



CHALMERS



Could ships use sails again?

Implementation of wind power in shipping

Bachelor thesis in Marine Engineering

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Department of Mechanics and Maritime Sciences
CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

In the year between 1600-1850 the sailing ship was a dominated role in the world's ocean, so called the "age of sails" (Houstoun, E., 2016). Since then there has been various of developments on technologies utilizing wind. Sails has been the most common means of propulsion during the age of sails however, time passes, and new innovations has surfaced with a more reliable system. Despite new technologies the international shipping is releasing roughly 13% and 12% nitrogen oxide (NO_x) and sulphur dioxide (SO₂) during 2007 to 2012 which have an environmental and health impact. The constant increase in environmental regulations is now posing a challenge for the shipping industry. This is forcing the industry to use cleaner fuels and to seek new methods of propulsion, since ships are widely recognized as a major source of pollutants and is contributing 90% of the global trade.

The purpose of this study is to evaluate whether it is viable to promote green ships concept by implementing wind power in today's shipping industry either as a replacement or as an addition to support our current propulsion system without any major compromises. Since wind is a clean and renewable energy source which will reduce the fuel consumption and result in less produced emissions. This paper will be specifically focusing the technologies of traditional sails, wind turbines, kites and Flettner rotors, using the methodology of literature reviews.

The techniques show fuel saving with up to 8,3% for sails, 33% for wind turbines, 32% for kites and 24% for Flettner rotors. While cost being mostly linear with the amount of fuel saving achievable, the kite is considered to be the best investment in terms of good fuel savings with reasonable cost compared to other technologies.

Sammanfattning

I åren mellan 1600–1850 hade segelfartyget en dominant roll i världens hav kallat "Seglets Ålder" (Houstoun, E., 2016). Sedan dess har det skett flera olika tekniska utvecklingar på att utnyttja vinden. Under detta århundradet så har segel dominerat som framdrivningssystem men eftersom, som tiden har passerat, så har nya innovationer uppstått med starkare och effektivare system. Trots de nya teknikerna så står den internationella sjöfarten för ungefär 13% och 12% kväveoxid (NO_x) och svaveldioxid (SO₂) under 2007 till 2012 som har en påverkan på både miljön och hälsan. Den konstanta ökningen i miljöbestämmelser skapar nu nya utmaningar för sjöfarten. Detta tvingar sjöfarten att använda renare bränslen och att hitta nya metoder för framdrivning, beroende på att fartyg är allmänt kända som en stor källa när det gäller föroreningar och står för 90% av den globala frakten.

Målet med denna studie är att utvärdera huruvida genomförbart det är att främja gröna fartygsidéer genom att implementera vindkraft i dagens sjöfart, antingen genom att ersätta eller att stödja nuvarande framdrivningssystem utan större kompromisser. Med tanke på att vind är en ren och förnybar energikälla som kan minska bränsleförbrukning och resultera i mindre utsläpp. Detta dokumentet kommer att specifikt fokusera på teknologin från traditionella segel, vindturbiner, drakar och Flettner rotor, med användning av metoden litteraturstudie.

Teknikerna visar en bränslesparning på upp till 8,3% för Segel, 33% for Vindturbiner, 32% för Drakar and 24% for Flettner rotorer. Samtidigt som kostnaden är till mesta del linjär med den bränslesparingen man kan uppnå, draken kan ses som den bästa investeringen i förhållande till en bra bränslesparning med rimlig kostnad jämfört med de andra teknikerna.

Keywords

Age of Sails, wind, renewable energy source, emissions, environmental and health impact, traditional sails, wind turbines, kites, Flettner rotors, Vindskip.

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List of Abbreviation

CO₂ Carbon Dioxide.....1, 3, 13

EGR Exhaust Gas Recirculation.....3

IMO International Maritime Organization.....1, 3

LNG Liquefied Natural Gas.....14

MARPOL International Convention for the Prevention of Pollution from Ships.....3

NO_x Nitrogen Oxide.....1, 3

PM Particulate Matter3

SCR Selective Catalytic Reduction.....3

SO₂ Sulphur Oxide.....1, 3

1. Introduction

Increasing environmental regulations is forcing the shipping industry to use cleaner fuels and to seek new methods of propulsion. The shipping sector contributes about 90% of the global cargo which makes it one of the major factors of importing/exporting large quantities of goods from around the world and it is thereby the source of global trade (Rutkowski, 2016). However, the industry also has a tendency of releasing wide variety of pollutants throughout the world which has an impact on environment and direct health effects. The international shipping is estimated to release emissions of approximately 18.6 million NO_x and 10.6 million tonnes of SO₂ which represents roughly 13% and 12% of global NO_x and SO₂ emissions during 2007 to 2012. During this period the shipping also accounted for 3.1% CO₂ emission annual globally (Smith, T. P., Jalkanen, J. P., Anderson, B. A., Corbett, J. J., Faber, J., Hanayama, S., & Raucci, C. 2015).

The Third IMO Greenhouse Gas Study 2014 also shows that the emissions are still going to increase considerably in the future. This study suggests that depending on future energy developments and economic growth the shipping industry projects an increase of CO₂ emissions by 50% to 250% in the period from 2012 to 2050 (Smith, et al., 2015). Yet, shipping was not included in The Paris Agreement which entered into force in 2016 whom limits the climate changes mitigation goal of setting the global temperature increase below 2° C and ideally 1.5° C (Traut, Larkin, Anderson, McGlade, Sharmina, & Smith, 2018). Even though shipping was absent from this it is highly recognized that all industries should contribute to this challenge and since modern day fuels contains harmful substances it is a valid reason to implement a cleaner and still practical alternative propulsion. Today's technology has not only opened new methods of propulsion but also made development and improvement of already existing ways.

Around 200 years ago, merchant shipping was dominated by sailing ships using the wind as propulsion. These ships released no emissions and were able to reach 16 knots or more without the use of fuels that harm the environment (Rutkowski, 2016). But as new technologies arrived sailing was forgotten, and very few modern sailing ships have been developed after the traditional sailing ships reached their end at the beginning of the 20th century.

Wind power is a renewable energy source and it leaves zero-emissions. Could it be possible to implement sailing ships again with today's technology, to reduce the dependency of fossil fuels

and harnessing the wind to use as a means of propulsion in modern ships? This would greatly lead to a considerable reduction in emissions from the industry considering that shipping today's emits for about 90% of world trade by volume (Rutkowski, 2016).

1.1 Purpose

The purpose of this work is to study viability and relevance concerning different types of technologies that harnesses wind as a source of propulsion power. Either as a replacement or as an addition to support our current propulsion system without any major compromises.

1.2 Research Questions

1. What improvements of harnessing wind power have been made since the *age of sails*?
2. What are the main obstacles for wind power in shipping?
3. Can wind power be a relevant source of propulsion and/or as an implementation to reduce emissions in today's shipping?

1.3 Delimitations

The foundation of our thesis will be focusing on the implementation of wind power in today's shipping industry and the different ways of harnessing it. The main focus will be on the environmental aspects, emissions only linked to fuels.

2. Theory and Background

The first part of this section will be explaining the environmental changes and health effects due to the impact of international shipping. This part will also mention The International Convention for the Prevention of Pollution from Ships (MARPOL) and its role to prevent emission. Furthermore, the different ways to utilize wind power with traditional sails, wind turbines, kites, Flettner rotors and Vindskip will be explained.

2.1 Impact of International Shipping

The shipping industry has been a part of this world for decades and it is one of the major factors of importing/exporting large quantities of goods from around the world which makes it important for the world economy. The sea transportation stands for around 90% of world trade by volume (Rutkowski, 2016). Over the decades the technologies have changed rapidly in shipping, making a change in the concept. However, at the same time the shipping industry has also had a major impact on the environment. The emissions are only increasing and between 1979 and 2009 the emissions have more than doubled (Traut, Gilbert, Walsh, Bows, Filippone, Stansby, & Wood, 2014). There is an estimation of 949 million tons CO₂ emissions released from shipping in 2012 which was equivalent to 2.7% global emissions. (Margaritou & Tzannatos, 2018). By comparison, the aviation industry estimates to release 2.0% CO₂ globally (Misra-Godwin, 2016). Furthermore, CO₂ is not the only emission released, emissions such as sulphur and nitrogen oxide from combustion in engines also have a direct effect to the environment.

