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Wind-powered auxiliary propulsion in cargo ships

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The maritime transport covers 90 percent of goods in global markets and produces 3 percent of global carbon dioxide equivalent emissions. Climate change forces governments to tighten the emission limits and legislation, which sets the pressure on shipyards to find solutions to handle the shipping more efficiently.

Wind power has been used as the main propulsion force until the start of the 20th century. Because of the stricter schedules and more reliable power production, engines surpassed the sails as the main propulsion device. After this the sails or other wind-powered devices have been suggested time to time to give an auxiliary or whole propulsion power. Earlier these were suggested for only money saving, but these days, because of the rising awareness of the climate change, the wind power has started to become a more tempting option to cut the emissions and costs.

Depending on the vessels sailing speed, and on the wind velocity the selected systems could provide between 1 and 44 percent of the required propulsion. Out of the selected systems, the Flettner rotor is providing highest average contribution on the propulsion, kite technology can provide the largest propulsion and the Dynarig sail is averaging both of these systems.

None of the systems can provide the full-required propulsion, but as the EU has set a target on 2050 to cut the emission levels with 40 percent from the 2005’s levels, it is plausible to fulfil these requirements.

Because shipping industry is facing this challenge a rising interest towards the subject is notable. It seems that the industry is still on the data-collecting step and it is unlikely that a rapid change would occur under next decade, but as more and more data is available and few rough edges on the technologies have been grinded off, it is likely that many of these technologies will be seen on use.

Keywords	shipping, wind power, sail, Flettner, kite, climate change, Dynarig

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Laivoilla kuljetetaan 90 prosenttia kaikista maailman tavaroista. Laivat myös vastaavat noin kolmesta prosentista vuosittaisesta hiilidioksidi ekvivalenteista päästöistä maailmanlaajuisesti. Kiihtyvä ilmastonmuutos on pakottanut hallitukset tiukentamaan päästörajoituksia, mikä on asettanut paineita kuljetusyhtiöille keksiä tehokkaampia tapoja toimittaa tavarat ajoissa perille.

Tuulivoima eli purjeet toimivat aina 1900-luvun alkuun asti pää-asiallisena voimanlähteenä. Aikataulujen tiukentuessa ja moottoriteknologian kehittyessä, polttomoottorit syrjäyttivät purjeet. Purjeet ovat nousseet aika-ajoin esille, kun öljykriisien aikoina on pohdittu miten pystyttäisiin vähentämään polttoaineen kulutusta. Tällä kertaa mukana yhtälössä on myös ilmastonmuutos ja kasvihuonekaasujen vähentäminen, mikä on tuonut päästöttömille tuulivoimatekniikoille lisäarvoa.

Aluksen nopeudesta ja tuulennopeudesta riippuen tutkitut tekniikat pystyivät tuottamaan yhden ja 44 prosentin välillä tarvittavasta työntövoimasta. Valituista tekniikoista Flettner roottorilla oli suurin keskiarvoinen tuotto. Leijalla taas oli suurin hetkellinen teho ja siipipurjeet olivat näiden kahden välillä. Mikään valituista tekniikoista ei pystyisi yksin tuottamaan tarvittavaa tehoa, mutta laivausyhtiöiden tavoitellessa tulevia päästörajoja, jotka Euroopan Unioni on asettanut, voivat nämä tekniikat olla avainroolissa. Jokainen tekniikka maksaa itsensä takaisin muutamassa vuodessa.

Laivausyhtiöiden painiessa tiukentuvien päästörajoitusten parissa, positiivista kiinnostusta aihetta kohtaan on selvästi ollut. Useimmat tutkielmat joita tätä lopputyötä varten luettiin oli tehty viimeisen viiden vuoden aikana. Telakoilla on useita projekteja käynnissä, joissa pyritään keräämään tietoa eri tekniikoiden soveltumisesta päästöjen vähentämiseen. On epätodennäköistä, että uusiutuvat energiatekniikat tulevat lyömään läpi nopeasti, mutta mitä enemmän uutta tietoa on saatavilla ja tekniikoista onnistutaan hiomaan pahimmat kauneusvirheet pois, on hyvin todennäköistä, että tulevaisuudessa monet näistä teknologioista ovat arkipäivää laivateollisuudessa.

Avainsanat	kuljetusala, tuulivoima, purje, Flettner-roottori, leija, ilmastonmuutos

Nomenclature

Adapted from [2], with slight modifications.

l	Length of the waterline
B	Waterline breadth of the hull
T	Draught amidships
Δ	Displacement of the hull (t)
∇	Displacement of the hull (m^3)
S	Wetted surface of the hull
V	Sailing speed
Fn	Froude’s number
C_B	Block coefficient
C_M	Midship section coefficient
C_P	Prismatic coefficient
M	Length displacement ratio
ρ	Water or air density
t	Water temperature (°C)
Rn	Reynolds number
v	Kinematic viscosity of water
C_T	Total resistance coefficient
C_F	Frictional resistance coefficient
C_A	Incremental resistance coefficient
C_{AA}	Air resistance coefficient
C_R	Residual resistance coefficient
TEU	Twenty-foot-equivalent unit

L	Lift
D	Drag
F_R	Driving force
F_H	Heeling force
v	True wind speed
A	Area
V_A	Apparent wind speed
$\mathrm{C_L}$	Lift coefficient
$\mathrm{C_D}$	Drag coefficient
C_M	Moment coefficient

g	Gravitational acceleration
z	Height
β	Apparent wind angle
λ	Leeway angle
Υ	True wind angle
P	Power

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Appendices

1 Introduction

The sea, where the industry, still heavily depends on fuel, transports 90 percent of the goods in global markets. Since the first energy crisis in the late 1970’s, sails have been suggested to lower the transportation costs and reduce the reliance of the industry to fuel. Because of the climate change and rising environmental awareness, the sails have been suggested to lower the environmental impacts caused by the industry. Also because of the technological breakthroughs, wind power solutions have become first of all cheaper. Secondly, easier to use. All of the technologies introduced in this thesis are almost fully automated and a few technologies have reached the point that they do not require any extra attention from the ship operator.

Usually the fuel consumption and pollution amounts go hand-in-hand, so the easiest way to lower the emissions is to improve the fuel efficiency of the ships. Typical problems with the traditional sails at the cargo vessels have been the cost of the equipment, difficulty to harness the wind power, riggings and structural modifications. None of the companies offering solutions have been able to solve all these difficulties so that the ship could only rely on the selected technology. Still the last decades, with the ever stricter environmental policies and legislation, have forced the shipyards to find solutions to lower the emissions. It has been calculated that if the shipping industry continues at the current rate, the maritime transport in 2100 would cause between 18 and 21 percent of the total greenhouse gases globally.

The thesis examines basic physics of how ship resistance is calculated and how sails create a propulsion force. It also presents some available technologies to lower shipping emissions. Also, some of these technologies are numerically assessed in terms of two different routes to see how much propulsion force they could provide and this way cut fuel consumption.

2 Boat Hydro- and Aerodynamics

Depending on the designed purpose for the ship, there can be massive differences in the performance. In this chapter, an introduction on factors affecting the ship's performance is given. It investigates the different resistances influencing the ship and how the propulsion needed is calculated.

2.1 Factors affecting on the emissions of boats

Hull shape is one of the most crucial parts affecting on the ships running costs. The resistance from the hull can be divided into two different factors; water resistance and air resistance. In this thesis, when trying to assess how much different techniques could lower the fuel consumption by the cargo vessels, it is crucial understand what kind of forces are affecting the ship and how much propulsion is needed to push the ship forward. This way it is possible to assume how big portion different techniques could take from the needed engine propulsion and thus lower the fuel consumption and emissions.

There are countless phenomena influencing the ship when it is sailing on the ocean. These could be for example wind, waves, ocean currents and other ships. To make things simpler, this thesis mainly focuses only on the drag coming from the resistance between the ships hull and water and air. When all the forces are in equilibrium, the ship's speed is constant. These forces are the gravity of the ship, air and water resistance on the ship and other external forces.

