10.1016/j.jweia.2019.02.006

Breukels, J., 2011. An engineering methodology for kite design (PhD Thesis). Aerospace Engineering.

Clarksons Research Services Ltd, 2017. Shipping Intelligence Network [WWW Document]. URL https://sin.clarksons.net/Timeseries (accessed 5.13.17).

Dadd, G.M., 2013. Kite dynamics for ship propulsion (PhD Thesis). University of Southampton.

Fagiano, L., Zgraggen, A.U., Morari, M., Khammash, M., 2013. Automatic crosswind flight of tethered wings for airborne wind energy: Modeling, control design, and experimental results. IEEE Transactions on Control Systems Technology 22, 1433–1447.

Glave, T., Joerss, M., Saxon, S., 2014. The hidden opportunity in container shipping [WWW Document]. URL http://www.mckinsey.com/business-functions/strategy-and-corporate-finance/our-insights/the-hidden-opportunity-in-container-shipping (accessed 12.20.16).

Hapag-Lloyd AG, 2016. Shipping Made in Hamburg - The History of the Hapag-Lloyg AG [WWW Document]. URL https://www.hapag-lloyd.com/en/about-us.html (accessed 12.20.16).

Hirdaris, S.E., Cheng, F., 2012. The role of technology in green ship design, in: Proceedings of the 11th International Marine Design Conference (IMDC), Glasgow, UK. pp. 11–14.

Hwang, S.S., Gil, S.J., Lee, G.N., Lee, J.W., Park, H., Jung, K.H., Suh, S.B., 2020. Life Cycle Assessment of Alternative Ship Fuels for Coastal Ferry Operating in Republic of Korea. Journal of Marine Science and Engineering 8, 660.

Iannaccone, T., Landucci, G., Tugnoli, A., Salzano, E., Cozzani, V., 2020. Sustainability of cruise ship fuel systems: Comparison among LNG and diesel technologies. Journal of Cleaner Production 260, 121069.

ICF, 2009. Current Methodologies in Preparing Mobile Source Port-Related Emission Inventories: Final Report (April 2009). U.S. Environmental Protection Agency.

IMO, 2017. International Maritime Organization moves ahead with oceans and climate change agenda [WWW Document]. URL http://www.imo.org/en/MediaCentre/PressBriefings/Pages/17-MEPC-71.aspx (accessed 8.28.17).

IMO, 2016. Sulphur oxides (SOx) - regulation 14 [WWW Document]. URL http://www.imo.org/en/OurWork/environment/pollutionprevention/airpollution/pages/sulphur-oxides-(sox)-—regulation-14.aspx (accessed 12.1.16).

Imray Laurie Noire & Wilson Ltd, 2012. North Atlantic Ocean Passage Chart [map]. Imray Laurie Noire & Wilson Ltd, St Ives.

Kang, C.A., Brandt, A.R., Durlofsky, L.J., 2011. Optimal operation of an integrated energy system including fossil fuel power generation, CO2 capture and wind. Energy 36, 6806–6820. https://doi.org/10.1016/j.energy.2011.10.015

Karslen, R., Papachristos, G., Rehmatulla, N., 2019. An agent-based model of climate-energy policies to promote wind propulsion technology in shipping. Environmental Innovation and Societal Transitions 31, 33–53. https://doi.org/10.1016/j.eist.2019.01.006

Kornei, K., 2017. Spinning metal sails could slash fuel consumption, emissions on cargo ships. American Association for the Advancement of Science. https://doi.org/10.1126/science.aap8915

Leloup, R., Roncin, K., Behrel, M., Bles, G., Leroux, J.-B., Jochum, C., Parlier, Y., 2016. A continuous and analytical modeling for kites as auxiliary propulsion devoted to merchant ships, including fuel saving estimation. Renewable Energy 86, 483–496.

Lin, M.T., 2017. Dry bulk's year of broken promises [WWW Document]. URL https://lloydslist.maritimeintelligence.informa.com/LL110687/Dry-bulks-year-of-broken-promises (accessed 8.7.17).

