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Review paper

Reduction of Greenhouse Gas (GHG) Emissions in the Maritime Sector

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Abstract: The maritime sector's greenhouse gas (GHG) emissions represent nearly 3% of global greenhouse gas emissions. The Marine Environment Protection Committee (MEPC), part of the International Maritime Organization (IMO), decides on all major actions the maritime sector needs to take globally to reduce GHG emissions. Several types of measures and events have an impact in this area. Regulatory-economic measures represent a very important aspect of this segment. Emissions Trading Schemes (ETS), taxation of GHG emissions, the U.S.-China trade war, the war in Ukraine and the COVID-19 pandemic all impact climate change. Significant contributions to reducing (GHG) emissions can also be made by implementing improved operational measures. Reducing ship speed, shortening port call times, determining optimal voyage frequency, introducing digital twin ports and, implementing cold ironing are important operational measures. The most critical factors in reducing GHG emissions are new technologies and improving existing technologies of dual-fuel engines, scrubbers' fuel cells, and the use of clean fuels. The article contains calculations on the external costs of transporting yachts from the North Sea to the Adriatic Sea. The performed analysis is based on yacht transport calculation and shipping costs between the North Sea and Mediterranean ports. Calculations were made on external costs when vessels had 80% of the load of the main engines. The research aims to perform calculations with 60% and compare the results.

Keywords: Greenhouse gas emissions (GHG), Marine Environment Protection Committee (MEPC), Technological measures.

1. Introduction

Maritime transport plays a central role in global trade and transportation, enabling the transport of more than 80% of the world's goods [1]. However, this extensive activity comes at a cost to the environment, particularly greenhouse gas (GHG) emissions. Ships, the workhorses of the maritime industry, contribute significantly to global GHG

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emissions by releasing carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other GHGs into the atmosphere. These emissions are a product of the combustion of marine fuels used for propulsion and onboard operations.

The challenge of reducing greenhouse gas emissions from the maritime sector is both urgent and complex. It encompasses several aspects: technical, alternative fuels, regulatory, economic, and operational. The International Maritime Organization (IMO), the United Nations body responsible for regulating shipping, has set ambitious targets to reduce the industry's carbon footprint. By 2050, GHG emissions from international shipping should be reduced by at least 50% compared to 2008 [2]. Achieving these targets will require a concerted effort across the industry, from ship designers and builders to operators and regulators, to introduce cleaner technologies, improve energy efficiency, and switch to low-carbon and carbon-neutral fuels.

The importance of tackling greenhouse gas emissions in the maritime sector is not just about the environment. It also impacts economic competitiveness, as regulations and market pressures increasingly favour low-emission operations. In addition, the sector's response to the GHG challenge is closely watched by stakeholders, including governments, environmental organisations, and the global community, as it is seen as a measure of the industry's commitment to sustainable development and its role in combating climate change. As the maritime industry navigates these waters, the journey towards sustainability and reduced GHG emissions is a legal mandate and a strategic imperative that will shape the future of global shipping.

2. Aspects of combating GHG emissions in the maritime sector

As mentioned, economic-regulatory measures are one aspect of reducing greenhouse gas emissions. Maritime emissions trading schemes are probably one of the most critical steps in this direction. [3] modelled an emissions trading scheme for the Arctic Northeast Passage (NEP) compared to the Suez Canal route. They concluded that a higher price on carbon emissions for the Arctic Northeast Passage in an ideal environment would reduce emissions by lowering the speed of ships. Still, a price too high for this route would divert ships to the Suez Canal direction, which would have the opposite effect, namely higher emissions, as the Suez Canal route is longer. [4] have highlighted some important regulations that impact reducing GHG emissions, including the IMO's proposed reduction of sulfur content in fuels from 3.5% to 0.5% from January 2020 and the Tier system's control of nitrogen oxide (NOx) emissions, also proposed by the IMO. They also emphasise the importance of awareness and research through modelling and real-time feasibility. [5] describe the phases of ETS application. First, the government determines the amount of carbon emission allowances; then, the initial allocation is made to shipping companies (free allowances and non-free allowances through government auctions). The third step is reporting emissions and verifying them by the shipping companies. Shipping companies can trade their carbon emission allowances (CEAs) on the carbon market and buy additional ones. During these processes, the government oversees and ensures that everyone complies. The ETS mechanism has major socio-economic benefits as it reduces emissions and makes additional tax money available for public programs. The biggest challenge in implementing a globally harmonised regulatory framework is posed by two UN principles: Common but Differentiated Responsibility (CBDR) and No More Favorable Treatment (NMFT). The first is favoured by low-income countries, and the second by high-income countries. [6] argues that this can be overcome by the following measures: Climate funds (financial support for poor countries to reduce greenhouse gas emissions), grant programs (subsidies for small countries to modernise their fleets), technical assistance for poor countries, technology transfer, and international cooperation.