2.1.1 Total resistance (R_T)

The total resistance can be received from the equation (1), with this equation the total drag caused by the air and water resistance on the ships hull can be calculated.

$$R_T = \frac{1}{2} \times \rho \times C_T \times S \times V^2 \qquad \text{Equation 1}$$

2.1.2 Wetted surface (S)

The wetted surface is the area that is in contact with the water. When ship is designed, a hydrostatic program is used to calculate the exact value for it. However, as this is not the main subject for this thesis, a rough estimation is enough. For this, there are many different methods and equations available, as example equation (2) below, known as Mumford’s formula.

$$S = 1.025 \cdot (\frac{\nabla}{T} + 1.7 \cdot l \cdot T)$$ Equation 2

According to the study of Kristensen and Lützen [2] there can be an error up to 7 percent. To lower this error the formula is adjusted depending on the ship type. In table 1 it is possible to see the adjusted equations for different ship types.

Table 1 - Wetted surface factor on different ship types (adapted from [1])

Ship type	Formula
Bulk carriers and tankers	$S = 0.99 \cdot (\frac{\nabla}{T} + 1.7 \cdot l \cdot T)$
Container vessels (single screw)	$S = 0.995 \cdot (\frac{\nabla}{T} + 1.7 \cdot l \cdot T)$
Twin screw ship’s	$S = 1.53 \cdot (\frac{\nabla}{T} + 1.7 \cdot l \cdot T)$
Twin skeg ship’s	$S = 1.2 \cdot (\frac{\nabla}{T} + 1.7 \cdot l \cdot T)$
Double ended ferries	$S = 1.11 \cdot (\frac{\nabla}{T} + 1.7 \cdot l \cdot T)$

2.1.3 Total resistance coefficient (C_T)

It is typical to present the drag and its components in dimensionless form to make the comparing easier in dimensional analysis [1]. On the below equation (3), is all the components belonging to the total resistant coefficient: frictional resistance coefficient (C_F), incremental resistance coefficient (C_A), Air resistant coefficient, (C_{AA}) and residual resistance (C_R).

$$C_T = C_F + C_A + C_{AA} + C_R$$ Equation 3

2.1.4 The frictional resistance coefficient (C_F)

The frictional resistance coefficient is received from the equation 4 below. It mainly is an effect from the surface roughness of the hull. Reynolds number is calculated by using the following equation 5. To be able to calculate the Reynolds number, the kinematic viscosity (υ) is needed; the formula for the kinematic viscosity is the lowest one on this set (6).

$$C_F = \frac{0.075}{(\log(R_n)-2)^2}$$

Equation 4

$$R_n = \frac{V \cdot l}{\nu}$$

Equation 5

$$\nu = ((43.4233 - 31.38 \cdot \rho) \cdot (t+20)^{1.72 \cdot \rho - 2.202} + 4.7478 - 5.779 \cdot \rho) \cdot 10^{-6}$$

Equation 6

2.1.5 The incremental resistance coefficient (C_A)

The incremental resistance coefficient, as the name might suggest is related to the frictional resistance coefficient above; it just adds the ship size as a factor affecting the total resistant coefficient. Table 2 gives a rough estimation for different ship sizes.

Table 2 - Incremental resistance coefficients (adapted from [1])

Ship weight	C_A value
$\Delta = 1\,000t$	$10^3 \cdot C_A = 0.6$
$\Delta = 10\,000t$	$10^3 \cdot C_A = 0.4$
$\Delta = 100\,000t$	$10^3 \cdot C_A = 0.0$
$\Delta = 1\,000\,000t$	$10^3 \cdot C_A = -0.6$

If an exact value is needed, it can be received by using the equation 7 below.

$$C_A = 0.5 \cdot \log(\Delta) - 0.1 \cdot (\log(\Delta))^2$$

Equation 7

2.1.6 Air resistant coefficient (C_{AA})

Air resistant causes from 2 to 3 percent of the total resistance of the ship [1]. Table 3 gives a good estimation for the air resistant coefficient is received.

Table 3 - Air resistant coefficient for different ship types (adapted from [1])

Ship type	$C_{AA} \cdot 1000$
Small tankers	0.07
Handysize tankers	0.07

Handymax tankers	0.07
Panamx tankers	0.05
Aframax tankers	0.05
Suezmax tankers	0.05
VLCC	0.04

For container vessels, equation 8 is used.

$$C_{AA} \cdot 1000 = 0.28 \cdot \mathrm{TEU}^{-0.126}$$ Equation 8

where TEU (twenty-foot-equivalent unit) is container capacity. One 20-foot-long container equals to one TEU.

2.1.7 Residual resistance (C_R)

Residual resistance as the name suggest can be given by distraction of the friction resistance coefficient of the total resistant coefficient. The residual resistance all the remaining forces that could be affecting on the ship's performance, these include wave resistance, viscous pressure resistance and additional resistance from the hull shape. Usually C_R is determined by model tests, but it is also possible to calculate by models that give a good estimation of the resistance. One of these models was developed by Guldhammer and Harvald and it is named as "Ship Resistance". The model gives a diagram as, which gives C_R as a function of Froude's number. There are also two other parameters having influence on the curve: The length-displacement ratio (M) and prismatic coefficient (C_P), equations (9) and (10) below.

$$M = \frac{l}{\nabla^{1/3}}$$ Equation 9

$$C_P = \frac{C_B}{C_M}$$ Equation 10

The Froude's number is one of the most important numbers representing ship's dynamics. It explains the ship's inertia as a ratio of gravitational forces. It is given by:

$$Fn = \frac{V}{\sqrt{gl}}$$ Equation 11

Effective power can be calculated with the total resistance multiplied with the speed of vessel, equation 12.

$$P_E = R_T \cdot V$$ Equation 12

As it can be seen from the above, the total resistance estimation can be quite tedious to assess. The scope of this thesis is not to produce an extensive ship efficiency model, but a model to estimate how much different technique can save from the ship's required propulsion, therefore it is reasonable to use a well-known standard hull model and reclaim it on the environmental impact model. If somebody wants to use the model for a specific ship and he has the total resistance, it is trivial to utilize the model for this.

3 Sail physics

To calculate how much the sails are saving fuel and giving driving force to the vessel, we first need to understand the basic physics of the sails. When calculating the efficiency of a wind turbine we can simply use the equation 13.

$$P = \frac{1}{2} pAv^3 \qquad \text{Equation 13}$$

3.1.1 Physics of the sails

With the sails the case is not quite as simple. As the boat moves from the force of the wind it is altering constantly the forces around it. The sailboats speed is a result of aerodynamic, hydrodynamic, buoyancy and gravity forces. Then again this forces alter from the wind strength, shape of the sails, type of the rig, hull shape, sea conditions and crew’s experience. On the figure 1 these forces and moments they generate are shown. These forces can then be simplified as six equations [3]:

- $Driving\ force\ (F_R) = Water\ resistance\ (R)$
- $Horizontal\ heeling\ force\ (F_{Hlat}) = Horizontal\ side\ force\ (F_{Slat})$
- $Vertical\ aerodynamic\ force\ (F_V) = Vertical\ hydrodynamic\ force\ (F_{VW})$
- $Aerodynamic\ pitching\ moment\ (M_{PA}) = Hydrodynamic\ pitching\ moment\ (M_{PW})$
- $Heeling\ moment\ (M_H) = Righting\ moment\ (M_R)$
- $Areodynamic\ yawing\ moment\ (M_{YM}) = Hydrodynamic\ yawing\ moment\ (M_{YL})$

