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Application of wind propulsion in the existing fleet of the Caspian Sea using real wind data

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APPLICATION OF WIND PROPULSION IN THE EXISTING FLEET OF THE CASPIAN SEA USING REAL WIND DATA

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A dissertation submitted to the World Maritime University in partial fulfilment of the requirements for the award of the degree of Master of Science in Maritime Affairs

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Declaration

I certify that all the material in this dissertation that is not my own work has been identified and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views and are not necessarily endorsed by the University.

(Signature): 

(Date): **22 Sep 2023**

Supervised by: **Assistant Professor Alessandro Schönborn**

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Abstract

Title of Dissertation: **Application of wind propulsion in the existing fleet on the Caspian Sea using real wind data**

Degree: **Master of Science**

This research assesses the propulsive power contribution of Flettner rotor and Wing sail technologies when used on an RO-PAX ferry operating in the Caspian Sea. The evaluation was conducted using a mathematical model calculating the forces produced by Wing Sail and Flettner rotor propulsion systems.

In order to address global climate change issues brought on by greenhouse gas emissions from the burning of fossil fuels, research will give solutions using renewable energy sources. In addition, will consider installing wind energy on board ships or explore the implementation of wind power energy and identify the most efficient technique for generating maximum power. First, the model calculated the optimum rigid wing sail angles under various wind conditions. Second, the model calculated the thrust force and power contribution of the Wing sail and Flettner rotor during selected months and days. The model was applied using real wind data for a specific region (Caspian Sea) in a selected route, from Baku Port to Kurik Port. Maximum thrust results were obtained in July for the Wing Sail, whilst the Flettner rotor generated higher values compared to the Wing Sail in October. While analysing and calculating the power generation of the Flettner rotor, the maximum value for the spin ratio of the rotors was limited to 2. Based on power values, total energy calculations with and without wind-assisted propulsion were conducted. Fuel savings for the Flettner rotor were found to be around 4-5% in October, however, average fuel savings were about 2% per year. Accordingly, 7.8 tons of CO_2 can be saved per year.

The cost-benefit assessments have shown that the implementation of these new technologies on the selected ferry is contingent upon many factors specific to the area and the chosen route. In addition, the sail angle optimization model may serve as a valuable tool for both design and operational purposes.

Keywords: Optimisation, Rigid wing sail, Flettner rotor, Wind power, spin ratio, Fuel/CO_2 savings, Cost-benefit analyses.

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List of Abbreviation

AIS	Automatic identification system
AWS	Apparent Wind Speed
CF	Cash Flow
CCF	Cumulative Cash Flow
CDCF	Cumulative Discounted Cash Flow
CFD	Computational Fluid Dynamics
DCF	Discounted Cash Flow
DWT	Deadweight Tonnage
ECMWF	European Centre for Medium-Range Weather Forecasting
FR	Flettner Rotor
GCR	Great Circle Route
GHG	Greenhouse Gas Emission
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
NACA	National Advisory Committee for Aeronautics
RES	Renewable Energy System
TWS	True Wind Speed
TWA	True Wind Angle
UNFCCC	United Nations Framework Convention on Climate Change
WASP	Wind-Assisted Ship Propulsion
WPT	Wind Propulsion Technology

Chapter 1 INTRODUCTION

Chapter 1.1 Background

The greenhouse effect is a result of greenhouse gases (GHGs) in the atmosphere preventing infrared radiation from escaping into space. The result of the artificial addition of greenhouse gases since the start of the industrial age (UNFCCC, 2001) is global warming, which produces numerous sorts of climatic changes on the earth's surface. These GHGs include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases.

The use of fuel oil in the production of in the energy and transportation sectors, is a significant contributor to global GHG emissions. Road transportation is one the important sources of GHGs in the transportation sector, according to the International Maritime Organization (IMO), the projected contribution of international shipping to global greenhouse gas (GHG) emissions is at 2.89%, in its Fourth GHG study (IMO, 2020). In addition, as per the Fourth IMO GHG Study, there was a 9.6% increase in the total greenhouse gas (GHG) emissions of international, domestic, and fisheries shipping, rising from 977 million tonnes in 2012 to 1,076 million tonnes in 2018 (IMO, 2020). The emissions in question include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), and are quantified in terms of carbon dioxide equivalent (CO_2e). There was a notable rise in carbon dioxide (CO_2) emissions, with levels escalating from 962 million tonnes in 2012 to 1,056 million tonnes in 2018, representing a 9.3% surge (IMO, 2020). As a result, worldwide shipping's share of GHG emissions grew from 2.76% to 2.89%. To address the issue of climate change and align with the United Nations' sustainable development goal 13, the International Maritime Organization (IMO, 2023) has established ambitious targets. These targets aim to decrease greenhouse gas (GHG) emissions by a minimum of 20% and aim for a 30% reduction by 2030. Furthermore, the IMO aims to achieve a reduction of at least 70% and strive for an 80% reduction by 2040, in comparison to the emissions recorded in 2008 and achieve a state of net-zero GHG emissions by approximately 2050.

The replacement of these conventional fuels with alternative clean energy sources has been acknowledged as an essential worldwide issue given that shipping heavily depends on fossil fuel combustion, which considerably contributes to air pollution (IMO, 2018a). Many studies and a number of scholars have concentrated on the application of renewable energy systems (RESs) and energy storage systems for ships, and have proposed various alternatives to fossil fuels. Since many alternative fuels have a low flashpoint, safety concerns related to storage and onboard use must be taken into consideration, such as hydrogen's strong flammability or ammonia's toxicity (Marketa, 2020). In addition, a life cycle analysis of the fuel should be taken into account when comparing the costs and environmental advantages of various fuels.

On the other hand, technologies based on renewable energy offer enticing alternatives for achieving the marine industry's zero-emission goal. Over the course of the last 150 years, there have been significant transformations in the propulsion energy sources used by ships. Notable shifts include the transition from sail power, which relied on renewable energy, to the utilisation of coal, heavy fuel oil (HFO), and marine diesel oil (NFNR Alkhaledi et al., 2023). The reason why is because wind-assisted propulsion is one of the few ship technologies that offer double-digit fuel and emissions reductions, Wind-Assisted Ship Propulsion (WASP) is a potential option and is anticipated to be a significant source of renewable energy for the shipping sector in the future. To harness the power of the wind and produce forward force, equipment like rotor sails, wing sails, or soft sails are used in wind propulsion. A readily available and sustainable energy source at sea, wind power may directly power ships without losing any energy (Konstantinos, 2020). Different wind propulsion systems, commonly referred to as wind-assisted propulsion, can be retrofitted to current ships as an additional power source (Konstantinos, 2020). In order to enhance fuel efficiency, optimise the thermal efficiency of the primary propulsion system, and align with forthcoming zero-emission objectives in the maritime sector, the integration of renewable energy technologies as auxiliary propulsion systems may offer a viable pathway towards sustainability across diverse ship categories within the marine industry (NFNR Alkhaledi et al., 2023).

In order to achieve better sustainable future shipping, comply with new regulations, to solve above mentioned issues, this thesis is mainly focused on implementation renewable energy sources, especially retrofitting to existing vessel which will be determine propulsive power contribution from wind technology on the selected route (from Baku Port to Kurik Port) in the Caspian region. Implementation of this technology will help to reduce fuel consumption and GHG emissions.

Chapter 1.2 Problem statement/motivation

The current use of fossil by society has a number of negative effects. These include the threats of air pollution, acid rain, and resource depletion. This succinct introduction focuses on one of these issues: global climate change brought on by greenhouse gas emissions from the burning of fossil fuels.

Technologies that increase the energy efficiency of systems using conventional, non-renewable energy sources are also a part of renewable energy and sustainable energy systems. Energy demand growth will be slowed down, the usage of fossil fuels will be drastically reduced, and pollutant emissions will be decreased through increasing the effectiveness of energy systems or creating cleaner and more efficient energy systems (*Climate change 2007: Synthesis report; an assessment of the intergovernmental panel on climate change*, 2008).

To address these issues, this research will give solutions using renewable energy sources. Also, will consider installing wind energy on board ships, or to explore the implementation of wind power energy and identify the most efficient technique for generating maximum power. Therefore, using renewable energy sources will help to improve energy efficiency, in addition, it aids in the reduction of fuel use while simultaneously decreasing operational expenses.

Chapter 1.3 Aim and objectives

The aim of this study is to investigate the possible contribution of implementation of wind propulsion technologies (Flettner rotor and Wing sail) on the RO-RO Passenger ferry in the Caspian region. The study will achieve the following objectives:

- Compare different renewable energy technologies for their suitability on various types of vessels, especially Ro-pax, to achieve energy efficiency and the possibility of reducing carbon emissions,
- Calculate and determine the effective power of FRs and wing sails on vessels in this region.
- To determine fuel saving and CO_2 emission reduction.
- To evaluate economic aspects in order to implement these technologies.

Chapter 1.4 Research questions

- What kind of technology is available to use on-board ships?
- What are the possible contributions of Flettner rotor (FR) systems and Wing sails to the propulsion power of Roll-on/Roll-off Passenger (Ro-Pax) vessels?
- How much fuel can be saved and CO_2 emission be reduced?
- What are the costs associated?

Chapter 1.5 Research limitations

The below mentioned the limitations of this study:

- The comprehensive evaluation of the socio-economic effects resulting from the application of these technologies has not been conducted.
- For the different months and days, one route was selected: From Baku Port to Kurik Port

- The selected days from various months for analysing was from AIS data provider (Marine Traffic), so, the vessel did voyages from Baku Port to Kurik Port only those days in selected months.

For the simplifications:

- For the retrofitting of wind technologies, it was assumed that the vessel going without any drift. It means there was no consideration about any hydrodynamics effects.
- In the context of retrofitting possibilities, it is believed that the weight of the Wing sail and FR (Flettner rotor) does not affect the stability of the vessel or its wetted surface area. Consequently, any resulting changes in total ship resistance may be considered minimal.
- For the simplification, ship heading is equal to ship course. It is not realistic, but for the first generation it is a reasonable simplification.

Chapter 2 LITERATURE REVIEW

Chapter 2.1 Chapter overview

This chapter mainly focuses on various wind assisted ship propulsion technologies, specially FRs and wing sails, their contribution to emission savings and reduction of the fuel consumption. Along with the key research on this technology, several contributions from various bodies of literature have been evaluated.

These new and current ships may become more energy efficient and depend less on fossil fuels by utilising a variety of technology (Delft & Fraunhofer, 2016). We can divide energy efficiency measures into two categories: technological procedures that reduce energy use by making design changes and operational strategies that modify how ships are utilized in order to use less energy. In addition to this, economic measures are another type, which are considered to be mid-term measures and are due to be evaluated and adopted by IMO in the coming years.

Renewable energy technologies present themselves as appealing alternatives for attaining the objective of zero emissions within the maritime industry. Therefore, there is a collective global endeavour to advance the utilisation of sustainable renewable energy as a means of propelling ships. Furthermore, the utilisation of renewable energy technologies as an adjunctive propulsion system for maritime vessels has the potential to serve as a viable remedy for mitigating the adverse consequences associated with the consumption of fossil fuels and the resultant emissions (Carlton et al., 2013). Renewable energy sources are both the most traditional and cutting-edge kinds of energy that civilization uses today. Alternative ship propulsion system designs must be developed and evaluated for performance and environmental impact in order to meet maritime emission reduction targets.

Chapter 2.2 Wind propulsion concepts

The wind energy industry grew as other technologies did, and researchers worked to provide effective ways to utilise wind energy. Wind propulsion methods are either in the early stages of development or have only been adopted by a few customers on a very modest scale, despite their promise to reduce fuel use and consequently lower GHG emissions from shipping. By using the wind energy source directly and physically converting it to propulsion, wind propulsion eliminates any energy conversion issues and delivers an efficient energy alternative that is compatible with all other energy sources selected (MEPC 79-INF.21). Over other forms of GHG mitigation, wind propulsion offers a number of notable advantages. In order to fulfil the carbon budgets required by the Paris Agreement, the sector must first quickly reduce emissions by using short-term carbon reduction strategies (Bullock et al., 2020). Action must be taken right now that uses refit technologies to target current ships. Both of these requirements are met by wind propulsion, which is now in use on some fleet boats that have retrofitted wind propulsion systems (Mason, 2021). Wind propulsion is considered to be one of the limited numbers of effective GHG mitigation options capable of reducing carbon dioxide emissions, as well as other pollutants such as SO_x and NO_x (Bows-Larkin et al., 2014). People who work in the shipping business are once again paying attention to wind propulsion technology as a result of pressure from international environmental policies. The sails lower the main engine's required power to maintain the same speed, hence reducing fuel consumption and carbon emissions (Mason, 2021) (Figure 1). The principal advantages of utilising wind energy on ships are, in essence, the same as those of using wind energy generally, decrease in the utilisation of traditional energy sources and the subsequent reduction in the release of hazardous gases (Wang et al., 2022). The optimization results indicate that the implementation of renewable energy systems on a ship may result in a significant reduction of 36% in CO2 emissions, in comparison to a ship that operates without such systems (NFNR Alkhaledi et al., 2023). According to the Fourth IMO GHG Study (IMO, 2020), the conventional fuel price of 375 USD can result in a CO_2 emission reduction of 36% through the implementation of cost-effective technologies. In the event that the price increases to 750 USD, a higher reduction of 80% in CO_2 emissions can be achieved through the same cost-effective technologies. Conversely, if the price decreases to 188 USD, a lower reduction of 25% in CO_2 emissions can be attained through the utilisation of cost-effective technologies. In the year 2050, the cost-effective reduction of carbon dioxide (CO_2) emissions constitutes 13% of the total, with a price of 375 USD for conventional fuel. A decrease of 26% in CO_2 emissions may be achieved by the use of cost-effective solutions, given a budget of 750 USD. Especially CO_2 abatement potential for wind power can be achieved around 1% for 2030 and approximately 2% for 2050. According to the 2023 GHG Strategy, a basket of candidate measure(s) that are capable of delivering on the reduction objectives should be created, and an economic element, on the basis of a marine GHG emissions pricing system, should be finalized as part of this process (IMO, 2023). In the future there most likely will be a price on carbon emission.

Wind propulsion technologies, also known as WPTs, provide a potential technological solution for reducing carbon emissions in the shipping industry. These technologies may be used alongside battery-powered or fossil fuel propulsion systems as an additional means of propulsion (Thies & Ringsberg, 2022). The proportion of vessels constructed during the period of 2010 to 2014 amounts to 29% of the total tonnage of the worldwide fleet. This signifies a significant market opportunity for implementing energy-efficient technology, such as wind-assisted propulsion or other forms of energy conversion, via retrofitting (Clarksons Research, 2022a). The use of wind as an energy source may be seen as both free and renewable due to its little frictional resistance in open seas as opposed to land. Consequently, wind exhibits a competitive advantage over other developing cleaner propulsion technologies in the shipping industry (Talluri et al., 2018). Numerous contemporary wind propulsion technologies are now being designed and refined, primarily with the objective of mitigating fuel consumption and minimizing emissions of air pollutants (Ballini et al., 2017). These technologies can be used either optimized with the combination with the primary engine or primary source of the propulsion where conventional engines are used only in exceptional.

The estimated power savings may then be securely turned into emissions reductions, and the economic impact can be measured, using reliable wind data. In order to evaluate the return on investment for wind-assisted ships, this is an essential financial factor. Although their volatility is unexpected, oil prices are known to have an impact on interest in more sustainable propulsion solutions (Khan et al., 2021).

Figure 1

Effects of design technologies on GHG savings

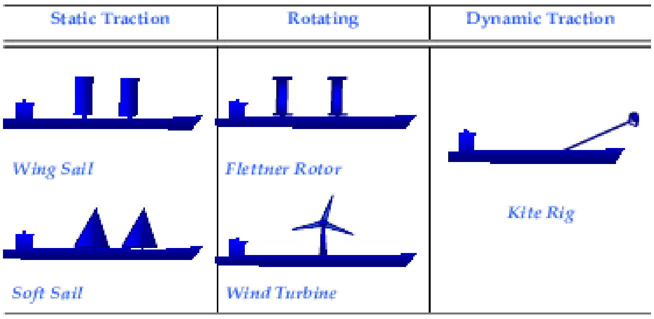
Technology	Potential GHG Savings
WASP	In excess of 30%
Slender Design	Up to 15%
Air Lubrication	Up to 13%
Increased Cargo	Up to 10% (large vessels)
Materials	Up to 10 %
Propeller design	Up to 10%
Bulbous Bow	Up to 7%
Heat Recovery	Up to 6%
Hull Surface	Up to 5%

Note. From "A review of wind-assisted ship propulsion for sustainable commercial shipping: latest developments and future stakes" by Khan, L., Macklin, J., Peck, B., Morton, O., & Souppez, J. B. R, *Proceedings of the Wind Propulsion Conference 2021*, Royal Institution of Naval Architects (https://research.aston.ac.uk/en/publications/a-review-of-wind-assisted-ship-propulsion-for-sustainable-commerc). Copyright 2021 by The Authors.

In general, the six major kinds of wind propulsion technology for ships are: rigid sails/wing sails, turbo sail/suction wings, soft sails, towing kites, Flettner rotors, and wind turbines (Figure 2). Among these technologies, Flettner rotors and wing sails are more common and effective technologies. In this research Flettner rotor and Wing sail will be discussed and analysed based on weather conditions and specific route for the performance of the wind assisted propulsion.

Figure 2

Various Wind Assisted Propulsion Technologies



Note. From "The role of technology in green ship design" by Hirdaris, S., & Fai, C, 11th International Marine Design Conference (volume 1, p 11-14), 2012, IMDC2012 Secretariat Department of Naval Architecture and Marine Engineering University of Strathclyde (http://doi.org/10.13140/RG.2.1.4242.0564). Copyright 2012 by Spyros E. Hirdaris.

Chapter 2.2.1 Rigid sails/Wing sails

Aerodynamically, rigid wing sails are aerofoils that resemble the wings of an aeroplane. Their vertical orientation and capacity to provide lift on either side are their key differences. As a sailboat must tack while following the wind, this final quality is essential. This is why rigid wing sails typically have symmetric NACA profiles.

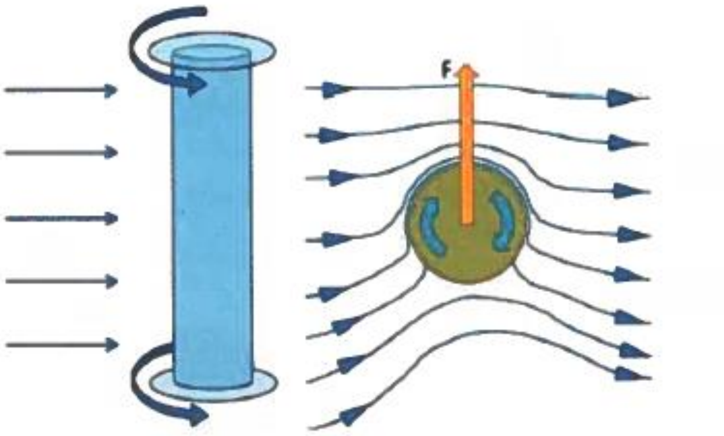
Increasing the aerofoil's effective camber allows trailing-edge flaps to provide more lift. Although employing trailing-edge flaps results in a larger maximum lift coefficient, the stall angle is decreased. The most popular trailing-edge devices used today in the maritime industry are simple flaps and slotted flaps (Reche-Vilanova et al., 2021). As mentioned before, two (2) types of sails can be used in the maritime industry. However, it has been demonstrated that rigid sails and wings provide higher lift coefficients than soft sails (Khan et al., 2021). Numerous properties of rigid wing sails make them an ideal option for wind-assisted propulsion. The shape of rigid wing sails offers better lift-to-drag ratio than conventional soft sails, enabling high performance sailing ships to cruise at previously unheard-of speeds. Its interior construction provides the aerofoil a consistent form that is independent of the tension in the lines, unlike traditional sails. This makes it considerably simpler and more exact to determine the ideal trim (the angle of attack can be modified rapidly and simply given wind conditions). After installing these devices, no personnel augmentation is necessary, and crew safety is always maintained. Commercial ship modified with rigid wing sails in a trial showed considerable fuel savings of 15% to 25% (Reche, 2020). The use of the wing sail device on a ship has the potential to decrease fuel consumption and CO2 emissions by around 10-20%, contingent upon factors like as the sailing area, speed, and size of the vessel. Importantly, this reduction may be achieved without compromising the ship's speed (Wang et al., 2022).

Chapter 2.2.2 Flettner rotor

Flettner rotors are rotating cylinders that can provide fluid dynamic lift by employing the Magnus effect when submerged in a fluid stream. The German engineer Anton Flettner, who examined the efficiency of spinning cylinders as a ship's propulsion system in the 1920s, is credited with the invention of this concept (De Marco et al., 2016) (Figure 3).

Figure 3

The Magnus effect on the Flettner rotor

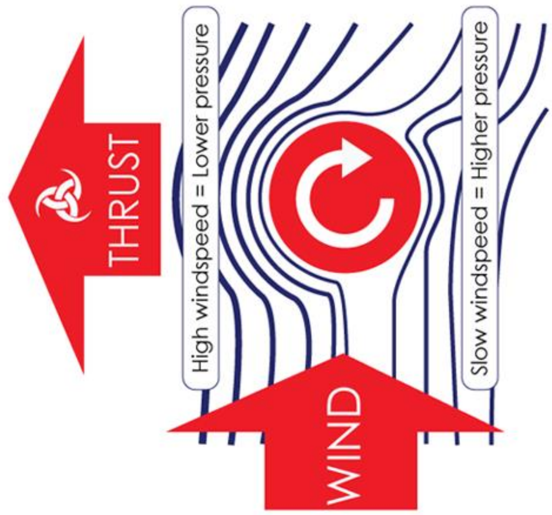


Note. From *Wind Propulsion Principles* (p. 27) by Konstantinos M. Fakiolas, 2020. Copyright 2020 by Konstantinos Fakiolas.

Similar to aeroplane wings, Flettner rotors provide lift, but the lift is much greater than it would be for a fixed sail with a similar geometry because of the rotor's rapid rotational speed. There develops a thin boundary layer surrounding the rotor as it rotates. This layer of air follows the cylinder's revolving surface; as a result, on one side, it flows against the wind's direction, slowing it down, while on the other side, the wind flow is simultaneously accelerating the rotor. Similar to the Bernoulli principle, this causes a pressure difference that causes a force to flow perpendicular to the wind from a place of high pressure (low relative air flow) to a region of lower pressure (high relative air flow) (Konstantinos, 2020) (Figure 4). Since the top pressure is greater than the bottom pressure, an upward lift force is produced.

Figure 4

An image showing the Magnus effect that a spinning Flettner rotor produces



Note. From "Rotor sail GHG reduction potential, modelling and sea trial validation" by Paakkari, V., Hurford, A., & Carddock, C, *5th Innov'Sail Conference, 2020. Copyright 2020 by The Authors*

The use of Flettner rotor technology for wind-assisted propulsion has considerable promise as a ship-assistance propulsion system, contributing to fuel conservation, enhanced thermal efficiency, and reduced emissions in the ship's primary power source (Talluri et al., 2018). Several previously finished research projects looked at designing and analysing Flettner rotors as a support marine propulsion system. Lu and Ringsberg (2019) compared the Flettner Rotor, a wind sail, and the DynaRig idea as three wind-assisted ship propulsion systems for the Aframax Oil Tanker travelling between Gabon and Canada. According to this study, the type of ship, speed, route of the voyage, and weather have a big impact on how much fuel can be saved. Additionally, the Flettner rotor earned the highest significant fuel-saving percentage in contrast to the other technologies, according to the results conducted by Lu and Ringsberg (2019). In 2015, two Norsepower rotors with dimensions of 18 m in height and 3 m in diameter were installed on a 9700 DWT Ro-Ro Carrier, which resulted in an annual 5% fuel savings.

Using a numerical model, Traut et al. (2012) calculated that a 50,000 DWT bulk carrier outfitted with three Flettner rotors might save up to 16% of fuel travelling from Tubarao to Grimsby. After modelling additional routes for five case studies, Traut et al. (2014) discovered that the average wind power contribution was between 193 kW and 373 kW per rotor, which equates to 2%–24% fuel savings for a normal ship. For a 14,700 DWT chemical tanker, Pearson (2014) calculated up to 10% yearly fuel savings per rotor using a software model to analyse the viability of placing Flettner rotors on board ships. According to Talluri et al. (2018), rotor sails might save up to 20% of fuel on commercial cargo ships when three rotors were deployed.

Figure 5

Rotor with end-plate

Note. From *Wind Propulsion Principles* (p. 27) by Konstantinos M. Fakiolas, 2020. Copyright 2020 by Konstantinos Fakiolas.

These days, the FRs are used by a vast majority of ships powered by wind (Table 1). These FRs offer ships (both newly constructed and older ships through retrofitting options) a fantastic opportunity to comply with stricter environmental regulations. The ship experiences thrust and sideways forces as a result of the lift (L) and drag (D) forces produced by the FR as a result of pressure differences surrounding it. Depending on the spin ratio, the flow around a Flettner rotor can be either steady or unsteady, and the forces that arise are influenced by the aspect ratio and Reynolds number (Kramer et al., 2016).

Table 1

Adoptions of WASP technology

Ship Name	Ship Type	DWT	Technology Characteristics	Ship Built Year [c]	Installation Year
Flettner-Rotor			**No. of Rotors/Diameter (m)/Height (m)**		
E-Ship 1 [a]	General Cargo/Ro-Lo	10,020	4/4/27	2010	2010
Estraden [a]	Ro-Ro	9700	2/3 [b] /18	1999	2014
Viking Grace [a]	Passenger	6107 [c]	1/4/24	2013	2018
Fehn Pollux [a]	General Cargo	4250	1/3/18	1997	2018
Maersk Pelican [a,b]	Tanker	109,647	2/5/30	2008	2018
Afros [d]	Bulk Carrier	64,000	4/-/-	2018	2018
Copenhagen [e]	Ferry	5088	1/5/30	2012	2020
Annika Braren [f]	General Cargo	5100	1/18/3	2020	Oct 2020 expected
SC Connector [g]	Ro-Ro	8843	2/35/5	1997	Q4 2020 expected
Kite			**Kite's dimension (m^2)**		
Michael A. [h]	General Cargo	4884	160	1994	2008
BBC Skysails [i]	General Cargo	9832	320 [i]	2008	2008 [j]
Theseus [i]	General Cargo	3667	160 [g]	2009	2009 [h]
Aghia Marina [i]	Bulk Carrier	28,522	320 [i]	1994	2012 [j]
Ville de Bordeaux [k,l]	Ro-Ro	5200	500	2004	Nov 2020 expected
TBA [k]	Bulk Carrier	TBA (Capesize)	1000	TBA	2021 expected
Suction Wing			**No. of wings/height (m)**		
Ankie [m]	General Cargo	3600	2/10	2007	2020
Frisian Sea [n]	General Cargo	6477	2/TBA	2013	2020
Rigid sails/wing sails			**No. of foils/height (m)/width (m)**		
MV Tharsis [o]	General Cargo	2364	2/9/3	2012	2021 expected
New Vitality [p,q]	Tanker	306,751	2/32/15	2018	2018
TBA [r]	Tanker	TBA(VLCC)	TBA	2022	2022

Note. From *New Wind Propulsion Technology: A Literature Review of Recent Adoptions*, by C. Todd, V. Kosmas, K. Renken, M. Acciaro, 2020, WASP (https://vb.northsearegion.eu/public/files/repository/20210111083115_WASP-WP4.D5B-NewWPTALiteratureReviewofRecentAdoptions-Final.pdf).Copyright 2020 by WASP.

