TOWARDS VERY LOW CARBON SHIPPING

M. Traut[1], A. Bows[2], P. Gilbert[3], C. Walsh[2] and R. Wood[3]

[1]Tyndall Centre for Climate Change Research, School of Earth, Atmospheric and Environmental Sciences, University of Manchester, M13 9PL, UK, michael.traut@postgrad.manchester.ac.uk
[2]Sustainable Consumption Institute, School of Earth, Atmospheric and Environmental Sciences, University of Manchester, M13 9PL, UK
[3]Tyndall Centre for Climate Change Research, School of Mechanical, Aerospace and Civil Engineering, University of Manchester, M13 9PL, UK

ABSTRACT
In order to meet broadly legitimised climate change mitigation targets, all sectors need to decarbonise over the coming decades. In this paper, the potential scope for decarbonising the individual ship is assessed, considering the case of a bulk carrier of 40,000 GT. The study comprises of three stages: (i) Reducing the demand for propulsion power by reducing speed and incorporating estimates of efficiency gains from hull shape modifications and propeller optimisation; (ii) Estimating the maximum feasible contributions from wind and solar power, using historical weather data and technology characteristics from the literature; (iii) Assessing and comparing marine diesel, LNG, biofuel, and hydrogen for their potential to deliver the remaining propulsive energy demand with low associated carbon emissions.
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1. INTRODUCTION

In order to attain a high probability of keeping average global surface temperature change from rising more than 2 degrees C above preindustrial levels, the global emission of greenhouse gases must be reduced drastically over the decades to come. Therefore there is a strong need to reduce CO_2 emissions from shipping very significantly. If shipping is to reduce its greenhouse gas emissions by the same proportion as other sectors, then shipping faces a great challenge (Gilbert et al. 2010). The aim of this paper is to outline a framework for exploring the potential of new shipping technology to meet this challenge.

The 2C target is intended to avoid dangerous climate change. In the Copenhagen Accord more than 140 parties agree to “take action to meet this objective” (UN, 2009). While the Copenhagen Accord is no binding agreement, individual parties are invited to make pledges to reduce their emissions of greenhouse gases. A global greenhouse gas emission trajectory describes the pathway of global greenhouse gas emissions as a function of time. Based on these pledges, Rogelj et al. (Rogelj et al., 2010) have built a trajectory into the year 2020. Under optimistic assumptions, they go on to calculate that global emissions will then have to be halved by 2050, with respect to their 1990 level, for a 51% chance of meeting the 2 degrees C target. Meinshausen et al. (Meinshausen et al., 2009) point out that cumulative greenhouse gas emissions in the first half of the century are a crucial indicator for determining whether the 2C target will be met, and for a chance of 50% of reaching that target, about 1 trillion tonnes of CO_2 may still be emitted in this time. Anderson and Bows (Anderson and Bows, 2011) use the tool PRIMAP (PRIMAP, 2010) provided by Meinshausen et al. to create a set of scenarios for the Kyoto basket of six greenhouse gases for the period 2000-2100 commensurate with stated mitigation targets. They assume a baseline emission of greenhouse gases from the food sector. All other sectors, including shipping, reach full decarbonisation around 2060 in each of their scenarios. On a political level, there is no global mechanism for controlling greenhouse gases from shipping in place. The Kyoto Protocol states that “Parties included in Annex I shall pursue limitation or reduction of emissions of greenhouse gases ... from ... marine bunker fuels, working through the ... International Maritime Organisation” (UN, 1997). However, the International Maritime Organisation (IMO) is based on the equal treatment of all member states, and this conflict renders the agreement on a global scheme a difficult task. Given the lack of policies on a global level, the EU has declared to develop a policy for shipping emissions to come into effect by 2013, should no global agreement be reached (EU, 2009). In its transport white paper (EC, 2011), the European Commission defines the target of reducing EU CO_2 emissions from maritime transport by 40% by 2050 compared to 2005 levels. Currently, according to the 2nd IMO Greenhouse Gas study (IMO, 2009), CO_2 emissions from global shipping are of the order of one billion tonnes per year, with significant associated uncertainties. The same study creates more than one hundred scenarios for shipping demand in 2050, with estimates ranging from 1.5 to 9.45 times the level of demand for shipping in 2007. While the uncertainty is naturally considerable, there seems to be a high degree of certainty that demand will increase. Combining the lower bound estimate of growth in shipping demand with a reduction target of 40% with respect to 2005 levels equates to an increase in the carbon efficiency of shipping by more than 60%.