Loyd, M.L., 1980. Crosswind kite power (for large-scale wind power production). Journal of energy 4, 106–111.

Luo, X., Wang, M., 2017. Study of solvent-based carbon capture for cargo ships through process modelling and simulation. Applied Energy 195, 402–413. https://doi.org/10.1016/j.apenergy.2017.03.027

Met Office, 2017. Beaufort wind force scale [WWW Document]. Www.Metoffice.Gov.Uk/Guide/Weather/Marine/Beaufort-Scale. URL http://www.metoffice.gov.uk/guide/weather/marine/beaufort-scale (accessed 8.9.17).

Naaijen, P., Koster, V., Dallinga, R.P., 2006. On the power savings by an auxiliary kite propulsion system. International shipbuilding progress 53, 255–279.

National Geospatial-Intelligence Agency, 2017. Pilot chart of the North Atlantic Ocean [WWW Document]. URL http://msi.nga.mil/MSISiteContent/StaticFiles/NAV_PUBS/APC/Pub106/106oct.pdf (accessed 1.5.17).

National Imagery and Mapping Agency- Department of Commerce, 2002. Atlas of Pilot Charts. United States Government, United States.

Neylan, P., 2016. Drewry Ship operating costs annual review and forecast: Annual report (2016/2017). Drewry Maritime Research.

Norsepower Oy Ltd, 2017. Home [WWW Document]. URL http://www.norsepower.com (accessed 1.5.17).

Palepu, K.G., Healy, P.M., Peek, E., 2016. Business Analysis and Valuation: IFRS edition, Fourth edi. ed. Cengage Learning - M.U.A, GB.

Pili, R., Romagnoli, A., Kamossa, K., Schuster, A., Spliethoff, H., Wieland, C., 2017. Organic Rankine Cycles (ORC) for mobile applications – Economic feasibility in different transportation sectors. Applied Energy 204, 1188–1197. https://doi.org/10.1016/j.apenergy.2017.04.056

Porter, M.E., 1998. Competitive strategy : techniques for analyzing industries and competitors ; with a new introduction. Free Press of Glencoe, UK.

Rehmatulla, N., Parker, S., Smith, T., Stulgis, V., 2017. Wind technologies: Opportunities and barriers to a low carbon shipping industry. Marine Policy 75, 217–226. https://doi.org/10.1016/j.marpol.2015.12.021

Royal Meteorological Society, 2017. Beaufort Scale [WWW Document]. URL https://www.rmets.org/weather-and-climate/observing/beaufort-scale (accessed 8.27.17).

Sahin, B., Senol, Y.E., Bulut, E., Duru, O., 2015. Optimizing technology selection in maritime logistics. Research in Logistics & Production 5.

Sahin, B., Yip, T.L., 2017. Shipping technology selection for dynamic capability based on improved Gaussian fuzzy AHP model. Ocean Engineering 136, 233–242.

Sand, P., 2011. Container shipping - Slow demand and the absence of resumed idling of vessels has proved to be a heavy burden in the battle for rate restoration [WWW Document]. URL https://www.bimco.org/News/Market_Analysis/2011/0624_Container_Shipping?pn=18 (accessed 1.4.17).

Saunders, M., Lewis, P., Thornhill, A., 2016. Research methods for business students, 7. ed. ed. Pearson, Harlow.

Saunders, M.N.K., Lewis, P., 2012. Doing Research in Business & Management: An Essential Guide to Planning Your Project. Pearson, UK.

Schmidt, A., 2013. Enercon E-ship 1: a wind-hybrid commercial cargo ship, in: Proceedings of the 4th Conference on Ship Efficiency; Sep. pp. 23–24.

Schuler, M., 2017. Maersk Tanker to Be Fitted with Flettner Rotor Sails [WWW Document]. URL http://gcaptain.com/maersk-tanker-fitted-flettner-rotor-sails/ (accessed 5.5.17).