Chapter 2.2.3 Flettner rotor and Wing sail comparisons

In research done by Kramer et al. (2016), a comparison was made between Flettner rotors (FRs) and Wing sails. Computational Fluid Dynamics (CFD) analysis has shown that the drift is influenced by many factors, including the specific characteristics of the sail, the hydrodynamics of the ship's hull, the sail control system used, and the presence or absence of retractable sails. Consequently, the extent of energy savings is contingent upon these aforementioned factors. The outcome revealed that, while exhibiting superior thrust output per unit area compared to sails, the FRs induced a greater amount of extra drift resistance, particularly in the non-retractable configuration, resulting in a diminished overall propulsive force. The research effectively elucidated the impact of drift on the efficacy of different technologies in ship propulsion. The fact that this technology takes up less space on deck than compared to other technologies is one of its benefits (Lu & Ringsberg, 2019)

In recent decades, there has been a development of hybrid sail designs that include design aspects from both soft sails and rigid sails. Researchers at the National Maritime Research Institute (NMRI) in Tokyo, Japan have put up a suggested example of this particular form of sail. According to the findings of Fujiwara et al. (2003), the performance of the NMRI hybrid sail, as determined by wind tunnel tests and calculations, exhibited superior characteristics in terms of lift and drag when compared to both soft and rigid sails. Despite its potential, the NMRI hybrid sail has not been installed on any commercial vessel so far. The extent to which fuel consumption can be reduced through the implementation of rigid sails exhibits significant variation and is contingent upon several factors, such as the overall sail area, the specific type(s) of rigid sails employed, and the prevailing wind conditions experienced during voyages (Atkinson & Binns,2018b; Smith, Newton, Winn, &Rosa,2013; Smulders,1985; Viola, Sacher, Xu, & Wang,2015). The most reliable predictions might potentially be derived from the operating experiences of vessels equipped with JAMDA sails. According to Ouchi et al. (2011), the Shin Aitoku Maru has reportedly achieved an average fuel savings of about 10%. In relation to carbon dioxide (CO_2) emissions, it has been observed that a Roll-on/Roll-off (Ro-Ro) vessel with a deadweight tonnage (DWT) of 27,000, engaged in a trip between Rotterdam and New York at a speed of 16 knots, would produce an estimated 77 tonnes of CO_2 emissions every journey (Laboratory for Maritime Transport,2013). If a fuel efficiency improvement of 10% is assumed, it is estimated that this might result in a decrease of roughly 7.7 tonnes of carbon dioxide (CO_2) emissions each journey. The extent of SO_x and NO_x emissions reduction would vary depending on the kind of fuel used.

Due to the significant difference in lift coefficients between the Wing sails and the Flettner rotors, a direct comparison of the performance is challenging. According to Thies and Ringsberg (2022), the Wing sails feature a trapezoid planform with a span of 77 m and a chord length of 12 m at the base, whereas the Flettner rotors are only 5: 30 m in size. Therefore, a single Wing sail can shade more than 40% of the deck area compared to a single Flettner rotor that may shade 20% or less. In addition, as a result of the tests of 2 types of wind technology (Flettner rotor and wing sails), the possible thrust coefficient and resulting needed sail area are two key differences between these sail types. In order to reach equal speeds throughout a range of 180 degrees actual wind angles in full sailing mode, it was demonstrated that the Wing sails needed to be more than 3.5 times larger than the Flettner rotors. The Wing sails, however, turned out to be more effective in wind-assisted propulsion mode. When it comes to performance, the Flettner rotors are more effective in reaching and downwind circumstances, while the Wing sails are more advantageous in headwinds. The use of both sail types on the same ship was not investigated, but it may be highly intriguing for future projects (Thies & Ringsberg, 2023).

When compared to the sail area, Flettner rotors produce enormous forces. A Flettner rotor can frequently produce substantially more thrust than a wing sail with an equal sail area, depending on the ship's speed and the wind direction. The side force to thrust ratio, on the other hand, is also higher, which implies that for a given amount of propulsion, the ship is also pushed laterally with a significantly greater force (Kramer et al., 2016). Kramer et al. (2016) analyzed 2 various sails, trust coefficient and side force to thrust ratio with different ships speed to wind speed ratios. The result shows that since the wind velocity makes the thrust coefficient non-dimensional, an increase in ship speed can actually result in a greater thrust coefficient for the wing sail. The Flettner rotor, which has a lower lift-to-drag ratio, is an exception to this. For a given amount of thrust, the Flettner rotor typically has a much larger side force. Kramer et al. (2016) conducted a comparison study between FRs and sails that used CFD found that the drift relies on the type of sail, the ship's hull's hydrodynamics, the sail control system, and whether or not the sails are retractable. As a result, the energy savings rely on these aspects as well. The result was that, despite having better thrust generation per unit area than sails, the FRs caused more additional drift resistance, especially in the non-retractable design, and ultimately delivered less effective propulsive force. The effects of drift on the contribution of various technologies to ship propulsion were clearly highlighted in this study.

Chapter 2.2.4 Fuel savings calculations on routes

The quantity of fuel that can be saved is the main topic of the articles and claims made by WASP technology developers. This serves the interests of shipowners and operators. Ship owners that have already embraced WASP technology made the significance of a genuine economic return on their investment very evident, as was shown at the GST 2020 Wind Propulsion Forum in Copenhagen. In other words, given the capital expenditure needed and operational risks involved, such as technological uncertainties, counterpart concerns, and port operations, pollution reduction alone is unlikely to persuade ship owners and justify an investment in WASP technology. To ensure that the potential financial upside outweighs the expenses and dangers, an economic case must be produced (Chou et al., 2020).

To determine the effect of wind propulsion on current routes, three main approaches are utilized in the literature: (i) a Great Circle Route (GCR) computation; (ii) using noon report data; and (iii) using an automated identification system (AIS) data. Each approach has one main thing in common. Studies use weather data to determine the power contribution of the sail at each waypoint, and they then determine the total power and cumulative fuel used along the entire voyage (Mason, 2021). Real-world shipping data, or noon report data, is gathered on board each vessel once every 24 hours. Numerous important performance indicators are included in this data, including the location, time, average speed, and weather (Aldous et al., 2013). Although the data can be used in many other research, studies on ship routing with wind assistance also use the data. According to Noon report data, some studies have been conducted in the literature along various routes. For example, Lu and Ringsberg (2019) used this information to determine the effectiveness of wind propulsion technology along two distinct routes: from the Netherlands to Brazil and from Canada to Gabon. The findings indicate that all three sail technologies (Flettner rotor, DynaRig and Wing sails) help reduce fuel consumption from 5.6% to 8.9%. On the examined itineraries, the Flettner rotor reduced fuel consumption the highest while utilizing the smallest sail area. Howett et al. (2015) also conducted studies along other different routes to determine the effectiveness of wind propulsion. Important essential performance measures of the ship's operation are described in the AIS data. For wind assisted vessels, this information is also utilized to compute the effectiveness of the wind propulsion. Comer et al. (2019) study involved calculating the Flettner rotors' influence using meteorological and AIS data. Delft & Fraunhofer (2016) conducted yet another study evaluating the effect of wind propulsion on particular routes. This method has benefits since it takes into consideration actual shipping activity, which improves the results' accuracy. The research' findings repeatedly shown that WASP technologies have the ability to significantly reduce fuel use on board ships under a variety of circumstances, as shown in Tables 2 and 3. It's vital to keep in mind that various studies use different factors in their models for things like technology specification (e.g., quantity, dimensions, technical specifications), ships (e.g., kind and size of the ships, speed), wind conditions, and routes. The table seeks to list research conducted on typical commercial ships, which account for the vast bulk of tonnage globally (Chou et al., 2020).

Table 2

Flettner rotors fuel savings review

Study	Dimensions of the Technology	Ship Type	Route	Fuel Saving Found
Tristan Smith et al. (2013)	Unspecified	10K dwt Chemical Tanker	Buenos Aires - Western Approaches	20% - 50%
Traut et al. (2014)	1 Flettner rotor: height (h) = 0 35 m, diameter (d) = 5 m	7k dwt Ro-Ro 8k dwt Product Tanker 6k dwt General Cargo 50k dwt Bulk Carrier 30k dwt Container Ship	Dunkirk - Dover London - Milford Haven Varberg - Gillingham Tubarao - Grimsby Yantian - Felixstowe	4% 14% 21% 5% 2%
Nelissen et al. (2016)	2 Flettner rotors: h = 22 m, d = 3 m 3 Flettner rotors: h = 48 m, d = 6 m 2 Flettner rotors: h = 24 m, d = 3.5 m 2 Flettner rotors: h = 48 m, d = 6 m	5k dwt Tanker 90k dwt Tanker 7k dwt Bulk Carrier 90k dwt Bulk Carrier	Worldwide trades of each ship type according to AIS data	5% - 7% 9% - 13% 5% - 7% 17% - 23%
Bentin et al. (2016)	1 Flettner rotors: h = 25 m, d = 4 m	17k dwt General Cargo	Baltimore - Wilhelmshaven	14% - 36%
De Marco et al. (2016)	2 Flettner rotors: h = 28 m, d = 4 m	75k dwt Product Tanker	N.A.	Up to 30%
Comer et al. (2019)	4 Flettner rotors: h = 27 m, d = 4 m 2 Flettner rotors: h = 18 m, d = 4 m 1 Flettner rotor: h = 24 m, d = 4 m 1 Flettner rotor: h = 18 m, d = 3 m 2 Flettner rotors: h = 30 m, d = 5 m	10k dwt General Cargo/Ro-Lo 10k dwt Ro-Ro 6k dwt (2.8k pax) Passenger 4k dwt General Cargo 110k dwt Tanker	Porto - Montevideo; Eemshaven - Porto Rotterdam - Middlesbrough Stockholm - Turku Livorno – Mostaganem; Huelva - Alexandria Sklkda – Singapore; Yeosu - Spain	8.3% - 47% 1.6% - 9.0% 0.4% - 2.8% 1.0% - 6.6% 1.8% - 4.7%
Lu & Ringsberg (2019)	1 Flettner rotor: h = 18 m, d = 3 m	Aframax Tanker	Cape Lopez - Point Tupper Angra dos Reis - Rotterdam	8.9% 6.5%
DNV GL (2019)	1 Flettner rotor: h = 18 m, d = 3 m	4k dwt General Cargo	Unspecified	10% - 20%

Note. From *New Wind Propulsion Technology: A Literature Review of Recent Adoptions*, by C. Todd, V. Kosmas, K. Renken, M. Acciaro, 2020, WASP (https://vb.northsearegion.eu/public/files/repository/20210111083115_WASP-WP4.D5B-NewWPTALiteratureReviewofRecentAdoptions-Final.pdf).

Table 3

Wing sails fuel savings review

Study	Dimensions of the Technology	Ship Type	Route	Fuel Saving Found
Ouchi et al. (2013)	9 wingsails: height (h) = 50 m, width (w) = 20 m	180k dwt Bulk Carrier	Yokohama - Seattle	20% - 30%
Tristan Smith et al. (2013)	Unspecified	10K dwt Chemical Tanker	Buenos Aires - Western Approaches	20% - 60%
Nelissen et al. (2016)	3 wingsails: h = 25 m, w = 9 m 5 wingsails: h = 50 m, w = 17 m 3 wingsails: h = 27 m, w = 10 m 5 wingsails: h = 50 m, w = 18 m	5k dwt Tanker 90k dwt Tanker 7k dwt Bulk Carrier 90k dwt Bulk Carrier	Worldwide trades of each ship type according to AIS data	5% - 8% 9% - 13% 5% - 7% 18% - 24%
Lu & Ringsberg (2019)	1 wingsail: h = 50 m, w = 20 m	Aframax Tanker	Cape Lopez - Point Tupper Angra dos Reis - Rotterdam	8.8% 6.1%

Note. From *New Wind Propulsion Technology: A Literature Review of Recent Adoptions*, by C. Todd, V. Kosmas, K. Renken, M. Acciaro, 2020, WASP (https://vb.northsearegion.eu/public/files/repository/20210111083115_WASP-WP4.D5B-NewWPTALiteratureReviewofRecentAdoptions-Final.pdf).Copyright 2020 by WASP.

As per above discussion, based on literature review, it shows that, there are not many research has been done based on real weather condition, specific route. Most of the research conducted numerical, experimental or CFD analyses. In addition, for specific region it is hardly to see such analyses. In order to examine and analyze with specific route, in specific region (Caspian Sea) based on real wind conditions and vessel coordinates in the selected route have been conducted in this research. From the next chapter, in Chapter 3 all the information about the analyze, calculations will be given. In Chapter 4, results and discussion will be mentioned.

Chapter 3 RESEARCH METHODOLOGY

Chapter 3.1 Chapter overview

The methodology consists of calculation of sail optimization model and effective power of the wind assisted propulsion technology in Caspian Sea region with the use of real wind data order to accomplish the objectives of this study. The sail optimization model done based on the previous work by Nyanya and Vu (2019). In order to calculate the power contribution, created a computer program that can forecast, assess, and compare the performance of wind-assisted cargo ships using two types of WASPS: rigid wing sails and Flettner rotor sails. In order to determine results and to achieve the aim, a mathematical model was implemented using the 3.11 version of the Python programming language and the Microsoft Excel software packages. The third chapter is divided into two main sections, for each WASP model.

Chapter 3.2 Wing sails. Sail optimisation model

A sailing ship uses the wind's force in relation to the motion of its sails to generate propulsion power. The apparent wind speed is the wind velocity that is blowing relative to the sails and is the consequence of the superposition of wind velocity and ship motion. It has a size and a direction, and when it hits the sail, it produces forces called lift and drag that are orthogonal to one another. The resultant force is the force produced by these two forces. The thrust force (Ft), which represents the total propulsive force component aligned with the ship's heading, is determined by multiplying this force with the angle formed between the resulting force and the ship's velocity. The suggested model computes the value of “Ft” by following a series of steps.

Step 1: Angle between ship heading and wind velocity calculation

$$\alpha = j.Anglestep.\frac{\pi}{180}(rad) \qquad \dots (1)$$

where α is the angle between ship heading and wind velocity, j.Anglestep is an increment of angle α in radians.

$$\theta = tan^{-1}(\frac{u \cdot \sin\alpha}{Vref + u \cdot \cos\alpha})(rad) \qquad \dots (2)$$

where Vref represents the ship velocity in meters per second, θ is the angle between ship velocity and apparent wind speed and u represents the velocity of wind in m/s.

Step 2: Apparent wind speed calculation

$$V_A = \sqrt{Vref^2 + 2Vrefu\cos\theta + u^2} \text{ (m/s)} \qquad \dots (3)$$

where Vref represents the ship velocity in m/s, u represents the velocity of the wind in metres per second.

Step 3: Calculation of Lift (L) and Drag (D) forces

$$L = \frac{1}{2} \cdot \rho \cdot C_L \cdot A \cdot V_A^2 \ (N) \qquad \dots (4)$$

$$D = \frac{1}{2} \cdot \rho \cdot C_D \cdot A \cdot V_A^2 \ (N) \qquad \dots. (5)$$

where ρ is the air density, CL, and CD are the lift and drag coefficients, respectively (Sheldahl & Klimas, 1981). The variable A denotes the surface area of the sail, whereas Va indicates the magnitude of the apparent wind speed.

For β, it can be calculated using the trigonometric ratio tangent as D and L, which is always perpendicular to each other:

$$\beta = tan^{-1}(\frac{D}{L}) \qquad \dots (6)$$

where L and D, are lift and drag force respectively.

Calculation of angle between the resultant force and ship velocity (Gamma)

$$\gamma = \frac{\pi}{2} - \theta + \beta \ (rad) \qquad \dots (7)$$

where θ the angle between the wind speed and the ship's velocity is, and the angle between the resulting force and lift force is β.

For the resultant force calculation will be as below

$$F_r = \sqrt{L^2 + D^2} \ (N) \qquad \dots (8)$$

Total propulsive force will be calculated as below

$$F_t = F_r \cdot \cos\gamma \ (N) \qquad \dots (9)$$

where Fr is resultant force, A is the area of the sail and γ angle between the resultant force and heading of the ship.
The power output will be calculated as below

$$P = F_t \cdot V_{ref}\ (W) \quad \dots (10)$$

The optimal sail angle (φ) that generates the most thrust force is determined by iteratively repeating this procedure for all possible sail directions, with angle increments of 5 degrees. Subsequently, the sail angle that yields the highest thrust force is chosen as the ideal sail angle.

Chapter 3.2.1 Definitions of variables

During this stage, the initial values of variables were established. Table 4 presents a comprehensive overview of the input variables utilised in the program, along with their corresponding definitions.

Table 4

Definition of the variables

Name	Variable name in program	Meaning
θ	theta	The angle between the apparent wind speed and the ship, measured in radians.
α	alpha	The true wind with respect to ship heading, is expressed in radians.
β	beta	The angular measurement between the resulting force and the lift force, expressed in radians.
γ	gamma	The angle between the resulting force and the velocity of the ship, expressed in radians.
ρ	rho	The air density (kg/m3)

V_{ref}	Vref	Ship velocity (m/s)
u	u	The velocity of the eastward component of wind (m/s)
v	v	The velocity of the northward component of wind (m/s)
C_L	Cl	The lift coefficient associated with the NACA Aerofoil
C_D	Cd	The drag coefficient associated with the NACA Aerofoil
F_r	Fr	Resultant force (N)
F_t	Ft	Total force generated to ship (N)
L	L	Lift force (N)
D	D	Drag force (N)
A	A	In the programme, a standard value of unity (1 m2) is used to represent the area. This allows for the sail area to be afterwards adjusted to the proper size of the sail. The unit of measurement for the sail area is square metres (m2).
	datapoints	The quantity of coefficients pertaining to drag and lift forces=360
	Va	Apparent wind speed
	Fthrust	Wind force (N) on a vessel.
	FhtrustOptimum	The maximal wind force (N).
	Fangle	The angle in actual value (degree) between the resulting force and the ship velocity.

	Forceangle	The angle of gamma that yields the most wind force, denoted as the optimal angle (in degrees).
	CLD	The input of constants of lift and drag coefficients.
	Optimumangledata	The optimal angle of attack between wind and sail, expressed in degrees
	Sailangle	The measurement of the angle formed between the direction of wind and the orientation of a sail, expressed in degrees.
	Apparentwindangle	

Note. Created by Author

Chapter 3.2.2 Explanation of the flow of the program

The program started with inputting the constant values and dimensions. Then these variables will be inserted in the changing different loops.

In the first loop in the program, "j", (0, Anglemax/Anglestep), the wind direction values start to change from 0 to 355 degrees with the angle increment (Anglestep) 5, 72 different sail positions were produced inside the loop. After that, the variable j was used to calculate alpha (α) as shown in equation (1).

After that, alpha was used for the next step, for the second loop. As shown in Appendix 1, loop 2 is inside loop 1. In this loop, wind speed "i" ranges from 1 to 25 meters per second (m/s) with increment=1, from Vsstart to Vsmax. In this loop, there were 3 cases using the "if" condition in order to make the atan function (inverse tangent) applicable to all angles.

- "If 1": $Vref = -u * \cos\alpha$ then θ=π/2;
- "If 2": α<=(π/2) or α>=(3π/2) then $\theta = tan^{-1}(\frac{u \cdot \sin\alpha}{Vref + u \cdot \cos\alpha})$;

- "If 3": α > (π/2) or α < (3π/2) then $\theta = tan^{-1}\left(\frac{u \cdot \sin \alpha}{Vref + u \cdot \cos \alpha}\right) + \pi$

Then the "θ" value will be used for the Apparent wind speed calculation as shown in equation (3).

After the calculation of the apparent wind speed, the coming step is loop 3. The third loop was applied to determine the resulting thrust force, and the process was then repeated for each sail angle to determine which is the most advantageous for the sailing situation. The program then goes back to loop 2 to determine the new value of the wind speed after the third loop has finished. The third loop (loop 3) is inside loop 2, which with the variable 'k' altering with each iteration, loop 3 calculates the sail angles for a full 360° rotation of the sail for each value of "i". The value "k" is used in order to put the data from the "NACA0015.text" file, which is used in the "Input Data" phase, consisting of the angle of attack, coefficient of lift (CL), and coefficient of drag (CD). In this loop, Lift force and drag force will be calculated based on equations (4) and (5) respectively. In order to calculate the angle beta by evaluating various combinations of the lift force, drag force, and their relationships, "If" conditions were used in this loop.

- "If 1": L=0 then β=π/2
- "If 2": L < 0 then $\beta = tan^{-1}\left(\frac{D}{L}\right) - \pi$
- "If 3": L > 0 then $\beta = tan^{-1}\left(\frac{D}{L}\right)$

As mentioned above, "If" conditions were used to determine the beta angle based on the relationship between the lift force and the drag force, considering various cases of their variables. It is necessary in order to handle accurately of the negative lift coefficient. This presumption, which was used to keep the model's complexity to a minimum, was that the ship had a highly effective keel that could keep it travelling in the intended direction despite the application of sideways forces.

In the end, the program determined and selected the best angle of attack between the wind and the sail as well as the maximum value of the force from the wind (FthrustOptimum). After that, the force angle and sail angle were calculated.

The final procedure of the written program was to export the results into data files in text format and graphs. The graph is a polar graph which is illustrated to determine the optimum sail angle for a given wind speed and direction, by plotting various angles.

The text files which will be shown in the program are shown below:

- 'FthrustOptimum.txt' - Maximum force from wind (N)
- 'optimumangledata.txt' - Best angle of attack between wind and sail
- 'sailangle.txt' – Angle between the sail and the ship velocity
- 'aparentwindangle.txt' – Angle between the apparent wind and the ship velocity.
- 'gamma.txt' - Angle between the resultant force and the ship velocity.

Chapter 3.3 Calculation of thrust force and power of Wing sail using real wind data

In order to get actual vessel operation data, the program was run based on real weather conditions and vessel data. Using its cutting-edge forecasting systems, the European Centre for Medium-Range Weather Forecasting (ECMWF) continually reanalyses its historical meteorological observations. The most recent stage in this procedure is the ERA-INTERIM project, which offers a global library of atmospheric reanalysis data from 1979 to the present (Howett et al., 2015). The data is available in various formats, but for the purpose of this study, the computer program (Wind Propulsion Program) was run using 36 years' worth of wind speed and direction data at a 10m reference height in NetCDF (experimental) format: 10m u-component of wind (an eastward component of the 10m wind) and 10m v-component of wind (a northward component of the 10m wind) were used for analysing and calculation of the Thrust force and Power.

We want to analyse during the voyage of the vessel from Baku Port to Kurik Port, what power can obtain from different wind speeds and wind angles and what is the reduction of fuel consumption and CO_2 emission in the selected route.

First, constant variables were inputted, like constant vessel speed, area of the wing sail and others, in order to define the other variables that will be used in the calculation. As the vessel did its journey for different months, days and times, start time and end time were added from the AIS data provider (Marine Traffic). In order to calculate vessel location, the thrust force and power output for every 1-hour frequency during the voyage, "time_points" were defined. It will be used for the calculations of thrust force and power for different wind speeds and wind angles, as the computer program will run for many iterations. Then the coordinates for the start point Baku Port and end point Kurik Port were inputted. The next step was, with the use of AIS data (Marine Traffic), the coordinates of the vessel during the voyage were inputted. Based on these coordinates, then the ship heading was calculated. Next, the main loop "y" was created, which will run as a range of length of time_points (0, len(time_points)). Inside this loop, TWS (True wind speed) over the time during the voyage, the angle difference between ship heading and wind, based on above mentioned ship heading calculation and the angle between ship and apparent wind were calculated. Then in order to define the different u (an eastward component of the 10m wind) and v (a northward component of the 10m wind) wind directions, need to have to put "if" statements and calculate the angle of the true wind (alpha). Inside this loop, another loop, a sail angle loop, "z", was created in order to calculate lift force and drag force with the use of the above-mentioned equation (equations 4 and 5, in Chapter 3.2). The "z" loop runs in a range of 0 to datapoint. Datapoint shows the number of C_L and C_D coefficients for the "NACA0015" aerofoil. Based on those forces, the angle between the resultant force and lift force and the angle between the resultant force and ship velocity was calculated. This then will be used to calculate the resultant force (equation 8, in Chapter 3.2), thrust force to the vessel from wind (equation 9, in Chapter 3.2), optimum thrust force and power (equation 10, in Chapter 3.2). After calculating the output power, the Energy was calculated with the use below formula:

$$E = P \cdot 3600 \ (J) \qquad \ldots (11)$$

where P is the output power and the number 3600 illustrates the time, as energy calculates power multiplied by time.

The results that will be discussed in Chapter 4 were generated with the use of Python software. All above-mentioned calculations in “Wind Propulsion Program” code were attached as Appendix 2.

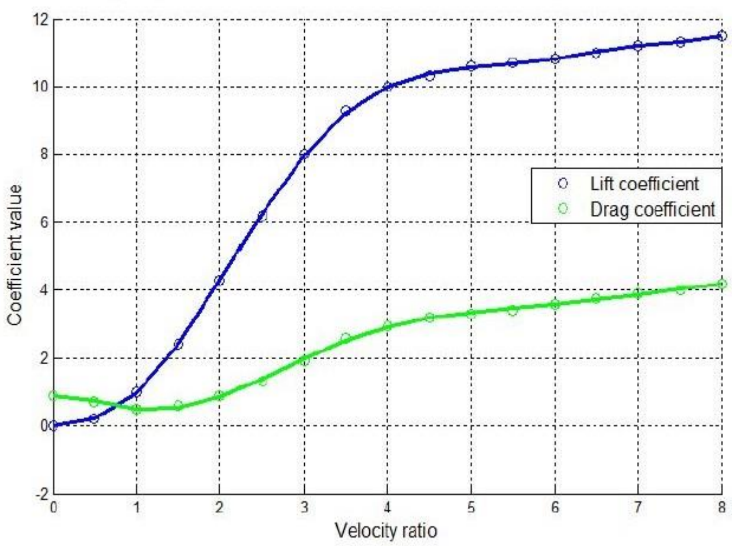
Chapter 3.3.1 Flettner Rotor

The propulsive power produced by the FRs was computed using CL and CD data obtained from early experimental findings based on Jakob Ackeret's work (Pearson, 2014), which was obtained from a different investigation. The decision to adopt the Ackeret results is based on two key factors: its widespread acceptance as high-quality data within the scientific community and its high-velocity ratio range (up to 8 when most of the sources are up to 4). The data of C_L and C_D were extracted (into the Excel sheet) from the curves (Figure 6) in Pearson (2014) with the help of a digitization software tool (WebPlotDigitizer version 4.6) with step lengths of 0.05 for the SR. A script-based computer program (Python 3.11) was used to iteratively determine the propulsive power generated under various situations. Next, the difference in fuel usage between the ship without FRs and the ship with FRs was used to compute the reduction in CO_2 emissions.

Here, the SR was limited to a number of “2”, because higher SR could negate the benefits of the rotors due to the exponential growth in power needed to spin the rotors.

