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A sustainable marine transport sector

Project report in the course TRA105 Emissions from Transportation

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A SUSTAINABLE MARINE TRANSPORT SECTOR
Project report in Emissions from Transportation
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Abstract

In today's highly globalised world, marine transport accounts for an important mode of travel as well as a key means of enabling transcontinental trade. There is an urgent need for a shift towards a more sustainable marine sector as the demand for at sea transport and shipping increases annually with rising levels of harmful emissions as a result. Moreover, the future of the fossil fuels currently employed for marine vessel propulsion is most unclear. The widely used Heavy Fuel Oil might become subject to highly volatile pricing as the global market moves towards reducing its fossil dependence. Also, stricter emission norms intended to bring the marine transport sector closer to the legislative levels already developed in land-based transportation are to be expected. This report introduces and discusses a selection of emissions-reducing measures which could contribute to a more sustainable marine transport sector, namely, biofuels, solar panels and electrification, hydrogen, fuel cells, methanol, speed reductions and wind power. Ultimately, wind power is chosen as a final suggestion with respect to lowering marine emissions. Wind is a free, renewable, and abundant form of energy especially suitable for marine transport and its extraction for marine vessel propulsion does not induce resource scarcity in other sectors. Biofuels are more expensive than the current fuels in use and pose environmental and ethical dilemmas related to land use change with the potential of creating distributional conflicts. When compared to other options, fully wind powered ships have the unparalleled benefit of zero emissions in theory. In contrast to solar power, wind power alone is sufficient for vessel propulsion although there is need for alternative methods if the wind direction and magnitude does not meet the requirements. Electric vessels struggle with low energy density in batteries and a complete lack of charging infrastructure, only permitting shorter voyages inadequate for meeting the demand for worldwide transport. Hydrogen fuels cause a considerable loss of usable shipping volume, and thus profit, due to its low volumetric density. Finally, from a stakeholder perspective it is argued that although initial investments may be high due to re-equipping or replacing of ships, wind power is a viable economic solution long-term as the "fuel" is inherently abundant and free. Also, a zero-emissions option like wind power is likely to be favourable in the eyes of authorities which are able to introduce policy instruments supporting the transition to a wind-powered marine future.

Key words: Marine transport, Shipping, Emissions reduction, Pollution, Sustainable transportation.

Table of contents

List of Figures

List of Tables

1. Introduction

Shipping and marine transport has played a key role historically. From Christopher Columbus's discovery of America to serving nations' defense forces during World War 2, ships have taken a prominent place in development. With the growth of transcontinental trade, marine transport has proven the most economical among all means of transport with as much 37% of the internal trades within EU and approximately 75% of the international trade carried out by EU taking place by means of marine transportation [1]. Due to an increasing demand, marine transport is also growing at a rate of 3.5% every year [2]. A direct result of this is the rise in emissions from the shipping industry. The emissions from ship operation can be divided into waterborne and airborne as presented in Table 1 [3]. The emissions from individual ships depend on the type of vessel and the fuel used.

Table 1. Emissions from shipping.

Discharges to the sea		Emissions to the air
– Antifouling paint	– Solid waste	– CO_2
– Noise	– Grey water	– SO_x
– Invasive species	– Sewage	– PM
– Bilge water	– Ballast water	– VOC
– Oil spills	– Cargo hold cleaning water	– NO_x

The ships mainly use a low speed two-stroke engine and some use four stroke medium speed engines with average power ranging between 7200 kW to 19200 kW [4]. The main emissions from these would be the SO_x and NO_x along with CO_2. Selective Catalytic Reduction (SCR) is used to reduce the NO_x emission to N_2, O_2 and H_2O [5]. Ammonia is sprayed on the exhaust gas in the presence of a catalyst which leads to reduction reaction thereby eliminating major part of NO_x emission. Likewise, SO_2 emission is countered by means of scrubbers. Exhaust gas is passed into a scrubber within which an alkaline material is used to remove any particulate matter and neutralize the acidic exhaust gasses. This scrubbing material is stored or disposed as the effluent along with wash water. The cleaned exhaust is passed out of the system and into the atmosphere [6].