Searcy, T., 2017. Harnessing the wind: A case study of applying Flettner rotor technology to achieve fuel and cost savings for Fiji’s domestic shipping industry. Marine Policy 86, 164–172.

SeaRoutes.com, 2017. Sea Routes [WWW Document]. URL https://www.searoutes.com/routing/4294968111/4294968578?speed=13&panama=true&suez=true&kiel=true (accessed 8.29.17).

Ship and Bunker, 2020. Global 20 Ports Average [WWW Document]. URL https://shipandbunker.com/prices/av/global/av-g20-global-20-ports-average#IFO380

Skysails GmbH, 2017. SkySails GmbH - home [WWW Document]. URL http://www.skysails.info/english/ (accessed 1.5.17).

Smith, T.W.P., Jalkanen, J.P., Anderson, B.A., Corbett, J.J., Faber, J., Hanayama, S., O’Keeffe, E., Parker, S., Johansson, L., Aldous, L., Raucci, C., Traut, M., Ettinger, S., Nelissen, D., Lee, D.S., Ng, S., Agrawal, A., Winebrake, J.J., Hoen, M., A., 2014. Third IMO Greenhouse Gas Study 2014. International Maritime Organization (IMO) 327. https://doi.org/10.1007/s10584-013-0912-3

Stopford, M., 2009. Maritime economics, 3. ed. ed. Routledge, London [u.a.].

Suisse Eole, 2017. Wind Profile Calculator [WWW Document]. URL http://wind-data.ch/tools/profile.php?h=10&v=10&z0=0.1&abfrage=Refresh (accessed 8.28.17).

Talluri, L., Nalianda, D.K., Giuliani, E., 2018. Techno economic and environmental assessment of Flettner rotors for marine propulsion. Ocean engineering 154, 1–15.

Tan, W.Z., 2016. Hanjin files for court receivership - Lloyd’s list [WWW Document]. URL https://www.lloydslist.com/ll/sector/ship-operations/article535262.ece (accessed 1.4.17).

Traut, M., Gilbert, P., Walsh, C., Bows, A., Filippone, A., Stansby, P., Wood, R., 2014a. Propulsive power contribution of a kite and a Flettner rotor on selected shipping routes. Applied Energy 113, 362–372. https://doi.org/10.1016/j.apenergy.2013.07.026

Traut, M., Gilbert, P., Walsh, C., Bows, A., Filippone, A., Stansby, P., Wood, R., 2014b. Propulsive power contribution of a kite and a Flettner rotor on selected shipping routes. Applied Energy 113, 362–372.

UNCTAD, 2020. Review of Maritime Transport 2020. REVIEW OF MARITIME TRANSPORT 159.

UNCTAD, 2019. REVIEW OF MARITIME TRANSPORT 2019. UNITED NATIONS, New York.

UNDOS, 2019. Environmental Impact Assessment for UN Field Missions (SOP).

UNEP, 2004. Environmental Impact Assessment and Strategic Environmental Assessment: Towards an Integrated Approach [WWW Document]. UNEP - UN Environment Programme. URL http://www.unep.org/resources/report/environmental-impact-assessment-and-strategic-environmental-assessment-towards (accessed 2.28.21).

UNFCCC, 2014. Introduction to the Convention [WWW Document]. UN Framework Convention on Climate Cange. URL http://unfccc.int/essential_background/convention/items/6036.php

Wang, F., Deng, S., Zhao, J., Wang, J., Sun, T., Yan, J., 2017a. Performance and economic assessments of integrating geothermal energy into coal-fired power plant with CO2 capture. Energy 119, 278–287. https://doi.org/10.1016/j.energy.2016.12.029

Wang, F., Zhao, J., Li, H., Deng, S., Yan, J., 2017b. Preliminary experimental study of post-combustion carbon capture integrated with solar thermal collectors. Applied Energy 185, 1471–1480. https://doi.org/10.1016/j.apenergy.2016.02.040