The operational perspective also plays a decisive role in combating emissions, as operational measures are also the easiest to implement. [7] point out that high port handling capacity and efficient repositioning of empty containers can contribute to the reduction of $CO2$ emissions in container transportation by sea through reduced idle time (the vessel has a shorter dwell time in port), efficient repositioning of empty containers (point-to-point and coordinated repositioning policy), improved operational efficiency (high port handling capacity leads to lower energy consumption) and environmental and economic benefits (improved operational efficiency reduces fuel consumption and thus overall costs). Reducing ship speed is the most effective operational tool for reducing greenhouse gas emissions. According to [8], this has environmental benefits (lower emissions), economic benefits (savings in fuel costs) and regulatory compliance and better compliance with the Carbon Intensity Indicator (CII). The extent of speed reduction also depends on other factors. [9] concluded that optimal speed reduction is a dynamic process that depends primarily on charter rates and fuel prices. Ports can also reduce emissions at an operational level. [10] suggested fuel-shifting measures (blending cleaner fossil fuels and renewables in the port's overall energy supply), retrofitting cargo handling equipment with emission control technology, retrofitting engines and introducing energy-efficient equipment, and implementing emission reduction measures (activities that save operational costs by reducing fuel and electricity consumption). The crew members on the ships [11] play a crucial role in reducing emissions by implementing energy efficiency measures (speed optimisation, conducting voyages, and weather routing), monitoring and maintenance of key components such as hull, propeller, and engine, compliance with regulations (e.g. SEEMP), training and awareness programs on energy efficiency practices, continuous improvement by implementing good feedback and suggestions in this area.

According to [12], there are several key technologies in reducing greenhouse gas emissions in the maritime sector. These include waste heat recovery systems, air lubrication systems, advanced propulsion systems (dual-fuel engines, hybrid propulsion systems) and solar hybrid systems (installation of solar cells on ships to harness solar energy). According to [13], hybrid propulsion offers several advantages, including load balancing (the battery can use the excess power generated by the prime mover, e.g. the diesel engine), optimal operating point (by using the energy storage system, the use of diesel propulsion can be optimised to run at minimum SFOC at loads), flexibility and optimisation of external emission control techniques, and energy availability in case the prime mover needs to run at lower power, e.g. in emission control areas. The most important technological measure is using ammonia, hydrogen, or methanol as primary fuels. These fuels are not yet competitive with fossil fuels due to their higher price and lower calorific value. [14] believe that low prices for ammonia on the market cannot compensate for the high operating costs due to the low energy content. This could only be overcome by comprehensive taxation of emissions around the world. Ammonia also requires solutions to reduce NOx emissions, increasing the overall cost. [15] also point out that total fuel emissions depend on their production routes. Alternative fuels produced from fossil sources (grey fuels) may not sufficiently reduce emissions compared to green fuels (renewable sources). They also pointed out that the infrastructure for bunkering and distributing alternative fuels is not yet fully developed in many cases. The legal framework for including alternative fuels is also not yet globally. [16] write that upgrading and retrofitting existing ships for the use of alternative fuels can be an obstacle due to the procedure's cost. Due to the lower calorific value of alternative fuels compared to fossil fuels, the load capacity of ships could decrease as more space is needed for fuel storage [17]. The toxicity of ammonia, the explosiveness of hydrogen, and the flammability of methanol must also be taken into account. These obstacles must be overcome before the full introduction of alternative fuels.