The sea is to a great extent an international area governed by the Law of the Sea under the United Nations Organization (UNO) [7]. Monitoring and regulation of this becomes a hard task given any disputes must go through the International Court of Justice [8]. As of 2020, emissions from land-based sources are given more importance than those from shipping [9]. Given the stringent regulations implemented on land-based transport, regulating the marine sector can be expected to gain more importance ahead [10].

Given the current regulations and the relatively low price, a majority of ships use Heavy Fuel Oil (HFO) [1], thereby producing high amounts of pollutants. In attempts to reduce pollution from shipping, the International Maritime Organization (IMO) adopted The International Convention for the Prevention of Pollution from Ships (MARPOL) with six annexes added between 1983 to 2005 [11]. The ban on use of HFO in Antarctic waters was implemented by IMO in 2011 and by July 2024 the same intends to be implemented in the Arctic region [12]. The SO_x emissions are regulated by means of Sulphur content in the fuel. In a Sulphur Emission Control Area (SECA) the Sulphur content in the fuel must comply to a maximum limit of 0.1% from Jan 2020 [13]. Outside the SECA, IMO limits the Sulphur content in the fuel to 0.5% mass of Sulphur per mass of fuel [13].

Given that shipping industry's share of global CO_2 emissions is expected to rise from 3 to 25% by 2050 [14], the demand for alternative sources to power marine vessels will rise. IMO has set a target of 50% reduction in CO_2 by 2050 as compared to the emission in 2008 [15]. Environmental, technological, economic, and regulatory factors are all contributing to the need for a transition of the marine transport sector where sustainable energy systems need to be deployed in marine vessels.

2. Literature review: Emission reduction in marine transport

There is an urgent need for change if the marine transport sector wants to avoid falling behind other sectors now rushing for sustainable solutions. The following section describes possible solutions for a reduced amount of emissions in marine transport with major focus on reduction of GHG.

2.1 Biofuels

In an article by Bouman et al. [3] potential CO_2 reducing measures are reviewed across approximately 150 studies focused on the shipping industry. The authors estimate that using an alternative fuel made from biomass results in the largest individual reduction potential, ranging between 25–84%, out of all the reviewed measures. A reduction of GHG emissions is accomplished by the “carbon neutral” characteristics of the biofuel’s components [16]. The concept of carbon neutrality is based on the idea that the amount of CO_2 emitted to the atmosphere during combustion is equal to the amount sequestrated by photosynthesis of the original plant [16].

Bouman et al. [3] provide two explanations as to why studies exhibit such a large variety with respect to the reduction potential of biofuels. Firstly, biofuels can be produced from many different types of feedstock (e.g. corn, sugarcane, or vegetable oil) which also vary internally in terms of quality. Each feedstock type requires a specific processing technique (e.g. fermentation of sugarcane to produce bioethanol, or esterification of rapeseed oil to produce biodiesel), resulting in different levels of environmental impact. Secondly, the reduction potential of a bio-derived fuel is affected by cultivation practices involved when producing feedstock from food crops, resulting in so-called first generation biofuels. The rotation scheme and location of the source crop as well as changes in albedo due to harvesting determine whether the feedstock really can be viewed as carbon neutral or not [3]. Change of crop or rotation in a given land results in change in the amount of radiation reflected back which accounts to variation in albedo.

Speaking in favour of an introduction of biofuels in the shipping industry is the technology’s high readiness level, as first generation biofuels are already being used in land-based transportation [17]. However, first generation biofuels are subject to controversy [16] as they contribute to for instance soil carbon loss [18], eutrophication [19], biodiversity loss [20] and an increased competition over scarce land [3] as a result of land use change. Moreover, as the price of biofuels is yet to reach the low cost of more traditional ship fuels, implementation in the marine sector has so far been limited [17].