Figure 6

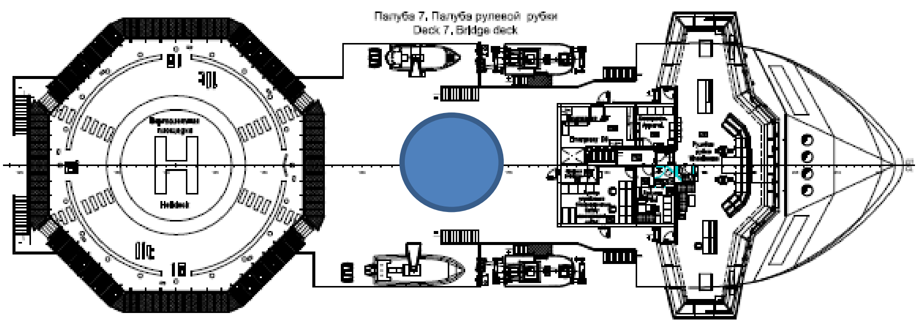
Substitution of SR for CL and CD



Note. From “The use of flettner rotors in efficient ship design”, by D. Pearson, *Influence of EEDI on Ship Design* (p. 162-196), 2014, ResearchGate (https://www.researchgate.net/publication/287081987). Copyright ResearchGate International Publishing.

Figure 7

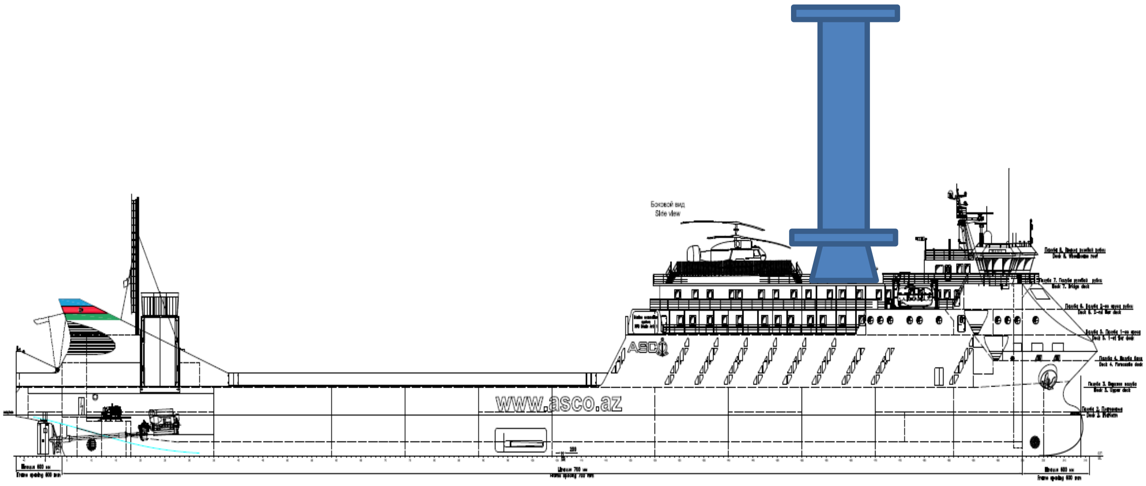
Plan view of the Azerbaijan RO-PAX with the indication of the positions of FR



Note. Created by Author

Figure 8

Profile view of the Azerbaijan RO-PAX with the indication of the position of FR

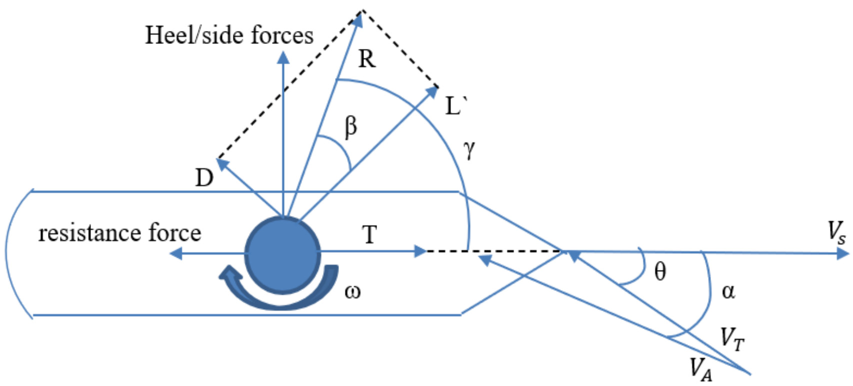


Note. Created by Author

The figure below shows the simplified presentation of the different forces and parameters involved in various operations of FRs. In order for the ship's course and its velocity to be in sync, this figure makes the assumption that there is very little drift.

Figure 9

Various forces produced by FR



Here, TWS: True Wind Speed

V_S: Ship velocity

V_T: True wind speed (TWS)

V_A: Apparent wind speed

R: resultant of L and D

α: angle between the ship heading and AWS

β: angle between L and R

γ: angle between R and ship heading

ω: Spin velocity of FR

Note. Created by Author

All calculations mentioned in Chapter 3.3 and loops were done for the Flettner rotor as well. However, the only difference was in the second loop. The main variable, "z" will run in the range of 0 to datapoint, but the datapoint in this code was different compared to the wing sail one. The difference was that the number was 26 and it shows S_R (spin ratio), C_L (lift coefficient) and C_D (drag coefficient) data obtained from early experimental findings based on Jakob Ackeret's work, as mentioned earlier. After calculating lift and drag force, further calculations, such as resultant force, thrust force, power and energy were the same as mentioned earlier in Chapter 3.3. For more details, the "Wind Propulsion Program" code is attached as Appendix 3.

Chapter 3.4 Fuel savings calculation and cost analyses.

The fuel savings were calculated for each voyage from different months and days considering the main engine fuel consumption with the constant speed without wind-assisted propulsion. Furthermore, the fuel consumption with wind-assisted propulsion was calculated and based on the difference fuel savings were identified. The analysis in order to determine cost-benefits, was conducted using the prevailing fuel oil prices and anticipated prices of the technologies based on information provided by suppliers.

Chapter 4 RESULTS AND DISCUSSION

Chapter 4.1 Chapter overview

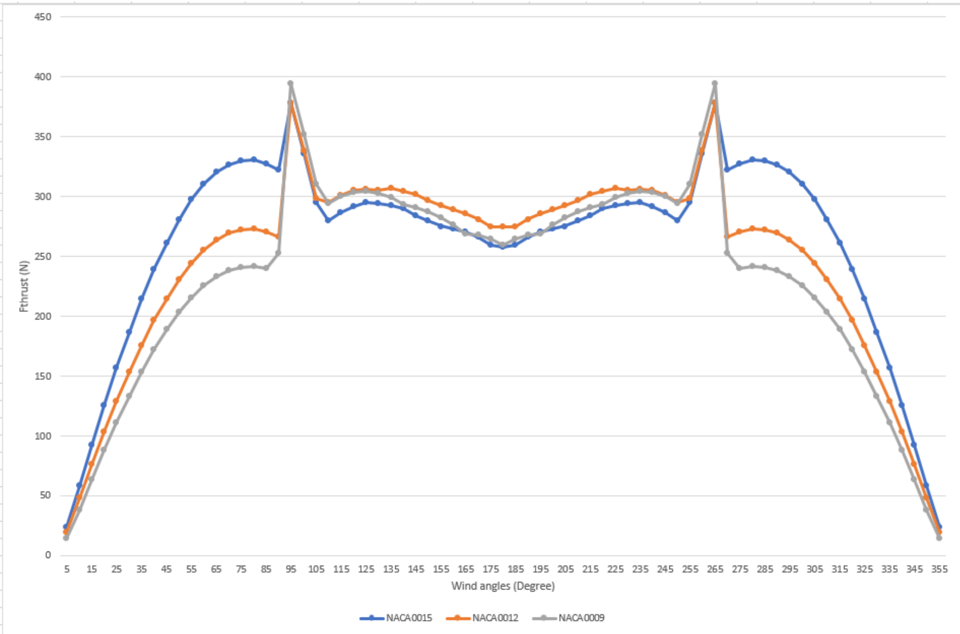
In this chapter, results from the sail angle optimisation model for wing sail and the results from the “Wind Propulsion Program” were analysed and discussions were given. The calculations were done using all the equations that were given in Chapter 3 and the “Wind Propulsion” program applied to the Ro-Pax ferry which was selected for the case study. The calculations were performed to determine the amount of effective wind power available from selected wind technology with the use of real wind data. This was accomplished using the outputs of the wind sail angle optimisation program's optimum force, which were then applied to the calculation for effective available propulsive power.

Chapter 4.2 Outputs from Sail Angle Optimisation Model

The program's results after three runs with three (3) cases of aerofoils are shown in this section: NACA0009 aerofoil, NACA0012 aerofoil and NACA0015 aerofoil are shown. After running several times, the program, the force thrust of 3 various aerofoils at wind speed 25m/s is analysed and shown in Figure 10. The figure shows that when comparing three different aerofoil designs, Aerofoil NACA 0015 offers the greatest values for optimal force thrusts in the range of wind angles from 0 to 75 degrees, from 80 to 110 degrees, and from 270 to 360 degrees. Furthermore, when calculating the Lift force, it is seen that the lift coefficient of the NACA0015 aerofoil exhibits higher values in comparison to other aerofoils. Based on the calculations and analyses conducted, the NACA0015 aerofoil has been selected for wing sail design for further examination and computation.

Figure 10

At a wind speed of 25 metres per second, the optimal force thrusts of three different aerofoils



Note. Created by Author

Chapter 4.2.1 Polar graphs of the NACA0015 aerofoil at wind speed 25m/s

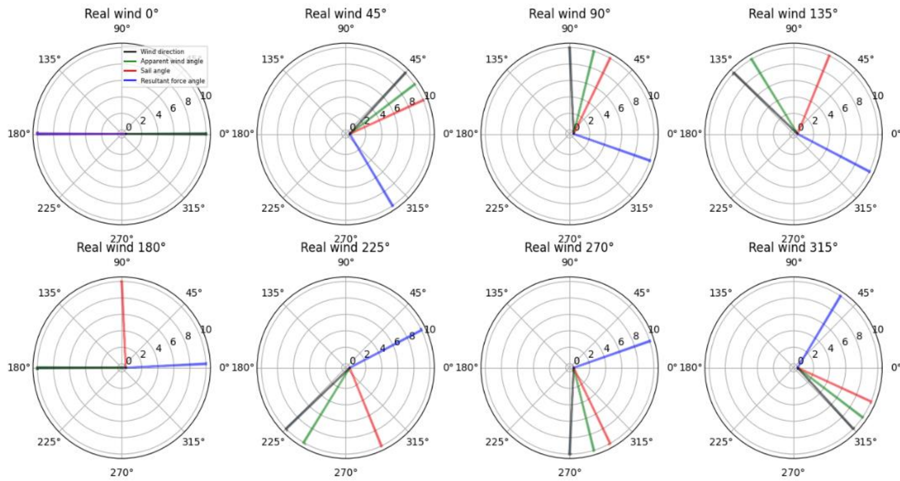
The ideal sail angles were found when the "Sail Optimisation Model" programme was run on the aerofoil NACA - 0015 at a wind speed of 25 m/s. There are 4 coloured lines in the following polar graphs (Figure 11). The full code of the “Sail angle optimisation model” is provided in Appendix 1.

- Black line represents Wind direction
- Green line represents Apparent wind

- Red line represents Sail angle
- Blue line represents Resultant force angle

Figure 11

The optimum sail angle of the NACA0015 aerofoil at wind speed 25m/s



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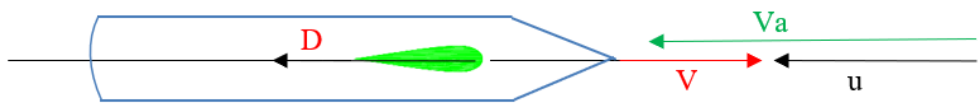
In order to understand the polar graph, discussion will be done in this section. In the following figures, it will be explained in detailed some of the polar graphs. Ship velocity will be shown as “v”, wind velocity will be “u” and apparent wind will be presented as “Va”.

1. The first polar graph shows that wind is blowing to the ship at the 0-degree angle. Figure shows that, wind blows in 0-degree wind angle to the ship. As shown from the figure, ship velocity and wind velocity are opposite and as a result apparent wind will be “Va=u-v”, which can produce a big drag force. Therefore, the sail must rotate at an angle of 180 degrees with respect to the wind direction. The goal is to as much as possible lessen the drag force.

Figure 12

Optimum sail angle 0 degree. Wind speed 25m/s, ship speed 14 knots

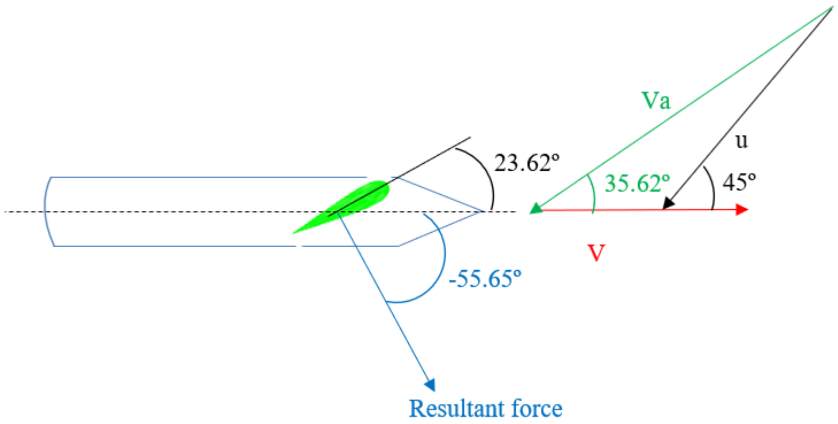


Note. Created by Author

2. The second polar graph, shows wind direction blows to the ship at a 45-degree angle and as a result, it produces apparent wind at a 35.62-degree angle. In order to achieve maximum force, thrust (Ft), the sail needs to turn to the 23.62-degree angle. From the polar graph and program, we can define the angle between the resultant force and ship heading which is a -55.65-degree angle. The figure below illustrates it.

Figure 13

Optimum sail angle at 45 degrees at wind speed 25 m/s, ship speed 14 knots



Note. Created by Author

3. The third polar graph shows wind direction blows to the ship at a 90-degree angle. It all adds to the apparent wind, which has an angle of 74.37 degrees towards to the

ship heading. In order to achieve maximum thrust force (Ft) sail needs to turn to the 62.37-degree angle. About -16.89 degrees of angle exists between the resulting force and the ship's direction.

From the polar graph, we can see that there is an opposite relationship between the values of wind angles 225, 270 and 315 degrees and the values of wind angles 135,90 and 45. This is because the lift coefficients, which correspond to wind angles from 0 to 180 degrees, have opposite values to those of the lift coefficients, which correspond to wind angles from 360 to 180 degrees.

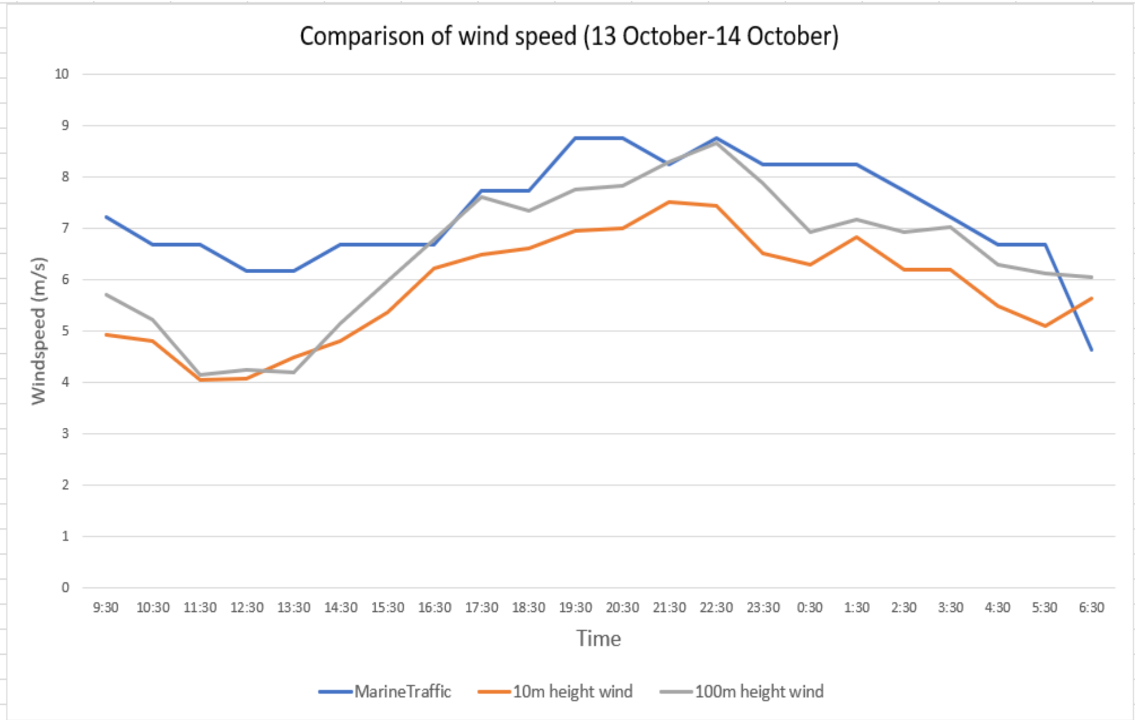
Chapter 4.3 Initial case. Data validation

As mentioned in Chapter 3, for our calculation wind data was obtained from Copernicus, ERA5 hourly data. To determine the accuracy of the analysis, we compared the information obtained with Marine traffic.

In the "Wind Propulsion Program", wind speed was calculated over the voyage time. Selected vessel (Ro-Pax) makes roughly 6-7 voyages from Baku Port to Kurik Port in a month. The comparison was done on the trip from Baku Port to Kurik Port, the voyage started on 13 October at 09:30 a.m. and ended on 14 October at 06:30 a.m. During the voyage of the vessel, wind speed ranged from 4 m/s to almost 9m/s. As mentioned earlier in Chapter 3, in this study, 10m height wind data was collected from the source (Copernicus, ERA5). Every model is slightly different. In order to validate our analyses, 100m height wind speed data was also collected and analysed. As seen from Figure 14, 100m height wind data is closer to the wind data from Marine Traffic compared to 10m height wind data. The wind data from Marine Traffic is quite an optimistic model and is somewhat different from Copernicus data. In this study, as mentioned, 10m-height wind data was chosen, to use a conservative approach. Because a 10m-height wind is closer to the sail area compared to a 100m-height wind (to the aerodynamic centre).

Figure 14

Wind Speed comparison (13 October-14 October)



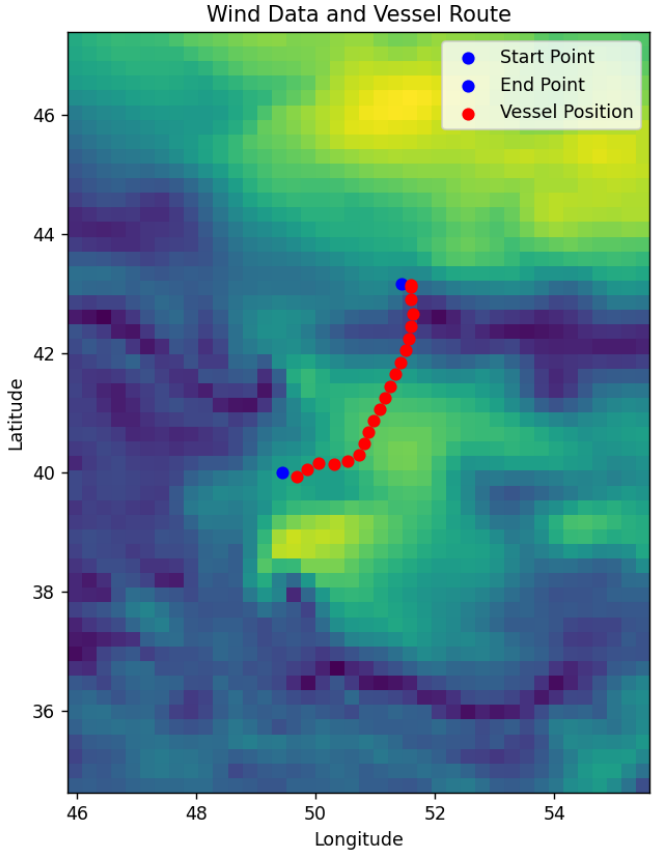
Note. Created by Author

As mentioned before, wind speed comparisons were done for various days also from different months, in order to validate our calculation with Marine Traffic.

In addition, the location of the vessel during the voyage coordinates for every 1 hour was obtained from AIS data provider (Marine Traffic) data and plotted with the use of a "Wind Propulsion Program" (Figure 15).

Figure 15

Vessel locations along the route



Note. Created by Author

Chapter 4.4 Case study: Application to Ro-Ro Passenger type of vessel.

For the purpose of this research, a Ro-Ro Passenger vessel with the IMO number 9843106 was chosen. The following Table 5, provides an overview of the vessel's specifications:

Table 5

RO-RO Passenger ferry specifications

Name of the ship	Azerbaijan
IMO number	9843106
Built year	2020
L_{OA}	154.5 metres
L_{BP}	148 metres
Depth (D)	7.5 metres
Breadth (B)	17.5 metres
Gross tonnage	8523 tonnes
Speed	14 knots
Engine Power	2x2600 kilowatts
Deadweight	5878 tonnes

Note. Created by Author

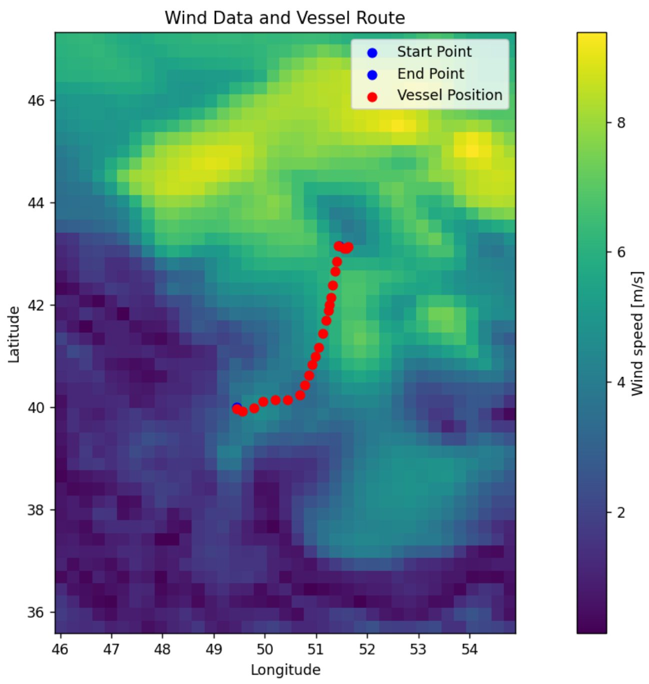
Chapter 4.4.1 Analyse the wind propulsion contribution.

As per Admiralty Sailing Direction, wind data for the year was divided into 4 quadrants: January, April, July and October ("Sailing directions (Pilots)," 2023). In our analyses, to compare different weather conditions, various days from the above-mentioned months were selected in order to calculate the Thrust force and Power over the route. The “Wind Propulsion Program” carried out various iterations, for different TWS (True wind speed), TWA (True wind angle) and for different best sailing angles for wing sails. For the Flettner rotor, the program also carried out above-mentioned values, in addition for various spin ratios of the FR. Basically, in various weather conditions, wind propulsion can show different results. Based on that, in this chapter, voyages from different days and months will be discussed.

First, the analysis was done at the beginning of the year, the winter season, on 27 January 2023. The voyage started at 23:30 p.m. on 27th January and ended at 23:30 p.m. on 28th January. The coordinates of the ship over the trip are inputted into the program in order to plot the vessel route on the map. From the start point (Baku Port) the ship goes in the South-West direction and accordingly the vessel heading is 189 degrees. Then according to the given coordinates, vessel heading changes respectively. The calculation of the heading is done throughout the route in order to validate the ship's movement.

Figure 16

Vessel position during the voyage

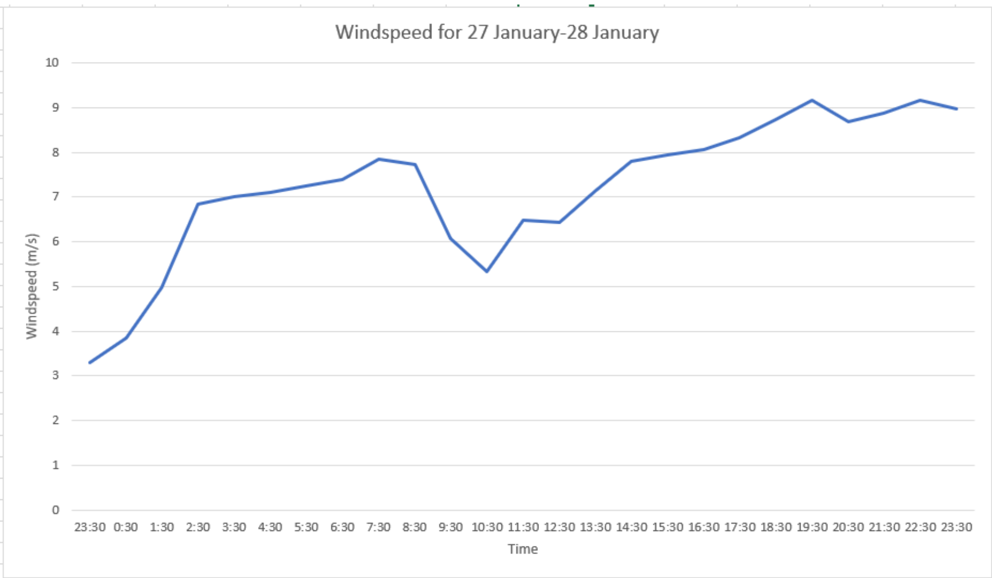


Note. Created by Author

The wind direction and speed can change over time. Based on the wind data from Copernicus, the wind speed and direction in the region of the selected route were calculated. As per Figure 17, the wind speed varies from 3-4 m/s to 8-9 m/s.

