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Ship of the future – A slender dry-bulker with wind assisted propulsion

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ABSTRACT

From the first days of our civilization sea transport has enabled trades. Today sea transport accounts for 80% of the Global trade measured in ton miles and 3% of Greenhouse gas (GHG) emissions. More than 40% of this sea trade is performed by the Dry bulkers, making them the real workhorses of the sea. Compared to other transport modes, Sea transport and Dry bulkers in particular, are energy efficient. Despite this, with the urgent need to reduce Global GHG emissions according to the Paris agreement (UNFCCC 2015), all sectors including shipping, needs to deliver major GHG reduction within the next decades. This paper focus on potential energy reductions through building more slender bulk vessels in combination with wind assisted propulsion (WASP). The results indicates that fuel consumption and hence GHG emissions can be reduced by up to 40% on an operational basis (EEOI) and 30% when shipbuilding is included (LCA).

1. Introduction

Current greenhouse gas emissions (GHG) from maritime transport represent around 3% of global anthropogenic GHG emissions (Lindstad et al., 2021). The main source of these GHG emissions is the exhaust gas from ships combustion engines, estimated to be around one billion-ton of carbon dioxide equivalents (CO_2eq) annually (Buhaug et al., 2009; Smith et al., 2015; Faber et al., 2020). These Tank-to-Wake GHG emissions, accounts for around 80% of conventional fuels Well-to-Wake emissions and energy usage, while their production (Well-to-Tank) accounts for around 20% of their emissions and energy usage (Edwards et al., 2014; Prussi et al., 2020). For shipping to contribute to the ambitions of the Paris agreement (UNFCCC, 2015), its emissions must be reduced at least with 50% by 2050 compared to 2008 (IMO, 2018). With continuous annual sea transport growth of 3% and 1% annual energy efficiency improvements as seen from 1970 (Lindstad, 2013; Lindstad et. al., 2018), this implies that the emissions per ton mile must be reduced by 75–85% up to 2050, to achieve the desired 50% reduction of the total maritime transport emissions (Bouman et al., 2017).

The International Maritime Organization (IMO) has established the Energy Efficiency Design Index (EEDI) as the most important policy measure to reduce GHG emissions from shipping (IMO, 2018). A vessel's EEDI is based on sea trials at delivery where vessels cannot exceed a threshold for emitted CO_2 per ton-mile as a function of vessel size and type. In June 2021 at MEPC 76 (IMO, 2021), the EEDI legislation was expanded from covering only ships built from 2013 onwards, to requiring that all ships above 5000 GT calculates

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their Energy Efficiency Existing Ship Index (EEXI). If the required thresholds are not meet, the options are either to perform the technical improvements or de-rate their engine to fulfil the requirements. Also, from 2023 onwards, all ships above 5000 GT employed in international trades will have to report their annual operational carbon intensity indicator (CII) and CII rating. Carbon intensity links the GHG emissions to the amount of cargo carried over distance travelled. Basically, the EEDI test and the EEXI verification measures the emissions per ton nm for a fully loaded vessels when the main engine delivers 75% of its maximum continuous power (MCR) at calm water conditions. The calm-water focus is not new, it just part of a tradition where research of hull shapes and propeller design has mainly focused on optimizing for calm-water conditions, with design cargo loads and design speeds at or above the boundary speed.[1] For any given hull form, the boundary speed can be defined as the speed area where the total calm water resistance coefficient goes from practically constant to rising rapidly, thus making further rise in speed prohibitively expensive (Silverleaf and Dawson, 1966). This despite that vessel's operate under real sea conditions with wind and waves (Faltinsen et al. 1980), rather than the calm-water conditions given by the EEDI (Kim et al., 2017, 2017a; Hizir, 2019).

Hirota et al. (2005) shows how to optimize the ship form to minimize fuel consumption in real sea with waves, instead of for calm water conditions. Similar results have been found by Kristensen (2010); Stott and Wright (2011); Lindstad et al. (2013, 2014, 2019a), which have investigated how to make hull forms more energy efficient under realistic sea conditions by modifying the main ratios between beam, draught, and length to reduce block coefficients[2] while keeping the cargo-carrying capacity unchanged. The key lesson learnt is that reducing the block coefficient makes the hull form slenderer, increases the boundary speed, and enables higher operational speeds. Or alternatively it gives lower fuel consumption when speed is kept at the same level as the more full-bodied designs. See Larsson and Raven (2010) for a more extensive discussion of how hull resistance depends on speed and hull form.

While the idea of using wind assistance for the propulsion of modern ships dates back to the early 1900s (Tokaty, 1994), the wind-assisted propulsion devices have been receiving an increased attention over the recent years (Ruihua and Ringsberg, 2020). This is mainly due to the increasing pressure for emission reduction and decarbonization of maritime sector (Councile of Europe Union, 2015). The potential benefits of wind-assisted ships come with a technical challenge (Chou, et al., 2021; Rehmatulla, et al., 2017). Because current ship hull and propulsion solutions are not constructed on the principle where additional thrust and side forces are generated from a sail (Rojon and Dieperink, 2014). Hence, the benefits of using wind capturing devices onboard the existing fleet are significantly smaller on retrofits than on newbuilds Kramer, et al., 2016.

In relation to EEDI, the legislation does not really encourage more slender ships, wind assisted propulsion or the combination of slender and wind: First, Lindstad et al. (2019) found that hull forms optimized with respect to performance in realistic sea-conditions are not rewarded with the current EEDI, which rather rewards full bodied 'bulky' hulls which performs well in calm sea, but in reality has much higher fuel consumption in real sea than their 'slender' counterparts; Second, the IMO guidelines for prediction and verification of CO_2 emissions savings with wind propulsion systems MEPC.1/Circ.815 tends to underestimate the available wind power for ships employed in trades with favourable wind conditions (Yoshimura et al., 2016; MEPC 77/6) since savings are based on the wind probability on the main global shipping routes; Third, since EEDI tends to underestimate the benefits of both slender and wind assisted, this disadvantage increases further when a vessel is built both slender and with wind assisted propulsion.