There might be a potential of second or third generation biofuels to resolve some of the issues associated with the first generation. Second generation biofuels can be produced from crop by-products or forest residues, which do not necessarily compete with food crops over arable land. Third generation biofuels are produced using algae which do not even require soil to be cultivated, hence, issues related to land conversion could be completely resolved using this technology. However, the later generations of biofuels face other issues (algae cultivation, for instance, requires large amounts of fertiliser) and, more importantly, have not yet been implemented on a large commercial scale.

2.2 Solar panels

The thought of utilizing solar panels as a renewable source of electricity to propel a large marine vessel is intriguing, but there are several aspects that must be considered before implementation. One big challenge facing large scale deployment of solar panels on commercial ships is the low photovoltaic effectiveness of the cells [21] and the lack of available space for installation [22]. For instance, if the entire surface area of the Stena Danica (measuring 154.9 m long and 28.5 m wide [23]) was available to be covered in solar panels, providing 212 W/m^2 of power [24], this would result in a total power generation of roughly 936 kW. Compared to the four CCM Sulzer engines onboard the Stena Danica, which produce 25 663 kW [23], solar panels would only provide 3.65% of the power required to propel the ship.

Even if a ship cannot be propelled entirely by solar panels, they can still provide enough electricity to cover parts of the auxiliary energy demand [25] and thus lower the fuel consumption, and subsequently the emissions. Nichioh Maru for example uses solar panels for electricity production and has resulted in 4200 tonnes annual CO_2 reduction and 1400 tonnes of fuel savings[26]. For a Japanese car carrier, onboard energy generation through the use of solar panels corresponds to a 0.2-12% reduction of CO_2 emissions, and a wind-solar hybrid combination could increase fuel savings by 10-40% [25]. However, module degradation accounts to 1% while dust and salt losses make up 2% and 2.5% losses are caused due to reflection and other electrical losses correspond to 4% of total losses [22], further reducing the effectiveness of solar panel implementation. Moreover, the cost of solar panels and the break-even point of the investment is still high, and discourage most companies from widespread implementation [27].

2.3 Electrification

While a large-scale solar solution has not yet been proven practical, the electrification of ferries has been under development with a few already in operation. The car and passenger fully electric ferry named Ellen that travels between Ærø to Als is equipped with a 4300 kWh battery, has a total range of 21.4 nautical miles and is estimated to annually reduce CO_2 emissions by 2000 tonnes, NO_X by 41.5 tonnes and SO_2 by 1.35 tons [28]. Ellen's electric powertrain also has a higher energy efficiency of 85% measured from grid to propeller, and has over twice the efficiency compared to a conventional diesel-powered ferry measured from tank to propeller [29]. Electrification offers significant noise reduction as well as lowers operating costs [30].

Electrification comes with its drawbacks where the main challenges are the low energy density of current battery technology which prohibits long voyages, the lack of high-power charging infrastructure and the high investment cost of the batteries [31]. The European Union energy mix (EU-27) from 2019 stated that 42.8 % of the energy produced was from fossil fuels and 26.7 % was from nuclear energy [32], this would essentially mean that the emission generation would shift from being at sea to being produced on land. In order for a battery electric solution to be environmentally sustainable in the future the source of the electricity must be renewable and cannot be dependent on fossil fuels [33].

2.4 Hydrogen fuels

Hydrogen can be utilized in three main ways to reduce emissions in marine transportation; as fuel in a combustion engine, as a way of creating electric currents in a fuel cell or used as a feedstock to produce electrofuels such as methanol. Reduction potential depends on the energy source used for H_2 production.

2.4.1 Hydrogen in a combustion engine

Hydrogen fuel can be burnt in a combustion engine and converted into mechanical energy [34]. This approach is flexible since other fuels can be utilized in the combustion engine. The emissions from hydrogen combustion are water vapor and NO_x, and carbon emissions depend on whether the hydrogen is made from renewable energy electrolysis or a carbon-based feedstock [35]. A large disadvantage of hydrogen fuel is the low volumetric energy density. Albeit light in weight, the large volume needed for fuel storage reduces the usable shipping volume. There is also no infrastructure in place for large scale hydrogen production and transportation.