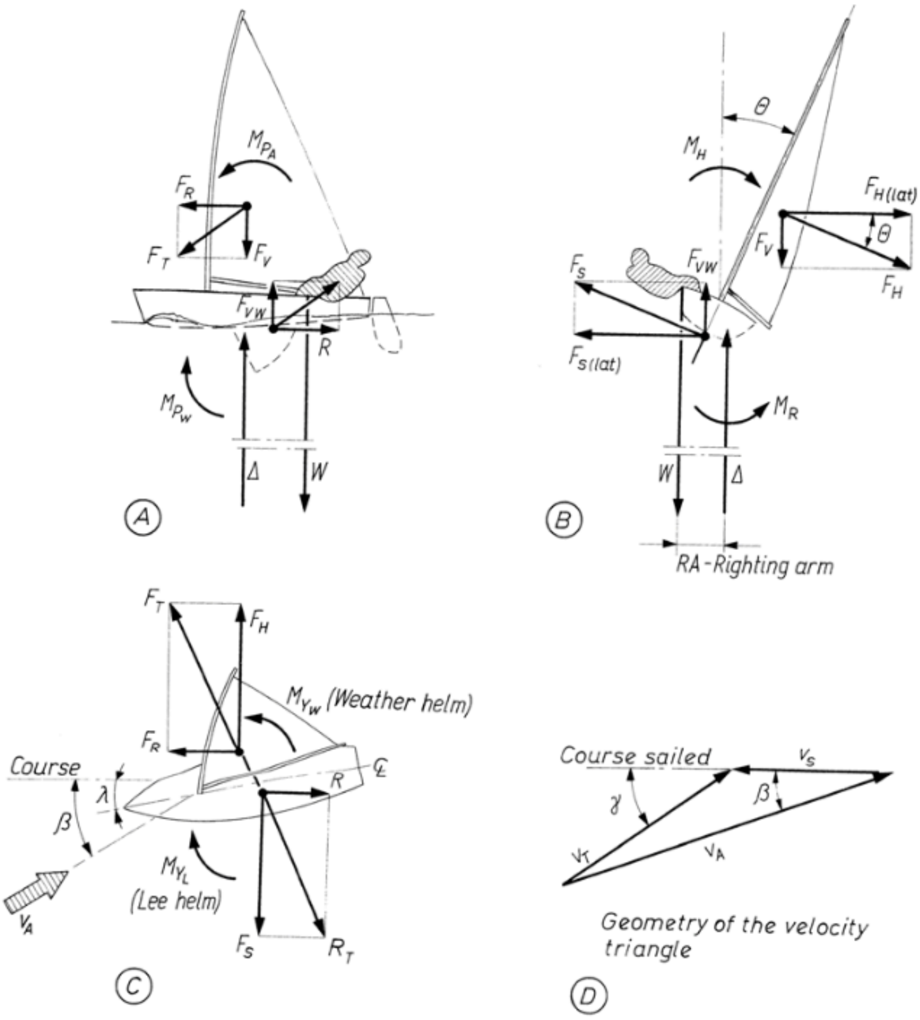

Figure 1 - Forces affecting on a sailboat (adapted from [1])

Then again, these forces are not so easy to determine. The aerodynamic force is especially hard to determine. It depends on the wind velocity, the rig, hull shape and sails used. The aerodynamic force also performs differently reliant on the angle of attack on the sails. Figure 2 shows how the angle of attack affects on the sails. The greater the angle is the closer the sails needs to be drawn, and all the time when the angle increases the sails open accordingly. Depending on the angle of attack, the airfoil acts differently, which affects the calculation of the aerodynamic forces.

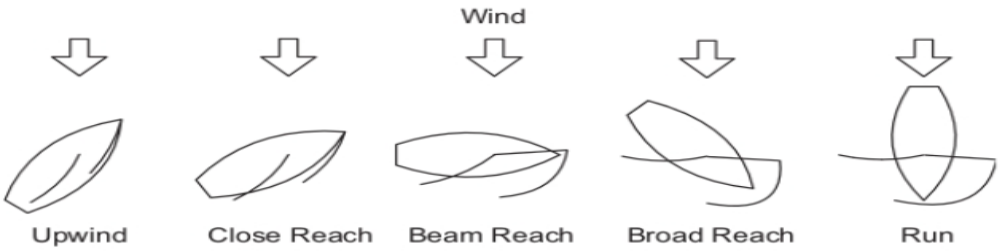

Figure 2 - Angle of attacks (adapted from [2])

The aerodynamic force follows Bernoulli’s principle, which states that due to the camber of the sail the leeward side has a higher velocity then the windward side. This high-speed flow causes a reduction on pressure and a suction comparing to the windward side of the sail as illustrated in the figure 3. The aerodynamic force is then a blend of the suction and pressure. It is possible to estimate the aerodynamic force from the difference between the curves in Figure 3.

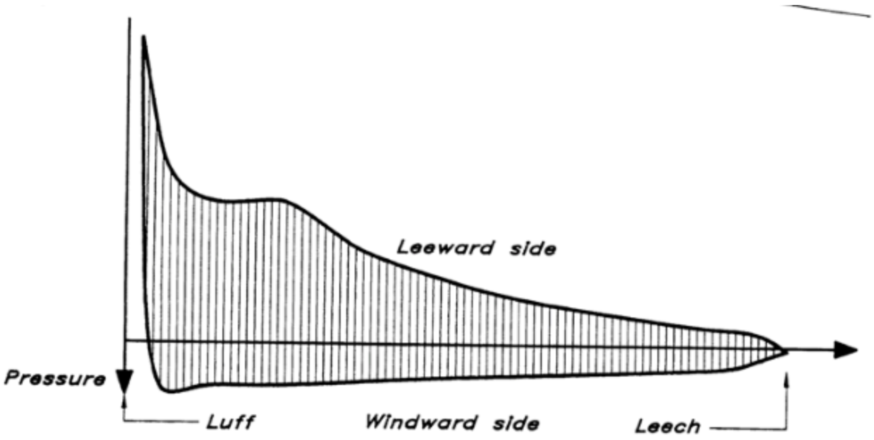

Figure 3 - Pressure differences on the sides of the sail (adapted from [3])

There are two ways to calculate the total aerodynamic force. One focuses on studying only the aerodynamics forces, and the other focuses studying the balance of aero-hydrodynamic forces. This thesis is interested in calculating the possible force given by the sail so that reliable assumptions can be made on how much energy the sails could save. This is why more interest is placed on the total forces effecting on the vessel instead of separating all the forces. If the aim was to study the optimization of the sail, it is clear that much more attention would be paid to the aerodynamic force alone.

When calculating the aero- and hydrodynamic balance the driving force (F_R) and the heeling force (F_H) are needed, and to calculate the forces, the force in lift (L) and drag (D) need to be decomposed. Drag is parallel on the apparent wing (explained later) on the equations singed as a beta) and the lift is perpendicular on these. When the lift and drag has values, finding forces for the driving and heeling is done through equations (14) and (15).

$$F_R = Lsin\beta - Dcos\beta$$ Equation 14

$$F_H = Lcos\beta + Dsin\beta$$ Equation 15

From these two equations the driving force (F_R) is the important one, considering the scope of the thesis. The lift (L) and drag (D) can be determined with the following equations:

$$L = \frac{1}{2} \cdot \rho \cdot {V_A}^2 \cdot A \cdot C_L$$ Equation 16

$$D = \frac{1}{2} \cdot \rho \cdot {V_A}^2 \cdot A \cdot C_D$$ Equation 17

The lift and drag coefficients (C_L and C_D) are usually based on experimental data. These aerodynamic coefficients are the sum of the salvaged energy on the leeward side and the windward side. The coefficients can be greater than 1, which allows the ship to cruise faster than the true wind (v) [4].

In this thesis, as no experimental study was conducted lift and drag coefficients from a book were used. These are based on Brummer's [5] personal velocity prediction program from 1992, which is based on the ORC tables of the lift and drag coefficients.