Albeit all of the uncertainties mentioned above, two points become very clear. Firstly, a reduction of global greenhouse gas emissions from all sectors by 40% with respect to 2005 will not make meeting the 2C target likely. To make attain a likely chance of meeting this target an even sharper cut in emissions would be needed. As it is commonly argued that developed countries (Annex I countries under the Kyoto Protocol) must reduce their emissions by a larger proportion than developing countries, the target is even less ambitious in a purely European context. (Implicit in this statement is the assumption that all sectors reduce their emissions by the same fraction, even though it is acknowledged that there is room for debate on this issue.) Secondly, given the expected growth in future demand for shipping, such a cut in emissions constitutes a great challenge. Again, this assumes that the shipping sector reduces its greenhouse gas emissions in proportion with other sectors.

As shipping plays a crucial role in world trade and furthermore represents and important business in its own right, there is a real need to address this challenge. This study investigates the scope for low carbon technology in shipping and lays out steps for exploring the potential to run ships with only a fraction of the currently associated CO_2 emissions.

2. BACKGROUND / RATIONALE

Most studies on technological innovations for reducing greenhouse gas emissions from shipping start from the status quo, assessing new technologies by estimating the incremental reduction of greenhouse gas emissions (or the percentage reduction in fuel consumption) associated with their deployment on a ship under consideration, e.g. (Faber et al. 2009 and Eyring et al. (2005). This study adopts a complementary view, by looking at the topic from the opposite angle. Rather than the current system, future needs define the starting point; the research question is framed around providing shipping services with very low carbon emissions, thus identifying technology that may provide large step change emission reductions. Establishing positive targets for shipping beyond fossil fuels and ensuing greenhouse gas emissions may prove useful in driving and informing mitigation efforts in the shipping sector.

To this end, the demand for propulsive power of ships is considered, and technological options are assessed by estimating the power share they may contribute to meet this demand (or to reduce the initial demand, where applicable). In order to define this task more clearly, a specific reference ship, on a specific journey, is chosen (see table 1 and figure 1).

Figure 1: Track of ship voyage from Santos to Singapore.

Table 1: Main parameters of the reference ship considered in this study.

Key Parameters Reference Ship	
Category / Size	Dry Bulk
	Gross Tonnage 40,000
	Deadweight 76,784 tons
Geometry	Length 225 m
	Beam 32 m
	Draught 14 m
Main Engine	Diesel
	Installed Power 9 MW

A bulk ship is chosen because it may have much deck space available for incorporating carbon reducing technologies. The ship size of 40,000 gross tonnage is large enough to be representative: if the feasibility of running a ship of this size with very low carbon emissions could be asserted, then this could provide a good indication to the feasibility of decarbonising shipping more generally. The route is heavily frequented, and the journey is based on the real voyage of the ship Lowlands Maine (IMO number 9304239) in June/July 2010. This scheme allows for categorising, assessing and setting into context a broad range of potential technological innovations. Most importantly, it offers an alternative perspective guided by the goal defined by the feasibility of shipping beyond fossil fuels and the greenhouse gas emissions associated with them.

3. METHODS

Three groups of measures for very low carbon shipping are identified in this study, grouped into those (1) reducing the propulsive power demand, (2) wind and solar power, and (3) alternative fuels.

3.1 REDUCING POWER DEMAND

The first part of this study into essentially decarbonising the reference ship is reducing its power demand. Two ways to do this are considered: reducing the travel speed, and combined optimisation of the ship's major components, such as its hull shape, coating, or propeller, as it is continuously being advanced by the shipbuilding industry.

Speed. Reducing the cruising speed of a ship reduces its power demand. The power consumption is commonly assumed to vary with the cube of the speed. This relation is based on the frictional resistance of a ship in calm water. Lindstad et al. (Lindstad et al., 2011) argue that savings will be smaller once a more realistic sea state and a dependency of the propeller efficiency on speed are included. The issues that need to be considered when calling for slow steaming include safety, fleet size, finances and how the market works: if ship speeds are reduced, and in turn the installed power gets lower, at some point attention must be paid to guaranteeing the safe manoeuvrability of ships in all operating conditions. If ships were to go much slower on a large scale, this would necessitate a larger fleet to serve the market, incurring investment costs and increasing the upstream share of life cycle emissions. Long cargo delivery times are associated with the cost of capital (in form of the cargo) being tied up. Furthermore, a number of different types of actors involved means that bringing about a change in the currently typical range of speeds is complicated. Having said that, the economic downturn beginning in 2007 did just that, and even as the economy shows signs of recovery, Maersk declared it will adhere to slower speeds (Maersk, 2010). In large part due to differences in the typical value of the cargo, typical speeds are very different in different market segments. The service speed of container ships for example is typically much larger than that of bulk carriers. In relation to this study this means that larger reductions in power demand by way of reducing speed may be possible for container ships but the installed engine power of container ships is comparatively larger to start with. Here, a speed reduction from the service speed of 14.5 knots down to 12.5 knots is incorporated. We follow the analysis by Lindstad et al. (Lindstad et al., 2011), that yields a reduction in an overall fuel consumption of 13% (In their analysis, this corresponds to the point of maximum speed reduction at zero abatement cost).[1]