Figure 17

Wind speed data for 27-28 January (m/s)



Note. Created by Author

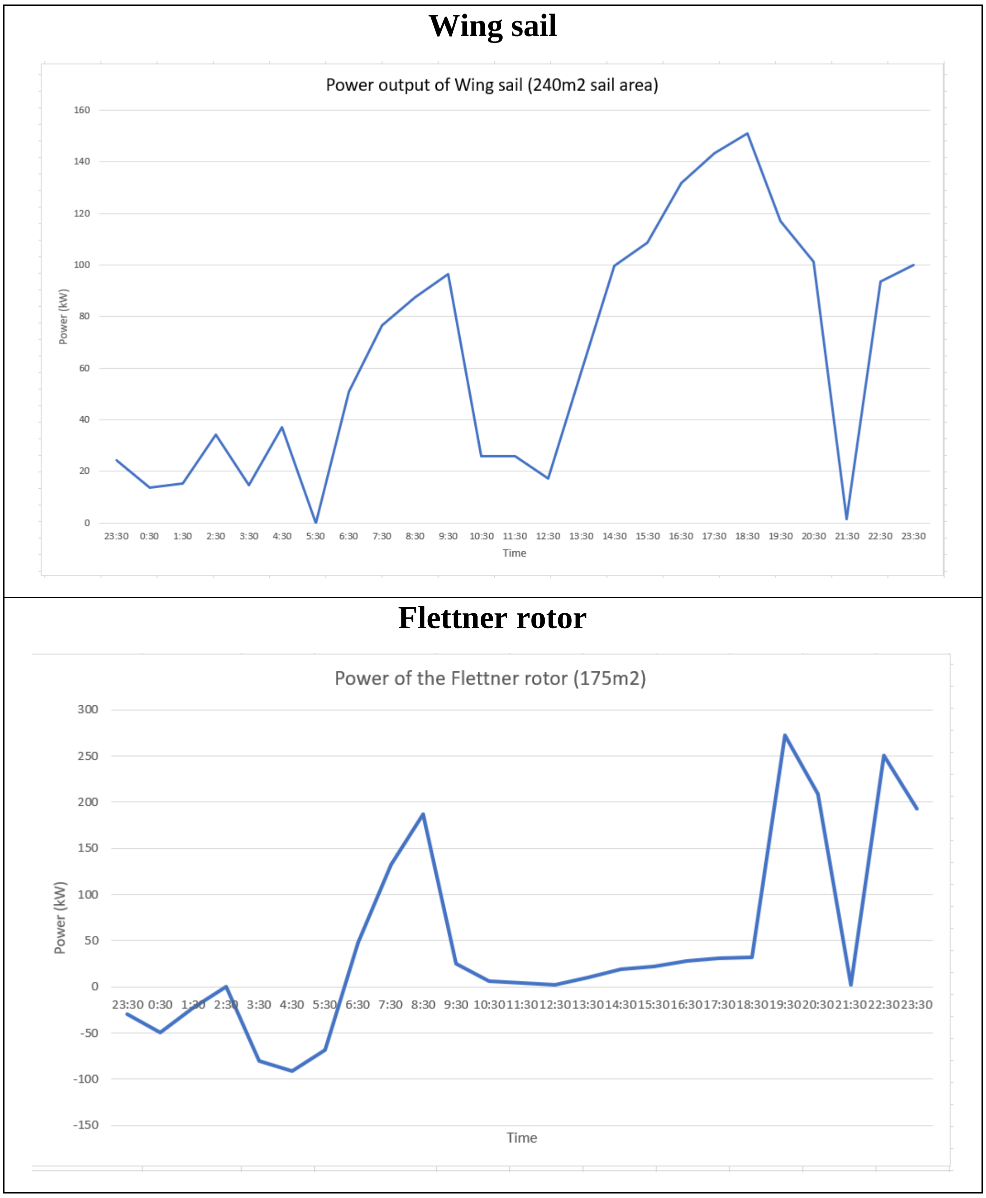
The optimum thrust force was calculated overtime during the voyage of the vessel using a "Wind Propulsion Program". As explained in Chapter 4.2.1, sails can be turned at various angles in order to obtain better lift force. For different wind angles thrust force can be changed and accordingly to achieve better thrust force calculations have been done. The optimum thrust force was found to average during the voyage to be 40.36 Newtons per 1 square meter (1m2). Then using the equation (10, in Chapter 3.2), the constant speed of 13.05 knots (6.712 m/s) multiplied by this time-averaged forward force produced a time-averaged propulsive power of 270.92 Watts per m2 of sail area. The wing sail specifications from (Konstantinos, 2020) were used. From the literature, the sail area was selected 240m2 and the average power output of this sail area will be around 65 kW. However, on the same day, if we look at the Flettner rotors analyses, it is clearly seen that Flettner rotors show much more power output compared to wing sails at the same wind speed. For the calculation of thrust force and the power output of FR, when implementing the "Wind Propulsion Program" code for spin ratio (SR), a constraint was imposed to limit the number to a maximum of 2. As seen below figure (Figure 18) it is obvious that the Wing sail was able to harness wind compared to the Flettner rotor and could produce higher power values.

This constraint was introduced with the aim of minimising the power required for FR. At each and every location along the route, the transient power contribution from the technology is determined and computed for each and every set of wind data. The average power output of the 175m2 Flettner rotor will be 45.41 kW. The obtained power was almost similar to the research conducted by Traut et al. (2014), which was at a ship velocity of 15 knots, the net power reaches its highest values within the range of 42.2-386.7 kW when subjected to wind speeds ranging from 5 m/s to 20 m/s. This is because the vessel speed in our analyses is 13.05 knots and the wind speed ranges from 3 m/s to 8 m/s as mentioned before. Figure 18 shows, the power produced during the trip of the vessel for the Wing sail and Flettner rotor. As per the graph, it is obvious that the Flettner rotor can get higher power output when the wind speed is over 8 m/s compared to the wing sail. And this is the basic idea of the wind propulsion technologies. You can get more power when the wind speed is high enough. However, at some points, because of various wind directions, the wing sail can get some amount of power while FR generated very low power.

Various days in January have been done analyses for Wing sail and for Flettner rotor, in order to see the impact of the different wind conditions. On January 17 at 00:00 a.m., the trip started and on the same day at 22:00 p.m., it ended. For the calculation of the thrust force and power were done above mentioned formulas. For the 1m2 wing sail, the average thrust force over time was found around 28.5 Newtons, for the average propulsive power was found almost 192 Watts per 1m2 of wing sail area. However, for the Flettner rotor for the same days, because of various power requirements, various conditions results were different compared to wing sails. On the same day, the average thrust force and the output power were found 9315.3 Newtons and around 65.53kW respectively for the 175m2 area (Figure 19).

Figure 18

The power output of Wing sail and Flettner rotor for 27 January



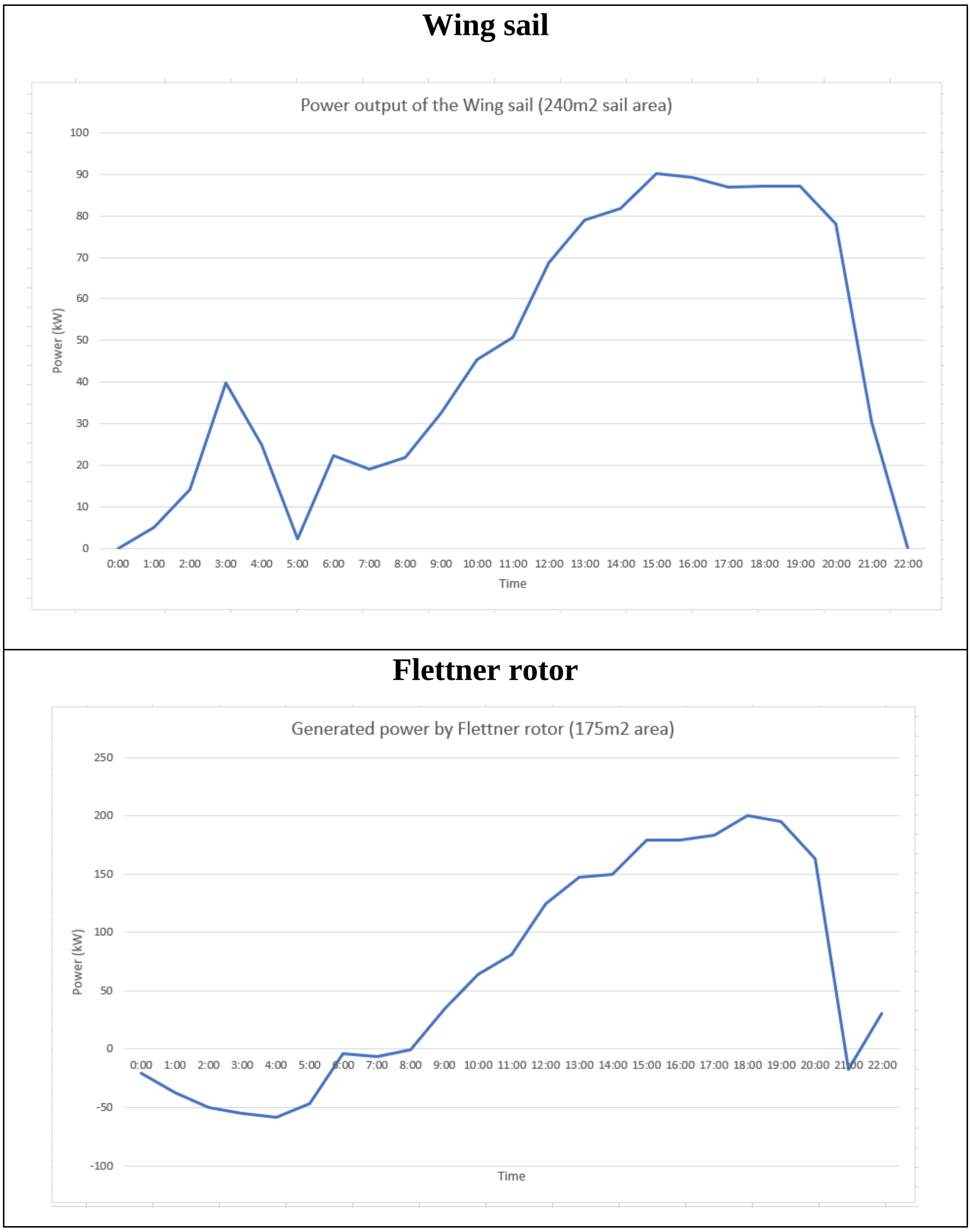
Note. Created by Author

On the next day, on January 25 results were slightly different. The voyage started at 10:00 p.m. on January 25 and ended at 07:00 a.m. on January 26. The average thrust force was found around 31.98 Newtons per 1m2 wing sail area and the calculated power output from thrust force was 224.40 Watts per 1 square meter wing sail area. For the Flettner rotor, on January 25, the results for the 175m2 area were 2465.15 Newtons and 12kW thrust force and power respectively. On this day, the wind speed was very low, as a result, the power output of both the Wing sail and Flettner rotor were very low. Even for the Flettner rotor, almost until the end of the journey, the generated power was below 20kW (Figure 20).

The last journey for January was on the 31^{st}. Because of the low wind speed and various wing angles, the results for this day were a little lower compared to other days in the same month. The results for this day were found 22.83 Newtons as an average thrust force and 153.29 Watts as an average power output for the 1m2 wing sail area. As mentioned at the beginning of this section, from the equation (equation 9, in Chapter 3.2), the thrust force and from the equation (equation 10, in Chapter 3.2) the output power was calculated for all months.

Figure 19

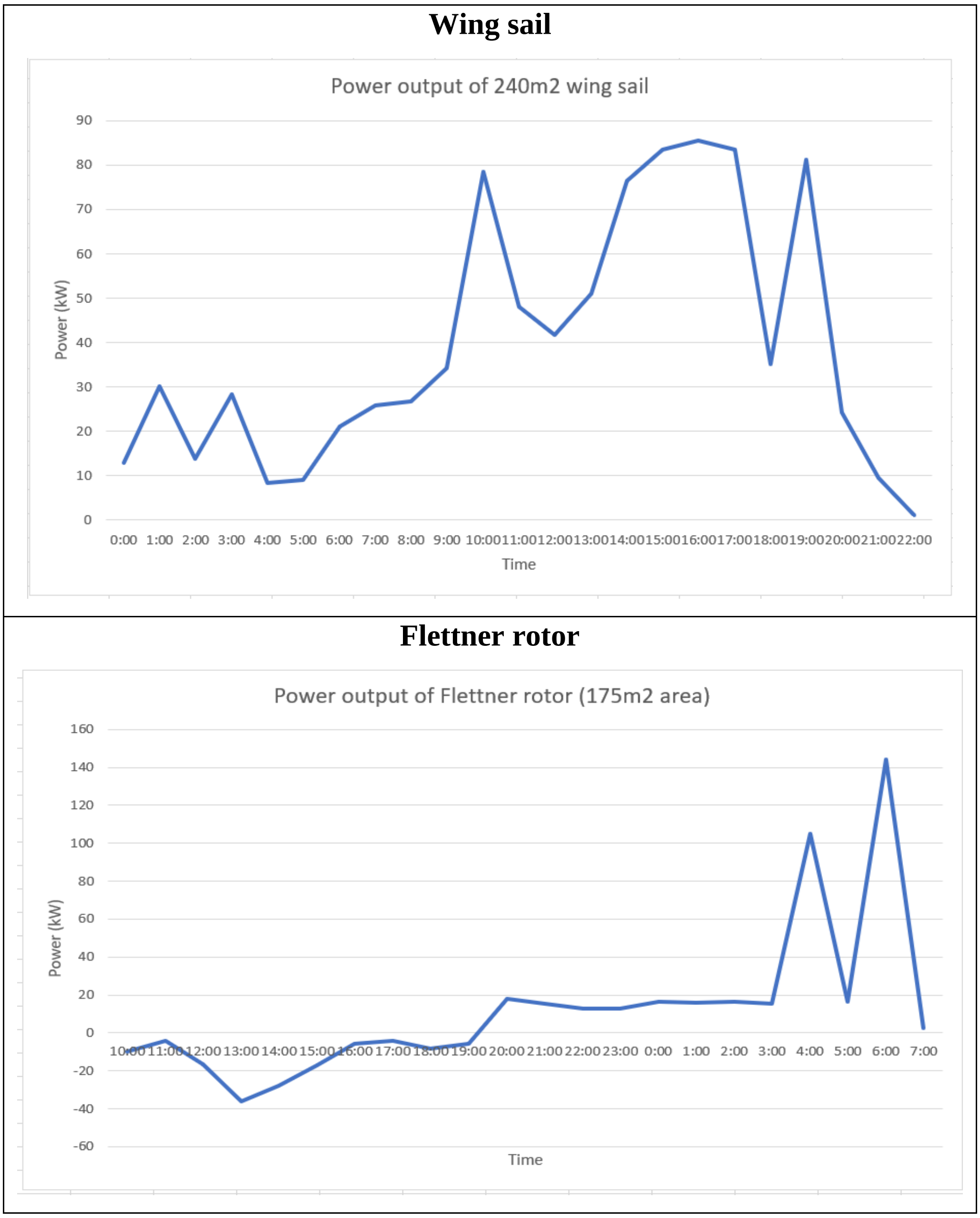
The calculated power of Wing sail and Flettner rotor for 17 January



Note. Created by Author

Figure 20

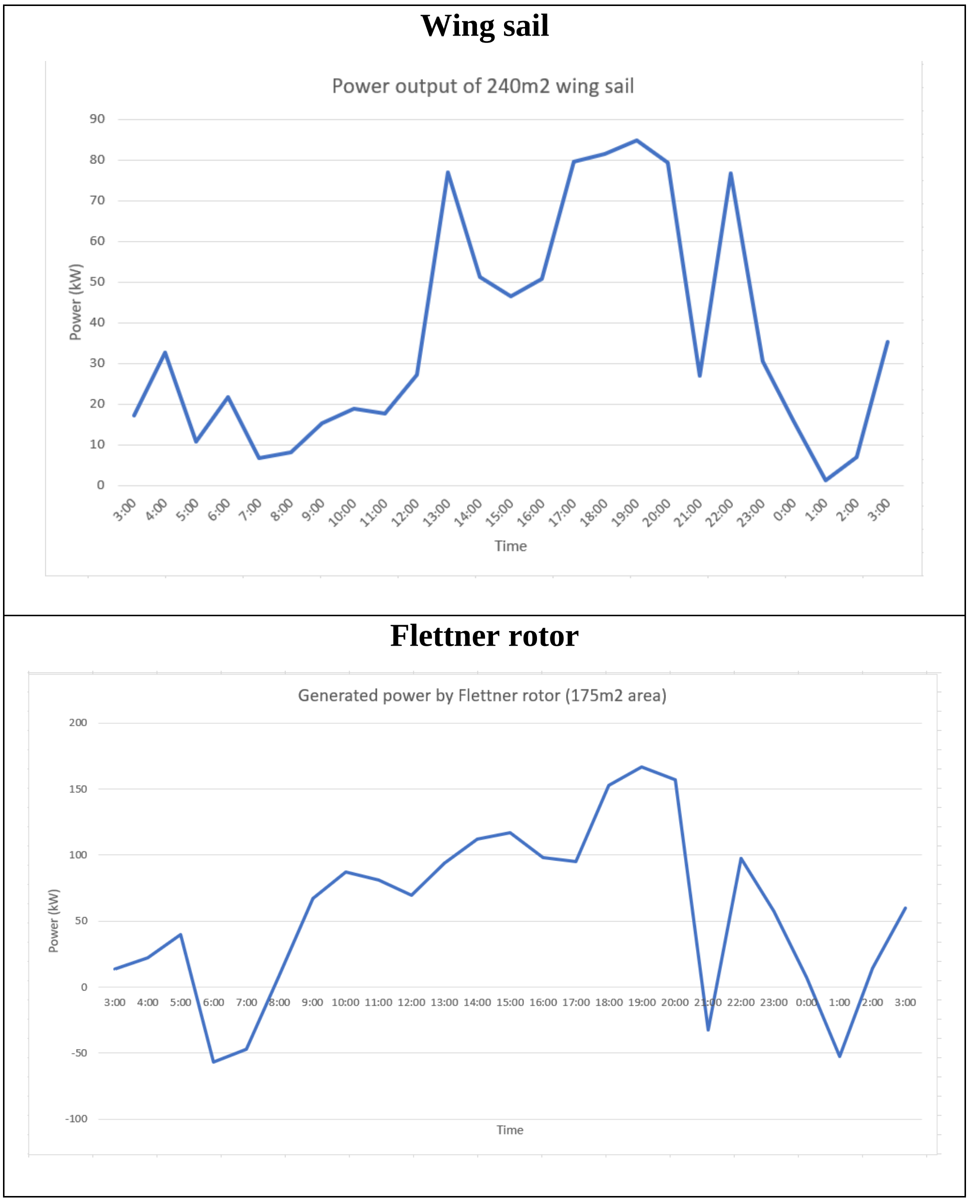
Power over the time of Wing sail and Flettner rotor (January 25)



Note. Created by Author

Figure 21

The power output of the Wing sail and Flettner rotor during the journey (31 January)



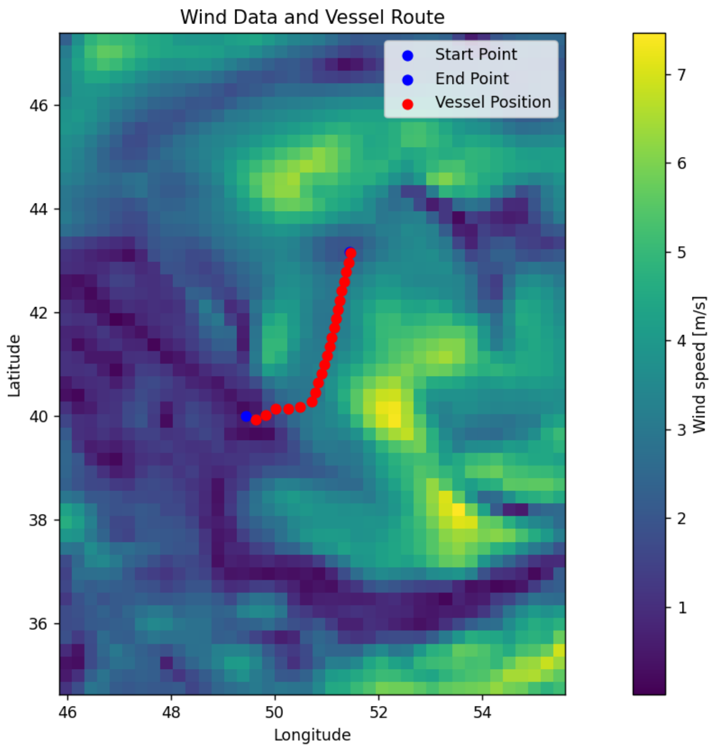
Note. Created by Author

The results for the 31st January were found for Flettner rotor 8527.59 Newtons as a thrust force and almost 58kW as an average power for 175m2 area during the trip from Baku Port to Kurik Port. Even though the wind speed was low, the Flettner rotor showed higher results compared to wing sails at some times during the trip (Figure 21).

The second analysis was done in the summer season, in order to show various wind speeds and their impact on the power output. The vessel starts its trip from Baku Port on 21 July at 18:34 p.m. and ends at Kurik Port on 22 July at 16:30 p.m.

Figure 22

Vessel positions along the route (21 July – 22 July)



Note. Created by Author

In order to plot vessel location every 1-hour frequency on the map (Figure 22), the calculation was conducted based on the coordinates taken from AIS Data (Marine Traffic). As you can see below table, using the coordinates taken from AIS data, all the ship headings were calculated separately for each coordinate using a "Wind Propulsion" program and shown as degrees (Table 6). This calculation has been done for all the voyage days in various months in order to check the vessel course in the given route.

Table 6

Ship heading calculations of the ferry

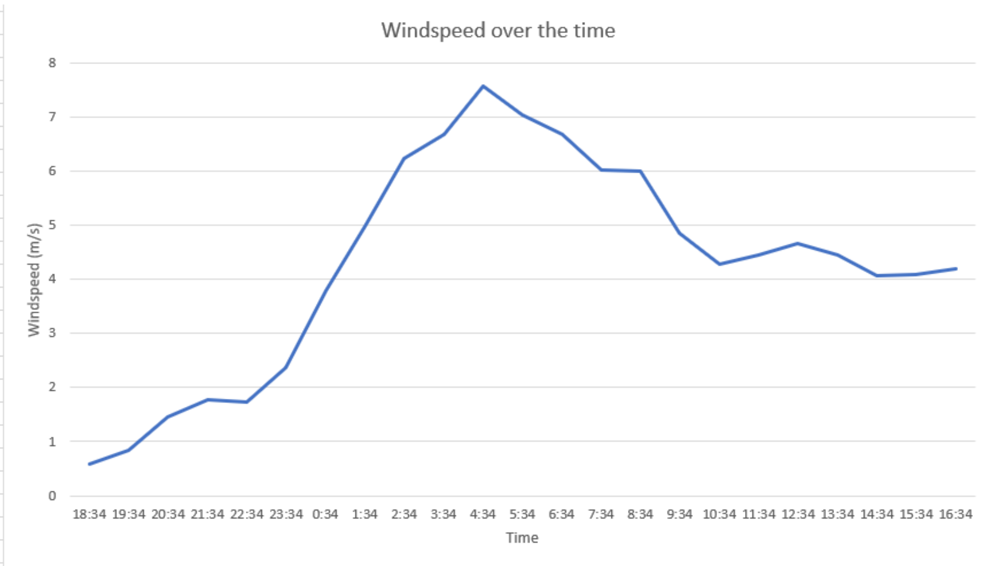
ShipHeading	from	(39.93461,	49.43374)	to	(39.93608,	49.62589):	89.37	degrees
ShipHeading	from	(39.93608,	49.62589)	to	(40.01468,	49.83113):	63.38	degrees
ShipHeading	from	(40.01468,	49.83113)	to	(40.14338,	50.01403):	47.34	degrees
ShipHeading	from	(40.14338,	50.01403)	to	(40.14381,	50.25091):	89.79	degrees
ShipHeading	from	(40.14381,	50.25091)	to	(40.16906,	50.49271):	82.14	degrees
ShipHeading	from	(40.16906,	50.49271)	to	(40.27474,	50.70481):	56.81	degrees
ShipHeading	from	(40.27474,	50.70481)	to	(40.45915,	50.7761):	16.39	degrees
ShipHeading	from	(40.45915,	50.7761)	to	(40.64483,	50.83535):	13.61	degrees
ShipHeading	from	(40.64483,	50.83535)	to	(40.82373,	50.9101):	17.54	degrees
ShipHeading	from	(40.82373,	50.9101)	to	(40.99843,	50.96093):	12.38	degrees
ShipHeading	from	(40.99843,	50.96093)	to	(41.17064,	51.00871):	11.8	degrees
ShipHeading	from	(41.17064,	51.00871)	to	(41.34593,	51.05479):	11.16	degrees
ShipHeading	from	(41.34593,	51.05479)	to	(41.51832,	51.09661):	10.29	degrees
ShipHeading	from	(41.51832,	51.09661)	to	(41.69711,	51.13912):	10.07	degrees
ShipHeading	from	(41.69711,	51.13912)	to	(41.87446,	51.17385):	8.3	degrees
ShipHeading	from	(41.87446,	51.17385)	to	(42.05012,	51.2089):	8.43	degrees
ShipHeading	from	(42.05012,	51.2089)	to	(42.23088,	51.24745):	8.97	degrees
ShipHeading	from	(42.23088,	51.24745)	to	(42.41514,	51.28875):	9.4	degrees
ShipHeading	from	(42.41514,	51.28875)	to	(42.59705,	51.33138):	9.79	degrees
ShipHeading	from	(42.59705,	51.33138)	to	(42.77999,	51.37344):	9.58	degrees
ShipHeading	from	(42.77999,	51.37344)	to	(42.96297,	51.42024):	10.6	degrees
ShipHeading	from	(42.96297,	51.42024)	to	(43.15104,	51.45464):	7.6	degrees

Note. Created by Author

The Thrust force was found to average during the voyage to be 28.90 Newtons per 1 square meter (1m2). In order to calculate power, equation 10, in Chapter 3.2 will be used with the constant speed of 13.05 knots (6.712 m/s) multiplied by this time-averaged forward force produced a time-averaged propulsive power of 193.9 Watts per 1m2 of wing sail area. It is because the wind speed in the selected route and over time is very low in order to get potential power for sail. The Flettner rotor on 21 July, in the selected route, shows various values compared to the wing sail. The average power of the Flettner rotor is around 24kW for a 175m2 area. From Figure 24, it can be seen that, at the beginning of the journey, whenever wing sail showed higher values while FR showed lower values. After some time, the power output of both technologies showed almost the same trend only with a difference in power values. In addition, FR, most of the time over the trip generated low power, almost less than 20kW. This is because on this day the wind speed was very low compared to other days in July. From the Figure below it is obvious that the highest wind speed is around 8 m/s just for some time during the journey. In addition, the wind angle has a significant impact in order to generate proper power.

Figure 23

Wind speed over time (21 July-22 July)



Note. Created by Author

As mentioned earlier, analyses were done for various journeys on different days. In the summer season, in July, the ferry did almost 7 trips from Baku Port to Kurik Port. Analyses for various days in July will be discussed below.