The motivation for this study has therefor been: First, to investigate potential energy and emission reductions through building more slender bulk vessels in combination with wind assisted propulsion (WASP); Second, to investigate costs and financial implications; Third to show the need for amending and updating IMO and European Union (EU) legislation to encourage and reward wind assisted propulsion. The paper proceeds as follows: The employed model is described in Section 2; the dataset is presented in Section 3; the results obtained are presented in Section 4 and their impact for policy development are discussed in the final section.

2. Model description

The main objective of the model is to calculate power, fuel consumption, and costs for the alternative designs as a function of their characteristics including hull form and WASP when employed in realistic sea trades. Equation one (1) which gives the power to be delivered by the ship engine(s) (Lewis, 1988; Lloyd, 1998; Lindstad et al., 2013, 2014; and Lindstad, 2015) considers the power needed for still-water conditions P_s, the power required for waves P_w, the power needed for air resistance P_a, the required auxiliary power P_{aux}, and the propulsion efficiency η. From which we deduct the wind Power P_{wind} generated by the installed Wind assisted Propulsion on the vessel.

$$P_i = \frac{P_s + P_w + P_a}{\eta} + P_{aux} - P_{wind} \quad (1)$$

In this study the software package NAPA has been used to create the alternative designs based on a reference vessel where we have the towing tank results, drawings, weights, and other technical data. The required calm-water power in this study are based on the regression models developed by Holtrop (1984), and the added resistance in waves is computed by the STA-wave method given by Eq. (2) (Boom and Haaselaar, 2014; ITTC, 2014).

[1] $V_b = (1.7 - 1.4 * C_b) * \sqrt{\frac{L}{0.304}}$ Here, C_b is the block coefficient and L is the length of a ship in the waterline from the forward stern or forward perpendicular, to the sternpost or aft perpendicular. The constant: 0.304 converts the ship length in meter to feet. The Boundary speed is given in knots.

[2] Block coefficient: $C_B = \frac{\nabla}{L \cdot B \cdot T}$ where ∇ is the displaced volume, L is length, B is beam and T is draught

$$R_{aw} = \frac{1}{16}\left(\rho \cdot g \cdot H_s^2 \cdot B\right)\sqrt{\frac{B}{L_{BWL}}} \tag{2}$$

Here, ρ is density of water, g is the gravity force, B is the vessel beam, L_{BWL} is the length of the bow to 95% of maximum beam on the waterline, H is the significant wave height.

Eq. (3) gives the building cost *Capex*, for the alternative designs based on the building cost of the reference vessel.

$$Capexv_{New} = Capexv_{Ref} \cdot \left(1 + \sum_{j=0}^{n}(\Delta_j)\right) \tag{3}$$

Here the cost adds pr deducts the cost delta Δ versus the reference vessel for the main cost parameters, such as steel weight, main measurements, installed power, cargo holds and cargo handling.

Eq. (4) gives the daily time charter equivalent cost (TCE), for the alternative designs.

$$TCE = Capex + Opex \tag{4}$$

Here the *TCE* expresses what is required to pay back the new vessel over the given depreciation period of 15 years, cover all the operational (Opex) and give the required return on the owner's capital (Capex). In real shipping markets, the achieved Time Charter (*TC*) will periodically be both higher (good market) and lower (poor market) than the *TCE.*

Eq. (5) gives the fuel consumption per voyage.

$$F = \sum_{i=0}^{n}\left(\frac{D_i}{v_i}\cdot\left(\left(K_f \cdot P_i\right)\cdot\left(1+\left(0.75-\frac{P_i}{P_{tot}}\right)^2\right)\right)\right) \tag{5}$$

During a voyage, the sea conditions will vary, and this is handled by dividing each voyage into sailing sections, with a distance D_i for each sea condition, and the total for the voyage is given by the summation of the sailing sections from zero to n. The second factor (D_i/v_i) gives the hours in each section of the voyage. The fuel consumption per section is given by $(K_f \cdot P_i)\cdot\left(1+\left(0.75-\frac{P_i}{P_{tot}}\right)^2\right)$ where K_f is the fuel consumption per produced kWh at the engines sweet spot, P_i is power required as a function of sea conditions, P_{tot} is total available propulsion power plus the power needed for auxiliary and hotel load. Basically, the approximation given by $\left(1+\left(0.75-\frac{P_i}{P_{tot}}\right)^2\right)$ replicates a typical fuel consumption curve with high fuel consumptions per kWh at low power, a nearly flat consumption area from 60 to 90% of max continuous power, and a gradual increase up to 100% of max continuous power. To simplify the assessment, we have chosen to ignore fuel consumption in ports and at anchor, because it will not vary as a function of neither Hull form nor Wind assisted propulsion.

Eq. (6) gives the CO_2 emissions per ton nm ε.

$$\varepsilon = \frac{F}{M \cdot D} \cdot K_{ep} \tag{6}$$

Here, K_{ep} is the emission factor for the CO_2 as a function of fuel. D is distance sailed and M is the mas of the cargo transported

Eq. (7) gives the cost per nautical mile sailed which comprises the fuel cost and time charter equivalent cost (*TCE*).

$$\mathrm{C} = \frac{1}{D}\left(\sum_{i=0}^{n}\frac{D_i}{v_i}\right)\cdot TCE_v + F \cdot Fuel_{cost} \tag{7}$$

Here D is the distance sailed including both the loaded and the ballast leg and $Fuel_{cost}$ is the cost per ton of fuel.