Incremental Optimisation. All other factors being equal, there is a clear incentive to increase the fuel efficiency of ships. Therefore, all components with relevance to a ship's fuel consumption may be subject to efficiency optimisation, including hull shapes, hull coatings, propellers, possibly active flow devices, and others. Disregarding entirely new concepts, for the purpose of this study, an efficiency improvement of 20% is assumed. In relation to the time horizon defined by the year 2050 mentioned above, this corresponds to an efficiency gain of about half a percentage point per year. Clearly, it is difficult to estimate an expected aggregate gain from a number of incremental changes. The chosen value is based on engineering judgement informed by numbers quoted in other studies such as the second IMO greenhouse gas study (IMO, 2009), and comparisons with the aviation industry, where large efforts went into the optimisation of fuel efficiency over the last decades. In relation to other studies, the value chosen in this study may be seen as fairly conservative.

3.2 RENEWABLE ENERGY SOURCES ON SEA

Solar, wind, and wave power are the renewable energy sources available on the high seas.[2] Current wave power plant designs suggest that, in order to use wave power for ship propulsion, an entirely new design concept would be needed. It is not considered in this paper.

Solar Power. By performing a model calculation, a maximum solar power contribution is estimated. The solar irradiation on the Earth's surface, where the sun is vertical in the sky is around 1 kW/m^2. Averaging over time and location, this amounts to $0.25kW{=}m^2$.[3] Assuming that almost the entire deck surface (5625 m2) of the reference ship be covered by photovoltaic cells with an efficiency of 20%, the generated power equals 281 kW. In addition, this assumes that the solar cells are oriented in parallel to the Earth's surface. More solar power could be harvested, if solar panels were oriented towards the sun, but it would not increase the collected power by a large factor. Therefore the estimate represents a good indicator of an upper limit of the power contribution of solar energy. This model calculation leaves open the question how the generated power be transferred onto the propeller. Solar power might prove useful in supplying auxiliary power, but in this study, only propulsion power is considered as it represents the largest share of a ship's power consumption - and therefore constitutes the main challenge.

[1] In deriving this number, Lindstad et al. figured in emissions costs associated with building the ship, using life cycle analysis. Financial costs include operating costs, capital investment costs and costs of binding up capital for the time of the voyage.

[2] Wind, solar, and wave power are emission-free when operating but there full life cycle emission cost is not zero, of course.

[3] On the reference voyage considered in this paper, the time-average irradiation should be somewhat higher, due to its geographic location at low latitudes. At the level of uncertainty of this model calculation, a factor of 1/4, reflecting the ratio between the Earth's surface and its cross/section as seen from the sun, should suffice.

Wind Power. Prior to the advent of the steam engine, ships sailed on the high seas. As wind is a renewable source of energy, it may again prove to be a viable option. In this work, five different wind power technologies are identified. (i) Automated sailing using computer-controlled sails. (ii) Solid body sails resembling fixed wings rather than classical sails. (iii) Kites pulling a ship through a single rope connection, typically flying a figure-of-eight in the wind (Schlaak and Kreutzer, 2009 and Naaijen et al., 2006). (iv) Flettner rotors, rotating cylinders that use the Magnus effect to convert wind from the side into forward propulsion (Flettner, 1925 and Mittal and Kumar, 2003). The first ship featuring a Flettner rotor was the Barbara, completed in 1926. The cargo ship E-Ship 1 is the most modern ship with Flettner rotors, featuring four rotors, each 27m tall and 4m in diameter. (v) Wind turbines complete the list of technologies for harnessing the power of the wind on the high seas. Only the last option, wind turbines, have been analysed at this stage.

The kinetic energy carried by the wind through an area perpendicular to the velocity of the wind per unit of time, Pa, is described by the formula $Pa=1/2\rho Av^3$, where ρ is the density of air, A the area considered, and v is the speed of the wind. In this study, a model calculation is performed for option (v) wind turbines. While the calculation on solar power presented above can be seen as a fairly robust estimate of what may be possible, the case is different for wind power. Results rely heavily on the assumptions that feed into the calculation. The other options (i-iv) will be analysed in future work. The analysis presented here highlights the approach, it may serve as a discussion point, and guide the analysis steps that will follow.