Figure 24

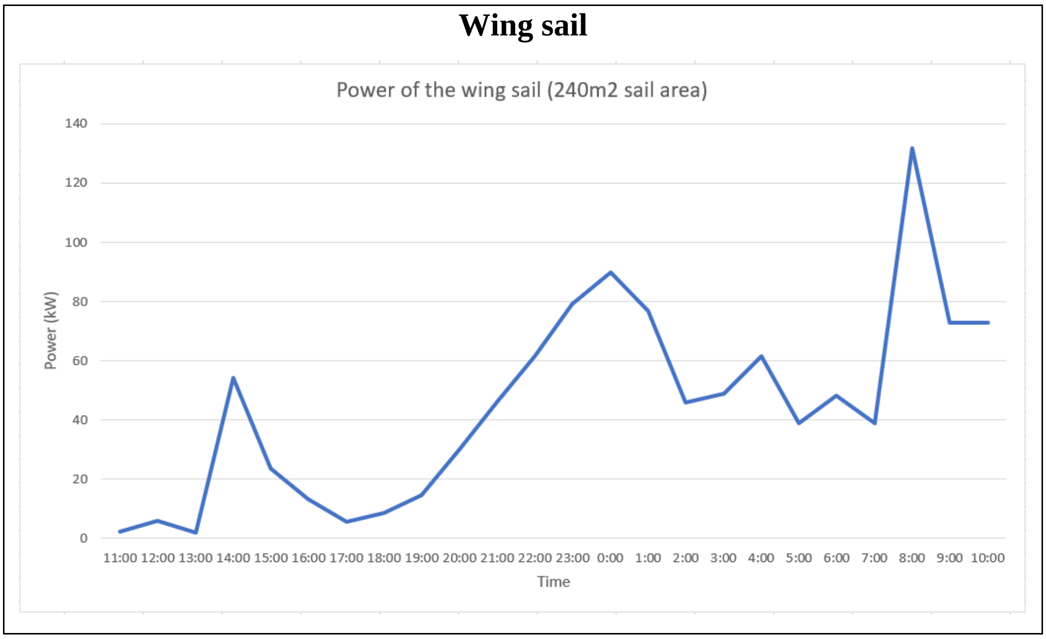
The power output of the Wing sail and Flettner rotor (21 July)

Note. Created by Author

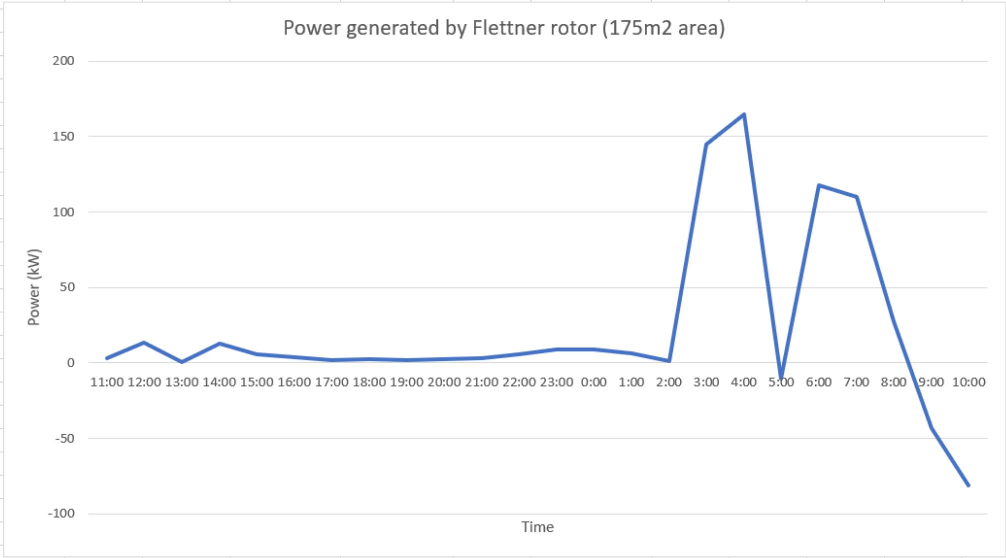
The first voyage was at the beginning of the month, 1 July. Using the equation (equation 9,10 in Chapter 3.2) in the "Wind Propulsion" program and after many iterations, the average thrust force for the 1m2 wing sail area was found around 27.80 Newtons. Therefore, the calculated average power over the time was around 186.64 Watts for the same wing sail area. Analyses were conducted for various days in July for Flettner rotors also. For the first voyage of this month, 1 July, results showed that even though wind speed was high for about 6-7 hours over time, the average thrust force was around 3191 Newtons and the average generated power was about 22kW.

Figure 25

The output Power of the Wing sail and Flettner rotor (1 July)



Flettner rotor

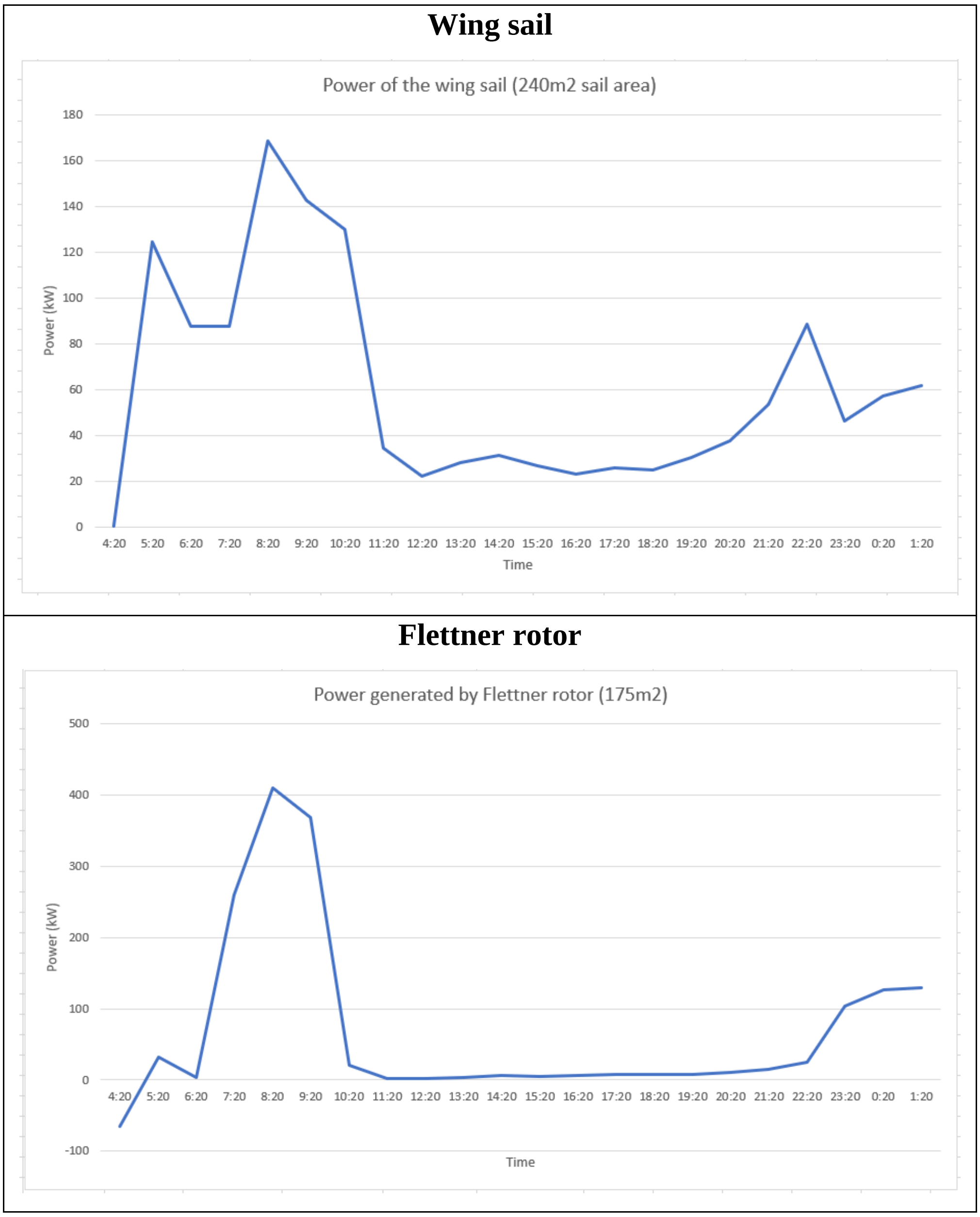


Note. Created by Author

The next trip started on July 5 and ended on July 6. After running the "Wind Propulsion" program, the average thrust force was found 37.58 Newtons per 1m2 wing sail area. The average power was calculated using the formula and was found 252.32 Watts for the same sail area. On the other day, 5 July, the results were found about 10066 Newtons as an average thrust force and almost 68kW power generated by FR for the 175m2 area. Figure 26 demonstrates generated power during the voyage. The maximum power above 300kW for the Flettner rotor was obtained only at the beginning of the trip, for about 1-2 hours.

Figure 26

The Power curve over the time for both wind propulsion (5 July)



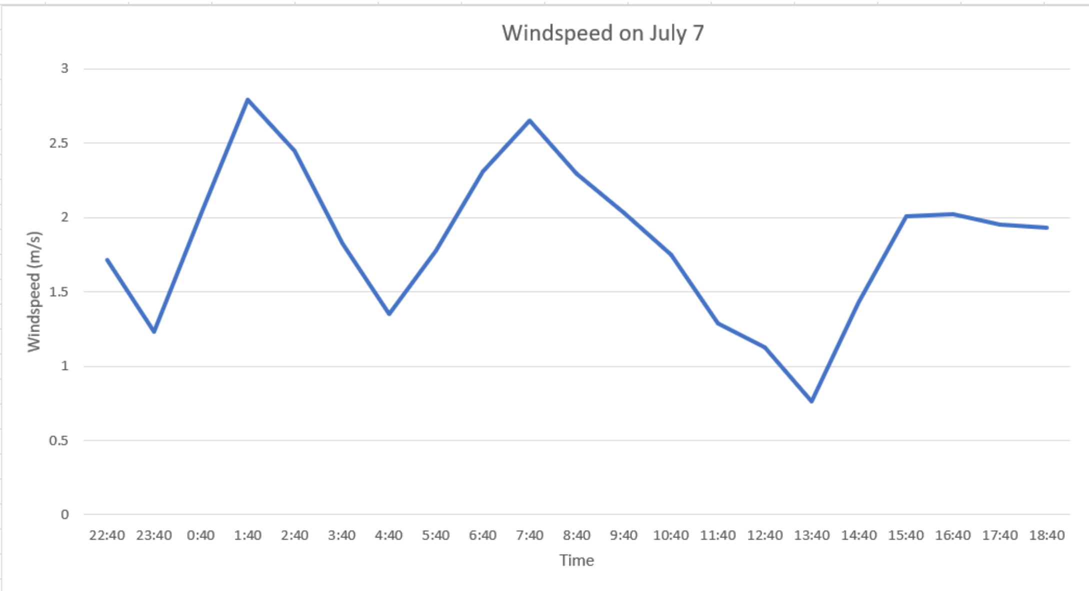
Note. Created by Author

On the other day, on 7 July, the results showed slightly lower values because of low wind speed. The calculated average thrust force was found 34.13 Newtons and the average power was 218.42 Watts per 1m2 wing sail area. On the same day, for the

Flettner rotor for 175m2 area, the calculated average thrust force and average power output were found about 2739 Newtons and 19kW respectively. According to wind propulsion technologies, this amount of power is very low, almost even to zero. This is because the TWS is very low (Figure 27) and TWA created more drag force rather than lift force. As per Figure 28, the generated power by the Flettner rotor was almost below 30kW during the voyage, however, the values for the wing sail showed slightly higher.

Figure 27

Wind speed during the voyage on 7 July



Note. Created by Author

The ferry made the next journey on 14 of July. For that day, the wind speed was very low as it was on 7 July and as a result, a small amount of the thrust force and power was obtained. The thrust force for the 1m2 wing sail area was found around 22.35 Newtons, therefore the amount of power was approximately 150 Watts for the same sail area (Figure 29). Nevertheless, similar results to the values on July 7 can be seen for the Flettner rotor on 14 July. The average thrust force was almost similar to the result on July 7, around 2590 Newtons.

Figure 28

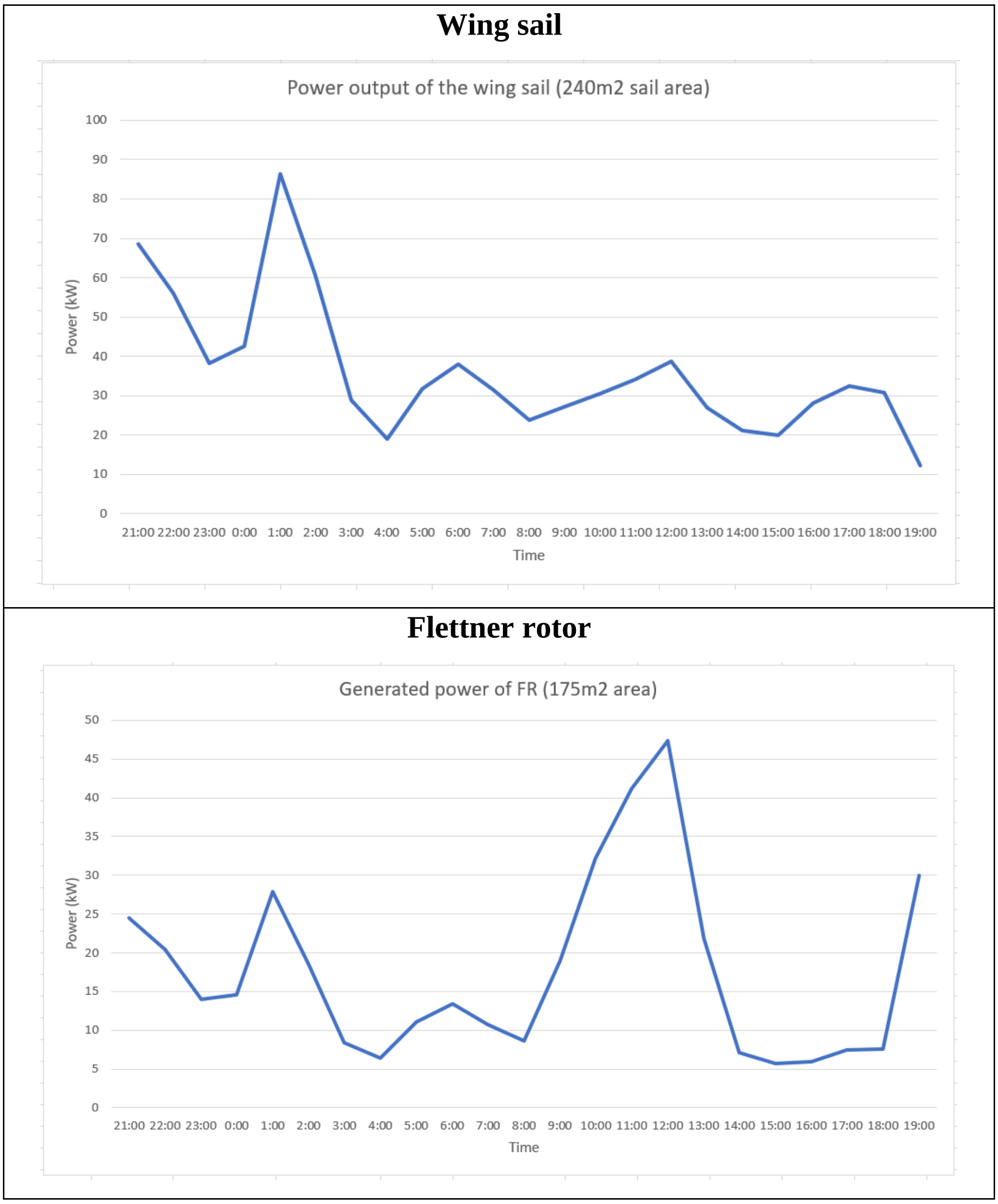
The power output of the Wing sail and Flettner rotor (7 July)

Note. Created by Author

Therefore, the average power was 17kW per 175m2 FR. The power fluctuated over time and the maximum power was less than 50kW over the journey.

Figure 29

Changing power over the time for Wing sail and Flettner rotor (14 July)

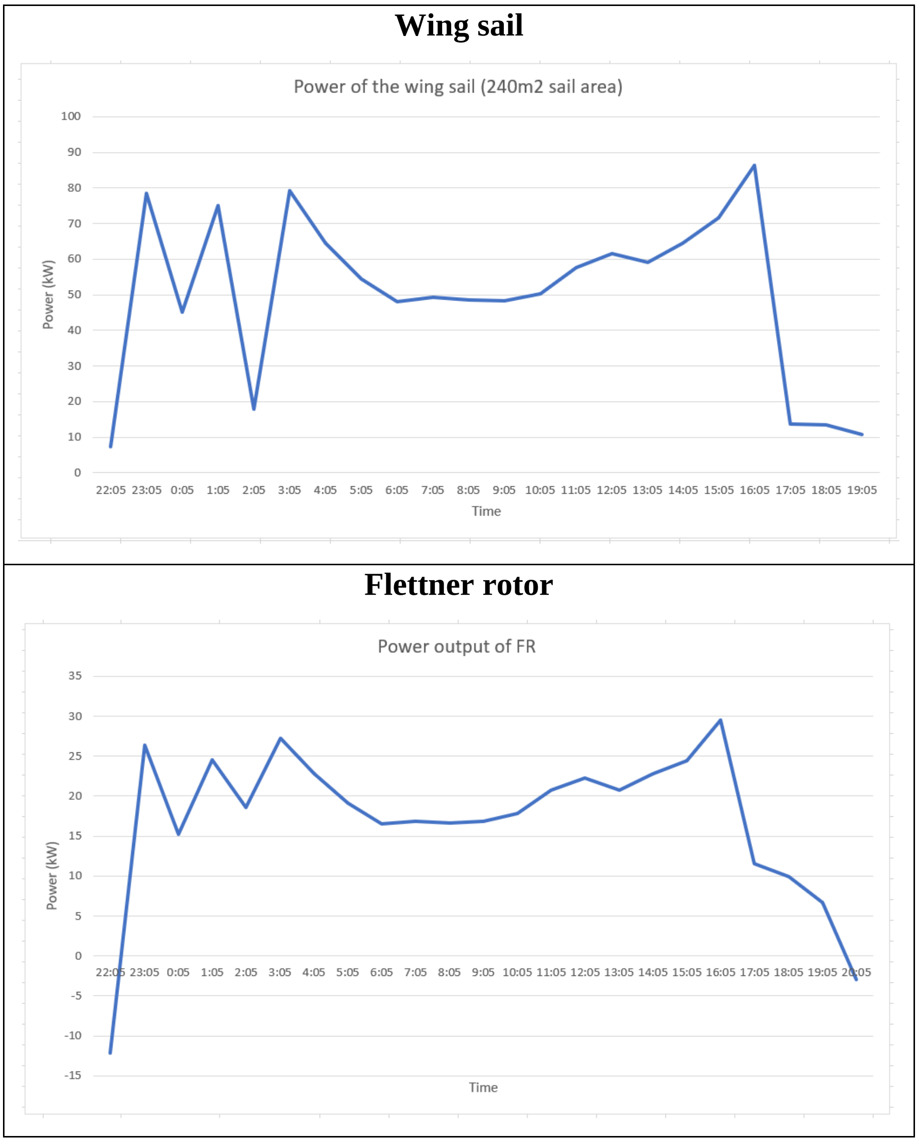


Note. Created by Author

However, on 18 July, the average thrust force was about 30.7 Newtons and power was obtained around 201.9 Watts per 1m2 wing sail area. Figure below shows the fluctuation of the power on this day, because of changing wind speed and angle. The result for the Flettner rotor for 18 July showed that, because of the low wind speed the obtained values were not enough in order to use as a propulsion.

Figure 30

The power output of Wing sail and Flettner rotor (18 July)



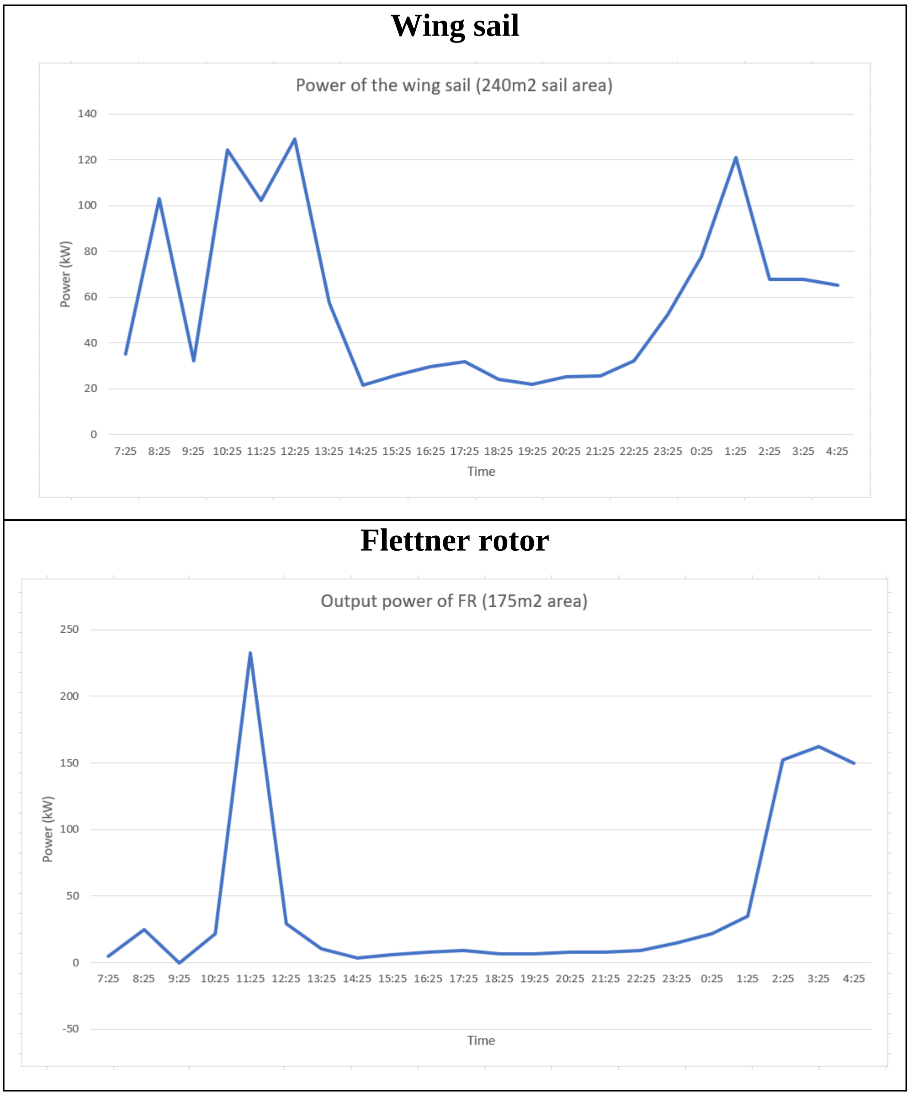
Note. Created by Author

The average thrust force was found 2541 Newtons and the average generated power was around 17kW for the 175m2 area of FR (Figure 30).

On the other hand, on the last voyage for July, on July 26, the results were slightly higher for wing sail compared to the previous day. The average thrust force was found 35.98 Newtons per 1m2 wing sail area. Therefore, the average power output was around 241.54 Watts for the same sail area (Figure 31).

Figure 31

The power output over the time for Wing sail and Flettner rotor (26 July)

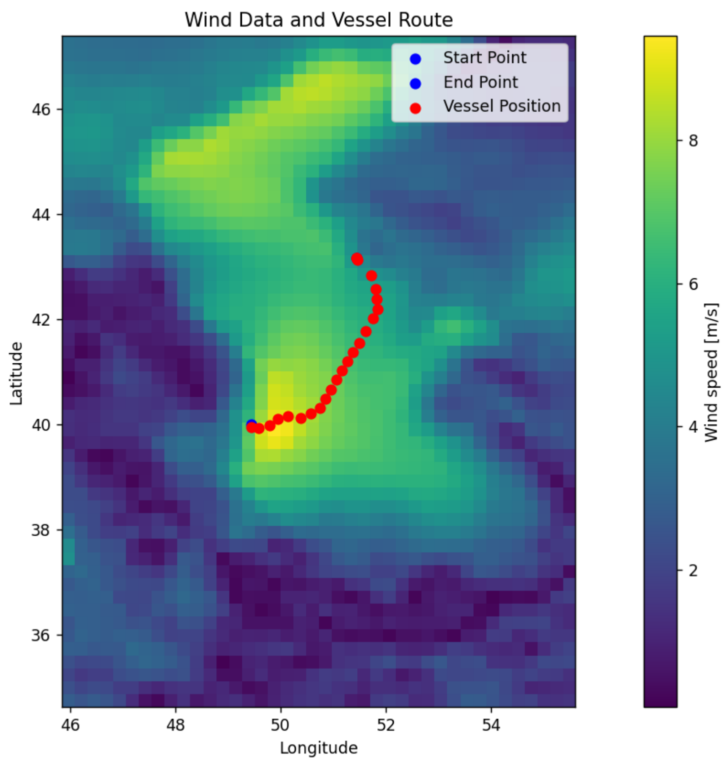


On this day, wind speed was higher some time of the trip compared to other days in the same month. As a result, the average thrust force was higher, about 6270 Newtons and the average power was found 43kW for the 175m2 area of the Flettner rotor.

The third analysis was done in the autumn season for the comparison of the wind speed and output Power. The vessel starts its journey from Baku Port on 15 October at 20:00 p.m. and ends at Kurik Port on 16 October at 20:00 p.m. The vessel positions every 1-hour frequency during the trip are shown below figure and the above-mentioned ship heading calculations are also done for this route.

Figure 32

Vessel positions during the voyage



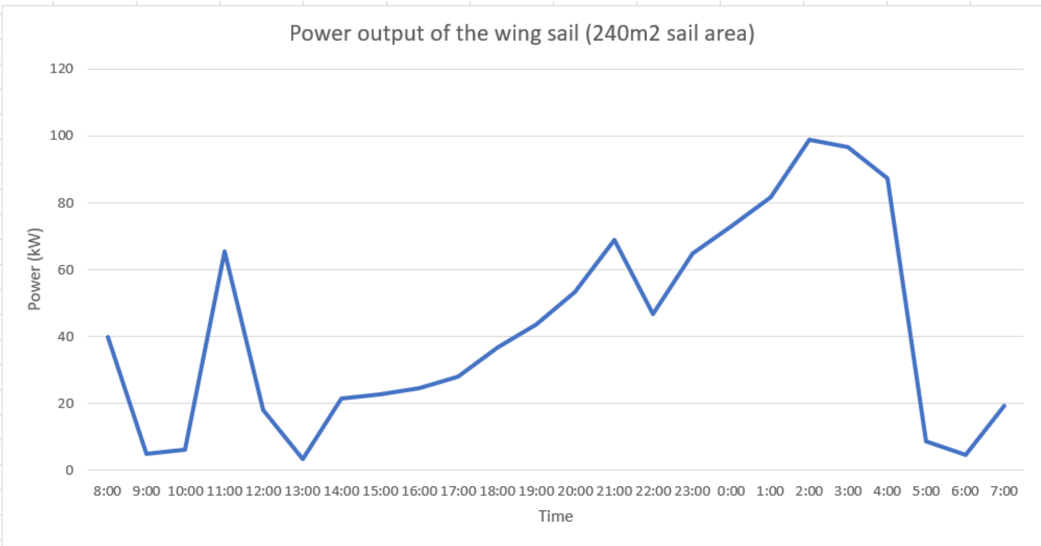
Note. Created by Author

In order to calculate the Power output first need to calculate the thrust force from the wing sail as per equation (equation 9, In Chapter 3.2) and based on the thrust force values the average thrust force will be approximately 20 Newtons. Using the equation (equation 10, in Chapter 3.2), the power was calculated for the wing sail and the value was 132.77 Watts per 1m2 wing sail area.

On the other days in October, analyses and calculations showed different values for wing sails and for the Flettner rotor. Firstly, the results for the wing sail will be discussed. On the first day of October, the ferry made a journey from Baku Port to Kurik Port. The calculated average thrust force was 26.4 Newtons for the 1m2 wing sail area. The average power for the same area was found 178 Watts (Figure 33).

Figure 33

The calculated power for 240m2 sail area (1 October)



Note. Created by Author

The other days in October will be illustrated below table. As per the below table, Table 7, the results for the 8 and 13 of October showed almost the same. That is because, on both of these days, wind speed was approximately the same and was not high enough in order to obtain proper power. However, if we look at the next days, 24 and 29 October, in those days results were higher compared to other days. Based on u and v data, during the voyage on these days, the wind speed demonstrated higher values. As a result, from the calculations with the use of the "Wind Propulsion" program, can be obtained some amount of power in order to use as a propulsion of the ferry.