In order to deal with air pollution from ships MARPOL Annex VI (The International Convention for the Prevention of Pollution from Ships) came into force in 2005 (IMO). This puts stricter regulations on pollution from shipping to avoid unwanted damage to the environment. With these changes the shipping industry had to adapt. Finding ways to reduce the pollution such as selective catalytic reduction (SCR) which can reduce NO_x emissions up to 95% with the help of a special catalyst and chemical agents. Other means for reducing pollutions could also be the exhaust gas recirculation (EGR). Simply put, a portion of engines exhaust gas is recirculated back to the engine. A very plain technique which can reduce NO_x

emission by up 30 to 50%. Apart from using different suitable techniques for reducing pollutions we also have alternative energy sources such as wind. An energy source which is still in its improvements, even after the end of age of Sails (Margaritou & Tzannatos, 2018).

The shipping industry does not only affect the environment but also human health. Particulate matters/pollutions (PM) such as nitrogen oxides (NO_x) and sulphur oxides (SO₂) which emits from ships can cause serious health problems. Particulate matters are inhalable and has been documented to cause premature mortality and morbidity effects. Effects such as lung cancer, cardiovascular disease and childhood asthma morbidity. According to an article from Nature Communications it is estimated around 400 000 premature deaths from lung cancer and cardiovascular disease and approximately 14 million childhood asthma cases annually (Sofiev, Winebrake, Johansson, Carr, Prank, Soares, & Corbett, 2018).

2.2 Different Ways to Utilize Wind Power

Wind is formed by a difference in the atmospheric pressure. Air flows from high pressure areas to low pressure areas to try to reach equilibrium which creates movement. This movement is stronger the closer the high and low areas are to each other resulting in different strength in winds (Green, Aranda, & Gordon, 2013, 28 October).

Throughout the years there have been developments on the existent wind technologies and also new ideas of how to utilize wind as efficient as possible to power a ship. There are a lot of technologies who utilizes the wind as a mean of propulsion, however these innovations are considered different in their capacity. This thesis will be specifically focusing about traditional sails, wind turbines, kites, Flettner rotors and Vindskip.

2.2.1 Traditional Sails

Sails has been the most common means of utilizing wind power on ships through the ages and they come in many different shapes and materials. Sails work similar to wings when wind passes through the sail it will generate high pressure on one side off the sail and low pressure on the other, creating what is called lift which makes the ship propel forward.

Some different examples of sails are square rig (See Fig. 1), Princeton sail wing, cat sail (See Fig. 2) and wing sail (See Fig. 3).

Square rig is a large forward-facing sail. In Princeton sail wing a cloth wraps over a rod with the other end acting as a trailing edge. Cat sail is a triangular piece of fabric stretched between a vertical unstayed mast and a horizontal boom. A wing sail is a structure like airfoil cross-section, like an airplane wing (Shukla & Ghosh, 2009).

2.2.1.1 Wing Sails

When it comes to sail types, the wing sail is the one that seems to be the most promising type of sail for future wind powered ships. The design of the wing sail can be compared to an airplane wing that is fitted vertically on the ship with the exception that a wing sail can create lift on both sides of the wing. A wing sail is shaped elliptical or semi-elliptical which is the most effective airfoil for generating lift (Nielsen, 2017). Traditional sails are connected through wires to a mast which forces the shapes of the sails to be triangular. This shape is very inefficient when it comes to generating lift, this is also the reason you rarely see triangular shapes on the wings of birds or insects (Nielsen, 2017).



Figure 1. Soren Larsen, mid Pacific (Anoldent, 2007). CC BY-SA.



Figure 2. Sailing a Cat, USA (Papushin, 2009) CC BY-SA.



Figure 3. Fujica ST Purple 34th America's Cup 3, San Francisco Bay (Jakobson, 2013). CC BY-NC.

2.2.2 Wind Turbines

Wind turbine is a popular means of utilizing wind power. Large turbines can often be seen arrayed at both land and sea in what is called wind farms which is seen as an important source of renewable energy worldwide (see Fig. 4). Wind turbines generate power by taking the kinetic energy from the wind and converting it into electricity. The most common type is three blades connected to a horizontal axis but there is a lot of different designs out there (Wagner, 2013). The vertical axis wind turbine is a turbine where the generator and gearbox are located at the bottom with a vertical rotor shaft in most cases. These wind turbines have found interest since they are more compact and cheaper to install compared to the horizontal axis wind turbine. They have also the advantage of not needing to be oriented towards wind since they are omnidirectional (Rezaeiha, Ivo & Blocken, 2017). However, they have the disadvantage of not being

able to compete to the horizontal axis wind turbine in power and need further optimization before being efficient enough (Rezaeiha, Ivo & Blocken, 2017).



Figure 4. Horizontal axis wind turbines, Germany (Tony, 2014). CC-BY.

2.2.3 Kites

The kite harnesses the wind power which in turn will act as the propulsion system and “pull” the vessel through a strong tether/rope attached to the bow (see Fig. 5). Having a kite equipped on a ship can potentially increase the speed which allows the engine to decrease the load, cutting down the fuel consumption and resulting in less emissions released (Misra-Godwin, 2016). Towing kites are operated at high altitudes, in front of the ship and flies in a certain pattern, such as the figure 8. This allows the kite to utilize even more of the wind speed and can potentially achieve five times the propulsion force compared to a traditional sail (NCTV7, 2011). The vessel could possibly pay themselves within three to five years through the reduction in fuel consumption (Misra-Godwin, 2016). There are two conditions when using kites (Traut, et al., 2014). The tail-wind condition and the headwind condition. The tail-wind condition is when the kite flies in the direction of the wind, creating a drag and lift force and pulls the vessel forward whereas the headwind condition is the opposite, an unfavourable condition. Furthermore, towing-kites is also most effective when the kite flies in the crosswind direction on a certain flight pattern to achieve faster speed thus providing more force. Predicting the weather forecast and routing could also potentially improve the efficiency. Ships equipped with

kites usually have weather forecast programs to continually see wind speeds. Kites is often computer controlled, fully automated and depending on the condition the kite will be either be launched or retrieved back (Traut, et al., 2014).

Kite is easy to install compared to traditional sails. The wind power technology needs a towing kite, towing rope, control pod (attached on the kite), winch, launch and recovery system and a control system on the bridge. The whole process is controlled through the control system and it has no disturbing systems to interfere with loading, off-loading operations or when passing over bridges (Konrad, 2009). Kites is easy to stow away and do not take a lot of space onboard a ship, for example the size of a folded 160 m² kite is equivalent to the size a telephone booth (NCTV7, 2011). The kites surface area is between 150 to 600 m² whilst a 3-masted clipper ship could have a sail area of 2000 m². Clipper ships can have a top speed of 17 knots whilst a kite can fly at speeds of 100 knots or more, capable of withstanding storms (Sanderson, 2008) (SkySails, 2019). The traditional sails also expose the ships safety and operations because of the minimal heel caused by the sail. The reason to why kites is better in terms of heeling is that the kite is connected directly in ships deck level which allows a shorter level arm, flexible and less heeling (NCTV7, 2011).



Figure 5. Kite (1) (Parlier, Y. and Wikipedia Commons, 2018). CC-BY-SA.