3. Data set

This paper focus on potential energy reductions through building more slender bulk vessels in combination with wind assisted propulsion (WASP). For this purpose, we use the large handy-size vessels, i.e., the Supramax dry-bulkers to show-how assessments of alternative designs can be made and displayed. The global dry bulker fleet consists of nearly 12,000 vessels (Lloyds List Intelligence, 2019) of which vessels with a dead weight of from 35 000 to 100 000 tons adds up to 7000 vessels, equal to 60% of the total fleet. Out of these 7000 vessels, around 40% are Supramax-es, where the largest are called Ultramax-es. In total, the dry bulk fleet performs more than 40% of the global sea transport work measured in ton-miles and nearly 50% when measured in tons transported (Bengtson, 2018). The Supramax vessels, are designed to maximize cargo carrying capacity within a maximum length of 200 m, a beam restricted to 32.3 m (the old Panama Canal locks) and a draught of around 13.5 m. This gives dead-weights (dwt) in the 58 000 - 67 000 tons range and block coefficients in the 0.86–0.90 range. They are built with 5 cargo holds and 4 slewing cranes and often with hatch covers and decks with enough strength to carry deck cargo. In sum this enables servicing ports without cranes; cargo-transshipments to or from barge or smaller vessels at sea; and the ability to carry cargo types on deck which are not suited for the cargo holds. In contrast the larger bulkers, such as Kasmarmax, Handy-Cape, and Capesize are all ungeared.

The hull surface of a designed and built Supramax reference vessel with a total length of 200 m, a block coefficient of 0.88 and a dead weight of 63 000 ton, where the detailed hull shape is known was defined in the NAPA system. By increasing the length of the Supramax to 229 m in NAPA, the block coefficient was reduced from 0.88 to 0.77 while the cargo carrying capacity remains unchanged at 63 000 dwt. Capacity wise this 229 m slender bulker is still a Supramax, but if built with the same maximum draught as the Kamsarmax, i.e., 14.6 m instead of 13.4 m as for Supramax, it will get a dwt and volume capacity in the middle between the two. In our calculation we have included these modifications in the building cost, but to keep the comparison transparent we compare both the Supramax, and the Slender 229 m dry bulker based on the same maximum draught and dwt. Basically that leaves us with two options, either to call the 229 m slender bulker a Slender Kamsarmax based on the length approach or call it a Slender Supramax based on its cargo carrying capacity. There will certainly be ports where the 229 m slender bulker is too long. Still, since this comparison is based on the cargo carrying capacity of the Supramax we call it a 229 m Slender Supramax. Local hull features near the vessel ends where manually adjusted into realistic hull shapes as scaling distorts local shapes near the bow and stern. With the length increase, we got six cargo holds instead of five, and five cranes instead of four, all of which increases the flexibility, but also building cost.

Table 1 displays technical specifications and building cost for a typical Supramax 200 m without and with WASP, the 229 m Slender Supramax without WASP and with WASP. Where the investigated WASP solution comes in the form of Flettner rotors. Flettner rotors are one of five alternative WASP options where the four others are: Kites; Rigid sails; Soft sails; Suction wings. Among these WASP technologies we consider the Flettner rotors to be the most mature for which Lloyds Register as an example has developed an online calculation tool for estimating potential savings on different routes (Flettner 2021). To enable smooth port operations and cargo loading and un-loading the Flettner rotors on dry bulkers both geared as in this study and for the un-geared dry bulkers needs to be tiltable without coming in conflict with hatches, cranes, or anything else on-board the vessel or outside the vessel. For these reasons we have designed the vessels with Flettner rotors with a height of 26 m (which is max allowed by vessel air draft), a diameter of 4 m and with 29.6meter or length distance between each Flettner rotor. Which gives us 4 rotors on the 200meter Supramax and 5 rotors on the 229meter Slender Supramax, all located in fixed positions at hatch ends on port side. Based on published literature, the vendors sites, and the wind calculation tool by Lloyds Register (https://flettner.lr.org/) we have used 100 kW as the net power from each Flettner rotor to quantify the net impact of the WASP and 250 kW as maximum attainable net power when combined with Sail Routing. The difference between WASP and WASP with Sail Routing, is that when the sail routing is included, it implies that the voyage route, is optimized to get most *out of the wind.* The cost figures in Table 1 are all based on new building and prices quoted in the market, so for retrofits the cost will be higher.

Installed power for propulsion is kept equal for all designs at 8500 kW and auxiliary consumption is set to 425 kW both in ports and at sea, equal to 5% of installed max continuous propulsion power. Specific fuel oil consumption (SFOC) in the engines sweet spot is set to 170 gram/kWh for the main engine, which in combination with Eq. (5) gives the specific fuel consumption per power unit from low to high power. Newbuilt cost for reference vessel reflects present newbuilding cost (2021), where the cost for the alternative designs is the delta versus the reference vessel. Daily capex is based on 8% annually of newbuilt cost for each design and the opex on 4% annually of newbuilt cost. It can be argued that opex will not increase when we expand the length from 200 to 229 m, but it will certainly increase for a vessel with WASP versus the same vessel without WASP. Cost includes Annual Capex + Opex + fuel at sea when steaming, divided on annual sailed distance as a function of speed and days at sea steaming. In bulk shipping 237 days per sea steaming is commonly used in calculations (65% of a year). This implies that all additional costs compared to the typical Supramax must be earned back at sea, and for this reason we compare their performance based on cost at sea when steaming. For fuel we use 500 USD per ton of oil equivalent (TOE) Fig. 1. shows the 229 m Slender Supramax with the WASP.

The main observations from Fig. 1 is that Compared to a typical Supramax 200 m we get 6 cargo holds and 5 cranes instead of 5 cargo holds and 4 cranes. In addition, with a block of 0.77 for the 229 m Slender Supramax instead of 0.88 for the Supramax 200 m, we get a longer bow section and longer aft section: Where the longer bow gives less additional resistance in waves; the lower block and the increased length gives a higher boundary speed; and the longer aft section contributes to improved propulsion efficiency.

4. Analysis

In this section we analyse the performance of the 229 m Slender Supramax with and without WASP and compare it with the

Table 1
The Investigated designs.