Table 7

Calculated average thrust force and average power for the 1m2 wing sail over time

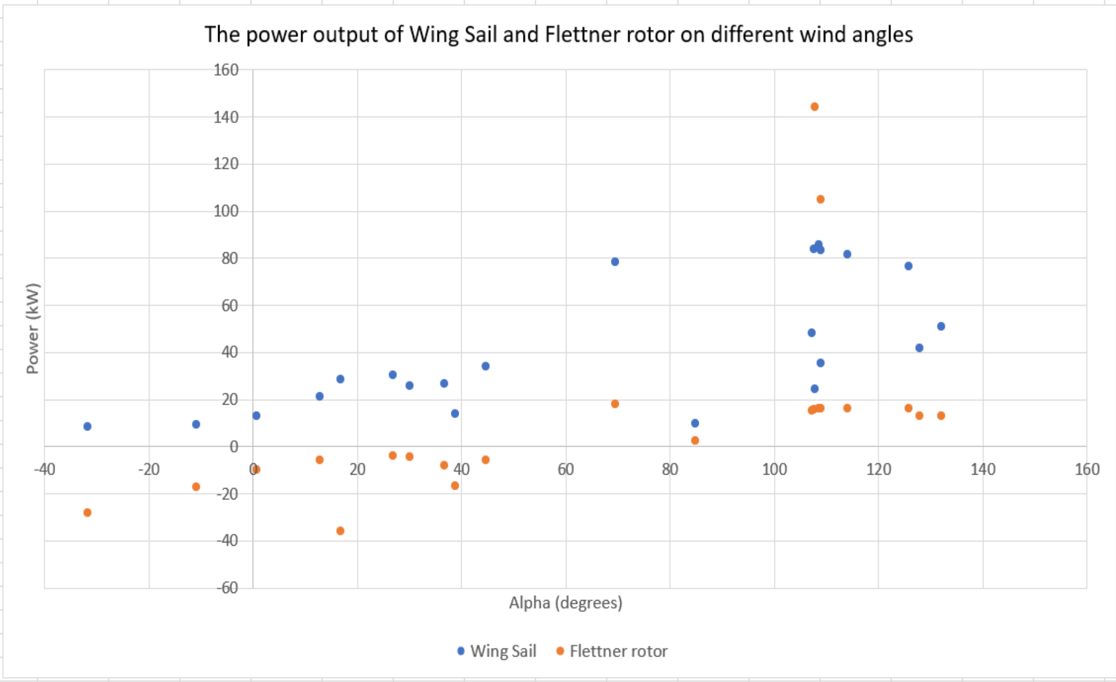
Average thrust force and average power for the 1m2 sail area over time			
Destination	Date and time	Average Thrust force	Average power
Baku-Kurik	1 October: 08:00 a.m. 2 October: 07:00 a.m.	26.4 Newtons	178 Watts (42.72 kW for 240m2 sail area)
Baku-Kurik	8 October: 00:00 a.m. 8 October: 23:00 p.m.	28.64 Newtons	193.31 Watts (46.32 kW for 240m2 sail area)
Baku-Kurik	13 October: 09:30 a.m. 14 October: 06:30 a.m.	28.38 Newtons	188.51 Watts (45.36 kW for 240m2 sail area)
Baku-Kurik	15 October: 20:00 p.m. 16 October: 20:00 p.m.	20 Newtons	132.79 Watts (31.92 kW for 240m2 sail area)
Baku-Kurik	24 October: 01:00 a.m. 24 October: 23:00 p.m.	30 Newtons	200 Watts (48 kW for 240m2 sail area)
Baku-Kurik	29 October: 05:00 a.m. 30 October: 07:00 a.m.	31 Newtons	207 Watts (50 kW for 240m2 sail area)

Note. Created by Author

On the other hand, the Flettner rotor showed slightly higher power outputs compared to wing sails in the same month. As per the below table, for almost all the days, the power generated by FR showed higher values compared to wing sail. The wing sail area was selected 240m2 however the Flettner rotor area was chosen 175m2. For comparison, for almost the same area FR generates more power compared to wing sail. When it comes to performance, the Flettner rotors are more effective in reaching and downwind circumstances, while the Wing sails are more advantageous in headwinds (Thies & Ringsberg, 2023). As per analyses during the voyages, below figures illustrate according to literature, during the headwinds, when the wind angle (alpha) was less than 50 degrees, wing sail can get positive power values, however Flettner rotor showed negative values (Figures 34 and 35). When the vessel was against the wind, the Wing sail showed better performance compared to the Flettner rotor.

Figure 34

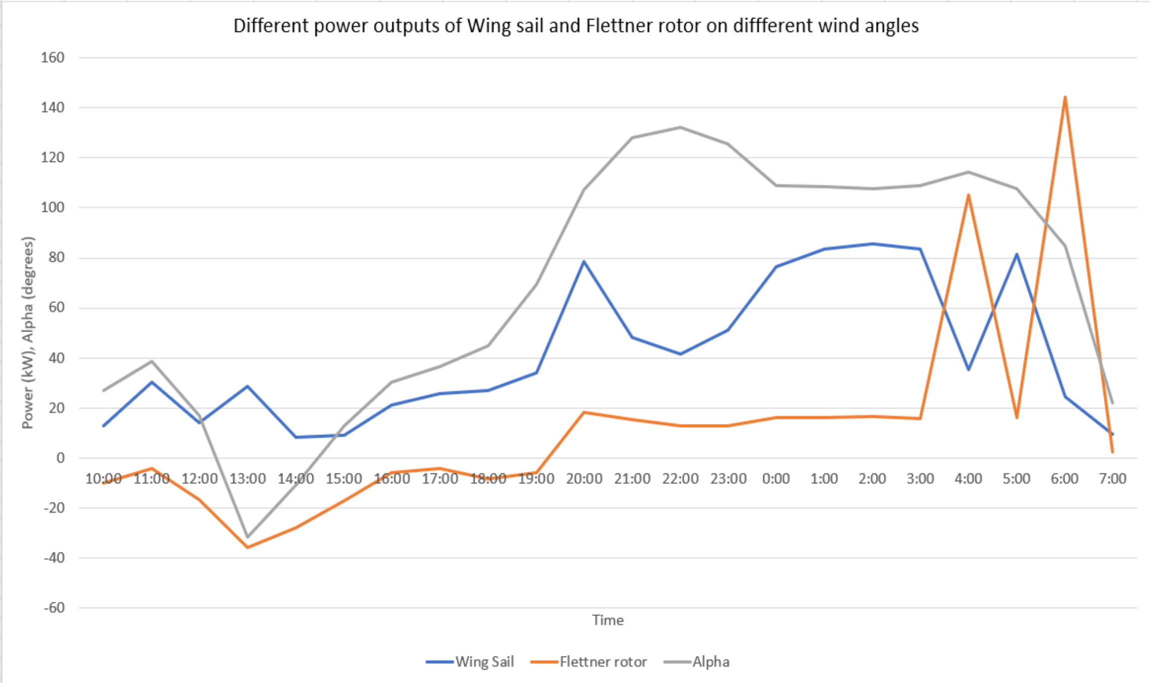
The power output of Wing Sail and Flettner rotor on various wind angle. Alpha- is the relative angle between true wind speed and ship heading.



Note. Created by Author

Figure 35

The power output of Wing Sail and Flettner rotor on various wind angle. Alpha- is the relative angle between true wind speed and ship heading.



Note. Created by Author

As seen from the aforementioned analysis, many elements of the Power showed negative values for the Flettner rotor, indicating that the corresponding wind speed and direction would result in a negative power output. In instances when these rotors produce a negative trust force, it is possible to reduce their speed, cease their operation, or retract them in order to mitigate power losses, since they will only encounter air resistance. In order to prevent power losses that FRs may produce if operated at improper wind speeds and directions or even SR, this highlighted the significance of good weather routing and wind condition data.

Table 8

The generated thrust force and power for a 1m2 area of FR over the time in October

The generated thrust force and power of the Flettner rotor for a 1m2 area over time			
Destination	Date and time	Average Thrust force	Average power
Baku-Kurik	1 October: 08:00 a.m. 2 October: 07:00 a.m.	12127 Newtons	465 Watts (82 kW for 175m2 area)
Baku-Kurik	8 October: 00:00 a.m. 8 October: 23:00 p.m.	15589 Newtons	598 Watts (105 kW for 175m2 area)
Baku-Kurik	13 October: 09:30 a.m. 14 October: 06:30 a.m.	13396 Newtons	514 Watts (90 kW for 175m2 area)
Baku-Kurik	15 October: 20:00 p.m. 16 October: 20:00 p.m.	20255 Newtons	777 Watts (136 kW for 175m2 area)
Baku-Kurik	24 October: 01:00 a.m. 24 October: 23:00 p.m.	7503 Newtons	288 Watts (51 kW for 175m2 area)
Baku-Kurik	29 October: 05:00 a.m. 30 October: 07:00 a.m.	9825 Newtons	377 Watts (66 kW for 175m2 area)

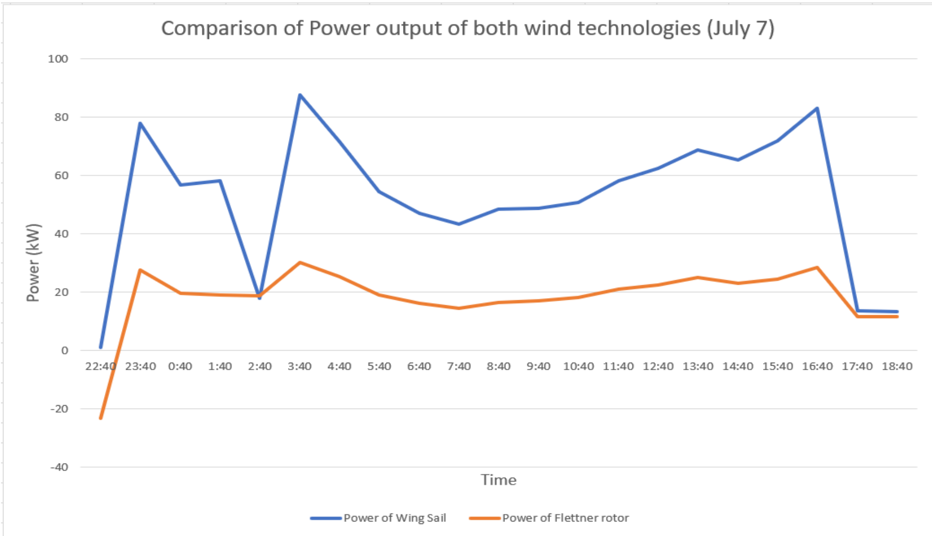
Note. Created by Author

To generalize all the above analyses and discussion, based on various wind speed and angle results showed different values. For the wing sail, it has the opportunity, can get better lift force and from that good amount of power while changing the sail direction. From this point of view, if the headwind is more dominant during the voyage, we can get better power values with the wing sail compared to the Flettner rotor. However, in July most of the day's wing sail showed better performance in comparison with FR. As per Figures 36 and 37, also as discussed earlier, for various days in July, the power output of Wing Sail (Blue line) on almost all the voyage days was higher compared to the Flettner rotor (Orange line).

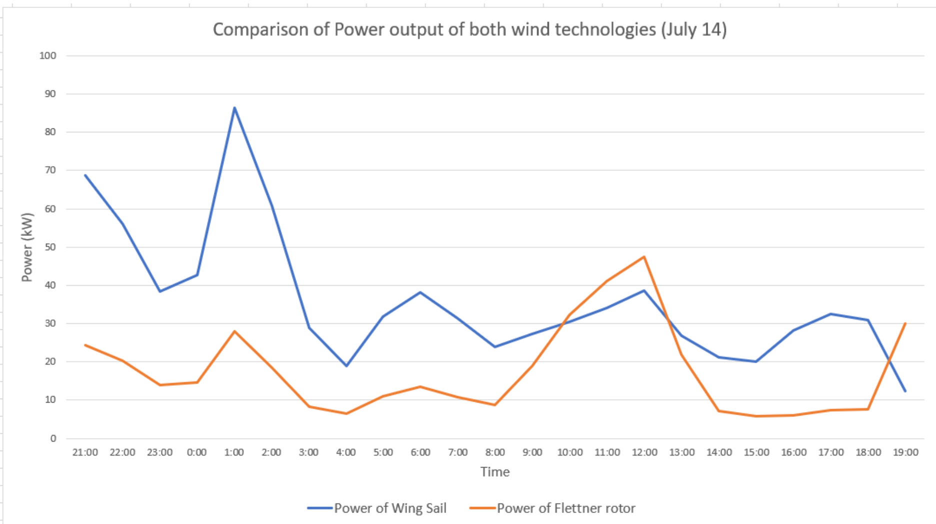
Figure 36

The comparison of the power of 240m2 area Wing sail and 175m2 area Flettner rotor

Power output on 7th July



Power output on 14th July

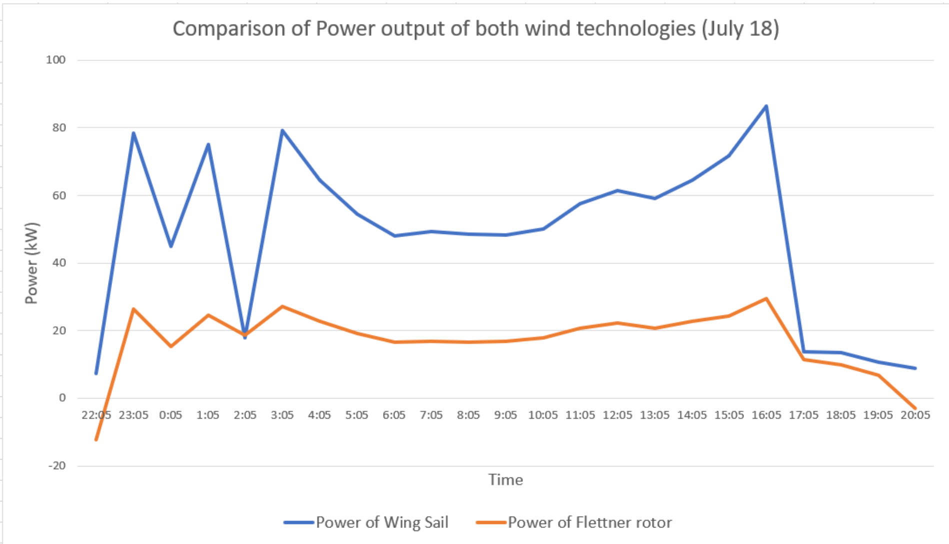


Note. Created by Author

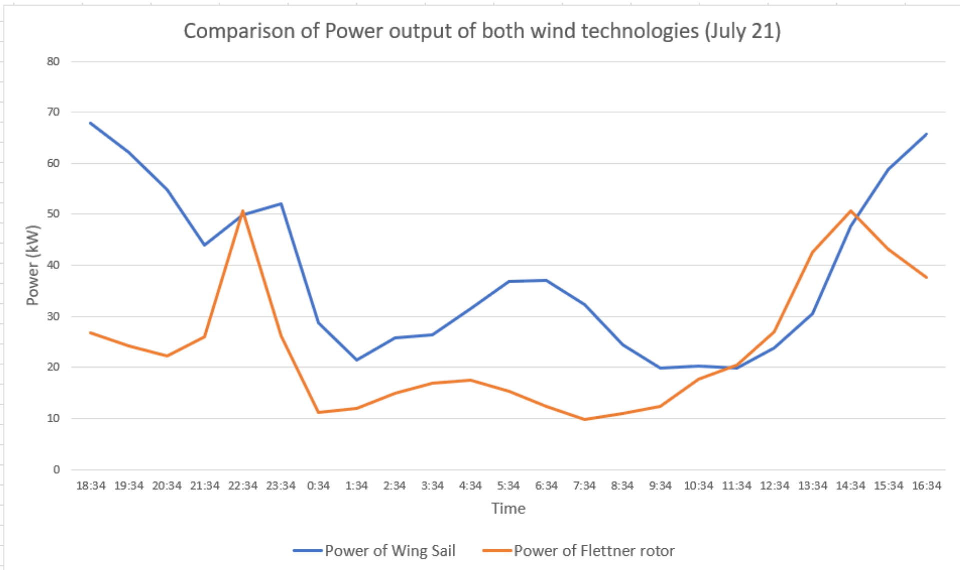
Figure 37

The comparison of the power of 240m2 area Wing sail and 175m2 area Flettner rotor

Power output on 18th July



Power output on 21st July

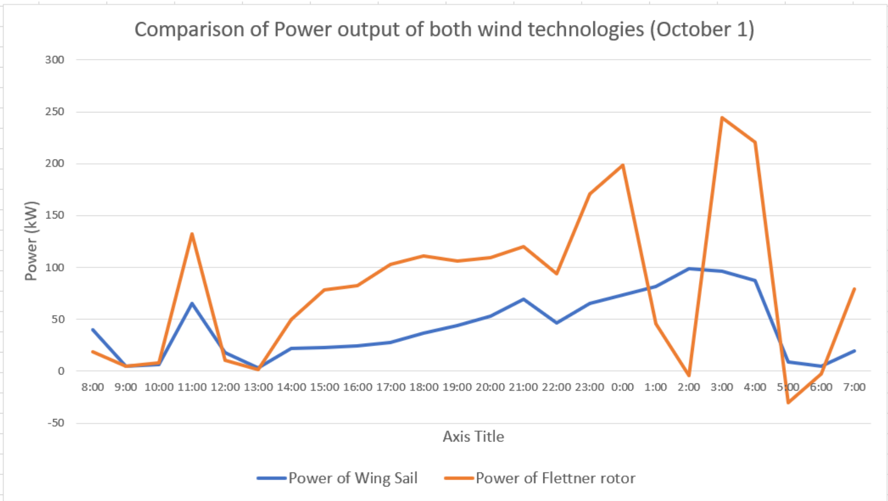


Note. Created by Author

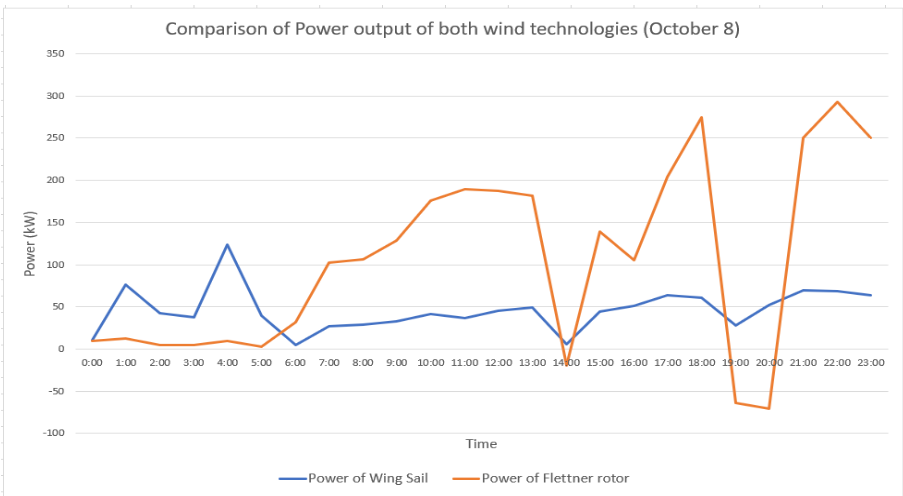
Figure 38

The comparison of the power of 240m2 area Wing sail and 175m2 area Flettner rotor

Power output on 1st October



Power output on 8th October

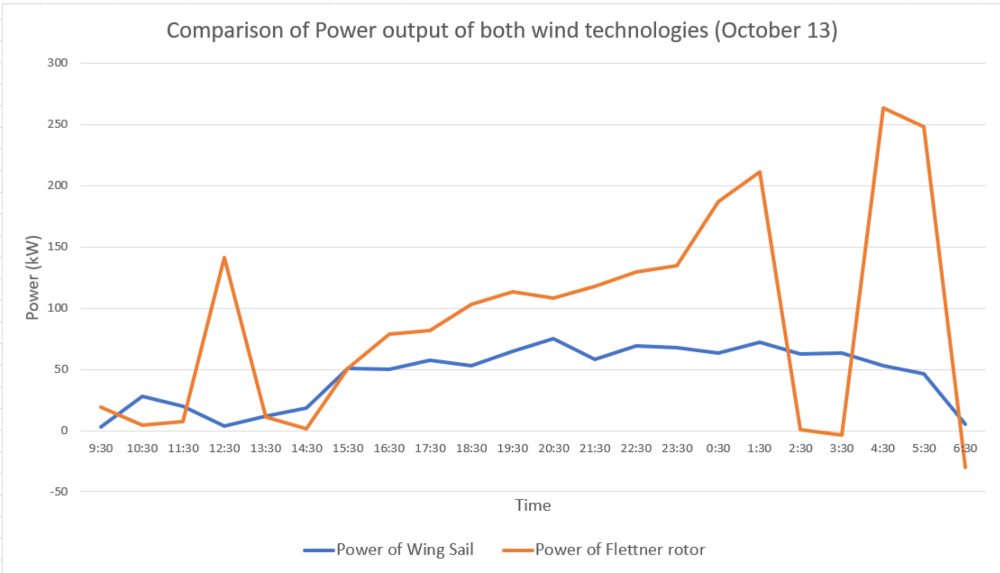


Note. Created by Author

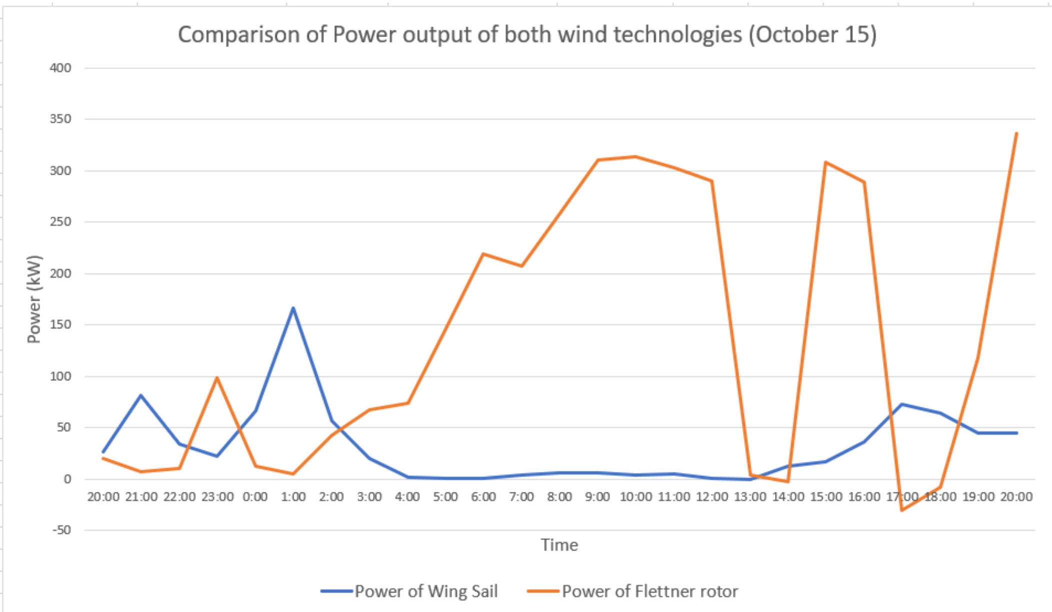
Figure 39

The comparison of the power of 240m2 area Wing sail and 175m2 area Flettner rotor

Power output on 13th October



Power output on 15th October



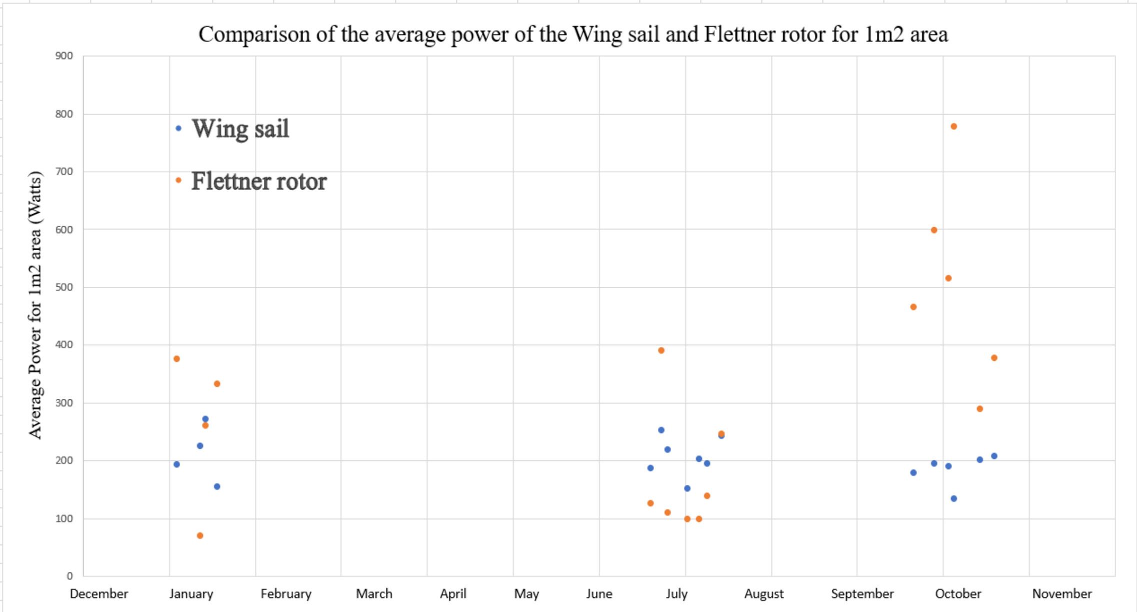
Note. Created by Author

On the other hand, in October all the voyage days FR had higher power values in comparison to wing sail. As mentioned earlier, for the same wind speed and angle, Flettner rotors can give higher lift force and power compared to wing sails. As per the above figures, Figures 38 and 39, as discussed before, in October the results for the Flettner rotor were higher than Wing sail. It is a quite an interesting point that seasonal factors played an important role in this region.

Summarizing all the above-mentioned analyses, the following figure shows the performance of both technologies in different months and days. It can be concluded that wind speed, wind direction and different seasons have very significant impacts on the performance of these types of technologies. The figure below demonstrates the average power for a 1m2 area for both the Wing sail and Flettner rotor for different months and days.

Figure 40

Comparison of the average power of Wing sail and Flettner rotor for different months



Note. Created by Author

Chapter 4.5 Fuel consumption reduction and economic analyses.

In Chapter 4.4.1 the thrust force and power output were discussed for the wing sail and for the Flettner rotor. As mentioned earlier, in general speaking Flettner rotor showed higher results on the same day in a specific selected route. So, in this Chapter fuel consumption reduction and economic analyses for the use of the Flettner rotor will be discussed for various days from various months.

For the analyses the vessel speed selected constant over the time (13.05 knots or 6.712 m/s). So, the power of the vessel also was constant at 3900 kW. For all the days, total energy without wind-assisted was calculated, then using the "Wind Propulsion" program, the energy for each day for the selected route for every hour was calculated and was summed as the total energy for the days separately. However, as the Flettner rotor cylinder spins, some amount of power is needed for spinning the rotor. For this study, for energy requirement for the spinning of the rotor, 10% of the Total energy with wind-assisted propulsion was chosen as an assumption in order to calculate fuel consumption reduction. As a next step, MASS of fuel was calculated for both scenarios and from that fuel savings calculations were conducted.