The contribution of wind power towards meeting the energy demand of the reference ship on the reference voyage (see figure 1) is calculated making the following assumptions. A wind turbine of 50m diameter is installed on the ship. Only the wind component perpendicular to the ship's velocity is considered. The efficiency of the wind turbine is 25%. The efficiency of transferring this energy onto the shaft is 75%. The wind speed is the daily mean field of wind velocity at 10m above surface level, for 1 July 2001, from the ERA-40 weather database from the ECMWF (European Centre for Medium-Range Weather Forecasts, Uppala, 2005). The average power on the shaft calculated in this way is 62 kW.

3.3 ALTERNATIVE FUELS

Any remaining power demand for ship propulsion may have to come from a fuel (or, more generally, stored energy that the ship may carry with it). Winebrake et al. (Winebrake et al. 2007) investigate the full life cycle emissions associated with heavy fuel oil (HFO), marine diesel oil (MDO), low sulfur diesel, natural gas, Fischer-Tropsch diesel from natural gas, and biodiesel from soybeans. Natural gas is the only fuel which has lower CO2 emissions of MDO or HFO, but the gain is small (<5%), and it is associated with higher emissions of methane, a potent greenhouse gas itself.[4] In the case of the fossil fuels, the CO2 emissions are mostly due to the carbon content of the fuel itself, and offer little promise of yielding the very low carbon energy that will be necessary in the future. In this selection, only biofuel constitutes a renewable energy source, and in principle, biofuels may be able to provide low carbon energy in the future. Except for nuclear fuel and coal, the authors are not aware of any other fuel that has been deployed on a ship any size comparable to that of the reference ship considered here.

Table 2: Power contribution (or reduction of power demand) by incremental technology change, reducing speed, solar, and wind power.

power demand [MW]	9	7.830	6.264	5.983	5.921
measure	initial	Speed red.	tech. optim.	solar	wind

However, in order to meet the energy demand aboard ships, it may be necessary to use other fuels, such as hydrogen, possibly in combination with renewable hydrolysis, in the future.

4. RESULTS

The power demand of the reference ship cruising at its service speed of 14.5 knots is assumed to be 9 MW.[5] Putting together the estimated reductions from reducing the speed to 12.5 knots, incremental technology improvement, and the energy contribution from wind and solar power, the power demand is still at 2/3 of its initial value, at 6 MW (see table 2). No estimates have been attempted for the use of alternative fuels, for two reasons. As of today, alternative fuels are not seen to yield a very significant reduction in greenhouse gas emissions. Their potential to do so in the future hinges to a large degree on the capacity for producing these fuels on land. In the next section

[4] Winebrake et al. include upstream emission costs of the assessed fuels. Under different assumptions the CO_2 emission savings potential of natural may be expected to be somewhat higher.

[5] The installed engine power is assumed to be 9MW, so the power consumption would be somewhat lower at cruising speed.

underlying assumptions and uncertainties are discussed.

5. DISCUSSION

Three complementary ways towards running a selected reference ship without the associated carbon emissions have been addressed: a reduction in the demand for power, the use of renewable energy sources available on the high seas, and alternative fuels.

The first of these ways comprises of incremental technology improvements and reducing speed. A reduction from technology optimisation has been estimated, while no fundamental changes to the ship design have been considered. In selecting a speed reduction and ensuing emission reductions this study follows the analysis of Lindstad et al. (Lindstad et al., 2011). As emissions (per voyage) are usually estimated to scale with the square of the ship's speed (IMO, 2009), this more involved analysis suggests significantly lower benefits from slow steaming, mostly due to the inclusion of the effect of a more realistic sea state rather than calm water and a dependency of propeller efficiency on ship speed.