		Supramax 200m		229 m Slender Supramax	
			WASP		WASP
LOA	M	200	200	229	229
LPP	M	190	190	223	223
Beam	M	32.3	32.3	32.3	32.3
Draft	M	13.4	13.4	13.4	13.4
Displacement	Ton	73 700	73 700	76 544	76 544
Block – Cb		0.88	0.88	0.77	0.77
Bow length (L_{BWL})	M	15.5	15.5	45.2	45.2
Boundary	Knots	11.7	11.7	16.8	16.8
LDT	Ton	10 700	10 900	13 200	13 450
Dwt	Ton	63 000	62 800	63 344	63 094
Main Power	kW	8 500	8 500	8 500	8 500
Newbuild Cost	MUSD	30	33.5	36	40

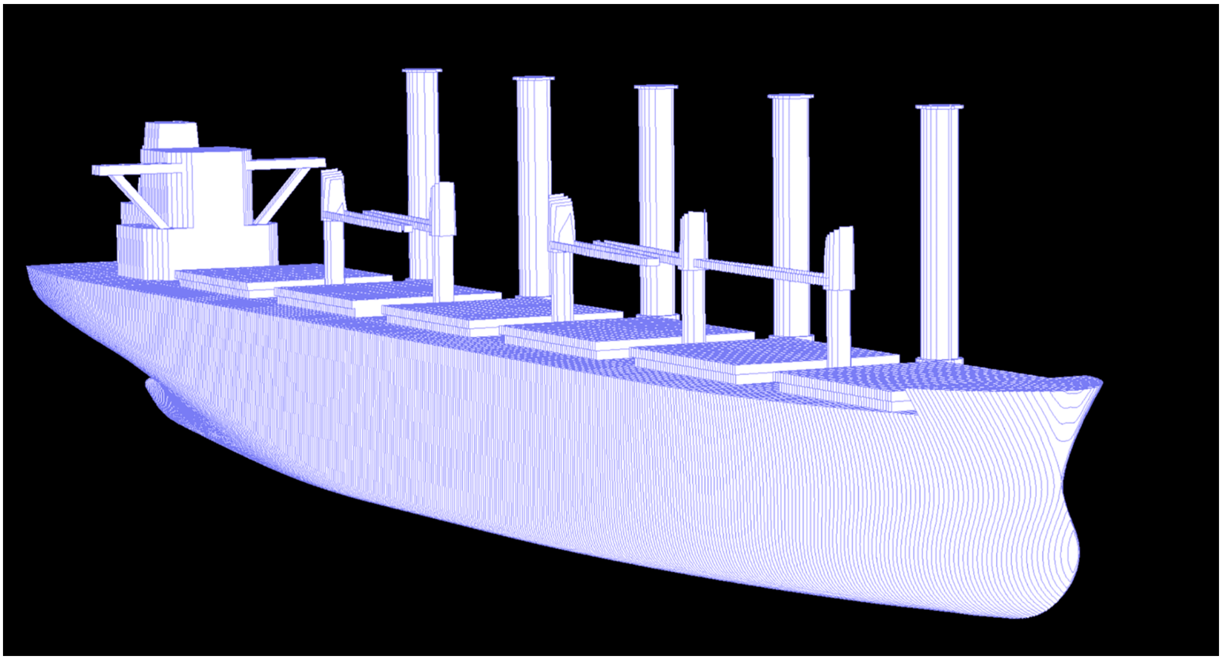

Fig. 1. The 229 m Slender Supramax with 5 Flettner rotors.

performance with the typical Supramax 200 m with and without WASP. The analysis is performed through a three-stage process. First, we compare the required power as a function of sea states and vessel speeds for the typical Supramax 200 m with the 229 m Slender Supramax; Second, we compare the required power as a function of vessel speed for the Supramax 200 m and the 229 m Slender Supramax with and without WASP; Third, we compare the GHG emissions and cost for the 229 m Slender Supramax with and without WASP with the typical Supramax 200 m.

Fig. 2 compares the required power for the 229 m Slender Supramax and the Supramax 200 m as a function of vessel speed under three sea conditions. First in calm water conditions in the left part of the figure; Second with 3 m significant head waves corresponding to 6 Beaufort wind scale in the right part of the figure; Third with a 50/50 mix of calm and 3 m head sea in the middle of the figure. The upper panel of the figure shows the absolute required power including auxiliary and the lower panel the achieved power saving for the 229 m Slender Supramax compared to the Supramax 200 m. Over a year, vessels experience waves from all directions, where following waves might give a small benefit compared to calm water if we average over all wave heights, side waves will give added resistance and Head waves gives the full added resistance. Simply using this annual pattern into a 50% - 50% distribution between calm sea conditions and 3 m head waves to reflect real global average sea conditions on an annual basis is in line with Lindstad et al. (2011) and Lindstad et al. (2018). In Fig. 2 the required total power (kW) also serves as a linear proxy for both tons of fuel use and CO_2 emissions.

The main observations from Fig. 2 are: First with calm water and low speeds the difference in required power for the two designs are marginal, with higher speeds this difference increases. The explanation is that at low speeds the 229 m Slender Supramax are punished for its larger wetted areas. Contrary at higher speeds its rewarded for its higher boundary speeds. With waves (right panel) the 229 m Slender Supramax have significantly lower power requirements across the full speed range. The main explanation is that it's rewarded for its longer bow sections. Averaging it out with a 50/50 mix of calm and head sea, the advantage of the 229 m Slender Supramax is larger than with calm sea and less than with head sea. Since a 50% - 50% distribution between calm sea conditions and 3 m head waves, also is a proxy to reflect average annual added resistance for an ocean-going vessel on an annual basis (Lindstad et al., 2011; Lindstad et al. 2019) we will use it as the reference sea condition for this analysis.

Fig. 3 shows the required power as a function of vessel speed with the reference 50/50 sea conditions for three different loading conditions: Ballast, a 50/50 mix between ballast and loaded, and when fully loaded. Five alternative options are compared: Supramax 200 m, Supramax 200 m with WASP, 229 m Slender Supramax, 229 m Slender Supramax with WASP, and 229 m Slender Supramax with WASP and Sail Routing. The difference between WASP and WASP with Routing, is that when the sail routing is included, it implies that the voyage route, when possible is optimized to get most out of the wind. Based on published literature, the vendors sites, and the wind calculation tool by Lloyds Register (https://flettner.lr.org/) we have used 100 kWh as the net power from each Flettner rotor to quantify the net impact of the WASP and 250 kWh when combined with Sail Routing. With 4 rotors on the Supramax 200 m and 5 on the 229 m Slender Supramax we get from 400 kWh up to 1250 kWh reduction in propulsion power to be delivered by the propeller.