Table 9 demonstrates fuel savings for the various days from different months in order to make obvious different cases. As seen below table (Table 9), the maximum fuel saving can be achieved by almost 5 % in the voyage on October 15. However, the lowest amount was found as 0.55 %. The results were slightly similar to the study for 3 various (Dynarig, Wing sail and Flettner rotor) WASP technologies conducted by Lu and Ringsberg (2019). According to Lu and Ringsberg (2019), when compared to a vessel that does not have sails, their statistics reveal fuel savings of 5.6% to 8.9%. From the above analyses and calculations, the generated power was higher in October, because of the seasonal conditions and high wind speeds. As a result, fuel savings achieved their higher values in this month. Generally, it has been shown that, while all other variables remain constant, an increase in wind speed leads to greater energy production from the WASP technology, hence yielding higher fuel savings. Seasonal differences showed that the Flettner rotor performed better in the autumn to winter seasons.

Table 9

Fuel savings of 175m2 FR

DATE	Total Energy without wind-assisted (kJ)	Total Energy with wind assisted (kJ)	MASS of Fuel (Without wind assisted) (tons)	MASS of Fuel (With wind assisted) (tons)	Fuel savings %
3-Jan	322920000	2732926.167	7.515010472	0.063600795	0.8463168
17-Jan	322920000	6657054.215	7.515010472	0.1549233	2.0615181
25-Jan	308880000	1685096.207	7.188270887	0.039215644	0.5455504
27-Jan	351000000	5255268.55	8.168489644	0.122300874	1.4972275
31-Jan	351000000	6624051.248	8.168489644	0.154155254	1.8871941
1-Jul	336960000	2379369.758	7.841750058	0.055372813	0.7061283
5-Jul	308880000	6880694.833	7.188270887	0.160127876	2.2276272
7-Jul	294840000	1786651.349	6.861531301	0.04157904	0.6059732
14-Jul	322920000	1868011.199	7.515010472	0.043472451	0.5784749
18-Jul	322920000	1815657.816	7.515010472	0.04225408	0.5622624
21-Jul	322920000	2538622.807	7.515010472	0.059078958	0.786146
26-Jul	308880000	4285478.725	7.188270887	0.099731876	1.3874251
1-Oct	336960000	9043138.748	7.841750058	0.21045238	2.6837425
8-Oct	336960000	11624456.84	7.841750058	0.270524944	3.4498032
13-Oct	308880000	9157003.878	7.188270887	0.213102255	2.964583
15-Oct	351000000	15733355.88	8.168489644	0.366147449	4.4824376
24-Oct	322920000	5361627.631	7.515010472	0.124776068	1.6603579
29-Oct	379080000	8241928.658	8.821968815	0.191806578	2.1741924

Note. Created by Author

While the absolute fuel savings for rotors and wing sails tend to grow as ship speed increases (for the real case), the relative fuel savings actually decrease. The rationale for this phenomenon is the fact that, with the escalation of energy demand, the ship's fuel consumption is more significantly influenced by the power demand rather than the contribution of rotors or wing sails (Lu & Ringsberg, 2019; Delft & Fraunhofer, 2016). In addition, any other factors such as wave height and ocean currents were not considered in this study. Based on the literature, these factors have a significant negative impact on the performance of the vessel (Smith et al., 2013). The cost of gasoline accounts for more than half of total ship expenditures in the vast majority of situations; hence, any reductions in fuel costs, regardless of how tiny they may be, represent enormous savings in terms of money (Chou et al., 2020). In addition, the program as it was written now does not retract the Flettner rotor during unfavourable wind conditions, to reduce its resistance. Hence, practical fuel savings may be higher than estimated in the modelling.

According to Tillig et al. (2020), the estimated price of 1 Flettner rotor will be around 1,160,000 EUR, including installation costs and it is generally assumed that annual maintenance expenses amount to 2% of the initial installation costs. It is known that generally speaking, 1 vessel's lifetime period is about 25 years. The determination of interest rates typically follows a commercial framework. However, several experts have suggested that a larger discount rate should be used from a socioeconomic perspective (IMO, 2020). Taking into consideration this, the analyses, it was conducted for a 25-year period with a discount rate of 5%. From the above figure, average fuel savings for all months were an average of 2%. As it is known that, fuel oil costs are not stable and fluctuate, so, for our study, it was assumed the fuel oil price was on average 600 USD per ton. The fuel consumption of the ferry for the whole year was 3479.11 tonnes and around 2,087,466 USD per year it cost for this vessel. Every ton of fuel emits 3.2 tons of CO_2 and if IMO in the mid-term will adopt Carbon prices in the future as a market-based measure, every ton of CO_2 will come on top of the fuel. As per above mentioned analyses and discussion, CO_2 emission can be reduced by around 7.8 tonnes. If the Carbon price enters into force in 2026 and assumed that the Carbon price will be around 100 USD per ton, based on that, monetary and CO_2 savings will be around 55,314.78 USD annually and the project will have a payback period (PP) of 20 years. Table 10 shows the economic analyses of the project.

Table 10

The project's economic assessments. Cash Flow (CF), Discounted Cash Flow (DCF), Cumulative Discounted Cash Flow (CDCF) AND Cumulative Cash Flow (CCF)

Year	CF	DCF	(1+r)^n	CDCF	CCF
0	-$1,160,000.00	-$1,160,000.00	1	-$1,160,000.00	-$1,160,000.00
1	$55,314.78	$52,680.74	1.05	-$1,107,319.26	-$1,104,685.22
2	$55,314.78	$50,172.14	1.1025	-$1,057,147.12	-$1,049,370.44
3	$55,314.78	$47,782.99	1.157625	-$1,009,364.14	-$994,055.66
4	$55,314.78	$45,507.61	1.21550625	-$963,856.53	-$938,740.88
5	$55,314.78	$43,340.58	1.276281563	-$920,515.95	-$883,426.10
6	$55,314.78	$41,276.74	1.340095641	-$879,239.21	-$828,111.32
7	$55,314.78	$39,311.18	1.407100423	-$839,928.03	-$772,796.54
8	$55,314.78	$37,439.22	1.477455444	-$802,488.81	-$717,481.76
9	$55,314.78	$35,656.40	1.551328216	-$766,832.41	-$662,166.98
10	$55,314.78	$33,958.48	1.628894627	-$732,873.93	-$606,852.20
11	$55,314.78	$32,341.41	1.710339358	-$700,532.53	-$551,537.42
12	$55,314.78	$30,801.34	1.795856326	-$669,731.19	-$496,222.65
13	$55,314.78	$29,334.61	1.885649142	-$640,396.58	-$440,907.87
14	$55,314.78	$27,937.72	1.979931599	-$612,458.86	-$385,593.09
15	$55,314.78	$26,607.35	2.078928179	-$585,851.50	-$330,278.31
16	$55,314.78	$25,340.34	2.182874588	-$560,511.17	-$274,963.53
17	$55,314.78	$24,133.66	2.292018318	-$536,377.51	-$219,648.75
18	$55,314.78	$22,984.43	2.406619234	-$513,393.08	-$164,333.97
19	$55,314.78	$21,889.94	2.526950195	-$491,503.14	-$109,019.19
20	$55,314.78	$20,847.56	2.653297705	-$470,655.58	-$53,704.41
21	$55,314.78	$19,854.82	2.78596259	-$450,800.76	$1,610.37
22	$55,314.78	$18,909.35	2.92526072	-$431,891.41	$56,925.15
23	$55,314.78	$18,008.91	3.071523756	-$413,882.51	$112,239.93
24	$55,314.78	$17,151.34	3.225099944	-$396,731.17	$167,554.71
25	$55,314.78	$16,334.61	3.386354941	-$380,396.56	$222,869.49

Note. Created by Author

Furthermore, the adoption of environmentally friendly practices has become increasingly prevalent across various transportation sectors. It is evident that shipping companies that prioritise sustainability will likely dominate future markets. Therefore, the perceived financial burden associated with investing in greening initiatives should not hinder companies, as such efforts will not only ensure a larger market presence but also facilitate a swift recovery of invested capital.

Chapter 5 CONCLUSION AND RECOMMENDATIONS

The study calculated the efficiency of a rigid wind propulsion system via the optimisation of its sail angle, with the aim of maximising power generation for ship-based applications. In addition, the main focus of this research was to calculate thrust force and power with the use of real wind data taken from satellite data (Copernicus, ERA5), in the Caspian region for the specific route (Baku Port to Kurik Port). For the optimisation model data for aerofoil was taken from NACA (National Advisory Committee for Aeronautics) wind tunnel tests in order to calculate wind power. According to the literature review and conducted analyses, the study found that there are various renewable energy technologies for various types of commercial vessels. Among these technologies, first FRs and second Wing sails are more promising as a WASP. The conclusions of this study are as follows:

- Based on the analyses, it revealed that the obtained thrust and power values significantly depend on the wind speed and wind angle. For the wing sail, the maximum average thrust force was found 40.36 Newtons and the maximum average power was around 271 Watts per 1m2 wing sail area (65kW for 240m2 wing sail area) at the beginning of the year, 27 January. For different times of the year obtained power values were 253 Watts, 218 Watts and 242 Watts per square meter, for the summer season, on different days in July, 194 Watts, 189 Watts, 200 Watts and 207 Watts for the autumn season, on various days in October.
- However, compared to Wing sail, Flettner rotor results were different. The maximum average thrust force was 116 Newtons per square meter and the maximum average power value was 777 Watts per square meter (137kW for 175m2 area). For different times of the year, the generated power was 375

Watts, 260 Watts and 331 Watts for the beginning of the year, on different days in January, 108 Watts, 97 Watts, 137 Watts, 245 Watts for the summer season and 465 Watts, 598 Watts, 514 Watts, 777 Watts, 288 Watts and 377 Watts for the autumn season, various days in October.

- From the analysis and results of the selected months, it can be concluded that roughly, 2.5% fuel savings per year were obtained for the Flettner rotor and accordingly, 7.8 tons of CO_2 can be saved per year by implementing this technology.

As seen above values, at the end of the year, especially in the autumn season when the wind speed is quite high compared to other days in the year, the Flettner rotor is more effective and efficient compared to the Wing sail. However, some other times in the year Wing Sail showed higher power values than FR. The use of wind energy in a selected region is not unambiguously efficient or inefficient. Based on the findings of the research, it is feasible to acquire enough power and energy during periods characterized by elevated wind speeds, both on a monthly and daily basis. Nevertheless, the use of this technique proves to be inefficient in conditions of low wind speed.

- Up to 55,314 USD could be saved annually and the project payback period considering mid-term market-based measures will be 20 years. In conclusion, based on this analysis and discussion, without market-based measures, it will not be beneficial however with market-based measures, after 20 years the project will get payback.

The research recommendations will be as follows:

- WASP technologies are considered a viable alternative for decarbonization due to their technological compatibility, affordability and already being implemented on ships.
- In the future more accurate wind data, for more journey schedules for more than 2 years, with more detailed analyses such as wind tunnel tests, Computational Fluid Dynamics (CFD) research, should be conducted.

- Additional investigation is necessary to enhance the optimisation of several factors that impact the efficacy of wind systems and the adoption of this technology. The factors under consideration include the impact of technologies on stability, extra resistance, drift and heel angle.
- It is also recommended that more studies be carried out in order to discover the true impacts that sails have on one another as well as the effects that the Flettner rotor has when it is mounted on the ship by using wind tunnel tests and Computational Fluid Dynamic models (CFD).
- In future research, a comprehensive socio-economic analysis may be conducted.

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Appendices

Appendix 1 Sail angle optimisation model (to the NACA0015 airfoil application)

Wing sail program-NACA0015.py - D:\WMU CLASS 2023\WMU - CLASS OF 2023- Suleymanli Mahmud\Dissertation\Python\Wing sales\NACA0015\Wing sail program-NACA0015.py (3.11.2)

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```
#Sail angle optimisation model. MEM dissertation 2023
#There are 3 codes in order to calculate 3 various cases- 3 different aerofoils. This code only for aerofoil NACA0015

import numpy as np
import matplotlib.pyplot as plt
import cmath as cmt
import math
import os
#Define constants and dimensions
Vsstart=1       #minimum Speed of ship
Vsmax=25        #maximum Speed of ship
Anglemax=360    #Maximum wind angle
Anglestep=5     #Increment of the wind angle
datapoint=360   #number of coefficients of drag and lift force
Fthrust=np.zeros((Vsmax,int(Anglemax/Anglestep),datapoint))  #Force to ship from wind [N]
FthrustOptimum=np.zeros((Vsmax,int(Anglemax/Anglestep)))     #Maximum force [N]
Fangle=np.zeros((Vsmax,int(Anglemax/Anglestep),datapoint))  #Angle between resultant force and ship velocity in real value
forceangle=np.zeros((Vsmax,int(Anglemax/Anglestep)))        #Optimum angle of gamma to have maximum wind force
CLD=np.loadtxt("NACA0015.txt")                              #Input of lift and drag coefficien
optimumangledata=np.zeros((Vsmax,int(Anglemax/Anglestep)))   #Best angle of attack between wind and sail
optimumsailangle=np.zeros((Vsmax,int(Anglemax/Anglestep)))   #Angle of attack between wind and sail
sailangle=np.zeros((Vsmax,int(Anglemax/Anglestep)))
aparentwindangle=np.zeros((Vsmax,int(Anglemax/Anglestep)))
Power=np.zeros((Vsmax,int(Anglemax/Anglestep)))
Energy=np.zeros((Vsmax,int(Anglemax/Anglestep)))
#Define contants values
Vref=6.7129                                       #[m/s] Velocity of the ship
rho=1                                            #[kg/m3] Density of air
A=1                                              #Are [m2]
t=60*60*24*31
#for the loop starts changing
for j in range (0,int(Anglemax/Anglestep)):
    alpha=(j*Anglestep)*cmt.pi/180

    #Loop changing wind speeds
    for i in range (Vsstart,Vsmax):

        u=i                                     #Velocity of wind [m/s]

        if (Vref==-np.real(u*cmt.cos(alpha))):
            theta=cmt.pi/2                      #Angle between apparent wind speed and ship [rad]
        elif (alpha<=cmt.pi/2) or (alpha>=cmt.pi*3/2):
            theta=cmt.atan((u*cmt.sin(alpha))/(Vref+u*cmt.cos(alpha)))
        elif ((cmt.pi/2)<alpha and alpha<(3/2*cmt.pi)):
            theta = cmt.atan(u * cmt.sin(alpha) / (Vref + u * cmt.cos(alpha))) + cmt.pi

        Va=cmt.sqrt(u**2+2*u*Vref*cmt.cos(alpha)+Vref**2)      #Apparent wind speed [m2/s]
```

Appendix 1: Sail angle optimisation model (to the NACA0015 airfoil application) (continued)

Wing sail program-NACA0015.py - D:\WMU CLASS 2023\WMU - CLASS OF 2023- Suleymanli Mahmud\Dissertation\Python\Wing sales\NACA0015\Wing sail program-NACA0015.py (3.11.2)

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```
        Va=cmt.sqrt(u**2+2*u*Vref*cmt.cos(alpha)+Vref**2)      #Apparent wind speed [m2/s]

        #Sail angle loop
        for k in range (0,datapoint):
            Cl=CLD[k,1]                                         #Lif coefficient from NACA Airfoil
            Cd=CLD[k,2]                                         #Drag coefficient from NACA Airfoil
            L=0.5*rho*Cl*A*(Va**2)                              #Lift force [N]
            D=0.5*rho*Cd*A*(Va**2)                              #Drag force [N]
            if (L.real==0):
                beta=cmt.pi/2                                   #Angle between resultant force and lift force [rad]
            elif (L.real<0):
                beta=cmt.atan(D/L)-cmt.pi
            else:
                beta=cmt.atan(D/L)
            gamma=-cmt.pi/2-beta+theta                          #Angle between resultant force and ship velocity [rad]
            Fr=cmt.sqrt(L**2+D**2)                              #Resultant force [N]
            Ft=Fr*A*(cmt.cos(gamma))                            #Force to the ship from wind [N]
            Fthrust[i,j,k]=np.real(Ft)
            Fangle[i,j,k]=np.real(gamma)



        aparentwindangle[i,j]=theta.real*180/cmt.pi
        FthrustOptimum[i,j]=np.max(Fthrust[i,j,:])              #Maximum of Ftrhrust
        optimumangle=CLD[(np.argmax(Fthrust[i,j,:],axis=None)),0] #Best angle of attack between wind and sail [degree]
        optimumangledata[i,j]=optimumangle                      #Input values for optimumangledata [degree]
        forceangle1=Fangle[i,j,(np.argmax(Fthrust[i,j,:],axis=None))] #Best angle between resultant force and ship velocity in radians [rad]
        forceangle[i,j]=forceangle1*180/cmt.pi                  #Best angle between resultant force and ship velocity in degrees [degree]
        sailangle[i,j]=aparentwindangle[i,j]-optimumangledata[i,j]  #Angle between the sail and ship velocity
        Power[i,j]=FthrustOptimum[i,j]*Vref
        Energy[i,j]=Power[i,j]*t

#Plot the value for polar graphs
fig     = plt.figure()

ax      = fig.add_subplot(241, polar=True)
ax.set_title('Real wind 0\N{DEGREE SIGN}')
arrow1=plt.arrow(0,0,aparentwindangle[24,0]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='green')
arrow2=plt.arrow(0,0,sailangle[24,0]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='red')
arrow3=plt.arrow(0,0,forceangle[24,0]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='blue')
arrow4=plt.arrow(0,0,0/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='black')
ax.plot(0,0, '-k', label='Wind direction')
ax.plot(0,0, '-g', label='Apparent wind angle')
ax.plot(0,0, '-r', label='Sail angle')
ax.plot(0,0, '-b', label='Resultant force angle')
ax.legend(fontsize=6)
```

Appendix 1: Sail angle optimisation model (to the NACA0015 airfoil application) (continued)

Wing sail program-NACA0015.py - D:\WMU CLASS 2023\WMU - CLASS OF 2023- Suleymanli Mahmud\Dissertation\Python\Wing sales\NACA0015\Wing sail program-NACA0015.py (3.11.2)

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```
ax.legend(fontsize=6)

ax      = fig.add_subplot(242, polar=True)
ax.set_title('Real wind 45\N{DEGREE SIGN}')
arrow1=plt.arrow(0,0,aparentwindangle[24,9]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='green')
arrow2=plt.arrow(0,0,sailangle[24,9]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='red')
arrow3=plt.arrow(0,0,forceangle[24,9]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='blue')
arrow4=plt.arrow(0,0,45/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='black')


ax      = fig.add_subplot(243, polar=True)
ax.set_title('Real wind 90\N{DEGREE SIGN}')
arrow1=plt.arrow(0,0,aparentwindangle[24,18]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='green')
arrow2=plt.arrow(0,0,sailangle[24,18]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='red')
arrow3=plt.arrow(0,0,forceangle[24,18]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='blue')
arrow4=plt.arrow(0,0,90/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='black')

ax      = fig.add_subplot(244, polar=True)
ax.set_title('Real wind 135\N{DEGREE SIGN}')
arrow1=plt.arrow(0,0,aparentwindangle[24,27]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='green')
arrow2=plt.arrow(0,0,sailangle[24,27]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='red')
arrow3=plt.arrow(0,0,forceangle[24,27]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='blue')
arrow4=plt.arrow(0,0,135/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='black')

ax      = fig.add_subplot(245, polar=True)
ax.set_title('Real wind 180\N{DEGREE SIGN}')
arrow1=plt.arrow(0,0,aparentwindangle[24,36]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='green')
arrow2=plt.arrow(0,0,sailangle[24,36]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='red')
arrow3=plt.arrow(0,0,forceangle[24,36]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='blue')
arrow4=plt.arrow(0,0,180/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='black')

ax      = fig.add_subplot(246, polar=True)
ax.set_title('Real wind 225\N{DEGREE SIGN}')
arrow1=plt.arrow(0,0,aparentwindangle[24,45]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='green')
arrow2=plt.arrow(0,0,sailangle[24,45]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='red')
arrow3=plt.arrow(0,0,forceangle[24,45]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='blue')
arrow4=plt.arrow(0,0,225/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='black')

ax      = fig.add_subplot(247, polar=True)
ax.set_title('Real wind 270\N{DEGREE SIGN}')
arrow1=plt.arrow(0,0,aparentwindangle[24,54]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='green')
arrow2=plt.arrow(0,0,sailangle[24,54]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='red')
arrow3=plt.arrow(0,0,forceangle[24,54]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='blue')
arrow4=plt.arrow(0,0,270/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='black')

ax      = fig.add_subplot(248, polar=True)
ax.set_title('Real wind 315\N{DEGREE SIGN}')
```

Appendix 1: Sail angle optimisation model (to the NACA0015 airfoil application) (continued)

```
ax      = fig.add_subplot(248, polar=True)
ax.set_title('Real wind 315\N{DEGREE SIGN}')
arrow1=plt.arrow(0,0,aparentwindangle[24,63]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='green')
arrow2=plt.arrow(0,0,sailangle[24,63]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='red')
arrow3=plt.arrow(0,0,forceangle[24,63]/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='blue')
arrow4=plt.arrow(0,0,315/180*cmt.pi,10,alpha=0.5,width=0.01,zorder=2,lw=2,edgecolor='black')

plt.show()

#Print results for Fthrust
print(Fthrust)

#Print results for Fthrustoptimum, optimumangledata,sailangle,aparentwindangle,gamma in txt files
np.savetxt('FthrustOptimum0015.txt',FthrustOptimum, fmt='%10.16f', delimiter='\t',newline='\r\n',header='Table format:FthrustOptimum 0015 \r\n')
np.savetxt('optimumangledata.txt', optimumangledata, fmt='%10.16f', delimiter='\t',newline='\r\n',header='Table format:optimumangledata \r\n')
np.savetxt('sailangle.txt', sailangle, fmt='%10.16f', delimiter='\t',newline='\r\n',header='Table format:sailangle \r\n')
np.savetxt('aparentwindangle.txt', aparentwindangle, fmt='%10.16f', delimiter='\t',newline='\r\n',header='Table format:aparentwindangle \r\n')
np.savetxt('gamma.txt', forceangle, fmt='%10.16f', delimiter='\t',newline='\r\n',header='Table format:gamma \r\n')
np.savetxt('sailPower.txt', Power[:,:],fmt='%10.16f')
```

Appendix 2: Wind Propulsion program for Wing Sail

*New route ALAT to KURIK- 5 July-6 July FINAL.py - D:\WMU CLASS 2023\WMU - CLASS OF 2023- Suleymanli Mahmud\Dissertation\Python\Wing sales\NACA0015\New with route\LATEST All months\Ju

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```
# Wind Propulsion Program for Wing Sail # MEM 2023 #

from netCDF4 import Dataset
import numpy as np
import matplotlib.pyplot as plt
import netCDF4
import pandas as pd
import cmath as cmt
import math
import os

#Data for wind direction, u and v
f=Dataset('adaptor.mars.internal-1693158855.3529463-7321-1-50e8c632-8045-46d0-bd49-3c0663d2a3f4.nc')

#Define constant values
Vref=6.7129                                    #[m/s] Velocity of the ship
rho=1.225                                      #[kg/m3] Density of air
A=1                                            #Are [m2]


time = f.variables['time']
t_unit =f.variables['time'].units
latitude = f.variables['latitude']
longitude = f.variables['longitude']
u_values = f.variables['u10'][:]
v_values = f.variables['v10'][:]
start_time = "2023-07-05 04:20:00"
end_time = "2023-07-06 01:20:00"
start_time = pd.to_datetime(start_time)
end_time = pd.to_datetime(end_time)

time_points = pd.date_range(start=start_time, end=end_time, freq='1H').tolist()

#Define constants and dimensions
Vsstart=1       #minimum Speed of wind
Vsmax=25        #maximum Speed of wind
Anglemax=360    #Maximum wind angle
Anglestep=5     #Increment of the wind angle
datapoint=360   #number of coefficients of drag and lift force
Fthrust=np.zeros((len(time_points),datapoint))  #Force to ship from wind [N]
FthrustOptimum=np.zeros((len(time_points)))     #Maximum force [N]
Fangle=np.zeros((len(time_points),datapoint))  #Angle between resultant force and ship velocity in real value
forceangle=np.zeros((len(time_points)))        #Optimum angle of gamma to have maximum wind force
CLD=np.loadtxt("NACA0015.txt")                  #Input of lift and drag coefficien
optimumangledata=np.zeros((len(time_points)))   #Best angle of attack between wind and sail
optimumsailangle=np.zeros((len(time_points)))   #Angle of attack between wind and sail
sailangle=np.zeros((len(time_points)))
```

Appendix 2: Wind Propulsion program for Wing Sail (continued)

*New route ALAT to KURIK- 5 July-6 July FINAL.py - D:\WMU CLASS 2023\WMU - CLASS OF 2023- Suleymanli Mahmud\Dissertation\Python\Wing sales\NAC

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```
sailangle=np.zeros((len(time_points)))
aparentwindangle=np.zeros((len(time_points)))
theta = np.empty(len(time_points))
Power=np.zeros(len(time_points))
Energy=np.zeros(len(time_points))
TotalEnergy=0

#Specify starting location
latBakuPort=39.9972
lonBakuPort=49.443
#Specify final location
latKurikPort=43.1612
lonKurikPort=51.443

# Route corrdinates
specific_route=[
    (39.97078,  49.44311),
    (39.93719,  49.43235),
    (39.93876,  49.62533),
    (40.0214,   49.84097),
    (40.15791,  50.03291),
    (40.13757,  50.29479),
    (40.18773,  50.53903),
    (40.30844,  50.7293),
    (40.49433,  50.8021),
    (40.6885,   50.85976),
    (40.87969,  50.92545),
    (41.07248,  50.99249),
    (41.26059,  51.063),
    (41.44409,  51.13167),
    (41.6254,   51.19992),
    (41.81182,  51.24815),
    (42.00085,  51.28401),
    (42.19845,  51.3203),
    (42.39805,  51.34403),
    (42.63557,  51.38085),
    (42.84388,  51.41617),
    (43.05173,  51.45509),
    (43.11918,  51.47503),
]