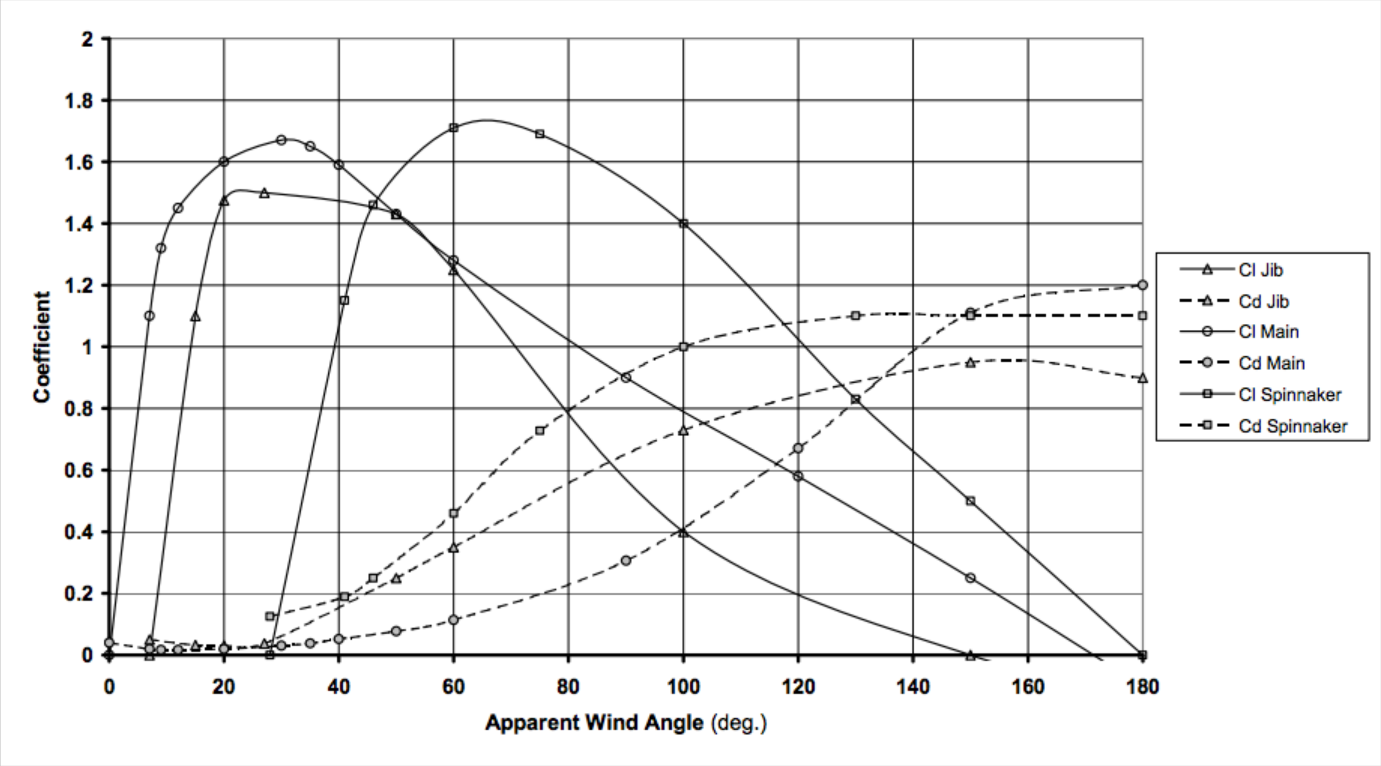

Figure 4 - Coefficient for lift and drag [4]

The aerodynamic efficiency can be assumed from the Lift/Drag ratio. That is why it is important to maximise the lift and minimise the drag. As the wind angle increases, the contribution of the drag to the driving force becomes more important. When the vessel is running to the downwind, the drag is equal to the driving force.

When two or more sails are hosted, the interaction between these sails is not only the sum of their forces. For example, if there is a mainsail and a jib hosted, the jib modifies the suction from the mainsail, which causes the main to lose some of its efficiency, but then again the jib's performance increases. If the crew is skilled, it is possible that the total thrust is going to be more than the sum of each sail.

One of the most important concepts when trying to understand the physics around the sails is the apparent wind. The apparent wind is a mixture of the true wind and the vessels speed. From figure 5 it is possible to see how the apparent wind builds up. It should be also noted how the velocity of the true wind changes when getting higher from the surface.

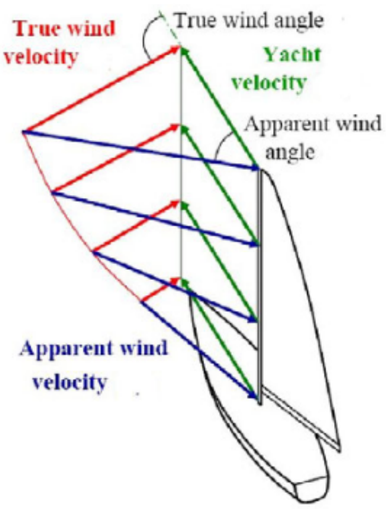

Figure 5 - Apparent wind vectors [5]

3.1.2 Height factor

The change in the true wind due to the height difference can be calculated by using equation (18) & (19), where the z is the height where the wind speed is calculated and Z_0 is the surface roughness factor. The roughness factor can be calculated with the following equation.

$$v(z) = v(z_{ref}) \frac{\ln(\frac{z}{z_0})}{\ln(\frac{z_{ref}}{z_0})} \quad \text{Equation 18}$$

$$z_0 \approx 5\times10^{-5} \frac{v(z_{ref})^2}{g} \quad \text{Equation 19}$$

According to these equations, the true wind changes between the 5 m/s and 20 m/s. This is a difference that has a large impact on the vessels speed. Then again, the equation is generalized and so it does not necessarily give an accurate value.

3.1.3 Apparent wind

The apparent wind angle (β) and speed (V_A) can be calculated by using the following two equations (20) and (21). Lambda is the leeway angle, gamma is the true wind angle and the V is the boat speed.

$$\beta(z) = tan^{-1} \frac{v(z)\sin(\gamma+\lambda)}{v(z)\cos(\gamma+\lambda)+V} - \lambda \quad \text{Equation 20}$$

$$V_A(z) = \sqrt{V^2 + v(z)^2 + 2Vv(z)\cos(\gamma+\lambda)} \quad \text{Equation 21}$$

By getting the values for the apparent wind speed and angle, it quite straight forward to calculate the thrust given by the sail.

4 Available technologies

In the history of naval architecture there has been numerous attempts to preserve fuel. In this chapter some of these technologies are introduced and evaluated in terms of their abilities in reducing fuel consumption.

4.1 Sails on masts

Sails have been the most typical way to travel on the sea for more than 5000 years now. The technology stayed quite unchanged to the modern ages and was dominated by the square sails, which are very efficient for the downwind sailing. These days, boats are required also to perform better on the upwind, which requires a triangle sail to allow a smaller angle of attack. From the 16th century, a large number of new sail types and riggings where developed, these were typically upwind sails like jibs, genoas and riggings, which allowed the use of these sails, like gaff rigging and Bermuda rigging. Bermuda rigging is the most typical type of rigging on the modern sailboats. Another rig type that is offered in large container vessels is called Dynarig (Figure 6). In this system wingliked masts are set behind each other offering large sail area. The systems main advantage is easy handling as the masts rotate and sails stay quite static. Dynarig is also interesting for large ships as the rig type is easy to automate. Dynarig is possible to build with soft sails or as a wing. There are several ship's already operating with Dynarig. Most famous one of these is probably the Maltese Falcon, which is an 88 meters long super yacht built in 2006.

Figure 6 - Dyna rig example [6]

On the modern vessels, sails on masts include both traditional sails (both square and Bermuda rigged ones) and wings, which are solid structures similar to airplanes wings called Dynarigs. There have been a few projects, from the oil crisis at 1970's, where ship's have been either converted or built with sails. In these projects, the typical fuel reduction has been between 27 and 30 percent [6]. There is also a modern project (although only concept) from the STX Europe called *Eoseas* (see Figure 7); it has six sails with a total surface of 12 440 m^2. According to the STX, the sails could reduce the fuel consumption for 50%. The ship would cost 30 percent more than normal cruise ship, but because of the fuel saving, the ship would eventually pay itself back.

There are few other projects going on the moment, which would use sails along with combustion engine. One is the Wallenius & Wilhelmsen logistics (WWL) *E/S Orcelle* vessel, which ambitiously attempts to be a zero emission ship, which does not release any emissions into atmosphere or into the sea. The project was started in 2005 and it is estimated to be ready at 2025 [7].

A sail on the mast is the first and most obvious system to reduce the fuel consumption. It has its potential advantages, which are relatively easy usage and bulletproof reductions on fuel consumption. The potential disadvantages are risk factors from the heeling; on tankers the riggings can cause restrictions on loading/unloading. The system can also be quite hard to convert into an old vessel and even on the new vessels the equipment costs can rise beyond the benefits of the system.

There are a considerable number of different modifications of the system, which are addressed in more detail later in the section 4.7 Hybrid vessels.

Figure 7 - Eoseas cruise vessel [7]

4.2 Flettner rotor

In 1924, Anton Flettner started designing two cylinder shaped “sails” to propel the sailing ship *Buckau*. The Flettner rotor is a cylinder spinning around its own axis by using the Magnus force. Flettner demonstrated the system for the first time in 1928, and at that time it span the propel straight. The system was less efficient than the conventional engines thus, it was not developed further [3].

There are at least two companies developing modern Flettner rotors these days, Enercon in Germany and Norsepower in Finland. Enercon has built a rotor sail ship called E-ship 1. It was launched in 2010, and it has covered more than 170 000 nautical miles. Norsepower’s technology (Figure 8) has been used in a co-operation build by NAPA and VTT (Technical Research Centre of Finland). VTT recorded for a one Flettner rotor a 2.6-percent saving in fuel consumption. Norsepower has estimated that the vessels could achieve an approximately 20-percent saving for vessels running with multiple rotors and in favourable wind conditions. The payback time for this kind of system was estimated to be four years [8].