The second way of reducing CO_2 emissions is harnessing solar and wind power. The potential power contribution from solar power has been calculated based on the assumptions of covering the largest part of the ship surface in photovoltaic cells of currently high efficiency standard, and using an average of solar irradiation on the Earth's surface. The issue of how this power is transferred onto the shaft is not addressed, and neither is the issue of energy storage, when solar irradiation clearly is an intermittent energy source.[6] The potential power contribution from wind is estimated by analysing wind speed data from the ERA-40 weather database (Uppala, 2005). The power contribution has been calculated as the average power on the reference journey as a function of the wind direction and speed along the route. The calculated value of 62 kW is very low in comparison to the reference ship's power demand. This value depends heavily on the wind speed and wind direction on the route, as well as on the size and efficiency assumed for the device designed to transform wind into propulsive force. While the small result is not promising, it will be compared to analyses of the other sailing technologies mentioned. It will provide some insight to compare different technologies resting on similar assumptions regarding routes and weather. Studies using wind data from the ERA-40 weather database (Uppala, 2005) have been performed modelling reductions in fuel consumption for a kite and solid body wings (Schlaak and Kreutzer, 2009 and Clauss et al., 2007, respectively). Both of these studies calculate higher or similar savings, but on different routes.[7] No comparable study in relation to the other mentioned concepts (i.e. traditional sailing and Flettner rotors) is known to the authors. The result presented here may therefore serve as a reference point for more detailed and comparative assessments of different technology options.

The third way that may help bring down future shipping emissions is alternative fuels. With respect to climate change, all life cycle emissions from a fuel are relevant. Winebrake et al. have studied currently feasible fuels for shipping. However, in their study, none of the considered fuels offer a significant reduction of greenhouse gas emissions compared to the heavy fuel oil that is currently most widely used. The future availability of alternative fuels with significantly lower associated greenhouse gas emissions will have to be taken into consideration, as it evolves over time. Some fuels, such as hydrogen, would require a different machinery setup and storage facilities on a ship. On the way towards very low carbon shipping, these issues need to be factored in.

6. CONCLUSION

Given the body of knowledge on climate change, severe reductions in greenhouse gas emissions are necessary in order to avoid its most harrowing effects. Assuming that shipping should reduce its emissions by the same relative amounts as other sectors,[8] it will be imperative to make available technologies that allow running a ship that emits only a fraction of the greenhouse gases that it would typically emit today. While the usual approach is to consider ships that employ technologies that are currently standard and estimating possible reductions of incorporating new technological features, this study provides a complementary approach. It outlines steps towards meeting the power demand for a ship without the associated emissions of the present. In essence, it studies the problem from another, complementary viewpoint.

[6] The issue of energy storage is of importance with intermittent energy sources. It is related to the topic of alternative fuels, as fuels are, in principle, media for storing energy.

[7] There is a number of difficulties in comparing results from different studies on wind power: Different selected routes, ship sizes, cruising speeds, and the appropriateness of assumptions regarding the size of the employed devices are among them, all of which have a large influence on calculated numbers with respect to their savings potential. E.g., the authors acknowledge that the underlying setup of this study may be seen as far-fetched by some. However, this shows the benefits of collating results in one combined framework.

[8] Shipping is of crucial importance to world trade and furthermore it is has much lower emissions than competing modes of transport. Some might argue, that this assumption is not justified. While this is a certainly an important debate, this paper simply uses the assumption to state things clearly.

It identifies three different strands of technologies: reducing the power demand of a ship; renewable energy sources available at sea; and alternative fuels. The initial analysis performed shows that this is not at all a simple endeavour. Rather it indicates that this task is indeed very challenging. It is, therefore, all the more important to develop the programme outlined, for two reasons. In the light of rapid progress towards dangerous climate change it is a necessity. In addition, it is an approach that seeks to identify positive aims - to spur progress in the shipping sector and to inform political processes.

This study is work in progress; it will guide future work that will assess all of the indicated steps in more detail. For instance, slow steaming deserves a closer analysis, taking into account the issue of guaranteeing safe operations (as a ship must not be underpowered, or, more precisely, be able to guarantee safe manoeuvrability) and optimisation of its propulsive system at other (i.e. slower) operating points. One estimate for the power reduction potential of the optimisation of a ship's components has been made, and clearly many viable (or possibly viable in the future) technologies deserve a more detailed analysis. Furthermore, more fundamentally new concepts have been not been considered here. As solar irradiation is a constant, the model calculation estimating its potential contribution towards meeting a ship's power demand can essentially be seen as a maximum estimate. The case is different for wind power, however. The analysis provided here serves to highlight how the potential wind power contribution will be explored further. First, the different suggested technologies need to be assessed further by detailing feasible sizes, and efficiencies. Second, more detailed wind data must be identified, and different routes as well as route optimisation will be considered. Alternative fuels, while not offering very significant reduction potential today, may be a absolute necessity for very low carbon shipping. Therefore, the availability of alternative low-carbon fuels in the future needs to be assessed. More generally (and possibly in conjunction with studies of wind power technology) issues of energy storage onboard ships may be explored. The technical feasibility of using alternative fuels, such as hydrogen, in a shipping context will be investigated.

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