2.4.2 Hydrogen in fuel cells

Fuel cells work through separating the hydrogen and an oxidiser allowing only protons to carry through, thus creating a current as the positive protons are exchanged. This current can then be used to propel an electric drive at high efficiency. Two examples of fuel cells are Proton Exchange Membrane (PEM) and Solid-Oxide Fuel Cells (SOFCs). PEMs have an efficiency of around 55% whereas SOFCs have an efficiency of 85% but require high temperatures to work [34]. Several examples of working ships with fuel cells exit, such as the Nemo H2 in Amsterdam [34]. Nemo H2 is powered by a hybrid powertain with a 30-50 kWh battery and 60-70 kW Fuel Cell. The H2 is stored at 350 bar in a 24 kg tank [26].

2.4.3 Hydrogen as a feedstock for methanol

Methanol combustion, like hydrogen combustion, utilises an internal combustion engine to create propulsion [36]. The difference is that methanol is a "regular" liquid fuel where the required infrastructure and systems are already in place through the current use of liquid fossil fuels. Methanol combustion generates emissions but, like hydrogen combustion, the amount of emitted CO_2 depends on whether the fuel is produced from electrolysis or carbon-based feedstocks. Methanol can be produced from hydrogen and captured CO_2, potentially making it a zero-emission fuel in terms of CO_2 [37]. Methanol having flash point as low as 60° can pose a serious danger of fire hazard [36].

2.5 Slow steaming

Slow steaming, or reduction of speed, has proven an effective measure in reducing emissions from shipping. Norway and Japan have already submitted proposals to the IMO requesting regulations of ship speeds [38]. Reynolds [39] suggests that a reduction of speed by 20% would reduce ship GHG emissions by 24-34% alongside reducing black carbon emissions. Reduction of ship speed also results in less noise pollution underwater. Reduction of ship speed below 11.8 knots results in less than 50% probability of fatal whale strikes [40]. Moreover, implementation of slow steaming does not require any additional modifications to existing ships but can be implemented right away.

The major problem of slow steaming is the extended duration of a ship's voyage, leading to additional operational expenditures for the stakeholder with the sourcing of more ships to maintain logistical standards. If the speed is significantly lowered, the CO_2 emissions will increase significantly as seen in the study by Lighthouse (the Swedish maritime competence centre) [38]. This is due to the engine efficiency being lower at lower speeds as well as the increase in total resistance as the frictional resistance increases along with a change in wave breaking mechanism due to change in speed. The study [38] also states that a major decrease in speed will have a significant negative effect on the speed dependent costs. There is also a growing concern on the total overall emissions when additional ships must be built to compensate for slower speeds. Widespread implementation of the speed reduction practice by logistical operators is challenging as it affects their profit margin. A study by CE Delft [41] shows that economic impacts in exporting countries can amount to approximately 10% of GDP. Another problem is an effective enforcement system which would deter ships from not complying to the norms. Many shipping companies have expressed their concern on the enforcement of this as a law by the IMO. A study conducted by Finnsgård et. al. showed that the shipping companies would adopt slow steaming given there is an increase in fuel price [42].

2.6 Wind power

The urgent need to shift to a more sustainable solution and the limitations posed by other technologies have led to a shift in the marine sector towards the long-term solution of wind-based propulsion systems, a transition described as "A renaissance of wind-powered ships" by SSPA [43]. The marine sector is the only transport sector that can harness and take complete advantage of wind, which is an abundant and free energy source. Wind propulsion of ships has the average CO_2 reduction potential of 50% [44] and 10-50% fuel savings for a tanker, calculated in the route between UK and Argentina [45].