Figure 8 - Flettner rotor [8]

4.3 Turbosails

Jacques Cousteau, professor Lucien Malavard and Dr. Bertrand Charrier introduced Turbosails in the 1980’s. The working mechanism was based on the Savonius principle. It was a hollow cylinder that had holes, which let the air to enter and escape. The sails also had a fan, which was run by an engine, on top of them to accelerate the wind velocity and this way give more propulsion [3].

The system was tested on a ship called *Alcyone*, but it was found out that the system did not work efficiently enough to make sense. It also has other drawbacks such as, need for a large area on the deck, price of the system compared to other systems and low efficiency [3].

4.4 Kites

Kites are probably the easiest system to add on an old cargo vessel. They are flown at height of 100 to 300 meters, where there are higher wind velocities (see section 3), which allow the kite to be 25 times more efficient than a conventional sail. Kites also require less space on board as no mast nor any reinforcements on the hull are needed. Modern kites have an automatic operation system, which makes them easy to handle and reliable. Also, because the propulsion is typically almost straightforward, no heeling occurs and that is why there is no need for a ballast system. A kite system is affordable compared to other systems, and it has much larger efficiency. The system is offered by at least two commercial suppliers on cargo ship scale, Germany-based SkySails and United States-based Kiteship [3].

Skysail has installed systems working although most of them are for R&D use. They claim that the kite provides from 10 to 15 percent annual savings in the fuel cost in average [9]. This obviously depends heavily on the size of the boat and wind conditions. Skysail is developing a 640 m^2 kite, which, according to the SSPA, could pull a Panamax sized tanker at speed of 8 m/s. If they succeed the kite could provide a 100 percent savings on fuel costs [10].

The system clearly has a lot of potential and numerous positive features. Still, there are some disadvantages this system as well, which has prevented the system from spreading to wider use. First of all, kites cannot be used in low winds, because this could lead to the kite falling in front of the ship, which would cause damage so expensive that the savings made from the kite would never cover those. Another disadvantage is that the kites can be flown only on the downwind. Furthermore, kites cannot be used in areas with dense ship traffic as it makes all the fast manoeuvres harder or impossible to accomplish, which is a clear safety risk [3].

4.5 Structural propulsion unit

There exist only few examples of the structural wing systems. One is the EU's CargoXpress project, and the other project is a design of a Norwegian ship builder Lade AS, which uses the hull as a sail.

These two projects have a very different approach to the subject. CargoXpress is a solid wing that is similar to a traditional sail; it can be lowered if the sail conditions are not favourable and give propulsion power very similarly to a sail on a mast. The Lade AS is a company established to develop the Vindskip vessel, which uses a symmetrical airfoil hull to generate a lift and give a driving force.

The CargoXpress project claims that they could provide 45 percent of the required propulsion force needed when driving at 15 knots. Figure 9 below shows how the force need evolves when ship's speed grows.

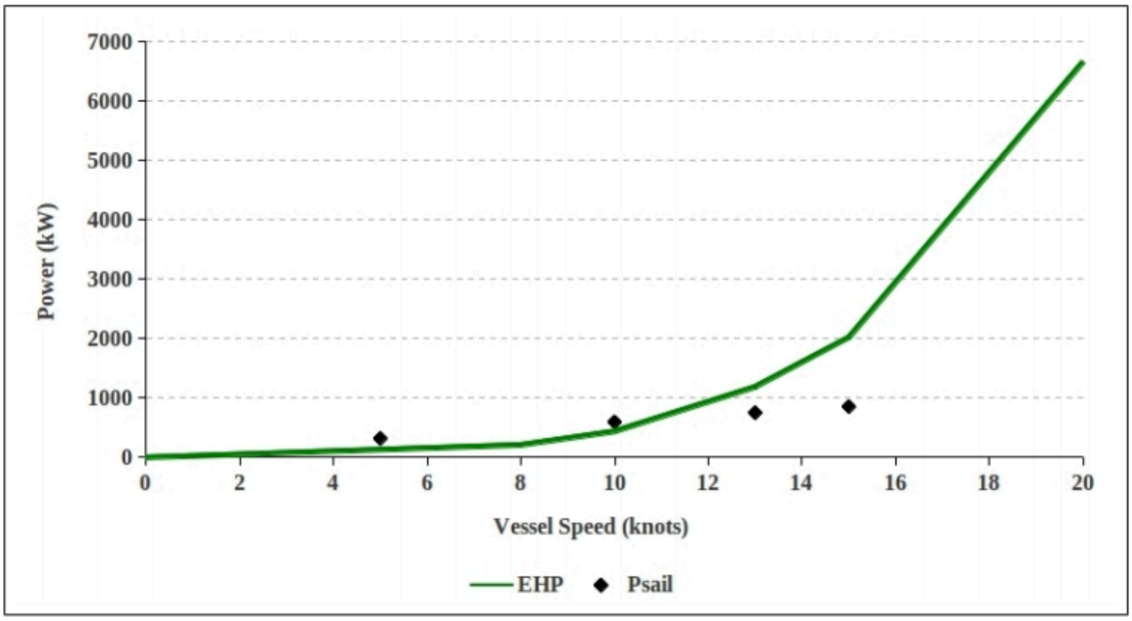

Figure 9 - Ship speed effect on the propulsion needed [9]

Vindskip is claimed to be able to save 60 percent of the needed fuel, but this includes all the savings from the concept ship when compared to a reference ship. Lade AS claims that the technology enables the ship to go as high as 18 degrees into wind.

4.6 Solar Power

Solar power would work as an auxiliary power source for the cargo ships. This would be done by inserting solar panels on the surface of the vessel and through that receiving electricity, which then could be used to drive the electrical engine. In big tankers there is enough surface area for the panels to be installed. There has been at least one ship using this technology. M/V Auriga Leader is a cargo boat owned by Toyota and designed as a joint project by Nippon Yusen Kaisha (NYK). It is used for shipping cars from Tokyo to California. After seven months of running, the panels had produced 32 300 kWh of electricity, which covered 0,5 percent of the propulsion need and 1 % of the electricity need. This saved 13 tons of fuel and 40 tons of CO_2 emissions [11].

The disadvantages of the system are that it produces quite little of the required power and, as NYK found, out it is difficult to produce a stable power supply as even the slightest changes in the weather cause a large influence on the power output. Also increasing the number of panels would cause problems with the variations in the power supply [11].

4.7 Hybrid vessels

A hybrid vessel is a boat that utilises two or more of the above techniques. This usually means wind and solar power and some kind of backup system. In the sails on the masts section STX's project ship Eoseas was introduced. It is a good example of a hybrid vessel as well. It is designed to have 8 300 m^2 of solar panels on board, which would provide a maximum of 108 MW. It would also harness wind power with its five masts and 12 440 m^2 sail area. Also there is a gasification system on board to collect the syn gas from the organic waste.

Eoseas have tons of other innovative systems in it (e.g. hull shape, propellers, and air lubrication). With them the ship is claimed to be able to reduce CO_2 emissions by 50 percent, SO_2 by 100 percent, NOx by 90 percent and ash by 100 percent.

The Eoseas is only a concept ship and it is unlikely that it will ever be build. There are also examples that are already operating. Ocius is an Australian naval design company that has built a solar sail ferry. One of these ferries has been operating in Hong Kong from 2009. Company claims that the hybrid vessel could cut 50 percent from the fuel consumption.

4.8 Conclusion

The above literature review suggests some technologies clearly have more potential than others. On the basis of the assumptions of the potential, only few technologies were selected for the closer assessment for the environmental impact assessment. The selected technologies are sails on mast, Flettner rotors and kites. Although the structural wing and airfoil hull are both interesting and both technologies clearly have strong potential, it was felt that these technologies are not stand-alone systems, instead their fuel savings involves many factors. Also because both of these projects have been studied closely, it was felt that the model made for the assessment would not give any new information.

As to solar power, hybrid vessels and turbosails, it was decided that these technologies did not have enough potential at the moment.

5 Environmental impact assessment for different techniques

In this chapter a model is built for evaluating the possible saves earlier mentioned techniques could create.

5.1 Methods

This section explains the formulas used to calculate the propulsive force received from the each technique.

5.1.1 Sails on the mast

Sails have been the most common way to give the propulsive force in the nautical history. When the requirements for the more accurate shipping started to increase after the 1900 century, the sails started to lose their position for the fuel-powered engines. Now because of the climate change usage of sails have been suggested to lower the emissions of the shipping. The main system offered on the container ship is the Dynarig type, which was presented in more detail in section 4.1.