2.2.3.1 Kites altitude and courses

In order to have the best use of a kite the optimal altitude is between 100 to 300 m high, where the wind is strong and constant (Konrad, 2009). Kites is designed to operate at 3 beaufort (3.6 m/s) and up to 8 beaufort (20,7 m/s). Launching a kite below 3 beaufort wind speed will produce less than optimal wind power. Some region in the world’s oceans have more winds generated compared to others and as a result from SkySails global analysis of the wind energy potential between 2003 to 2009 it has shown high wind potential on the Northern Europe, North Atlantic and North Pacific. Most of the shipping industries occupies these routes (Konrad, 2009). Because of the kite’s design which is like a wing of an airplane it allows the kite to operate well not just in the tail-wind condition but also courses from 50°. According to the analysis from Konrad (2009), high propulsion power can be generated from 90° to 270° but the best possible scenario would be between 120° and 140° (see Fig. 6).

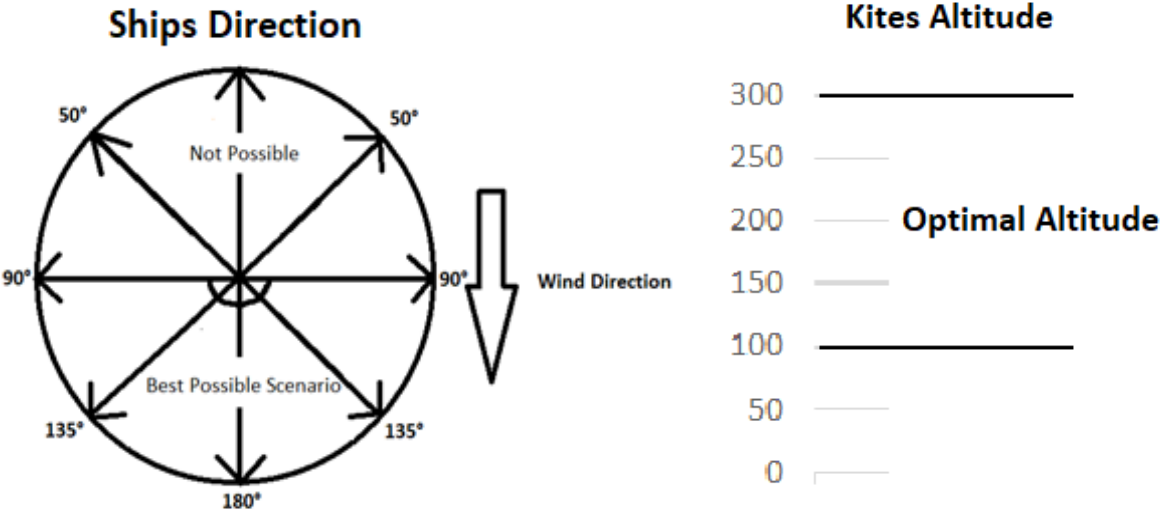


Figure 6. Possible courses. Author's own copyright. Figure 6. Kites Altitude. Author's own copyright.

2.2.4 Flettner Rotors

The Flettner rotor is a large cylinder mounted on the vessel to aid the ship’s propulsion system (see Fig. 7). The Flettner rotors gets rotated by the ship’s engines, which in most cases is an electric motor. When the wind comes in contact with the cylinder while it is spinning a force is created, “the Magnus force”. This force can then be used for propulsion and propel the vessel

forward. Flettner rotors was invented by Anton Flettner in the 1920s (Talluri, Nalianda, & Giuliani, 2018).



Figure 7. E-Ship 1, Germany (Alan, 2015). CC-BY.

2.2.4.1 Flettner rotors history

This technology was invented by Anton Flettner in the 1922. With the help of his friends, Betz, Ackeret and Prandtl they applied this technology to a vessel which created it is first prototype, named “Buckau” (see Fig. 8). Buckau was a vessel which only utilized the wind as the source of propulsive power. Anton Flettner saw this as a promising technology and launched the vessel in the 1924. The attempt of using the Flettner rotors as the primary source of propulsion was seen as a failure (Talluri, Nalianda, & Giuliani, 2018). The main reason was the poor performance in the overall operation and the economics of the vessel. Furthermore, they did not account for the fossil fuels price, which was more attractive because it was cheap at the time (Ahlborn 1939). But as a limited resource, solutions were sought and a new interest was surfaced, a company ENERCON had launched their first prototype of Flettner rotors equipped with 4 Flettner rotors, each cylinder with the height of 27 m and 4 m in diamater. It was reported that the vessel “E-Ship 1” (see Fig. 7) had a fuel consumption reduction up to 25% (ENERCON, 2013).

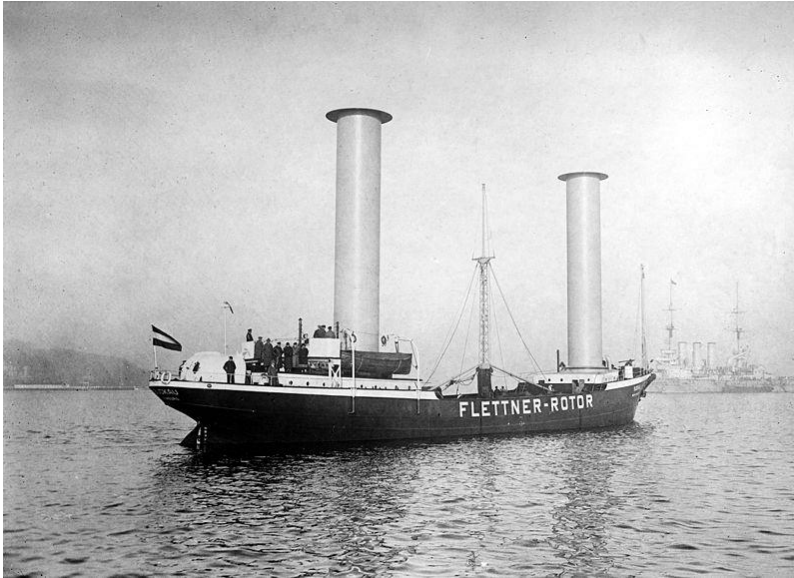


Figure 8. Buckau Flettner Rotor Ship LOC 37764u. (Bain, G. G. and Wikipedia Commons, 1924). CC-BY-SA.

2.2.4.2 The Magnus Effect

Air is considered a heavy fluid and affects the flight of all kinds of projectiles, such as a tennis ball, cannonball and cylinders. When a projectile is thrown into the air the object is somehow affected by a force, the Magnus force. This force is well known in sports such as, tennis, football, and many others. It was first discovered by a German physicist Heinrich Gustav Magnus in the early 1900s when he investigated why a cannonball curved as they flew through the air (Veritasium, 2011). Magnus found out that when a rotating object comes in contact with the fluid which in this case is the air, it will accelerate or decelerate on the side that either moves in the same or opposite direction as the flow, because of the friction between air and the object (Talluri, Nalianda, & Giuliani, 2018). This perpendicular force depends on the direction of rotation and which side the air hits the object, the density and pressure will increase or decrease, causing a differential pressure which acts on the object and in this case is the Flettner rotors (See Fig. 9 and Fig. 10). The Flettner rotors gets rotated by the ship's engines, which in most cases is an electric motor. The rotors will then act like sails and propel the vessel forward (Talluri, Nalianda, & Giuliani, 2018).