The main observations from Fig. 3 are that simply retrofitting WASP to a Supramax 200 m gives the smallest reduction, i.e., 5 – 14%. In comparison the 229 m Slender Supramax reduces required power with 7 – 22% compared to the Supramax where the largest reduction is seen when fully loaded. The 229 m Slender Supramax with WASP reduces power with 17–40% compared to the Supramax. While the 229 m Slender Supramax with WASP and Sail Routing reduces power with 30 – 70% compared to the Supramax. The retrofit

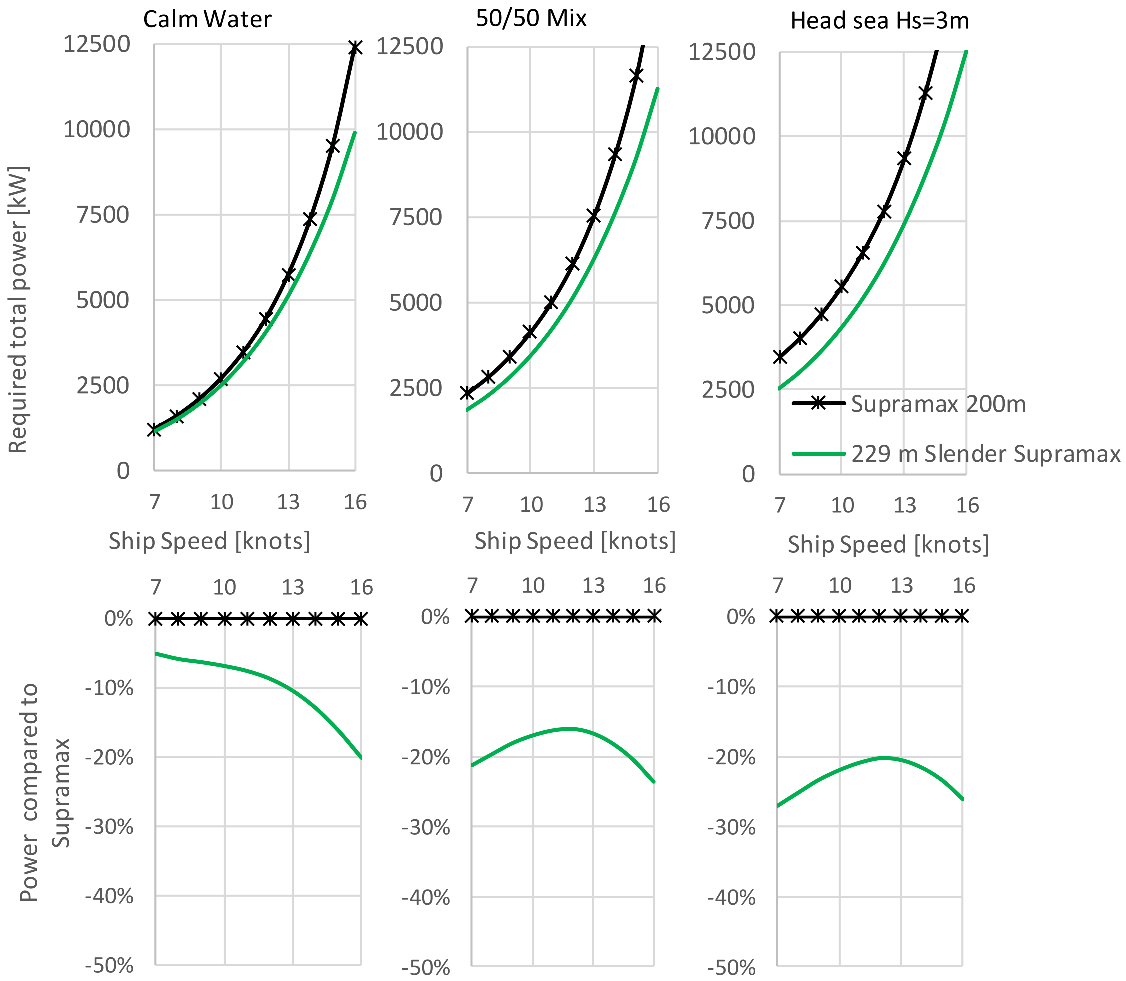

Fig. 2. Required power as a function of speed and sea conditions.

saving of 5 – 14% for a Supramax are well in line with the around 10% typically quoted for retrofitting of WASP on bulkers and tankers. Combined with sail routing as shown for the 229 m Slender Supramax an additional 10 −15% is achievable when employed in wind favourable trades with sail routing. Lloyd Register indicates that savings of this magnitude, i.e., 20 - 25% are achievable when retrofitting Flettner Rotors on tankers and bulkers (https://flettner.lr.org) and the vessels are operated on routes with very favourable wind conditions. Regarding the operational profile, the results indicates that the 50/50 mix of ballast and loaded gives a good average of the advantage of WASP solutions both with Sail Routing and without. The combination of 50/50 for ballast and loaded and 50%50 for calm and head sea are therefore used for the economic and environmental assessment in this study Fig. 4. shows Daily cost and required power as a function of speed in the upper panel, and Power and Cost per nm as a function of speed in the lower panel.