Lift (L) and drag (D) were calculated in the same manner as explained in section 3.1, and the formulas are given below for practicality. The apparent wind speed is basing on the wind data, which is explained in more detail below. The lift and drag coefficients were based on the Brummer's [5] personal files, and, as explained above, they are based on ORC formulas and wind tunnel tests. Unlike with the Flettner and kite systems, the coefficients change constantly depending on the apparent wind velocity and angle.

The ship's mast was decided to be a 40 meters tall and the beam was 13 meters. This gave a total 614 m^2 sail area.

$$L = 0{,}5 \cdot \rho \cdot {V_A}^2 \cdot A \cdot C_L \qquad \text{Equation 16}$$

$$D = 0{,}5 \cdot \rho \cdot {V_A}^2 \cdot A \cdot C_D \qquad \text{Equation 17}$$

$$F_R = Lsin\beta - Dcos\beta \qquad \text{Equation 14}$$

$$F_H = Lcos\beta + Dsin\beta \qquad \text{Equation 15}$$

The total propulsive power is the driving force multiplied with the ship's speed:

$$P = F_R * V_{ship}$$ Equation 22

5.1.2 Kite

The kite auxiliary propulsion system is maybe the easiest to install on any vessel. It does not take any deck space and the systems provided by some companies are fully automatic. Because the kite is flying at a higher altitude, it has higher wind velocities. Also, because the kite is continuously moving by itself, it creates, a stronger apparent wind around it, increasing the efficiency even further. It is assumed that the kite is released only when the wind conditions are suitable.

The lift and drag were calculated in the same way as explained in the previous section, using equations (22) and (23), respectively. The lift and drag coefficients were based on the Traut et al. [12], and they were 1.0 for lift (C_L) and 0.268 for the drag (C_D). In this study a 1.2 lift coefficient was used based on the coefficients received from Brummer [5]. The driving force and the heeling force are received from the equations (14) and (15), and the total propulsive force was calculated in the same way as that for the sails. The size of the kite is selected accordingly to the size of the ship. In this thesis the reference ship was heavy and large, so the kite was selected to be as large as possible as well. The largest kite Skysail offers is 320 m^2.

5.1.3 Flettner rotor

Flettner rotor is raising its head decades after its invention; at least two companies are offering the system for container vessels. Norsepower, which is one of the modern developers of Flettner rotor systems, has assumed that on Flettner rotor could provide a 2,6 percentage of the needed propulsion. An advantage of on the Flettner system is that it is possible to add several rotors in one boat, lifting the propulsion power all the way up to 20 percent, but this is obviously very dependable to the ship characteristics [8].

All the results on this study are calculated on a single rotor. For evaluating the lift and drag coefficients and for other background information, study from Traut et al. [12] used a lift coefficient (C_L) of 12.5 and a drag coefficient of 0.2 (C_D). In this thesis the lift coefficient was selected to be only 8 because in this way the results where closer the ones provided by the Norsepower. The power consumed by the motor spinning the rotor (P_m), was calculated with the equation below. The moment coefficient (C_M) was based on subjective evidence and on studies at the university of Manchester. The alpha represents a spin ratio, which is the ratio of the surface speed of the rotor and the apparent wind, in this thesis, the value was been borrowed from Traut et al. The area was the cross sectional area of a Flettner rotor which is a straight cylinder-shaped object. As a reference, it was decided to use Norsepower's rotor, which they have installed to an almost similar ship. This rotor is 18 metres tall and 3 metres in diameter, which gives a 54 m^2 on a cross sectional area.

$$P_m = 0{,}5 \cdot \rho \cdot {V_A}^3 \cdot A \cdot C_M \cdot \alpha \qquad \text{Equation 23}$$

The propulsive force is perpendicular to the ship's speed, which can be seen from the equation below. The total received propulsive force is then just the difference between the propulsive force and the power consumed by the motor.

$$P_{l\&d} = (l + d) \cdot V \qquad \text{Equation 24}$$

$$P_{prop.} = P_{l\&d} - P_M \qquad \text{Equation 25}$$

When the propulsive drive is negative, it is assumed that the rotor is turned off. Also, when the rotor exceeds 250 kN on the combined lift and drag force, it is calculated that the power production is kept at a constant level.

5.2 Wind data

For the wind data, Vortex's open wind maps where used (figure 10). They give reliable wind estimation for the average wind speed annually on the area. It was measured with Google's Earth program to see how long each wind speed section where and the trip was distributed by these sections. After that the wind speed was distributed by using the Rayleigh's method to get an assessment how much wind resources there are annually in the area. The wind speed was also multiplied with the height factor according to technique. For Flettner it was 30 meters, for kite 130 meters and for sails on mast also 30 meters.

Unfortunately, the data did not include anything form the wind directions thus, it was decided that three different set angles would be used to calculate the apparent winds.

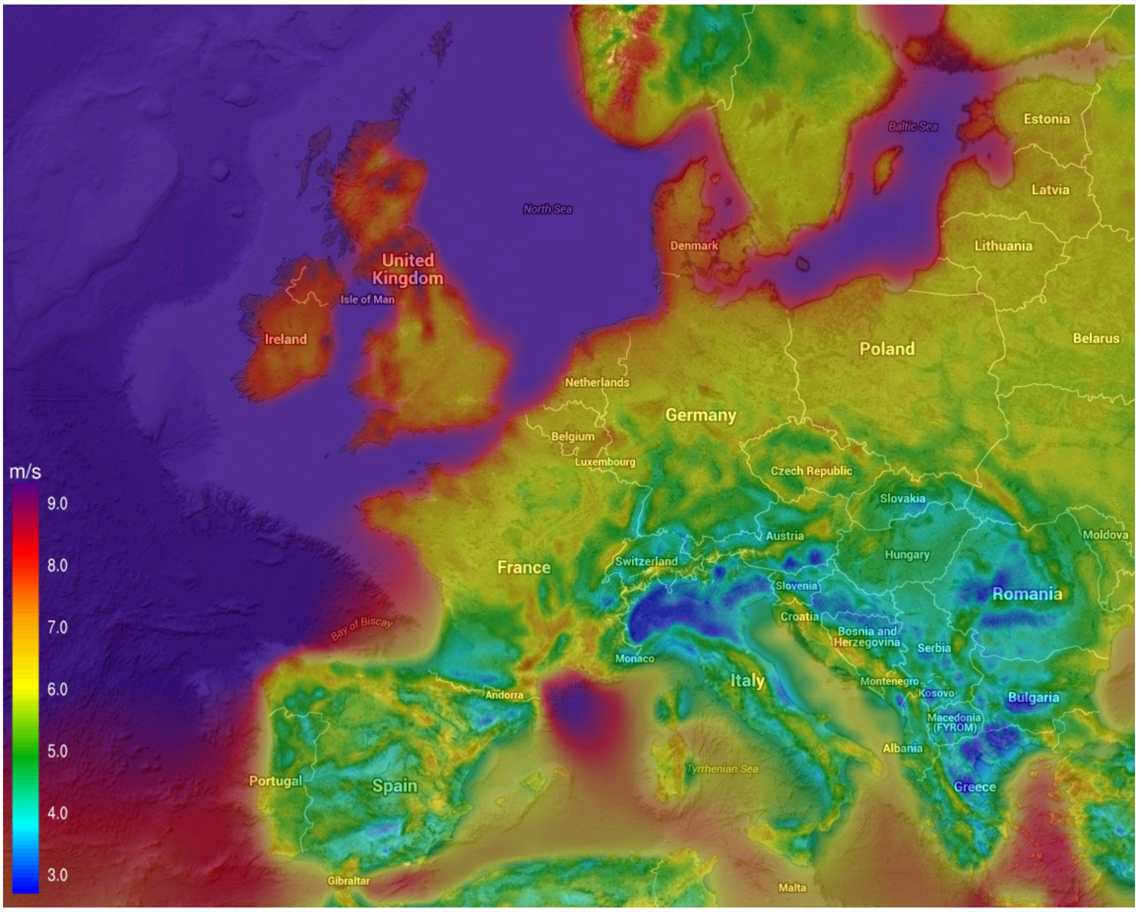

Figure 10 - Average annual wind speeds [10]

5.3 Ship

The reference ship used in this thesis is from the University of Michigan a 600-footer ship, which has 18 544 dead weight tons (DWT) as loaded [13]. The characteristic of the rise of the propulsion need against the vessels speed can be seen in Figure 11.