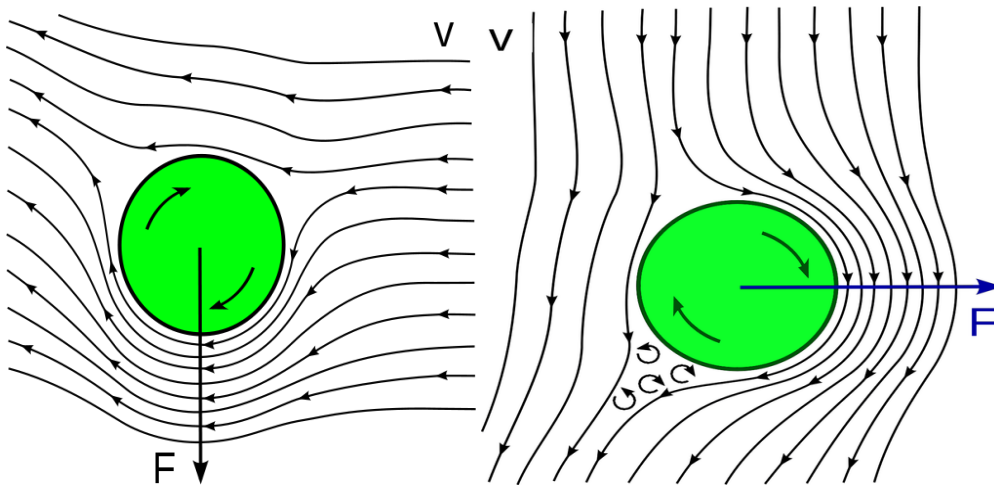


Figure 9. Magnus effect (Kosiorek, B., 2007). CC. Figure 10. Magnus effect Strömung (Kosiorek, B., 2018). CC

2.2.5 Vindskip

Vindskip is a unique and innovative technology for utilizing the wind power. Vindskips concept is introduced in the hull itself (Walther, Jahn, & Lade, 2015). The ship's hull is shaped like a symmetrical airfoil, similar to a wing or a propeller. Ships form is shaped both above and below the waterline. When the hull comes in contact with the wind it will generate an aerodynamic lift which in turn acts as propulsive thrust. Depending of shape and angle whilst in contact with the wind it will either generate a lift and/or a drag which acts as a resistance in water, just like friction.

3. Method

In this section the thesis strategies and chosen methods will be described. Our approach has been to study numerous of articles in order to extend our knowledge on the subject. The reason to this approach is because we believe the use of wind power technologies is not popular which makes it difficult to find information with a different approach, such as interviews and surveys. In the approach of this bachelor thesis we will be using a “*Literature review*”. The advantages of literature review are best suited for this subject. This strategy will be explained more in details on the next section (Randolph, 2009). Furthermore, according to Holme and Solvang (1997) the data collected was to be categorized into primary and secondary information. In order to determine the primary and secondary category for an article, the authors participation to the referred subject was an important factor.

We collected data on the subject through the academic databases and chose articles which give us a wide information about the wind power technologies and its advantages such as fuel reduction meanwhile trying to search for the most cited scientific papers which would ensure a quality of the work. These articles were called “primary data”. We then choose the most relevant articles for each technology to use as a baseline for our work. If some information were lacking and needed further explanation we then sought other articles to fill in the gaps, if we deemed necessary. This articles were called secondary data. Meanwhile under the reviewing of articles we constantly compared to other less cited but newer articles to reflect the relevant information for our thesis. This procedure was done to further ensure an even more up to date information and credibility.

In order to find relevant articles and scientific papers academic databases such as *Chalmers Library*, *Google Scholar* and *Web of Science* were used. The aim is to find qualitative data from the articles/papers and the search for this was conducted as such. Theory and background and result section was based on academic sources with specific topics to each technology. Having a small number of chosen articles with the most relevant information being reviewed. In order to find the most suitable articles and scientific papers a framework of search terms was established which includes:

Search terms:

- Wind power/energy/turbine/sails
- Traditional/ wingsails
- Kites
- Flettner rotors

3.1 Literature Review

The goal with a literature review is to integrate and generalize findings and to create a debate or a bridge within a field. For example, to integrate quantitative outcomes across studies or to critically analyse previous research and identify central issues to create an argument within a field (Randolph, 2009).

4.0 Result

In this section, chosen scientific articles and papers from trustworthy sources mentioned before will be reviewed and summarized in author's perspective of their research. Each chosen article has information about the technologies this thesis specifically focuses about. Traditional sails, wind turbines, kites and Flettner rotors. Furthermore, the wind power concept Vindskip will also be introduced in this section.

Back in the Age of Sails the shipping industry was mostly using sails to operate the vessels however since new technologies arrived the sails have been forgotten. But with increasing environmental regulations the shipping industry is forced to find other solutions. In Shukla & Ghosh (2009) they cover an extensive research about the potential of reducing the diesel fuel consumption with a hybrid vessel equipped with diesel engines and wingsails. This article listed three steps for their research in order to archive a thoroughly result. The calculation of maximum possible sail area, the water resistance on a specific vessel and a presentation of how much they can reduce the diesel fuel consumption using wind energy. They estimate that a hybrid vessel could potentially save around 8.3% of diesel fuels, given the right circumstances (Shukla & Ghosh, 2009).

Another chosen article is written by Traut et al. (2014). This article has studied two technologies, kite and Flettner rotors. Their study reviews the potential of fuel savings as well as the wind power output generated by wind. For their advantage they have a methodology to assess these technologies in three steps. Their methodological analysis comprises of a mathematical model of kite and Flettner rotor, trade routes of which the vessel occupies and furthermore, the analysing of data wind speed for both of the technologies and each trade route. Retrofitting a Flettner rotor could potentially save between 2-24% fuel consumption and 1-32% for a kite, under the right condition. The Flettner rotor could save about 600 USD and the towing kite could save about 900 USD per day at sea, for the specific route, Varberg to Gillingham, fuel price of 650 USD and a specific fuel consumption of 180 g/kWh. Their chosen trade routes were not inevitably the most optimal choice in regard of wind speed. Furthermore, it shows that it can still produce more propulsion power and less CO₂ emissions (Traut et al., 2014).

Bøckmann & Steen (2011) study the possibility of putting a wind turbine on top of a ship to use as auxiliary propulsion which can provide propulsive force when sailing directly upwind. Something other mentioned solutions are not able to (Bøckmann & Steen, 2011). They come up with a new concept of wind turbine that is especially designed for ship propulsion and put it to test by theoretically putting it on a route to test its fuel savings. Their result is a fuel saving of 33,1%. Compared a wind turbine designed for power output would only achieve a fuel saving of 24,4%. Their wind turbine is also on pair with wingsails of equal area that according to their study will provide a fuel saving of 31,8% over the same route (Bøckmann & Steen, 2011).

4.1 Revival of the Modern Sails

Shukla & Ghosh (2009) made an extensive research about the potential of reducing the diesel fuel consumption with a hybrid vessel equipped with diesel engines and wingsails. A tanker vessel has been retrofitted with wingsails. This wingsail is built and structured similar as an airfoil cross-section. However, in order to reconstruct a ship with wingsails a few factors have to be considered. The propulsion performance of the sail rig, initial cost of installation of the rig, operating cost, weight, size, safety while operating rig, cargo handling interference and visibility. The vessels data such as, engine capacity, deadweight tonnage, length of ship and much more has also been provided to complete their calculation. Shukla & Ghosh (2009) have chosen the Mumbai-Durkan route in their research as this is a significant route for the Indian overseas shipping trade. It is estimated to be around 4450 km (2402 nm) between Mumbai and Durkan however, wingsails will only be used for 3650 km (1970 nm) because of the doldrum. The doldrum is the equatorial belt between 5° N latitude and 5° S latitude. In this region there will be calm winds and low pressure. The average wind speed is estimated to be 3.6 m/sec (3 beaufort) between the route in exception of the doldrum region (Shukla & Ghosh, 2009).

Shukla & Ghosh (2009) have listed three steps of calculations in their research. The first step is calculating the maximum possible wingsail area which can be installed on the vessel. The tanker vessel can have a total of 3291.73 m² of possible wingsail area however, it has to be considered that the decks area shall not be affected by the sails and its dimensions cannot be too long as this can cause instability.