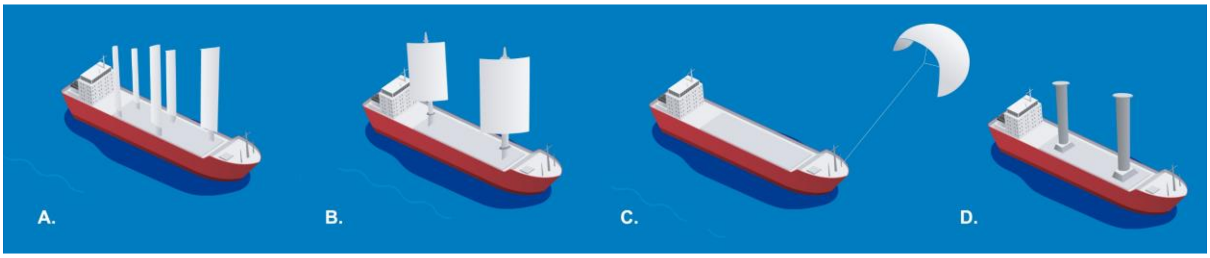

Figure 1 Wind power-based systems: A. Retractable sails, B. Rigid sails, C. Kite sail, D. Flettner rotor [46]

There are four major wind power solutions currently being used, as shown in Figure 1. The Flettner rotors are hollow cylindrical rotating structures working on the Magnus effect [47]. First developed back in 1920, this technology was used commercially in 2010 by Enercon in the E-Ship 1. It has covered 150,000 nautical miles [48] and has proven to provide 15% savings in fuel and speeds up to 12 knots solely on wind power [49]. Research carried out at Chalmers on the Viking Grace [50] equipped with Flettner rotors has estimated an annual fuel saving of 320 tonnes. Fuel savings of 30% was attained on a tanker equipped with

4 flettner rotors travelling along the Pacific ocean route [51]. The retractable sails-based Wind-Powered Car Carrier (wPCC) developed by Wallenius Lines is expected to reduce 90% of emissions and can have a wind only trans-Atlantic voyage duration of 12 days [52]. Kite sails have been tried experimentally and commercially [21] but are found to be difficult to control. The Wingsail has only 8% reductions in fuel consumption when travelling between Cape Lopez and Point Tupper [53].

Another way of utilizing the wind power is by producing electricity required to run various components such as cold storage, infotainment systems and various electronic equipment. Carlson and Nilsson [54] carried out research on wind turbines on ships and found 16% annual fuel savings which is equivalent to a 16% reduction of emissions, however adding a wind turbine which affects the stability of the ship based on the design. The power provided by wind sources can fluctuate as it depends on the wind availability, thereby creating reliability issues.

3. Discussion

Several suggestions to make the marine transport sector more sustainable have been presented in this report. One that is unique for the marine sector and for which the propulsion technology going forwards is wind power. Compared to the other propulsion systems, wind is a free and abundant energy, and it is (given the circumstances) capable to propel a vessel on its own. No other mode of transport can utilise this power source in the same way marine transport can, making it an interesting choice. Biofuels are available and working but is also sometimes labelled as the saviour of road based and aerial transportation, making the competition for biofuels stiff. Solar power cannot on its own propel a marine vessel, and batteries have too low power density to make a trans-Atlantic journey feasible. Hydrogen, fuel cells and methanol show great promise, but the technology is not yet mature and brings large disadvantages. The wind power, albeit with its own problems, at least has greater opportunities compared to the alternatives.

3.1 Impacts on emissions

The implementation of a wind propulsion system reduces the need for fossil fuels in the marine transportation system. The retractable sails-based wind powered car carrier leading to 90% reduction in emissions [52] has a positive effect on the surrounding air quality and can be cost saving by using a free energy source. Furthermore, a ship equipped with six flettner rotors can save around 32% - 36% based on the positioning of the rotors [55]. The fuel savings result in reduced air pollutants responsible for several adverse health and environmental effects (see Figure 2). Figure 2 is based on the Wadi Alkarm ship travelling between Damietta in Egypt to Dunkirk in France with 10 round trips a year at an average of 26 to 30 days per voyage [56]. The emission per trip is approximately 745.68 tonnes of CO_2 [57] resulting in a total of 14,913.6 tonnes of CO_2 emission per year. Addition of four flettner rotor results in emission reduction of 9272 tonnes per year [56] which is equivalent to 62.17% reduction in CO_2 emission per year.