The main observations from Fig. 4 are that both power and cost increases in absolute values when the speed increases as shown in upper panels. Moving from absolute values to power and cost per nm in the lower panel we observe: First that speed of around 13 knots gives the lowest cost per nm for all the assessed options; Second that for speeds up to 13 knots the typical Supramax 200 m is most cost competitive; Third the Supramax 200 m has highest power consumption per nm of all the investigated options. Fourth, all the investigated vessels have lowest power at the lowest investigated speed, so basically 7 knots give the lowest power per nm. This fits well with the general assumption made in environmental discussions in IMO (IMO, 2014, 2020; Berthelsen and Nielsen, 2021) that speed reductions are a low hanging fruit. However, to find the speed which gives the lowest fuel consumption and emissions we must include the impact of shipbuilding. The explanation is that if average operational speeds are reduced, we need more ships to perform the required freight work, since each ship will transport less cargo per year. Contrary if average operational speeds are increased, we need less ships and the Global fleet can be reduced. Lindstad et al. (2011) found by applying Environmental Extended Input Output Life Cycle Assessment that 4.3 kg CO2 per kg ship to be built was a robust estimate for the impact of shipbuilding. For a Supramax 200 m with a weight of 11 000 tons as stated in Table 1 that gives 47 300 tons of CO_2 from the shipbuilding, equal to 2365 tons CO_2 per year if the ship is used for 20 before it is scrapped.

Fig. 5 shows the impact of including shipbuilding (LCA) in the assessment on the right side of the figure versus when we only include the operational emissions (EEOI) on the left side. The lower panel shows cost per nm with two alternative fuel price, 500 USD

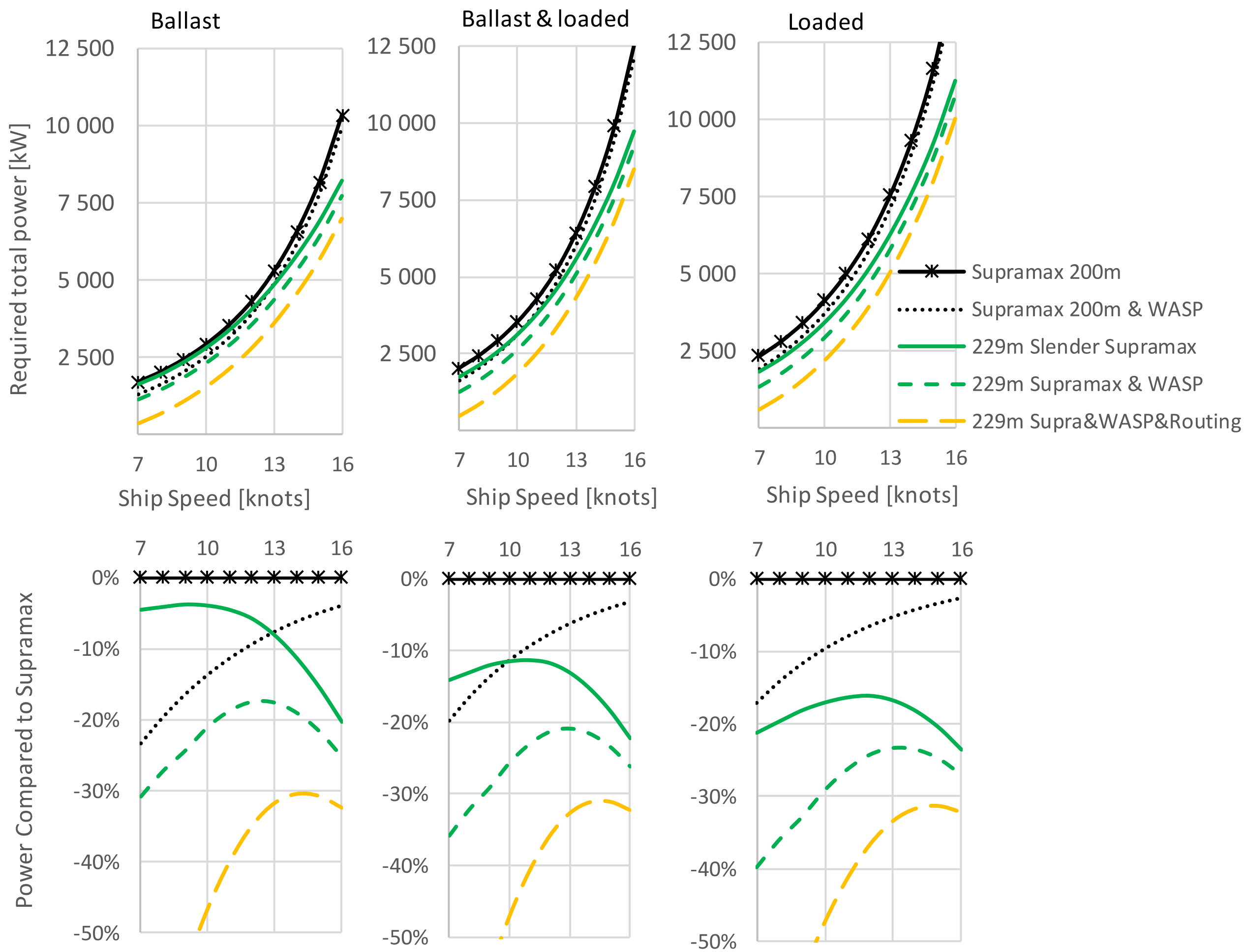

Fig. 3. Required power as a function of loading condition and speed.