The vessels following dimensions will be a 15 m wing sail span with an aspect of 3, wing sail chord length 5 m, distance between two consecutive masts 1.1 times the chord length of the wingsail. Furthermore, the vessel can have 22 applied wingsails on deck which is a total area of 1650 m² and within the limit of maximum possible area, 3291.73 m² (Shukla & Ghosh 2009). At the second step the water resistance for the ship will be computed. In order to determine the water resistance, one has to calculate the wetted area first. The wetted area can be calculated through height, beam and draft of the ship, the displacement volume and the length between perpendiculars. For this specific ship the wetted area is 6773.29 m². The water resistance is proportional to the area and its calculation estimates to be 145389.5 N at the average wind speed mentioned before. The authors last step will present us how much they can reduce the diesel fuel consumption using the wind energy. The wingsails can only be deployed for 3650 km on the Mumbai-Durkan route mentioned before. Shukla & Ghosh (2009) assumes that a ship is operational for 70% of a year and the rest will be for maintenance and loading. Of the 70% only 29% will be wind energy harnessed due to the doldrum regions. The drag and lift force could also be a factor regarding diesel fuel consumption however, this will not be mentioned on this article. From the data computed the total energy gain per year for using wingsails as a mean of propulsion is 2744738.3 MJ/year. Diesel fuels calorific value is 45 MJ/kg which gives us 8.3% saving of diesel fuels and this equals around 61000 kg. Considering India imports around 70% of their oil requirements, it would benefit the environment (Shukla & Ghosh, 2009).

4.2 Kite and Flettner rotors Propulsive Power Contribution

Traut et al. (2014) made a methodology to assess two specific technologies, kites and Flettner rotors. Their study reviews the wind power output and the potential of fuel savings. To resolve their study their methodology covers three steps. First, is a mathematical model of kite and Flettner rotor. Secondly, trade routes of which the vessel with these technologies occupy. Thirdly, analysing the data of wind speed for both of the technology and each trade route. Combining these steps helped them make an estimation of the power output and potential fuel saving. It is also worth considering that wind is not the only factor that has an impact on fuel consumption. Information such as waves and ocean currents are also a factor in fuel saving (Traut et al., 2014).

Kites and Flettner rotors are two technologies whom utilizes the wind in order to generate a propulsive thrust, but they are considered different in their capacity. Kites operates on high altitudes where there is the potential of stronger wind speeds. It is always in motion and flies ahead of the vessel. Kites will not take up any space or change the stability. In this study the kite's area is 500 m² and 350 m long rope. It is controlled automatically and will deploy when the condition is meet. Two of these criteria worth mentioning is the ropes drag force which cannot exceed 1000 kN and the angle between apparent wind speed on the ship and ships course cannot be more than 135°. The Flettner rotors on the other hand is a cylinder mounted on the vessel. Flettner rotors gets turned by the ship's engine and when it comes in contact with the cylinder it will start propelling the vessel forward. Flettner rotors area is 175 m², cylinder height is 35 m and the diameter are 5 m (Traut et al., 2014).

There are five chosen trade routes which follows the shortest patch in Michael et al. (2014). The selected trade routes are as following: Dunkirk to Dover, London to Milford Haven, Tubarao to Grimsby, Yantian to Felixstowe and Varberg to Gillingham. Each of these trade routes were chosen because of its geographic location, trade, diverse route distances and also the chosen vessels for this research are the ones occupying these routes. While sailing these routes the vessels shall slow steam. Slow steaming means that it will travel at significantly less than their typical speed and in this case a speed reduction of 20% on respectively routes. Slow steaming is considered a good thing for both the shipping industry and environment (Traut et al., 2014).

To have a realistic translate of fuel savings the wind data also has to be considered. The wind data were provided by the UK Met Office's Unified Model which gave westerly and southerly wind speed data and also provided height ranges from 1024 by 769 cell grid. These data are recorded four times a day at 0th, 6th, 12th and 18th hour. A total of 53 data series were collected in this project. The average wind power contribution along these routes and the average power contribution was collected, computed and presented into polar graphs and charts. Data concerning lift-, drag-, moment coefficient and maximal rope force for Flettner rotor and kites was also included to determine the average power. The highest power contribution for these technologies were sailing on different routes. For example, Flettner rotor had the highest on Dunkirk to Dover route while Kite had the highest average power contribution on London to Milford Haven route. This is because of the wind direction. In Michael et al. (2014) it is stated that the kites and Flettner rotors behaves differently depending on the wind direction. Kites

responds well with tail wind condition and especially when the wind speed is faster than the ship speed, which can provide an power input between 126.7 - 460.6 kW. Flettner rotors however responds poorly on a tail or head wind condition where the power output could be low or even negative. These cylinders work best at sideways wind direction where it can provide a power input between 193.1 - 362.5 kW. The result also shows that the Flettner rotor contributes power input on a wider set of wind direction while the kites could only deliver propulsive power on a very narrow range of wind direction however, it has a higher peak of input. Their conclusion is that this study shows a fuel saving between 2-24% for a single Flettner rotor and 1-32% for a kite. Traut et al. (2014) have showed evidence that retrofitting a Flettner rotor could save about 600 USD per day at sea and 900 USD for a kite, assuming that the fuel price is 650 USD and the specific fuel consumption is 180 g/kWh.

4.3 Wind Turbine Propulsion of Ships

In an article written by Bøckmann & Steen (2011) the possibilities of putting wind turbines on ships to work as auxiliary propulsion to help reduce CO₂ emissions is studied. The major benefit with a wind turbine is that it can provide propulsive force when sailing directly upwind (Bøckmann & Steen, 2011). This is impossible with other wind power solutions for example, kites, sails and Flettner rotors (Bøckmann & Steen, 2011).

To study this further the article focuses on trying to design and calculate the optimal wind turbine for a ship, theoretically putting this wind turbine on a 150 m tanker and then calculate how efficient this would work on a certain route with fuel savings and also see how it compares to using wingsails on the same ship. The route they choose is between Peterhead (United Kingdom) to Bremerhaven (Germany) since this route is in close proximity of weather stations where statistical wind data is available (Bøckmann & Steen, 2011).

Starting with design, they calculate that they will need a different blade design than that of a wind turbine designed for maximum power output. The many bridges that cross the world major ports restricts air draft to 60 m, so unless it can be folded down the horizontal axis is limited to about 40 m, considering freeboard, safety clearance and the blade tips to the deck (Bøckmann & Steen, 2011). The wind turbine should be designed for optimal performance upwind, since this is the most important and critical direction (Bøckmann & Steen, 2011). Their calculations prove that a wind turbine designed for ship propulsion has a net forward force of 23% higher compared to a wind turbine optimized for power. After further calculations they chose to use a

four-bladed 39 m diameter horizontal axis. It is also important that the wind turbine features controllable pitch (Bøckmann & Steen, 2011). Afterwards they put this wind turbine on their 150 m tanker and set this to sail between Peterhead-Bremerhaven.

They choose to divide the route into eight parts and take the wind data from each part from their respective closest weather station to get the best possible data. According to calculations this route would provide a 33,1% in fuel savings. They also compared this to a wind turbine design named Vestas V39/600 which would only provide a fuel saving of 24,4%, showing that the wind turbine especially designed for propulsion is more efficient (Bøckmann & Steen, 2011).

To compare this with wingsails, they choose the same ship design and route while replacing the wind turbine with wingsails. They choose to use 10 halfelliptical wingsails with a maximum chord length of 6,08 m and a height of 25 m, total area 1194,1 m² which would be equal to the rotor disk area of the wind turbine. Calculated these wingsails would provide a fuel saving of 31,8%, slightly less than that of the wind turbines 33,2% (Bøckmann & Steen, 2011). They conclude that if there is a concern about wingsails turning-system fails it would be preferable to use a wind turbine. Overall a wind turbine would be weakly preferable over wingsails if energy efficiency and heeling moments are of main concerns (Bøckmann & Steen, 2011).