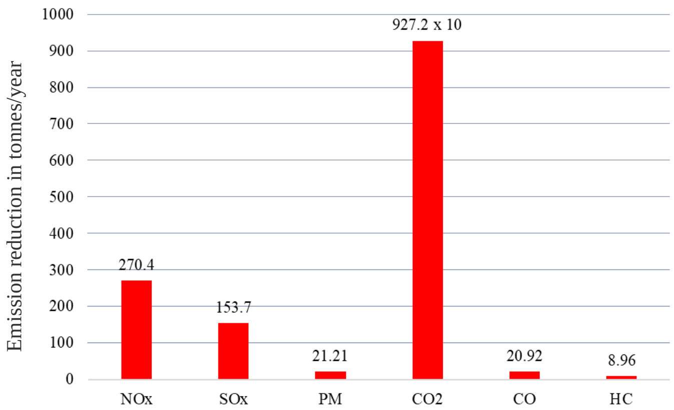

Figure 2 Emission reduction in ton per year for four flettner rotor. [56]

In order to reduce the emissions from the marine sector, a combination of short-term measures such as slow steaming, medium term measures such low sulphur fuels and long-term measures such as zero emission propulsion systems is needed. To aid the transition towards a sustainable marine transportation system, a widespread implementation of any method or methods should be accepted by the various stakeholders without taking only the economic factors into consideration.

3.1.1 Wind power combined with slow steaming:

Olsson and Carlsson [58] carried out research on the wPCC and found that operating this ship across the Atlantic at 11.4 knot would result in 799 045 tonnes CO_{2eq} emission in its entire life cycle. This is 81.12% reduction as compared to an LNG carrier in the same route. This CO_{2eq} emission would drop even further to 311 965 tonnes of the ship is operated at 8 knot speed. This is about 60% reduction in emission as compared to the wPCC travelling at 11.4 knots and 99% reduction as compared to an LNG carrier travelling in the same route at 11.4 knots. These numbers can make combination of wind power and slow steaming a more attractive and eco-friendly choice. But one has to keep in mind that the requirement of flexible logistical time involved with this solution.

3.1.2 Wind power combined with solar power:

There are several concept designs of solar-wind hybrid ships and Pan et al. describes different utilization of such a hybrid solution, ranging from super-tankers to passenger ships [59]. The super-tanker described measures 400 m long, 31 m wide and intends to transport drink worthy fresh water at a maximum speed of 15 knots powered only by wing-sails and arrays of solar panels [59]. This, according to the authors, can result in around a 50% reduction in both fuel consumption as well as emissions compared to a conventional oil tanker of the same type [59]. For the smaller passenger ship named Solar Sailor which is equipped with solar panels that can simultaneously act as sails and it was estimated that it will save 250 000 litres of diesel annually, reduce GHG emissions by 670 tonnes yearly and the payback time was estimated to be 5 years with the fuel prices at the time [60].

3.2 Stakeholder analysis

There are several different stakeholders affected by and affecting the shipping industry, and regulation would impact them differently. Here, the stakeholders discussed will be similar to the ones presented by Hansson et. al [61], i.e. authorities, ship-owners, fuel manufacturers and engine manufacturers. Other stakeholders to consider would be consumers, international organisations and inhabitants of affected areas.

In general, the industry values economic factors significantly higher than other perspectives while authorities on the other hand prioritise social and environmental issues [61]. In total, economy, and particularly fuel price, is regarded the most important perspective today [61].

With this background, it is natural that the shipping industry still uses HFO since it is the cheapest alternative. The consequences for ship-owners if the fuel is changed due to new regulation or more efficient new technology would initially be higher costs. In the case of wind powered ships, the investment costs would probably be high since the existing fleet of ships would need to be rebuilt or exchanged. Authorities could create incentives for ship-owners to change propulsion system in various ways, e.g. by subsidising desirable options, taxing unwanted ones or applying standards, regulations or bans. In the long run however, a wind-powered marine transport sector could be cost saving since the actual “fuel”, i.e. wind, is free.