Latitude = np.zeros(len(latitude))
Longitude = np.zeros(len(longitude))

for j in range (1, len(Latitude)):
    Latitude[j] = latitude[j]
for j in range (1, len(Longitude)):
```

Appendix 2: Wind Propulsion program for Wing Sail (continued)

*New route ALAT to KURIK- 5 July-6 July FINAL.py - D:\WMU CLASS 2023\WMU - CLASS OF 2023- Suleymanli Mahmud\Dissertation\Python\Wing sales\NACA0015\New with route\LATE

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```
for j in range (1, len(Latitude)):
    Latitude[j] = latitude[j]
for j in range (1, len(Longitude)):
    Longitude[j] = longitude[j]

lat_vessel = [coord[0] for coord in specific_route]
lon_vessel = [coord[1] for coord in specific_route]

# Create matrix of zeros for windspeed
windspeed=np.zeros([len(time_points)])
windplot=np.zeros([len(time_points),len(latitude),len(longitude)])
dates=netCDF4.num2date(time[:].squeeze(), t_unit, only_use_cftime_datetimes=False, only_use_python_datetimes=True)
prealpha=np.zeros([len(time_points)])
alpha=np.zeros([len(time_points)])
shipheading=np.zeros([len(time_points)])

alpha_values=[]

# Calculate resultant wind plot
for i, time_point in enumerate(time_points):
    windplot[i] = np.sqrt(u_values[i,:,:]**2 + v_values[i,:,:]**2)

def calculate_shipheading(point1, point2):
    lat1, lon1 = math.radians(point1[0]), math.radians(point1[1])
    lat2, lon2 = math.radians(point2[0]), math.radians(point2[1])

    delta_lon = lon2 - lon1

    y = math.sin(delta_lon) * math.cos(lat2)
    x = math.cos(lat1) * math.sin(lat2) - math.sin(lat1) * math.cos(lat2) * math.cos(delta_lon)

    initial_bearing = math.atan2(y, x)
    initial_bearing = math.degrees(initial_bearing)
    compass_bearing = (initial_bearing + 360) % 360

    return compass_bearing

for m in range(len(specific_route) - 1):
    point1 = specific_route[m]
    point2 = specific_route[m + 1]
    shipheading[m] = (calculate_shipheading(point1, point2))*cmt.pi/180
    print(f"ShipHeading from {point1} to {point2}: {shipheading[m]*180/cmt.pi:.2f} degrees")

#Route over the time(Main loop)
for y in range (0,len(time_points)):

    lat_vessel_point = lat_vessel[y]
```

Appendix 2: Wind Propulsion program for Wing Sail (continued)

*New route ALAT to KURIK- 5 July-6 July FINAL.py - D:\WMU CLASS 2023\WMU - CLASS OF 2023- Suleymanli Mahmud\Dissertation\Python\Wing sales\NACA0015\New with route\LATEST All months\Jul

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```python
#Route over the time(Main loop)
for y in range (0,len(time_points)):

    lat_vessel_point = lat_vessel[y]
    lon_vessel_point = lon_vessel[y]
    indexLat=np.abs((lat_vessel_point -Latitude[:])).argmin()
    indexLon=np.abs((lon_vessel_point-Longitude[:])).argmin()

    #Calculate true wind speed
    windspeed[y] = np.sqrt(u_values[y+4,indexLat,indexLon]**2 + v_values[y+4,indexLat,indexLon]**2)

    #Calculate true wind direction

    if (u_values[y, indexLat, indexLon]>0 and v_values[y, indexLat, indexLon]>0):
        prealpha[y]=np.arctan(u_values[y,indexLat,indexLon]/v_values[y,indexLat,indexLon])
    elif (u_values[y, indexLat, indexLon]<0 and v_values[y, indexLat, indexLon]>0):
        prealpha[y]=np.arctan(-u_values[y,indexLat,indexLon]/v_values[y,indexLat,indexLon])+(cmt.pi*2)
    elif (u_values[y, indexLat, indexLon]<0 and v_values[y, indexLat, indexLon]<0):
        prealpha[y]=np.arctan(-u_values[y,indexLat,indexLon]/-v_values[y,indexLat,indexLon])+cmt.pi
    elif (u_values[y, indexLat, indexLon]>0 and v_values[y, indexLat, indexLon]<0):
        prealpha[y]=np.arctan(-v_values[y,indexLat,indexLon]/u_values[y,indexLat,indexLon])+(cmt.pi/2)

    if (prealpha[y]>cmt.pi*2):
        prealpha[y]=prealpha[y]-cmt.pi*2

    alpha[y]=prealpha[y]-shipheading[y]

    alpha_values.append(alpha)
    print(alpha[y]*180/cmt.pi)

    if (Vref==-np.real(windspeed[y]*cmt.cos(alpha[y]))):
        theta=cmt.pi/2                                                  #Angle between apparent wind speed and ship [rad]
    elif (alpha[y]<=cmt.pi/2) or (alpha[y]>=cmt.pi*3/2):
        theta=cmt.atan((windspeed[y]*cmt.sin(alpha[y]))/(Vref+windspeed[y]*cmt.cos(alpha[y])))
    elif ((cmt.pi/2)<alpha[y] and alpha[y]<(3/2*cmt.pi)):
        theta = cmt.atan(windspeed[y] * cmt.sin(alpha[y]) / (Vref + windspeed[y] * cmt.cos(alpha[y]))) + cmt.pi

    Va=cmt.sqrt(windspeed[y]**2+2*windspeed[y]*Vref*cmt.cos(alpha[y])+Vref**2)         #Apparent wind speed [m2/s]
    print (Va)

    #Sail angle loop
    for z in range (0,datapoint):
        Cl=CLD[z,1]                                    #Lif coefficient from NACA Airfoil
        Cd=CLD[z,2]                                    #Drag coefficient from NACA Airfoil
        L=0.5*rho*Cl*A*(Va**2)                         #Lift force [N]
        D=0.5*rho*Cd*A*(Va**2)                         #Drag force [N]
        if (L.real==0):
```

Appendix 2: Wind Propulsion program for Wing Sail (continued)

*New route ALAT to KURIK- 5 July-6 July FINAL.py - D:\WMU CLASS 2023\WMU - CLASS OF 2023- Suleymanli Mahmud\Dissertation\Python\Wing sales\NACA0015\New with route\LATEST All months\July\5 July-6

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```
        if (L.real==0):
            beta=cmt.pi/2                                   #Angle between resultant force and lift force [rad]
        elif (L.real<0):
            beta=cmt.atan(D/L)-cmt.pi
        else:
            beta=cmt.atan(D/L)
        gamma=-cmt.pi/2-beta+theta                          #Angle between resultant force and ship velocity [rad]
        Fr=cmt.sqrt(L**2+D**2)                              #Resultant force [N]
        Ft=Fr*(cmt.cos(gamma))                           #Force to the ship from wind [N]
        Fthrust[y,z]=np.real(Ft)
        Fangle[y,z]=np.real(gamma)

    aparentwindangle[y]=theta.real*180/cmt.pi
    FthrustOptimum[y]=np.max(Fthrust[y,:])                  #Maximum of Ftrhrust
    optimumangle=CLD[(np.argmax(Fthrust[y,:],axis=None)),0] #Best angle of attack between wind and sail [degree]
    optimumangledata[y]=optimumangle                      #Input values for optimumangledata [degree]
    forceangle1=Fangle[y,(np.argmax(Fthrust[y,:],axis=None))] #Best angle between resultant force and ship velocity in radians [rad]
    forceangle[y]=forceangle1*180/cmt.pi                   #Best angle between resultant force and ship velocity in degrees [degree]
    sailangle[y]=aparentwindangle[y]-optimumangledata[y]  #Angle between the sail and ship velocity
    Power[y]=(FthrustOptimum[y]*Vref)/1000
    Energy[y] = (Power[y] * 3600)
    TotalEnergy+=Energy[y]

    print(f"FthrustOptimum[{y}]: {FthrustOptimum[y]:.2f}")
    print(f"Vref: {Vref}")
    print(f"Power at time {time_points[y]}: {Power[y]:.2f} kW")
    print(f"Energy at time {time_points[y]}: {Energy[y]:.2f} kJ")
    print (windspeed[y])

alpha_array = np.array(alpha_values)

#Visualize
plt.plot(time_points,Power[:],label='WindPower [kW]')
plt.plot(time_points,prealpha*180/cmt.pi,label='prealpha [degrees]')
plt.plot(time_points,shipheading*180/cmt.pi,label='Shipheading from North [degrees]',c='c')
plt.plot(time_points,alpha, label='True wind angle on deck [degree]')
plt.plot(time_points,windspeed, label='Wind Speed [m/s]')
plt.xlabel("Time")
plt.ylabel("Power [kW], angle(degrees), Windspeed [m/s]")
plt.legend()
plt.grid()
plt.show()

# Visualize the wind data and vessel's route
plt.imshow(windplot[0, :, :], extent=[longitude[:].min(), longitude[:].max(), latitude[:].min(), latitude[:].max()])
plt.colorbar(label='Wind speed [m/s]')
plt.scatter(lonBakuPort, latBakuPort, c='b', label='Start Point')
```

Appendix 2: Wind Propulsion program for Wing Sail (continued)

*New route ALAT to KURIK- 5 July-6 July FINAL.py - D:\WMU CLASS 2023\WMU - CLASS OF 2023- Suleymanli Mahmud\Dissertation\Python\Wing sales\NACA0015\New with route\LATEST All months\July\5 July-6 July\New

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```
plt.scatter(lonBakuPort, latBakuPort, c='b', label='Start Point')
plt.scatter(lonKurikPort, latKurikPort, c='b', label='End Point')
plt.scatter([lon_vessel[y] for y in range(1, len(time_points))],
            [lat_vessel[y] for y in range(1, len(time_points))], color='red', label='Vessel Position')
plt.xlabel("Longitude")
plt.ylabel("Latitude")
plt.title(f"Wind Data and Vessel Route")
plt.legend()
plt.show()

# Visualise the wind data
image1=plt.imshow(u_values[0,:,:], extent=[longitude[:].min(), longitude[:].max(), latitude[:].min(), latitude[:].max()])
plt.colorbar(label='Wind speed [m/s]')
plt.scatter(lonBakuPort, latBakuPort, c='b', label='Start Point')
plt.scatter(lonKurikPort, latKurikPort, c='b', label='End Point')
plt.scatter([lon_vessel[y] for y in range(1, len(time_points))],
            [lat_vessel[y] for y in range(1, len(time_points))], color='red', label='Vessel Position')
plt.xlabel("Longitude")
plt.ylabel("Latitude")
plt.title(f"Wind Data for u_values and Vessel Route")
plt.legend()
plt.show()

# Visualise the wind data
image1=plt.imshow(v_values[0,:,:], extent=[longitude[:].min(), longitude[:].max(), latitude[:].min(), latitude[:].max()])
plt.colorbar(label='Wind speed [m/s]')
plt.scatter(lonBakuPort, latBakuPort, c='b', label='Start Point')
plt.scatter(lonKurikPort, latKurikPort, c='b', label='End Point')
plt.scatter([lon_vessel[y] for y in range(1, len(time_points))],
            [lat_vessel[y] for y in range(1, len(time_points))], color='red', label='Vessel Position')
plt.xlabel("Longitude")
plt.ylabel("Latitude")
plt.title(f"Wind Data for v_values and Vessel Route")
plt.legend()
plt.show()

np.savetxt('FthrustOptimum0015.tx',FthrustOptimum, fmt='%10.16f', delimiter='\t',newline='\r\n',header='Table format:FthrustOptimum 0012 \r\n')
np.savetxt('windspeed.txt', windspeed, fmt='%10.16f')
np.savetxt('datesatm.tx',dates,fmt='%str')
np.savetxt('optimumangledata.tx', optimumangledata, fmt='%10.16f', delimiter='\t',newline='\r\n',header='Table format:optimumangledata \r\n')
np.savetxt('sailangle.tx', sailangle, fmt='%10.16f', delimiter='\t',newline='\r\n',header='Table format:sailangle \r\n')
np.savetxt('aparentwindangle.tx', aparentwindangle, fmt='%10.16f', delimiter='\t',newline='\r\n',header='Table format:aparentwindangle \r\n')
np.savetxt('gamma.tx', forceangle, fmt='%10.16f', delimiter='\t',newline='\r\n',header='Table format:gamma \r\n')
np.savetxt('sailPower.txt', Power,fmt='%10.16f')
np.savetxt('alpha.txt', alpha_array, fmt='%10.16f', newline='\r\n')
```

Appendix 3: Wind Propulsion program for Flettner rotor

*Flettner rotor-ALAT to KURIK- 15 October .py - D:\WMU CLASS 2023\WMU - CLASS OF 2023- Suleymanli Mahmud\Dissertation\Python\Wing sales\NACA0015\New with route\LATEST All months\Fle

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```
# Wind Propulsion Program for Flettner rotor # MEM 2023 #

from netCDF4 import Dataset
import numpy as np
import matplotlib.pyplot as plt
import netCDF4
import pandas as pd
import cmath as cmt
import math
import os
import xlrd

#Data for wind direction, u and v
f=Dataset('adaptor.mars.internal-1693063443.2415047-7099-14-0546c326-6bb3-4aa5-b48c-efd4214f451b.nc')

#Define constant values
Vref=6.7129                                       #[m/s] Velocity of the ship
rho=1.225                                            #[kg/m3] Density of air
A=175                                              #Are [m2]
Rfr=35                  #Fr cylinder radius
omega=500               #rpm

time = f.variables['time']
t_unit =f.variables['time'].units
latitude = f.variables['latitude']
longitude = f.variables['longitude']
u = f.variables['u10'][:]
v = f.variables['v10'][:]
start_time = "2022-10-15 20:00:00"
end_time = "2022-10-16  20:00:00"
start_time = pd.to_datetime(start_time)
end_time = pd.to_datetime(end_time)
u_values=u[:]
v_values=v[:]

time_points = pd.date_range(start=start_time, end=end_time, freq='1H').tolist()

#Define constants and dimensions
Vsstart=1        #minimum Speed of wind
Vsmax=25         #maximum Speed of wind
Anglemax=360     #Maximum wind angle
Anglestep=5      #Increment of the wind angle
datapoint=26   #number of coefficients of drag and lift force
Fthrust=np.zeros((len(time_points),datapoint))  #Force to ship from wind [N]
FthrustOptimum=np.zeros((len(time_points)))     #Maximum force [N]
Fangle=np.zeros((len(time_points),datapoint))  #Angle between resultant force and ship velocity in real value
forceangle=np.zeros((len(time_points)))        #Optimum angle of gamma to have maximum wind force
```

Appendix 3: Wind Propulsion program for Flettner rotor (continued)

*Flettner rotor-ALAT to KURIK- 15 October .py - D:\WMU CLASS 2023\WMU - CLASS OF 2023- Suleymanli Mahmud\Dissertation\Python\Wing sales\NACA0015\New with route\

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```
forceangle=np.zeros((len(time_points)))        #Optimum angle of gamma to have maximum wind force
CLD=("D:\\WMU CLASS 2023\\WMU - CLASS OF 2023- Suleymanli Mahmud\\Dissertation\\Python\\Cl and Cd.xls")
wb=xlrd.open_workbook(CLD)
sheet=wb.sheet_by_index(0)
sheet.cell_value(0,0)
#optimumangledata=np.zeros((len(time_points)))   #Best angle of attack between wind and sail
#optimumsailangle=np.zeros((len(time_points)))   #Angle of attack between wind and sail
#sailangle=np.zeros((len(time_points)))
aparentwindangle=np.zeros((len(time_points)))
theta = np.empty(len(time_points))
Power=np.zeros(len(time_points))
Energy=np.zeros(len(time_points))
TotalEnergy=0
#Specify starting location
latBakuPort=39.9972
lonBakuPort=49.443
#Specify final location
latKurikPort=43.1612
lonKurikPort=51.443
# Route corrdinates
specific_route=[
    (39.97079,  49.44311),
    (39.94961,  49.43457),
    (39.93029,  49.58374),
    (39.98184,  49.78271),
    (40.10205,  49.94626),
    (40.15285,  50.14424),
    (40.12777,  50.38015),
    (40.20618,  50.5799),
    (40.32261,  50.73867),
    (40.49159,  50.84269),
    (40.66564,  50.94999),
    (40.84541,  51.06055),
    (41.02814,  51.17063),
    (41.20028,  51.27512),
    (41.37502,  51.37942),
    (41.55667,  51.48667),
    (41.78,     51.61),
    (42.015,    51.745),
    (42.18999,  51.84273),
    (42.38522,  51.82327),
    (42.575,    51.80333),
    (42.84,     51.72667),
    (43.12597,  51.46445),
    (43.16,     51.44167),
    (43.16,     51.44167),
]
```

Appendix 3: Wind Propulsion program for Flettner rotor (continued)

*Flettner rotor-ALAT to KURIK- 15 October .py - D:\WMU CLASS 2023\WMU - CLASS OF 2023- Suleymanli Mahmud\Dissertation\Python\Wing sales\NACA0015\New with route\LATEST

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```
Latitude = np.zeros(len(latitude))
Longitude = np.zeros(len(longitude))

for j in range (1, len(Latitude)):
    Latitude[j] = latitude[j]
for j in range (1, len(Longitude)):
    Longitude[j] = longitude[j]

lat_vessel = [coord[0] for coord in specific_route]
lon_vessel = [coord[1] for coord in specific_route]

# Create matrix of zeros for windspeed
windspeed=np.zeros([len(time_points)])
windplot=np.zeros([len(time_points),len(latitude),len(longitude)])
dates=netCDF4.num2date(time[:].squeeze(), t_unit, only_use_cftime_datetimes=False, only_use_python_datetimes=True)
prealpha=np.zeros([len(time_points)])
alpha=np.zeros([len(time_points)])
shipheading=np.zeros([len(time_points)])

alpha_values=[]

# Calculate resultant wind plot
for i, time_point in enumerate(time_points):
    windplot[i] = np.sqrt(u_values[i,:,:]**2 + v_values[i,:,:]**2)

def calculate_shipheading(point1, point2):
    lat1, lon1 = math.radians(point1[0]), math.radians(point1[1])
    lat2, lon2 = math.radians(point2[0]), math.radians(point2[1])

    delta_lon = lon2 - lon1

    y = math.sin(delta_lon) * math.cos(lat2)
    x = math.cos(lat1) * math.sin(lat2) - math.sin(lat1) * math.cos(lat2) * math.cos(delta_lon)

    initial_bearing = math.atan2(y, x)
    initial_bearing = math.degrees(initial_bearing)
    compass_bearing = (initial_bearing + 360) % 360

    return compass_bearing

for m in range(len(specific_route) - 1):
    point1 = specific_route[m]
    point2 = specific_route[m + 1]
    shipheading[m] = (calculate_shipheading(point1, point2))*cmt.pi/180
    print(f"ShipHeading from {point1} to {point2}: {shipheading[m]*180/cmt.pi:.2f} degrees")
```

Appendix 3: Wind Propulsion program for Flettner rotor (continued)

*Flettner rotor-ALAT to KURIK- 15 October .py - D:\WMU CLASS 2023\WMU - CLASS OF 2023- Suleymanli Mahmud\Dissertation\Python\Wing sales\NACA0015\New with route\LATEST All months\Flettner rot

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```
    print(f"ShipHeading from {point1} to {point2}: {shipheading[m]*180/cmt.pi:.2f} degrees")

#Route over the time(Main loop)
for y in range (0,len(time_points)):

    lat_vessel_point = lat_vessel[y]
    lon_vessel_point = lon_vessel[y]

    indexLat=np.abs((lat_vessel_point -Latitude[:])).argmin()
    indexLon=np.abs((lon_vessel_point-Longitude[:])).argmin()

    #Calculate true wind speed
    windspeed[y] = np.sqrt(u_values[y,indexLat,indexLon]**2 + v_values[y,indexLat,indexLon]**2)
    print (windspeed[y])

    #Calculate true wind direction

    if (u_values[y, indexLat, indexLon]>0 and v_values[y, indexLat, indexLon]>0):
        prealpha[y]=np.arctan(u_values[y,indexLat,indexLon]/v_values[y,indexLat,indexLon])
    elif (u_values[y, indexLat, indexLon]<0 and v_values[y, indexLat, indexLon]>0):
        prealpha[y]=np.arctan(-u_values[y,indexLat,indexLon]/v_values[y,indexLat,indexLon])+(cmt.pi*2)
    elif (u_values[y, indexLat, indexLon]<0 and v_values[y, indexLat, indexLon]<0):
        prealpha[y]=np.arctan(-u_values[y,indexLat,indexLon]/-v_values[y,indexLat,indexLon])+cmt.pi
    elif (u_values[y, indexLat, indexLon]>0 and v_values[y, indexLat, indexLon]<0):
        prealpha[y]=np.arctan(-v_values[y,indexLat,indexLon]/u_values[y,indexLat,indexLon])+(cmt.pi/2)

    if (prealpha[y]>cmt.pi*2):
        prealpha[y]=prealpha[y]-cmt.pi*2

    #Calculate the relative angle between true wind speed and ship heading

    alpha[y]=prealpha[y]-shipheading[y]

    alpha_values.append(alpha)
    print(alpha[y]*180/cmt.pi)

    if (Vref==-np.real(windspeed[y]*cmt.cos(alpha[y]))):
        theta=cmt.pi/2                                              #Angle between apparent wind speed and ship [rad]
    elif (alpha[y]<=cmt.pi/2) or (alpha[y]>=cmt.pi*3/2):
        theta=cmt.atan((windspeed[y]*cmt.sin(alpha[y]))/(Vref+windspeed[y]*cmt.cos(alpha[y])))
    elif ((cmt.pi/2)<alpha[y] and alpha[y]<(3/2*cmt.pi)):
        theta = cmt.atan(windspeed[y] * cmt.sin(alpha[y]) / (Vref + windspeed[y] * cmt.cos(alpha[y]))) + cmt.pi

    Va=cmt.sqrt(windspeed[y]**2+2*windspeed[y]*Vref*cmt.cos(alpha[y])+Vref**2)         #Apparent wind speed [m2/s]


    #Sail angle loop
```

Appendix 3: Wind Propulsion program for Flettner rotor (continued)

*Flettner rotor-ALAT to KURIK- 15 October .py - D:\WMU CLASS 2023\WMU - CLASS OF 2023- Suleymanli Mahmud\Dissertation\Python\Wing sales\NACA0015\New with route\LATEST All months\Flettner rotor\Oc

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```
    #Sail angle loop
    for z in range (0,datapoint):
        SR = sheet.cell_value(z+1, 0)          #Importing Spin ratio
        Cl = sheet.cell_value(z+1, 1)          #Importing Lift coefficient
        Cd = sheet.cell_value(z+1, 2)          #Importing drag coefficient
        L=Cl*(rho/2)*A*Va**2                   #Lift force [N]
        D=Cd*(rho/2)*A*Va**2
        if (L.real==0):
            beta=cmt.pi/2                                   #Angle between resultant force and lift force [rad]
        elif (L.real<0):
            beta=cmt.atan(D/L)-cmt.pi
        else:
            beta=cmt.atan(D/L)
        gamma=-cmt.pi/2-beta+theta                          #Angle between resultant force and ship velocity [rad]
        Fr=cmt.sqrt(L**2+D**2)                              #Resultant force [N]
        Ft=Fr*(cmt.cos(gamma))                            #Force to the ship from wind [N]
        Fthrust[y,z]=np.real(Ft)
        Fangle[y,z]=np.real(gamma)
        angle=gamma-beta

    aparentwindangle[y]=theta.real*180/cmt.pi
    FthrustOptimum[y]=np.max(Fthrust[y,:])                  #Maximum of Ftrhrust
    forceangle1=Fangle[y,(np.argmax(Fthrust[y,:],axis=None))] #Best angle between resultant force and ship velocity in radians [rad]
    forceangle[y]=forceangle1*180/cmt.pi                   #Best angle between resultant force and ship velocity in degrees [degree]
    Power[y]=((FthrustOptimum[y]*Vref)/0.7)/1000
    Energy[y] = (Power[y] * 3600)
    TotalEnergy+=Energy[y]

    print(f"FthrustOptimum[{y}]: {FthrustOptimum[y]:.2f}")
    print(f"Vref: {Vref}")
    print(f"Power at time {time_points[y]}: {Power[y]:.2f} kW")
    print(f"Energy at time {time_points[y]}: {Energy[y]:.2f} kJ")

alpha_array = np.array(alpha_values)

#Visualize
plt.plot(time_points,Power[:],label='WindPower [kW]')
plt.plot(time_points,prealpha*180/cmt.pi,label='prealpha [degrees]')
plt.plot(time_points,shipheading*180/cmt.pi,label='Shipheading from North [degrees]',c='c')
plt.plot(time_points,alpha, label='True wind angle on deck [degree]')
plt.plot(time_points,windspeed, label='Wind Speed [m/s]')
plt.xlabel("Time")
plt.ylabel("Power [kW], angle(degrees), Windspeed [m/s]")
plt.legend()
plt.grid()
plt.show()
```

Appendix 3: Wind Propulsion program for Flettner rotor (continued)

*Flettner rotor-ALAT to KURIK- 15 October .py - D:\WMU CLASS 2023\WMU - CLASS OF 2023- Suleymanli Mahmud\Dissertation\Python\Wing sales\NACA0015\New with route\LATEST All months\Flettner rotor\October\15 Octob

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```python
plt.show()
# Visualize the wind data and vessel's route
plt.imshow(windplot[0, :, :], extent=[longitude[:].min(), longitude[:].max(), latitude[:].min(), latitude[:].max()])
plt.colorbar(label='Wind speed [m/s]')
plt.scatter(lonBakuPort, latBakuPort, c='b', label='Start Point')
plt.scatter(lonKurikPort, latKurikPort, c='b', label='End Point')
plt.scatter([lon_vessel[y] for y in range(1, len(time_points))],
            [lat_vessel[y] for y in range(1, len(time_points))], color='red', label='Vessel Position')
plt.xlabel("Longitude")
plt.ylabel("Latitude")
plt.title(f"Wind Data and Vessel Route")
plt.legend()
plt.show()
# Visualise the wind data
image1=plt.imshow(u_values[0,:,:], extent=[longitude[:].min(), longitude[:].max(), latitude[:].min(), latitude[:].max()])
plt.colorbar(label='Wind speed [m/s]')
plt.scatter(lonBakuPort, latBakuPort, c='b', label='Start Point')
plt.scatter(lonKurikPort, latKurikPort, c='b', label='End Point')
plt.scatter([lon_vessel[y] for y in range(1, len(time_points))],
            [lat_vessel[y] for y in range(1, len(time_points))], color='red', label='Vessel Position')
plt.xlabel("Longitude")
plt.ylabel("Latitude")
plt.title(f"Wind Data for u_values and Vessel Route")
plt.legend()
plt.show()
# Visualise the wind data
image1=plt.imshow(v_values[0,:,:], extent=[longitude[:].min(), longitude[:].max(), latitude[:].min(), latitude[:].max()])
plt.colorbar(label='Wind speed [m/s]')
plt.scatter(lonBakuPort, latBakuPort, c='b', label='Start Point')
plt.scatter(lonKurikPort, latKurikPort, c='b', label='End Point')
plt.scatter([lon_vessel[y] for y in range(1, len(time_points))],
            [lat_vessel[y] for y in range(1, len(time_points))], color='red', label='Vessel Position')
plt.xlabel("Longitude")
plt.ylabel("Latitude")
plt.title(f"Wind Data for v_values and Vessel Route")
plt.legend()
plt.show()

np.savetxt('FthrustOptimum0015.tx',FthrustOptimum, fmt='%10.16f', delimiter='\t',newline='\r\n',header='Table format:FthrustOptimum 0012 \r\n')
np.savetxt('windspeed.txt', windspeed, fmt='%10.16f')
np.savetxt('datesatm.tx',dates,fmt='%str')
np.savetxt('aparentwindangle.tx', aparentwindangle, fmt='%10.16f', delimiter='\t',newline='\r\n',header='Table format:aparentwindangle \r\n')
np.savetxt('gamma.tx', forceangle, fmt='%10.16f', delimiter='\t',newline='\r\n',header='Table format:gamma \r\n')
np.savetxt('sailPower.txt', Power,fmt='%10.16f')
np.savetxt('Energy.txt', Energy,fmt='%10.16f')
np.savetxt('alpha.txt', alpha_array, fmt='%10.16f', newline='\r\n')
```