4.4 Vindskip – A Viable Concept?

Project Vindskip is an innovative concept based on the Norwegian company, Lade AS. This concept was developed by the company because of the concern they had on environment caused by shipping. Terje Lade is the Norwegian designer of Vindskip and he said “I often describe Vindskip™ as a cross between sailing and flying on water. Inspired by the aerospace industry and sailboat environment where the relative wind is a crucial factor in designing aircrafts, propellers and sailing boats, Vindskip™ is designed to exploit the wind for propulsion.”. He said that the concept is so simple that you do not really have to think about it. When a vessel starts moving it will generate an aerodynamic lift from the wind which in turn will propel the vessel forward because of the unique hull. Additionally, the vessel is a hybrid equipped LNG-powered propulsion system (liquified natural gas), a natural gas which is widely recognized for producing less carbon dioxide and sulphur emissions than other fossil fuels (Project Vindskip, 2014). A state-of-the-art weather routing module was also developed to assist the Vessel equipped with Vindskip. This module is based on Vindskips characteristics, weather forecast

and general restrictions in order to use the force generated by the wind as efficiently as possible. The vessel has an estimation of 80% reduction in emissions and 60% in fuel savings (Walther, Jahn, & Lade, 2015).

4.5 Advantages and Disadvantages of the Technologies

In conclusion, these technologies have their pros and cons, but it is all too dependable on the wind speed which is decided on the routes and season. According to an article from Rehmatulla, Parker, Smith, & Stulgis (2017) the average annual wind speed for the different sea regions ranked from least windy to the most windy is of following: South Atlantic, South Pacific, Indian Ocean, Baltic, North Atlantic, North Pacific and North Sea (See Fig. 11).

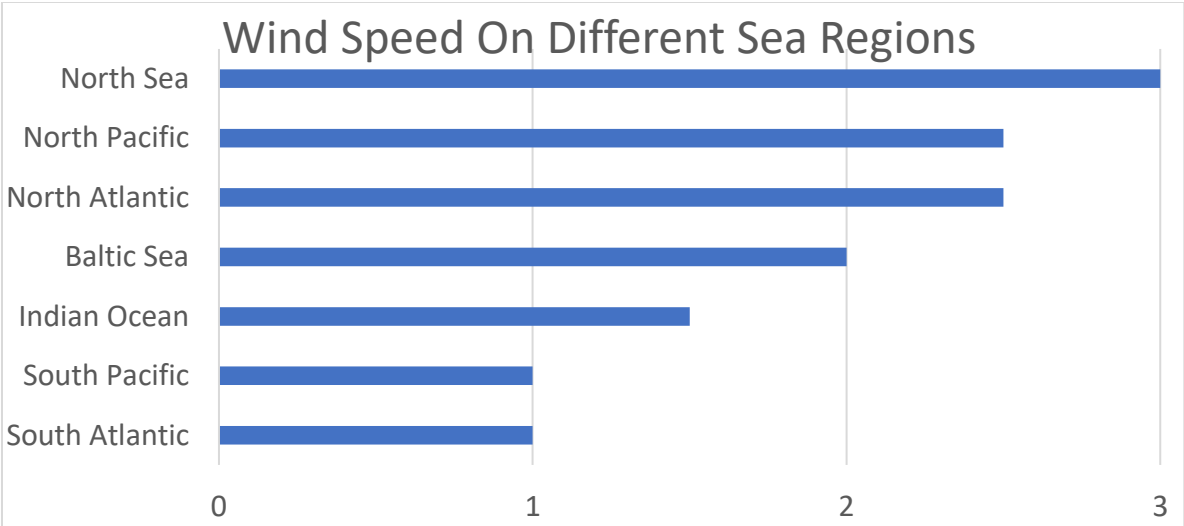


Figure 11. Wind Speed On Different Sea Regions, 3 = High, 2 = Medium, 1 = Low. Author's own copyright.

For example, retrofitting a wingsail to a vessel on the Indian ocean can only profit around 8.3% diesel fuel, on the entire route. The average wind speed in these regions is estimated to be around 3.6 m/sec (Shukla & Ghosh, 2009). Meanwhile the Baltic sea have the average wind speed of 8 m/s which for example for a vessel equipped with a kite could reach up to 15% in reduction of fuel consumption. For kite and Flettner rotor technology shown on Traut et al. (2014) the northern parts of Atlantic and Pacific oceans are a desirable region, thus giving a favourable fuel saving. To provide an even more fuel saving in regards of wind speed the North

Sea is the best choice for all the technologies because the ocean reaches the highest wind speed. Bøckmann & Steen (2011) calculated their fuel savings for their wind turbine ship in this region and managed to get a fuel saving of 33%. In Traut et al. (2014) they managed to reduce the fuel consumption up to 32% for a kite and 24% for Flettner rotor when the wind speed reached 15 m/s. However, even when a vessel equipped with wind technologies on a windy sea region the problem is that the ship must be on the right direction of the wind to utilize the energy source, which is dependable on the shipping routes.

The figure below is an estimation of the fuel savings. “High” is equal the “highest” fuel savings in percent from all of the discussed articles which is 33% and “Low” is the lowest fuel savings which is 8.3% (see Fig. 12).

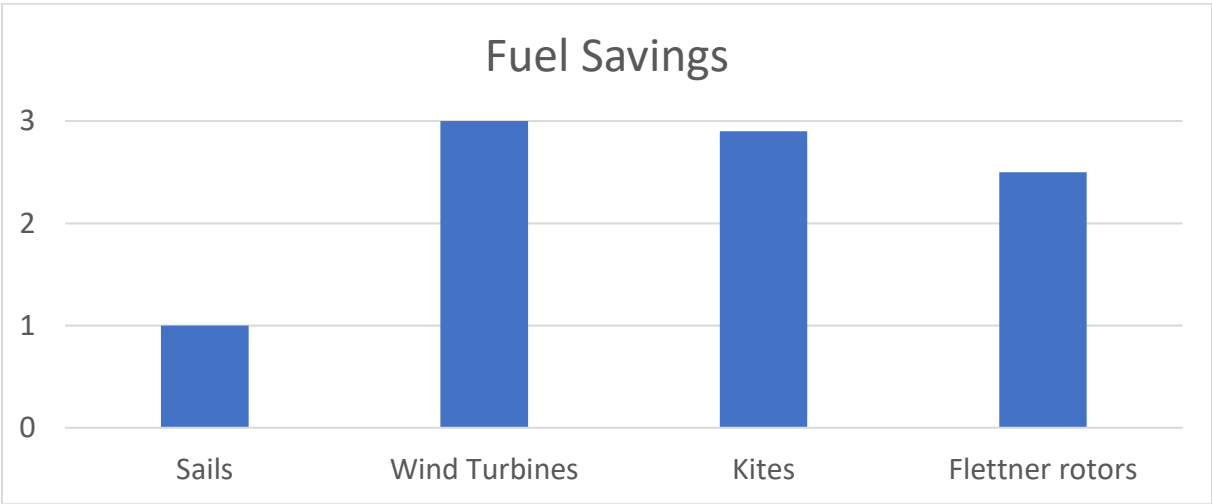


Figure 12. An Estimation Of Fuel Savings, 3 = High, 2 = Medium, 1 = Low. Author's own copyright.

4.6 Cost and Reliability for Wind Powered Vessels

When installing a wind powered technology on a ship, the ship owners and operators are usually concerned of the cost and reliability of the vessel affected. Depending on the technology installed (sails, wind turbines, kites and Flettner rotors) the cost and reliability are weighted differently.

In terms of cost there are two factors where the ships owners are most concerned. The installation cost and hidden cost (Rehmatulla, Parker, Smith, & Stulgis 2017). Now the

installation cost differs from technology to technology. According the Global Maritime Energy Efficiency Partnerships (2019) the price per mast which includes the installation differs depending on which sails installed (Square rig, Princeton sail wing, cat sail and wing sail) and how many. Therefore, the cost could be from \$170 000 to \$300 000 per mast. So, installing five masts on a vessel would cost around \$850 000 to \$1 500 000. The cost of implementation, depending on the model of the Flettner rotors could range from \$400 000 to \$950 000 for a single rotor. A usual estimation for a vessel powered by four Flettner rotors can cost around \$1 000 000 to \$3 000 000. Meanwhile, the implementation cost of kites differs even more. Depending on the size of the kite which could range from 160 m² up to 5000 m². For example, a 160 m² generates around 600 kW which estimates a cost of \$280 000. The largest kite, 5000 m² generates around 19 200 kW and cost as much as \$3 420 000 according to the Global Maritime Energy Efficiency Partnerships (2019). IRENA (2012) calculates that the price for wind turbines in offshore is between 3300-5000 USD/kW. This makes a 600kW turbine which is the power they used as comparison to cost about \$1 980 000 to \$3 000 000.