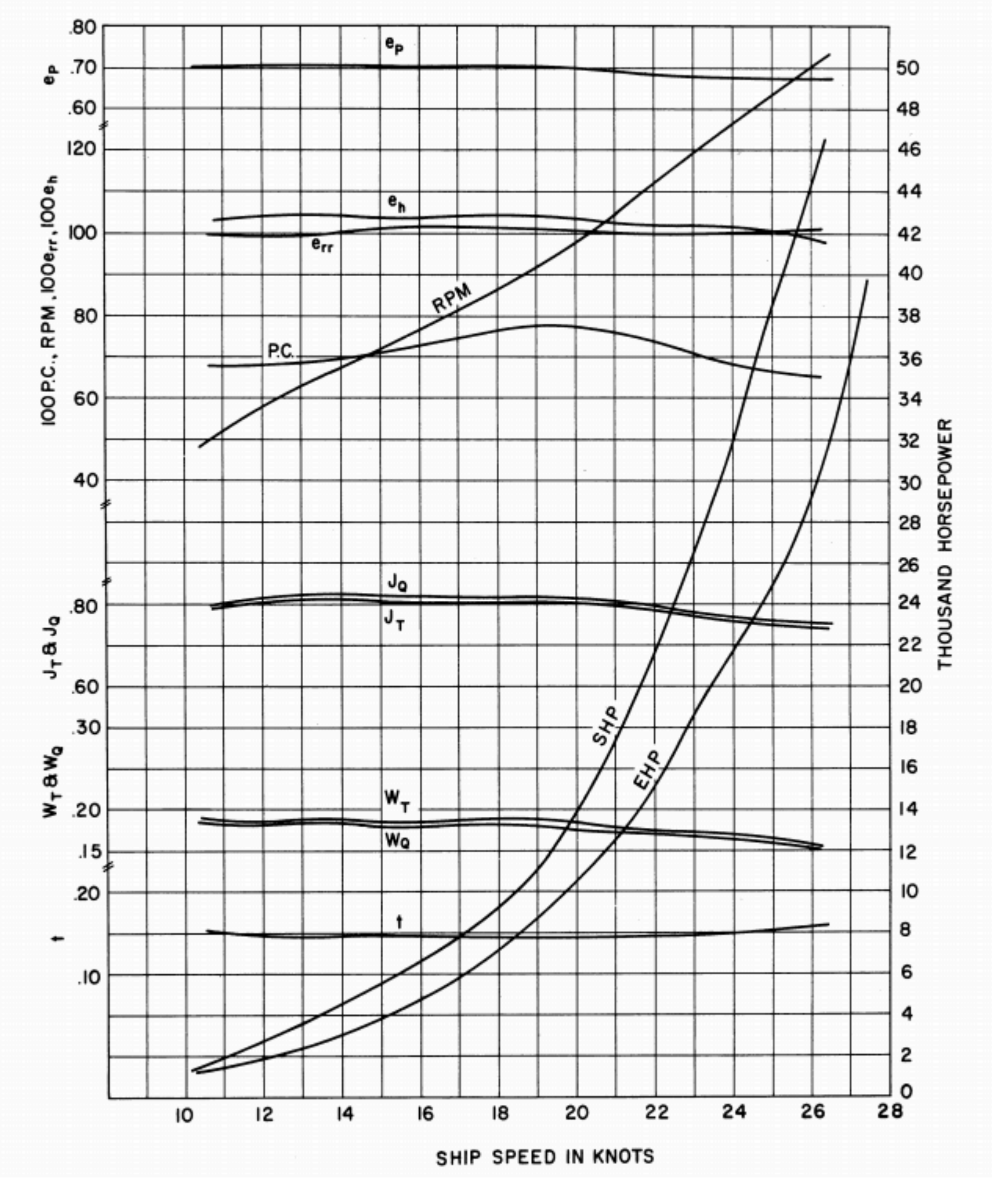

Figure 11 - Ship resistance characteristics [11]

5.4 Routes

Both of the routes where calculated by using the Marine-Traffics voyage planner (marinetraffic.com). These routes are the shortest routes between the ports and they do not include any optimization according to wind conditions. Ship is calculated to go at a constant speed of 12 knots, which equals to 22.3 km/h.

5.4.1 Route 1: Helsinki - Rostock

The nautical distance between Helsinki and Rostock is 1 087 km, which means total 134 MW hours of propulsion power need on the example ship. This equals close to 26 t of marine diesel.

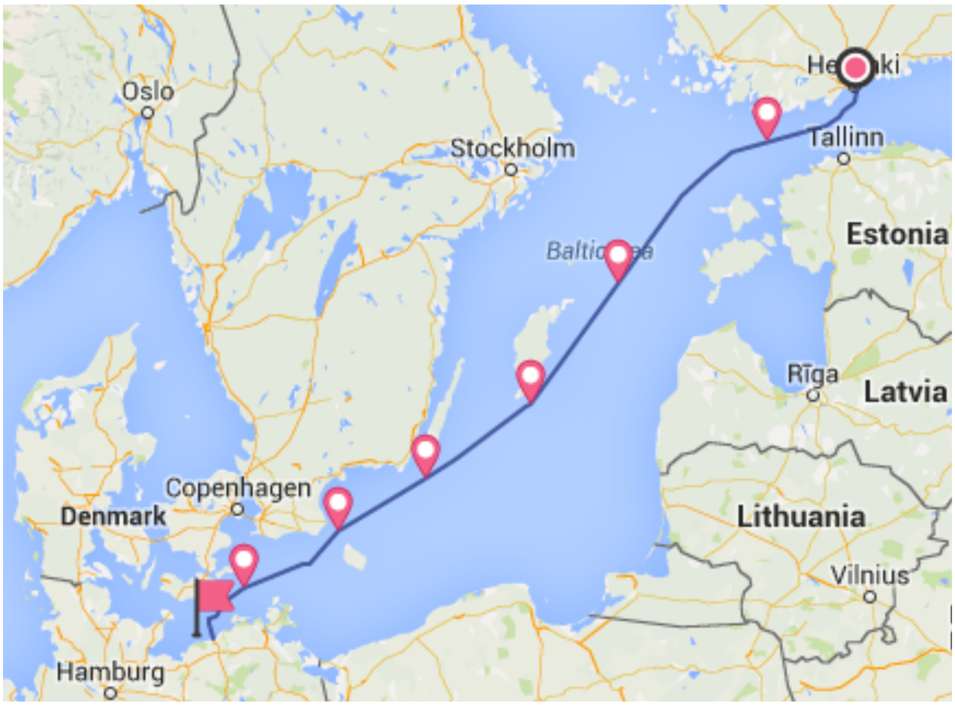

Figure 12 - Route 1 [12]

5.4.2 Route 2: London – Marseille

The route between the London and Marseille is 3 861 km long. This equals to 480 MW hours of propulsion power, which equals to total 101 t of fuel.

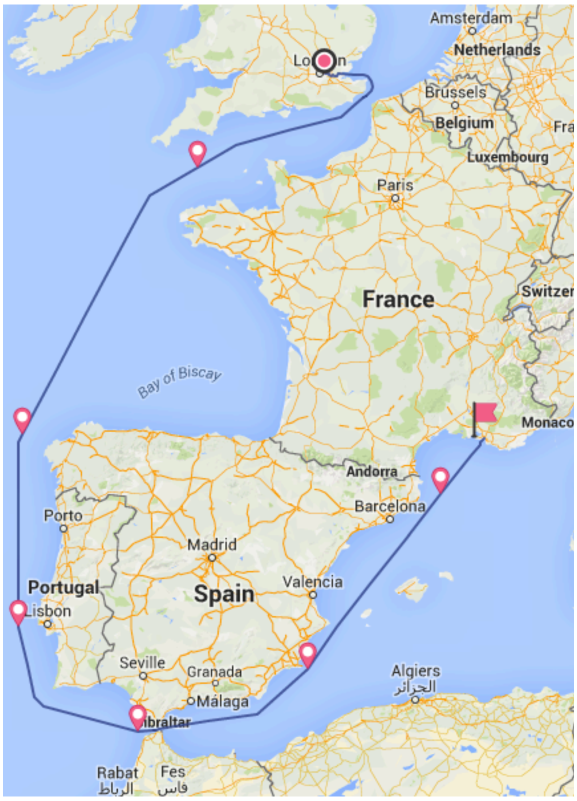

Figure 13 - Route 2 [12]

5.5 Results

The thesis focused on the environmental impacts that the engine is creating when fuel is combusted. The propulsive power needed to move ship at constant speed was compared to the amount of power that is possible to produce with the auxiliary system. From this it was calculated how much fuel would saved and through this could be concluded how much emissions would be saved. The ship speed was kept constant at 6,2 m/s (12 knots), and all the systems were measured for a single device. As to Dynarig and Flettner, it is likely that there is more than one device providing propulsion. In Flettner this means more rotors, and in the Dynarig systems this would mean more masts. Each addition provides close to 100 percent more propulsion.