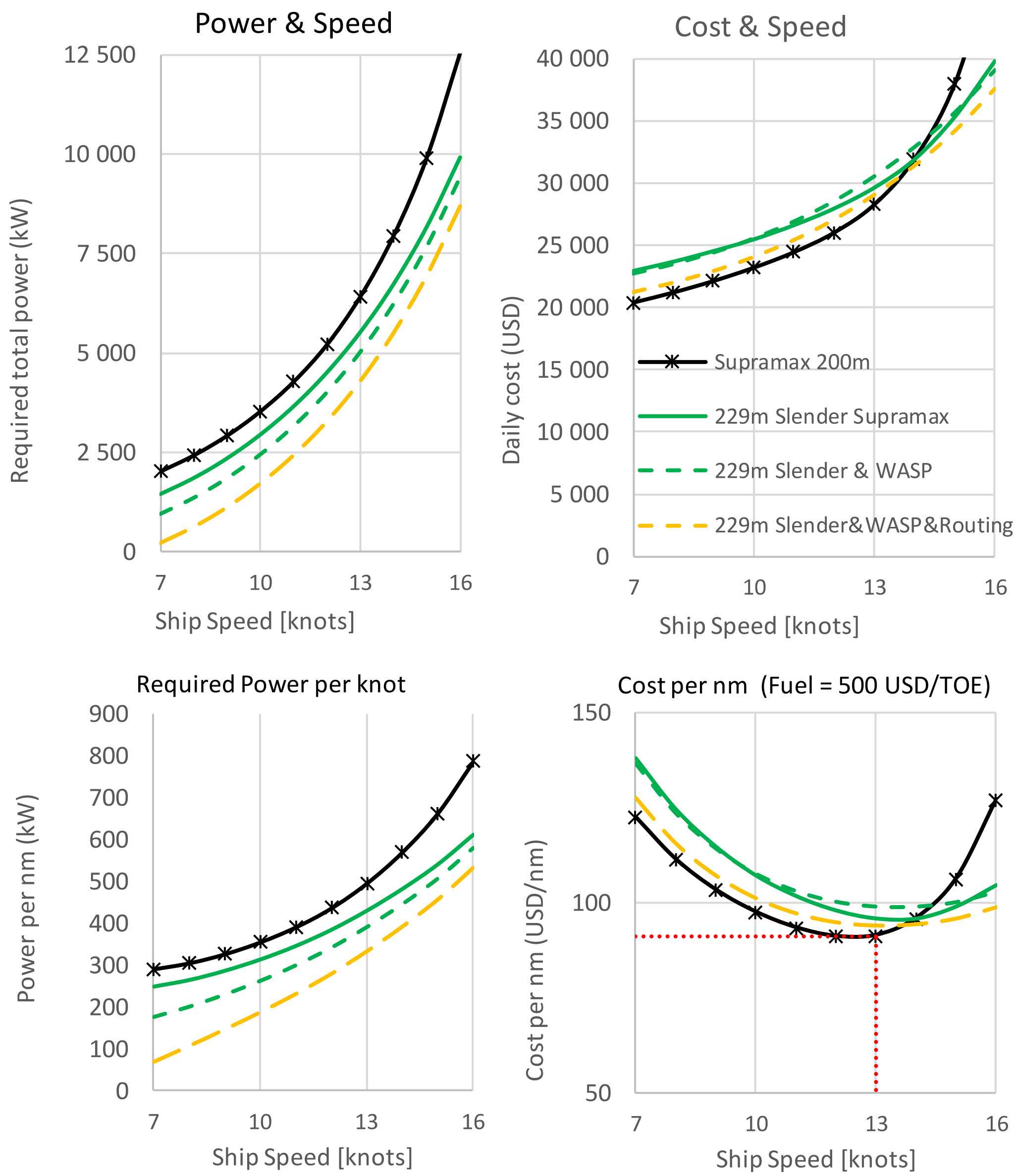

Fig. 4. Daily cost and required power in absolute values and per nautical mile.

per TOE on the right side and 1000USD per ton on the left side.

The main observations from the upper panel of Fig. 5 are that when we focus on operational emissions only (EEOI) the lowest investigate speed, i.e., 7 knots give the lowest emissions for all the investigated designs. When shipbuilding is included, we observe that speeds of around 10 knots gives the lowest emissions (LCA) for both the 229 m Slender Supramax and the typical Supramax 200 m. Higher speeds increase emissions per ton mile and for lower speeds the plotted emission curve is flat, indicating that further speed reductions give no additional emission reductions. For the 229 m Slender Supramax with WASP we do not find any speeds which gives minimum emissions, but here model and full-scale test will be needed to further investigate this. If we compare a 10 knots average operational speed with the 13 knots cost minimizing speed for the Supramax 200 m as shown with a fuel cost of 500USD per TOE in the lower panel, we find that 10 knots give 20% operational emission reduction (EEOI) and a 15% reduction when shipbuilding is included (LCA). If the Supramax 200 m is replaced by the 229 m Slender Supramax we get around 15% lower operational emissions (EEOI) and around 10% lower life cycle emissions when operated at 10 instead of 13 knots.

While the really large reductions come with the 229 m Slender Supramax with WASP: First, we observe that at 13 knots when operated under a Sail-routing the operational emissions are reduced by 28% (EEOI) and the life cycle emissions are reduced by 23% (LCA) compared to Supramax 200 m; Second at 10 knots the saving compared to the Supramax 200 m increases to 40% for the operational emissions (EEOI) and 30% lower life cycle emissions (LCA); Slender Supramax