The figure below is an estimation of the cost. “High” is equal the “highest” cost in percent from all of the discussed articles which is \$3 420 000 and “Low” is the lowest fuel savings which is \$280 000 (see Fig. 13).

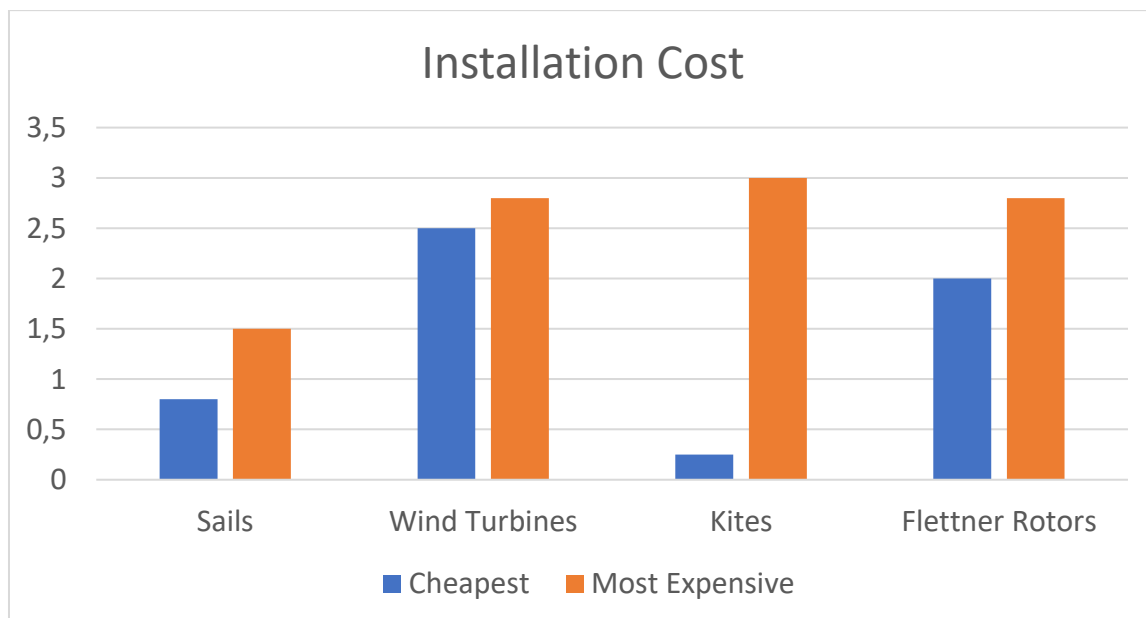


Figure 13. An Estimation Of Installation Cost, 3 = High, 2 = Medium, 1 = Low. Author's own copyright.

Regarding the hidden cost which could be the possibility of compromising the deck space and stability. By putting a Flettner rotor on top of a vessel the deck space has to be reconstructed in order to fit 4 rotors which will therefore affect the stability. When installing a wind power technology, it affects the ships usual shipping routes because of the importance of a ship sailing in a windy sea region whereas a diesel-powered vessel does not care for wind. So, it would be more beneficial for a sailing ship to use a different route. Another hidden cost can also be the reduced amount of cargo space on a container ship because of the newly installed wind technologies (Rehmatulla, Parker, Smith, & Stulgis, 2017).

Even though the cost and reliability for implementing such a technology (sails, wind turbines, kites, Flettner rotors) it suggests that the investment of implementing (buying and installing) the technology would be paid back within five years through fuel savings, where some are more favourable and shows short payback time (Rehmatulla, Parker, Smith, & Stulgis, 2017).

5.0 Discussion

In this following section, the reports result and method will be discussed. The result from each article summarised will be discussed and a possible interpretation of how each technology described could benefit the shipping industry. Afterwards, the method will be discussed by reviewing the reliability and validity, thus determine the relevance to the subject. Furthermore, the limitation of literature review will also be evaluated.

5.1 Result Discussion

The goal for a wind power technology is to perform and have a reliability as good as the modern vessels, without the major emission release. Each technology utilizes the wind as a means of propulsion, however these innovations are considered different in their capacity. In order to determine if the use of wind power technologies is viable again in today's shipping industry the authors have had to do research regarding its operational profile. As such Shukla & Ghosh (2009), Traut et al. (2014) and Bøckmann & Steen (2011) have all used similar methods to calculate the potential of fuel savings. Their methods involve the calculation of the model (traditional sail, kite, Flettner rotor and wind turbine), any resistance that affects the ships movement and chosen trade routes. If a vessel was to retrofit a sail, kite, Flettner rotor or a wind turbine then certain calculations has to be made because putting in a new system onboard a ship could change its dimension and weight.

Wind is not the only factor of resistance discussed in result. Traut et al. (2014) also noted that waves and ocean current is a crucial element, regarding resistance. Furthermore, when conducting researches for any energy losses when using sail, kite or Flettner rotor or any kind of wind power technology the side slip, rudder losses caused by the misalignment of ships bearing, the generated thrust from wind, transmission and propeller losses is also relevant variable. Shukla & Ghosh (2009) also had the same idea of calculating the resistance, specifically the water resistance caused by currents. The difference between these two involving resistance was that the Shukla & Ghosh (2009) conducted an operational profile of the vessel and route and calculated an average wind speed of 3.6 m/sec throughout the whole route meanwhile Traut et al. (2014) had a more circumstantial approach where they recorded the wind

speed at each grid cell, presenting a realistic result. Bøckmann & Steen (2011) choose to take statistics from known weather stations and decided their route as close to these as possible in order to get as accurate data as possible for their tests. The result was a route between Peterhead-Bremerhaven and demonstrated a significant reduction in fuel consumption. The other authors also demonstrated a considerable reduction in fuel consumption made on specific trade routes for example the Mumbai-Durkan, Yantian-Felixstowe and Tubarao-Grimsby routes. They were selected because of the similarity to other existing trade routes in the world. But Traut et al. (2014) did mention that “From a practicality perspective it should be noted that this analysis was completed along existing shipping routes – which are not necessarily optimal with respect to wind gain.” – Traut et al. (2014).

Regarding fuel savings all of the authors have shown studies of their conclusion. Traut et al. (2014) study shows a saving between 2-24% for a single Flettner rotor and 1-32% for a kite. Meanwhile Shukla & Ghosh (2009) estimates savings around 8.3% for a traditional sail. Shukla & Ghosh (2009) estimation is still within the range of fuel savings and considering their trade routes are different which indicates different wind speed calculations, the conclusion could still be reliable. Bøckmann & Steen (2011) managed to theoretically achieve a fuel saving of 33,1% with their wind turbine designed for ship propulsion on the route between Peterhead-Bremerhaven. This also showed a considerable fuel saving of 31,8% with wingsails over the same route.

Apart from kites. Flettner rotor, traditional sails technologies and wind turbines there is also Vindskip, a concept yet to be tested out in the ocean. According to Lade AS, they believe that this project has potential of facing the challenges that the shipping industry has yet to manage. The design is so unique compared to kite and Flettner rotors. It is only a concept so a fully calculation has not yet been done however, there has been research regarding this, and they estimate an 80% reduction in emissions and 60% in fuel savings (Walther, Jahn, & Lade, 2015).