There are large differences between the systems when comparing conditions where propulsion power is produced. The kite is very sensitive on the wind angle and velocity, but in ideal conditions it can be very effective. Flettner rotor then again is working in wide variety of wind angles and velocities. Dynarig is between these two.

On the first route from the Helsinki to Rostock, Flettner rotor would provide the largest share of the needed propulsion as can be seen from table 4. Both Dynarig and kite would also provide large savings on certain wind conditions, but Flettner would provide steady propulsion throughout the trip.

Table 4 - Route 1 results

Helsinki-Rostock	Flettner	Kite	Dyna	Demand
Propulsion (MWh)	10,08	7,66	9,08	134,4
Rate	7,50%	5,70%	6,76%	100%
Fuel need (kg)	23 618	24 078	23 808	25 533
Fuel saved (kg)	1 915	1 456	1 725	

In the Table 6, these fuel saves are given as the saved emissions. The values are based on a study performed at technical university of Denmark [14]. The emissions amounts are based on a tier 1 engine that is running only on marine diesel.

Table 5 - Route 1 emission cuts

	CO_2 saved	SO_2 saved	NOx Saved	CO saved	HC saved	PM saved
	In kg					
Flettner	6 139	40,2	121,0	5,0	5,0	4,4
Kite	4 667	30,6	92,0	3,8	3,8	3,3
Dyna	5 532	36,2	109,0	4,5	4,5	4,0

In the second route, the results are almost equal to those of the first route, mainly because of the scarcity of the wind data. Similarly, the Flettner rotor is the most efficient system, while the kite remains the least efficient, mainly suffering from the numerical method.

Table 6 - Route 2 results

London-Marseille	Flettner	Kite	Dyna	Demand
Propulsion (MWh)	35,5	26,5	31,93	479,7
Rate	7,40%	5,53%	6,66%	100%
Fuel need (kg)	84 393	86 098	85 075	91 141
Fuel saved (kg)	6 748	5 043	6 066	

Table 7 - Route 2 emission cuts

	CO_2 saved	SO_2 saved	NOx Saved	CO saved	HC saved	PM saved
	In kg					
Flettner	21 634	141,7	426,5	17,7	17,7	15,5
Kite	16 168	105,9	318,7	13,3	13,3	11,6
Dyna	19 448	127,4	383,4	16,0	16,0	14,0

For the fuel consumption a value of 190 kg/MWh was used [14]. This value includes all the efficiency losses of engines and possible other losses and it is based on a measured value. The fuel price was checked on the 12th of August. In the Table 8 it is possible to see how much these technologies could save in fuel costs on a one-way trip [15].

Table 8 - Money saved in us Dollars per one-way trip

	Flettner	Kite	Dyna
Route 1	982,38	746,71	885,17
Route 2	3 461,72	2 587,05	3 111,86

For providing a wider perspective to these results, a comparison in terms of propulsion power against ship's speed was also done. In the Figure 14 the ship resistance is on the primary axis on the left, and the propulsion received from each system is on the right axis in mega Watts as well. Figure 14 demonstrates that the kite is actually providing the largest propulsion when the conditions are ideal, but because in the reality the wind is not usually blowing from the perfect angle, the Flettner rotor is providing more stable propulsion, due to the flexibility on the wind angle.

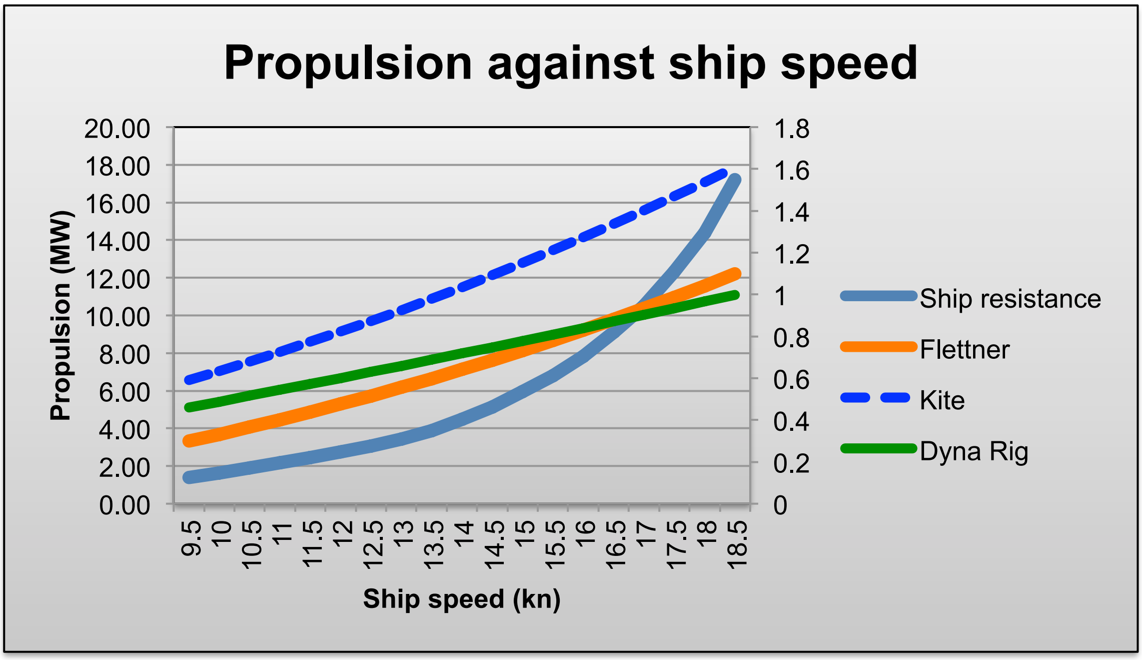

Figure 14 - Propulsive power against ship speed

5.6 Sensitivity analysis

The biggest factor leading to unrealistic results is the scarcity of the wind data. Wind speeds are easily available, but because the typical wind angles are unknown, production was calculated by using three different angles and from these an average production was provided. Also, all the seasonal variation from the winds is missing. The results give the average propulsion per year, but to get more realistic results, these should be divided with the probability of supposed wind conditions. These factors also explain why the results from the two different routes where so identical.

To simplify the model, the propulsion was calculated for only one ship speed and for only one ship type. Also, none of the systems has a cut out region, which means that if the wind velocity would go to infinity; the power produced would as well go to infinity (if the propulsion was negative, this was naturally concluded as zero).

Assumptions were made with the technological setup, such as the sizes of the devices, no downtimes and the coefficients are selected with the best available information. The results are plausible, but because it is a simplified model, they are still at best only approximates.

6 Conclusion

The auxiliary propulsion device systems where modelled by a numerical method, which give an approximation to how much fuel the selected systems could save. There is a growing demand for technical solutions that could help to lower emissions in shipping, which causes a total three percent of all carbon dioxide equivalent emissions globally. None of the presented systems are able to provide the whole required propulsion, but even though the partition is relevantly small, the savings on the fuel costs pay itself back in a couple of years.

It is also notable that the legislation is likely to get even stricter. Even stricter legislation will lead to a point where shipping companies do not have any alternatives, but to adapt these technologies. EU has set targets that in 2050 the shipping industry emissions should be cut by at least 40 percent. The presented technologies in this study could help achieving these targets, if not yet making the shipping to go 100 percent green, but still giving a significant reductions in fuel consumption. The oil price is also assumed to rise; this will shorten the payback time of the systems even further.

The area is raising interest in both shipping yards as well on the global research society. Now it seems to still be at a data collection stage and nothing suggests that the industry would see a rapid change in the coming decade. Nevertheless, there are numerous projects underway, and if these projects show potential, it is highly possible that the modern ship’s will be using wind propulsion mechanisms to give an auxiliary propulsion to turn the shipping industry one step greener.

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14 Ship propulsion against the ship speed

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4 Route 1 results

5 Route 1 emission cuts

6 Route 2 results

7 Route 2 emission cuts

8 Money saved in us Dollars per one-way trip

Appendix 1. Propulsion against ship speed