Another drawback for the industry regarding wind propelled ships is the journey duration. Since the availability of wind is not constant this makes the journey time vary. For fuel and engine producers specifically, there would be a need to redirect business to remain on the market since the demand for conventional ICEs and ship fuels would decrease. On the other hand, manufacturers of equipment for wind propulsion systems would experience a growing demand. Authorities would regard wind power as a preferable solution, since it reduces emissions, thus creating environmental and social benefits. Due to negative health effects caused by air pollution, this could also reduce costs for the health care systems. A positive feature of wind power is that the marine transport sector would not have to compete with other sectors over energy, which would benefit the operators. All the other alternative fuels will probably be sought-after by other sectors such as land-based transportation, residential and industry.

3.3 Problems with widespread implementation

The major disadvantage of wind-powered ships is their wind-dependence. This can be partly resolved by conducting long term wind assessments. Another major issue is the energy efficiency gap, or implementation gap. Jaffe and Stafins [62] studied the phenomenon of the energy paradox which is the difference between a technology being cost-effective and energy-effective. Wind-powered ships are entangled in this as from an investor’s perspective, they are not an economically efficient alternative while from an environmental and energy utilisation perspective, it is a very effective alternative. The height of bridges limits the rig height, and limited space on the deck of a container ship can prove to be a challenge in widespread implementation. Although Wallenius has claimed a journey duration of 12 days to cover the Atlantic and this seems to be a reasonable time, this is still 1.5 times the conventional ship voyage duration of 8 days [63] which from a transportation company's point of view can be a huge setback. Due to the increased voyage duration the ship traffic would rise resulting in other complications.

Like wind, sunlight is also an abundant energy form, but the utilisation of this energy is hindered by the inefficient method of converting it to usable electricity. Electrification on the other hand does not struggle with low energy conversion efficiency but instead the challenges are the low energy density of current batteries, high costs and insufficient charging infrastructure which only permits shorter voyages and discourages ship builders [31].

The challenges of biofuels lie in the production process. Since biodiesel is mainly sourced from first-generation biofuels [16], it introduces several new ethical, environmental and economical dilemmas. Utilising fertile farmland to produce first-generation biofuels can lead to an increased competition over scarce land [3], increased costs of food items [64], loss of biodiversity from land use change [20] and soil carbon losses [18].

The main disadvantage for a hydrogen-based powertrain is that the low volumetric energy density of the fuel results in loss of usable shipping volume, therefore decreasing profit per voyage. Furthermore, the current infrastructure does not support large scale hydrogen production or transportation and the environmental gain is dependent on whether the production process is fossil or renewable [35]. Fuel cells have the same drawbacks as combustion of hydrogen.

Much like the hydrogen powertrain, the methanol-based powertrain also uses an internal combustion engine but unlike more traditional fossil-based fuels it is not compatible with the diesel engines used today [65]. However, retrofitting can be an option to considered but can lead to high cost. Furthermore, the high toxicity of methanol has been a concern and the availability as well as the production of the fuel continues to hinder a large scale deployment [66].

Speed reduction in order to lower emissions is not implemented mainly due to the more time-consuming voyages, implying higher costs for the shipping companies [38]. There is also the issue of enforcing such policies globally. However, increased fuel prices can provide the necessary boost for the implementation [42].

3.4 Distributional conflicts

In the process of reviewing different ways of contributing to a more sustainable marine transport sector, bio-derived fuels first appeared to be the most attractive option due to a large potential reduction in GHG emissions. However, considering only the benefits in terms of reduced CO_2 emissions might lead to an overly simplified picture. At present, only first-generation biofuels made from food crops are used on a commercial scale for land-based transportation. Any increase in demand for fuels based on food crops would likely also increase the demand for arable land to cultivate the necessary feedstock. When a piece of natural land is converted into farmland, adverse environmental impacts follow as described in Section 2.1. Moreover, the likelihood of further land use change is not evenly distributed across the world as some geographic regions are already extensively farmed. For instance, Europe's share of the world's total amount of cropland has decreased during the last century whereas Africa and Brazil now occupy a larger fraction of the global available cropland [67]. At the same time, average GDP per capita in Europe exceeds both the African and the Brazilian per capita averages. Pushing the production to a low-economy countries while the produce is used majorly by the richer countries is not fair from a humanitarian point of view. The second-generation biofuels such as Lignocellulosic biofuels are affected by moisture [68]. The volume of Lignocellulosic feedstock increases with increase in moisture thereby creating major issues in the supply chain. The costs of cultivation of third generation are considerably higher [69]. Given the technology of third-generation biofuel production is in nascent stage with very low productivity for the amount of land used [70], and the very high demand of the marine transport sector this cannot ideally be a go to option for the industry.