5.2 Fuel Saving and Cost comparison

If we compare the fuel saving and cost of our four technologies (see Fig. 14), we can see that the fuel saving is increasing when the cost of the technique increases in all cases except kites. Kites have a medium cost but a high fuel saving in comparison with the other techniques, but this could also be due that the kite has the most varying cost when it comes to the cheapest and

most expensive type. If we exclude the kites the result is linear showing that the more money you put into the technique the better the result in fuel saving will become. Wind turbine will achieve the highest fuel saving but will also be the most expensive investment. This investment could be seen more daring for a company since it is a lot of money put into a less known technique making it less likely for companies to adopt it without more certainty that it will be awarding. Sails on the other hand is a less costly investment that can still provide a small fuel saving. Because of this companies can find it easier and less daring to invest in this technique. Kites could also prove to be a great investment for a company. It is in most cases more expensive than sails, but it shows great promise in fuel savings for its price while not being a big investment such as in a wind turbine and could therefore be considered as the most favorable technology for investment. A less expensive kite might not award the best fuel saving but a fuel saving is still guaranteed making it a good investment.

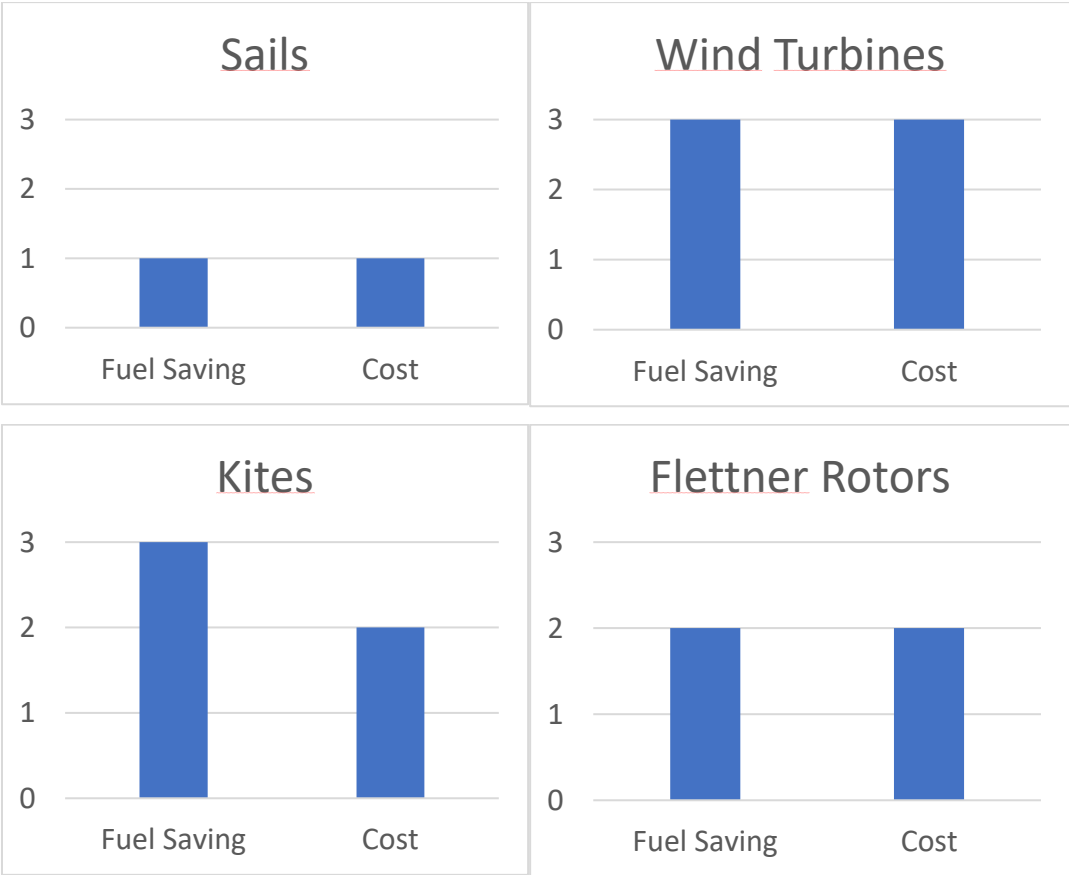


Figure 14. An Estimation of Fuel Saving and Cost, collected from figure 12 and 13, 3 = High, 2 = Medium, 1 = Low. Author's own copyright.

5.3 Method Discussion

A well-established literature review will seek support for grounded theory to resolve a debate within a field (Randolph, 2009). Collecting data from academic databases and devising a framework where potentially relevant information was separated from evidently irrelevant information. In the data evaluation process the reliability was important. Extracting data from each article by searching for keywords and keywords combination while documenting the procedure. It is essential to carefully chose the most relevant information as primary data to provide reliability. Furthermore, filling lacking information with secondary data. As mentioned by Holme and Solvang (1997). However, since the topic of this thesis is specific and it is from a qualitative data approach, it was difficult to collect relevant data, so the methods framework had to add more keywords in order to seek further research and insights, regarding the main focus. The restriction of a less popular subject gave further complications so additional approach such as interviews, surveys and a combination of quantitative and qualitative literature review could have provided a higher reliability of the result, but it was still within its margin. For example, quantitative approach via a survey could have been useful because the information could have given us an even wider view of the subject at hand. This approach could have given a theoretical and practical perspective which could establish a better understanding of the research questions structure. The initial approach for this report was to have a literature review and interviews, however, the possibility never occurred thus giving the study a rather low reliability.

In conclusion, the literature review approach with the focus of primary- and secondary data gave us a good reliability, even with a limitation of a less popular subject. Furthermore, the advantages of qualitative data analysis did allow a high validity whereas the different authors reached a somewhat similar conclusion. The goal of this report was to maintain a recognition for the authors regarding the use of sails in today's shipping which it did provide in a certain degree.

6.0 Conclusion

With the increasing environmental regulations, the shipping industry is forced to use cleaner fuels and to seek new methods of propulsion. Since the age of sails the industry have brought up new technologies which replaced the sails because its efficiency and better usefulness than the sails. However, harnessing wind power technologies have developed a great deal and it is still improving. The chosen technologies on this thesis such as the Flettner rotor, a large cylinder mounted on the vessel and kite, designed to “pull” the vessel forward. Furthermore, sails, wind turbines and Vindskip has also proven to be just efficient as the other technologies used in modern shipping, such as diesel engine, given the right circumstances. However, Vindskip has been disregarded in the conclusion section as the technology is a concept, still on its early stages but Lade AS have made rough calculations regarding reduction in emissions, around 80% and fuel savings around 60%.

The reports result show that these technologies could reduce the fuel consumption and potentially save fuels between 1-33,1%. The differences of fuel savings various because each technology is designed differently thus giving us a different fuel saving with the same wind speed. However, there are a few factors whereas the wind power technology is very dependable on to achieve the best possible efficiency. Wind speed and wind direction is the most important factors and a few other elements does also play a big role to the efficiency factor. A few of these factors could be, water resistance (waves & ocean), trade routes, ships stability once the technologies are installed, side slip and various of energy losses on the ship. All these elements have proven to be obstacles for using wind power in the shipping industry. However, the main obstacle to implement wind power in shipping is the issue that it can be an expensive and daring investment for a company to invest in a less known and used technology. Companies need higher certainty that the investment will be rewarding to use and will not adopt wind power if not this factor is achieved unless other factors like environmental regulations forces the company to do so. Less expensive wind power solutions could prove to be the best answer to this since it is a less bet for a company to adopt it. Even though the cheaper technologies do not provide the best fuel savings, they could prove to be a good start to move towards more wind power in shipping and increasing the knowledge about it. This could in the long run make it less of a bet for a company to adopt a more expensive and more fuel saving wind technology in the future.

In conclusion, wind power technologies have advanced a lot since the age of sails. It is still improving its efficiency to make it as good as the currently technologies and with less emissions released. The report has shown that these types of propulsion system could potentially act as an addition to support the current propulsion system and greatly reduce the pollution caused by shipping and to avoid unwanted damage to the environment and health. However, it is still unlikely that these technologies, traditional sails, wind turbines, kites and Flettner rotors have the capacity and efficiency to replace the current propulsion without any major compromises.

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