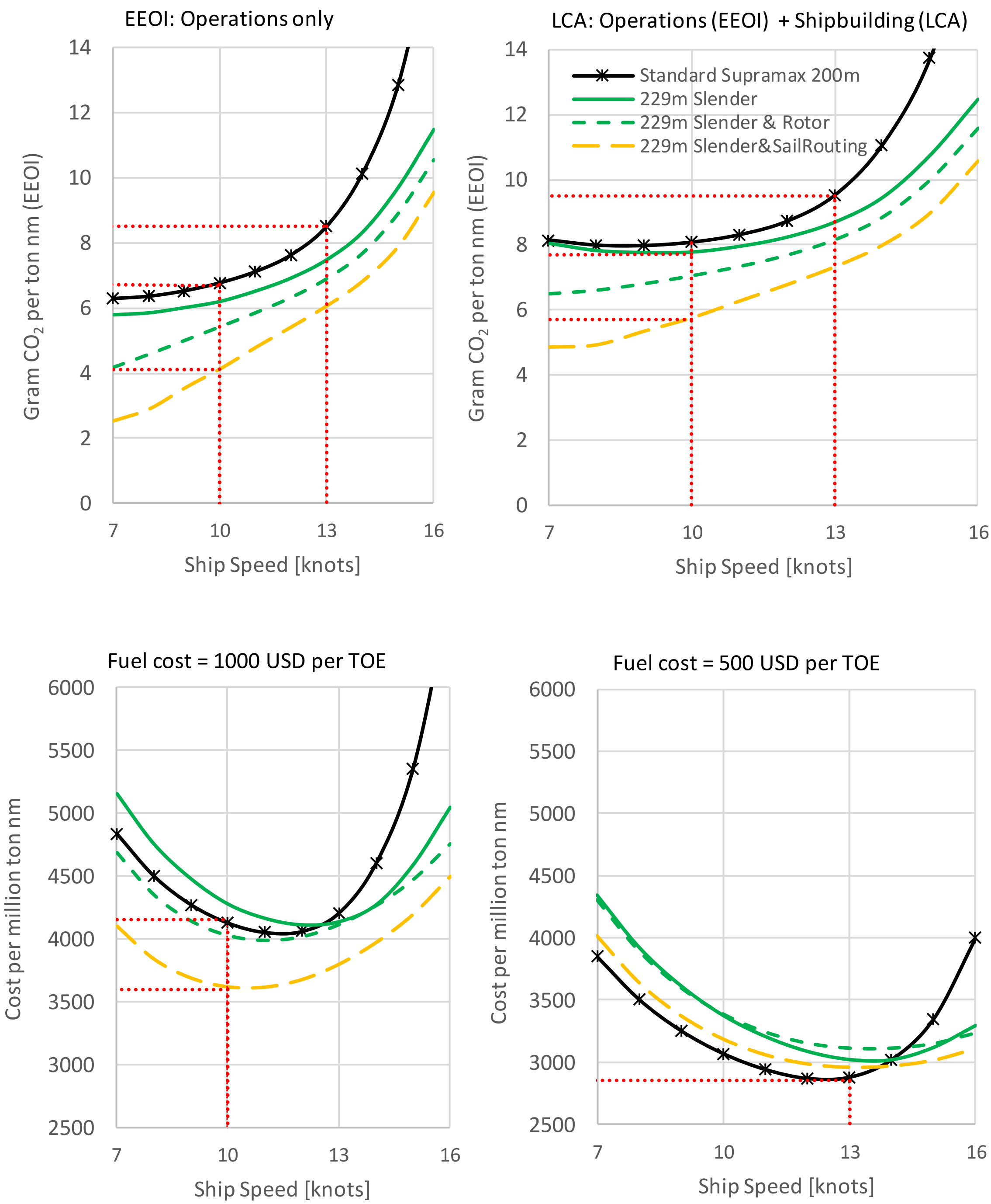

Fig. 5. Emission minimizing speed with and without shipbuilding and fuel price needed if emission minimizing speed shall be equal to cost minimizing speeds.

Back in 2018 the average speed of Supramax vessels were 11.4 knots according to the IMO fourth GHG study (Faber et al. 2020), which fits well with cost minimizing speeds of around 12–13 knots as indicated by the lower panel of Fig. 5 for a fuel price of 500 USD per TOE. With today's peak freight market and high freight rates average speeds have rather increased than decreased, because with high freight rates the additional income by going faster is much larger than the additional fuel cost caused by higher consumption and higher fuel. Where prices for compliant fuels now exceeding 600 USD per TOE for VLSFO and 700 USD for MGO per TOE. Still, even higher fuel prices are needed if the 229 m Slender Supramax with and without WASP shall outcompete the typical Supramax 200 m as we can observe from the comparison with a fuel price of 500USD per TOE versus 1000USD per TOE. With 1000 USD as a function of the fuel price on its own or the fuel price in combination with Emission trading (ETS) as now suggested by the European Union, the 229 m

Slender Supramax with WASP and with WASP and Sail-Routing gives lower transport cost than the typical Supramax 200 m. For Sail-Routing the cost advantage is around 15% at 10 knots and around 10% at 13 knots. While with the WASP and conventional routing the cost advantage is rather marginal even with a fuel price of 1000 USD per TOE.

So, despite that the WASP technology comes at only a moderate increase of newbuilding cost, i.e., around 10% and delivers operational emission and fuel reductions of up to 28% at 13 knots and up to 40% at 10 knots, WASP solutions still need a high fuel price to be cost competitive assessed on financial KPI's only. Which partly explains why we so far only has seen a limited number of vessels being fitted with WASP, despite its potentially high GHG reduction potential. There is hence a need for amending and updating legislation to encourage and reward wind assisted propulsion to ensure that its utilized as one of the core measures to reach shipping's 50% reduction target by 2050. This can be done by: First, change the wind matrix so that the wind matrix to be applied fits the intended geographical operational pattern of the new vessel when the EEDI is tested and certified; Second to include real sea conditions in the EEDI assessment to encourage hull forms optimized with respect to performance in realistic conditions which also gives better opportunities to handle additional thrust and side forces generated when WASP are used on a vessel; Third ensure that the new Carbon intensity indicator (Cii) to be introduced from 2023 does not get loopholes, so that WASP ships are fully credited for the fuel and emission savings.

5. Conclussions

This study has focused on potential energy reductions through building more slender bulk vessels in combination with wind assisted propulsion (WASP). The results indicates that fuel consumption and hence GHG emissions can be reduced by up to 40% on an operational basis (EEOI) and 30% when shipbuilding is included (LCA), when operated at an average speed of 10 knots with Sail Routing, i.e., that the vessel operates in ocean areas with good wind conditions and that the voyage route is optimized to get most out of the wind. With 10 knots speed the WASP accounts for 2/3 of the saving and the slender hull for around a 1/3. With higher speeds the total saving is gradually reduced, i.e., 28% (EEOI) at 13 knots and then the slender hull accounts for more than 50% of the saving and the WASP for less than 50%.

However, despite that the WASP technology comes at only a moderate increase of newbuilding cost, Both WASP solutions on their own and in combination with more slender hull forms needs a high fuel price to be cost competitive assessed on financial KPI's only. There is hence a need for amending and updating legislation to encourage and reward wind assisted propulsion to ensure that it utilized as one of the core measures to reach shipping's 50% reduction target by 2050.

Submission declaration and verification

The authors declare that the work described is not under consideration for publication elsewhere in the same form nor in other language, and that its publication is approved by all authors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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