If a majority of land use change occurs in countries or regions where economic development is not as far advanced, there is a risk of negative impacts associated with an increased biomass production becoming concentrated to poor regions. Furthermore, abatement of environmental impacts might not get prioritised in a country which is already struggling with poverty. Increasing the demand for arable land to supply biofuels could thus be assumed to enhance distributional conflicts between the rich and poor parts of the world. These kinds of conflicts can be avoided by opting for a marine propulsion system not dependent on access to arable land, such as wind power. Moreover, it makes sense to distribute the bio-based resources among sectors which lack other viable options whereas the marine transport is unique in its capability of utilising wind for vessel propulsion.

Large-scale implementation of other GHG reducing measures described in this report also have the potential of creating distributional conflicts. One issue with e.g. solar panels and batteries used in electrically propelled vessels is that the components require several types of rare-earth elements (REEs). Extraction of REEs can have severe impacts for the environment as well as for the people working in the mines [71]. Countries with large reserves of REEs do have the benefit of being able to extract and export a resource which is becoming increasingly important as the demand is rising for energy storage and renewable energy solutions. However, along with the potential financial gains comes the need to handle the negative effects on the local environment and population caused by REE extraction.

When it comes to hydrogen, the production determines the resulting environmental impact. Hence, differing opportunities with respect to renewable electricity production should be considered in a context of potential distributional conflicts associated with hydrogen. If the marine transport sector were to invest in large-scale hydrogen technology, a larger burden of pollution abatement might be placed on countries that want to produce hydrogen to fuel its shipping industry but lack sufficient access to a renewable energy infrastructure. Wind power, however, is both renewable and globally accessible (though regionally varying depending on local climate conditions). Considering that wind resources are readily available and completely independent of geographical borders, export policies and trade relationships, it can be argued that a wind-powered marine transport sector is the most promising option for the future with respect to avoiding distributional issues. Life cycle analysis have to be conducted to understand the overall effect of using lightweight composites on sails in order to better understand the total environmental impacts.

4. Conclusions

The main conclusion of this report is that wind would preferably constitute part of a new sustainable marine sector. The advantages of wind-powered marine vessels are large potential reductions in fuel consumption as well as a possibility of zero emissions from propulsion. There are obstacles to overcome, such as developing a new fleet of vessels, alternatively retrofitting the existing one. Also, the occasional unreliability of wind implies that a secondary propulsion system or a flexible logistical time is required, potentially reducing the positive impact of a wind-powered marine fleet. However, as discussed in the report the benefits of the wind system outweigh the advantages of other systems such as biofuels, solar power, electrification, hydrogen combustion, fuel cells and methanol combustion. It should be noted this report does not provide any recommendation on how to implement the technologies, but rather provide a comparison on different technologies and their effect on a future marine transport sector.

Appendix

Statement of individual contributions

The workload has been evenly distributed. Each person conducted the research for the specific parts they were responsible to write about. **Carl Alvelid**: Hydrogen fuels (hydrogen combustion, fuel cells, methanol combustion), Discussion (introductory parts), Conclusions. **Daniel Schmidt**: Solar panels, Electrification, Major problems with widespread implementation, review and editing, Presentation slides and structure. **Jonna Ljunge:** Abstract, Biofuels, Discussion (Distributional conflicts), Original draft review. **Julia Gutke**: Introduction, Discussion (Stakeholder analysis), Original draft review. **Rahul Rajendra Pai**: Wind power, Major problems with widespread implementation, review and editing, presentation slides and structure. **Shruthik Krishnan**: Slow steaming, Discussion (Impact on emissions).

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