3. Case study of transporting yachts from Rotterdam to Split

The most important operational measure to reduce greenhouse gas emissions is to reduce speed. This reduces the power required for propulsion and reduces emissions. [18] conducted an emissions-based study on the transport of yachts from Rotterdam to Split during the summer months. In their study, the yacht to be transported was the Beneteau Swift Trawler 47, displacing 13 t. The transport vessel for the yachts was the general cargo vessel MV Deo Volente (Gross tonnage: 2999 GT, Dead Weight Tonnage: 3650 t, Displacement 5486 t, Lightship weight: 1736 t, Maximum container capacity in hold: 73 TEU, Maximum container capacity on deck: 163 TEU, Total container capacity 236 TEU) [19]. One of the objectives of their research was to find out which would be more advantageous from an emissions point of view: e.g., either each yacht would make the journey alone, or it would be better to transport them from Rotterdam to Split using the mentioned transport vessel, both with 80% utilisation of the main engines. Their study concluded that transporting yachts by cargo ship is more environmentally advantageous, with external costs of € 9,899 compared to € 76,448 for the general cargo vessel. Still, in the case of the general cargo vessel, the unit external costs must be taken into account, as the vessel used in the study could carry up to 15 yachts, reducing the unit external cost to € 5,097, almost twice the unit external cost of the yachts. The authors of this article attempted to determine at what power/speed the external costs of the yacht would reach those of the general cargo vessel at 80% of the main engine load. Previously, the authors of this study thought that [18] used an incorrect SFOC value for the Beneteau Swift Trawler 47 at 80% engine load (275 g/kWh). The authors of this study concluded that the SFOC at 80% engine load is 214.8 g/kWh by using the official data from the engine manufacturer Cummins [20]. The SFOC calculations were also performed for 60%, 50%, 40%, and 30% engine load, as shown in Figure 1.

The authors of this study have also drawn their power curves for the Cummins QSB 6.7 engine (Figure 2).

The engine generates more power than the propellers require (Extra power available). The engine accelerates until the power curve of the propeller and the engine intersects in the upper right corner. The propeller can absorb the maximum power from the engine as defined by the propeller curve.

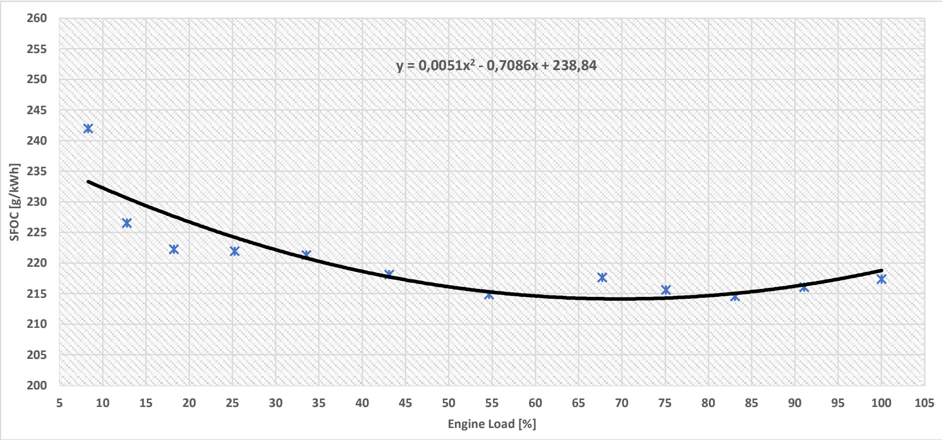

Fig. 1 - *SFOC curve of Cummins QSB 6.7 engine.*

Unfortunately, insufficient data is available to generate propeller curves for the ship in different loading conditions (design conditions and loading conditions with yachts on board).

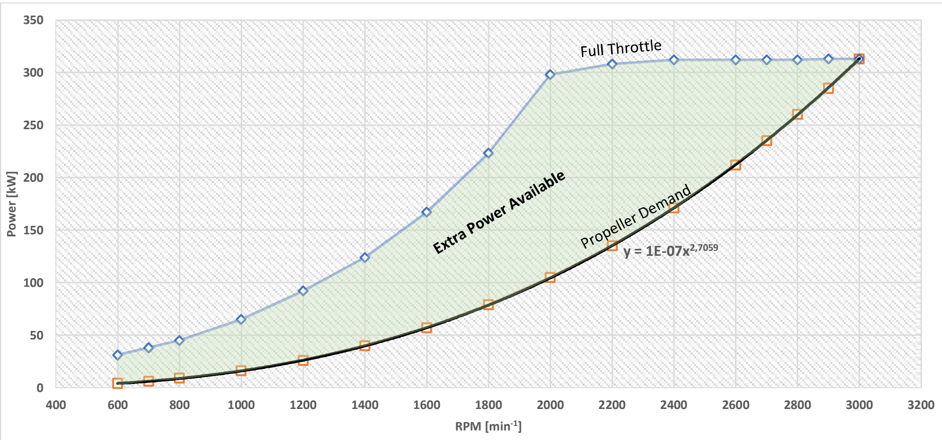

Fig. 2 - *Power curves of Cummins QSB 6.7 engine.*

For this study, the external costs for different main engine loads had to be calculated. First, the new speeds had to be determined using the formula:

$$\frac{P_{80\%}}{P_{x\%}} = \frac{v_{80\%}^3}{v_{x\%}^3} \tag{1}$$

where P is the power and v is the speed. The ship's main engine produced 2944 hp at 80% load; at this power, the ship reached a speed of 13 knots. On the other hand, the yacht has an output of 499.2 hp at 80% load and a speed of 20.25 knots. The speeds achieved at different loads are given in Table 1.

Table 1- *Speeds of vessels at different loads.*

Load (%)	Ship speed [kn]	Yacht speed [kn]
60	11.81	18.39
50	11.11	17.31
40	10.31	16.07
30	9.37	14.6

The travel times must increase because the route length does not change at lower speeds. In addition, the times were calculated separately for the Atlantic and Mediterranean parts of the voyage, as the external emissions costs differ in the two regions. The formula used was:

$$t_{x\%} = \frac{v_{80\%}}{v_{x\%}} \cdot t_{80\%} \tag{2}$$

where t is the calculated voyage times of the vessels for the following loads (for the Atlantic voyage-AV and the Mediterranean voyage-MV) given in Table 2.

Table 2 - *Voyage times of vessels at different loads.*

Load (%)	Ship voyage time MV [h]	Ship voyage time AV [h]	Yacht voyage time MV [h]	Yacht voyage time AV [h]
60	136.25	140.6	87.5	90.14
50	144.79	149.24	92.98	95.79
40	155.97	160.76	100.16	103.18
30	171.67	176.94	110.24	113.57

The fuel consumption for the different engine loads can be calculated using the following formula:

$$FC = (P * t) * SFOC \tag{3}$$

FC stands for fuel consumption, and *SFOC* for specific fuel oil consumption. Again, fuel consumption must be calculated for the Atlantic and the Mediterranean with different engine loadings. For the ships, the consumption of the auxiliary engines had to be included in the calculation. As in [18], the authors of this article leave the utilisation of auxiliary engines at 30%. The calculated fuel consumption of vessels at different loads is provided in Table 3.

Table 3 - *Fuel consumption of vessels at different loads.*

Load (%)	FC of ship MV [t]	FC of ship AV [t]	FC of yacht MV [t]	FC of yacht AV [t]
60	67	69.1	7	7.2
50	61.6	63.4	6.3	6.5
40	55.4	57.1	5.5	5.6
30	49.2	50.7	4.6	4.7

The next step was to determine the amount of emissions using the formula:

$$EPA = FC * EF \qquad (4)$$

EPA is the amount of pollutants emitted, and *EF* refers to emission factors. Each type of fuel causes different emissions. The cargo ship runs on MDO (0.1% S), and the yachts use Euro Diesel V Euro (0.001% S). The EPA values for different vessel loadings are provided in Table 4.

Table 4 - *EPA values of vessels produced during the voyage for different loadings.*

Load (%)	EPA of ship MV [t]	EPA of ship AV [t]	EPA of yacht MV [t]	EPA of yacht AV [t]
60	215.9	222.6	22.6	23.2
50	198.1	204.2	20.1	20.7
40	178.5	183.9	17.5	18.16
30	158.4	163.2	14.7	15.1

For the conclusion, the external costs for the different cargoes were calculated according to the formula:

$$EC = EPA * APC \qquad (5)$$

Different emissions have different external costs depending on the area (the Atlantic differs from the Mediterranean). The combined external costs (Atlantic and Mediterranean) for vessels at different loads are stated in Table 5.

Table 5 - *External costs produced by the vessels during voyage.*

Load (%)	EC of ship [€]	EC of ship per unit [€]	EC of yacht [€]
60	70930	4729	6373
50	65072	4338	5688
40	58620	3908	4959
30	52024	3468	4159

In Table 5 and Figure 3, the external costs of the ship per unit have been taken into account, as the ship can carry up to 15 yachts of this type. One can see that the point at which the yacht reaches the exact external costs as the cargo ship per unit at 80% load of the main engine is around 41% load of its main engine (€ 5073). From an ecological point of view and disregarding the economic factor, the Beneteau Swift Trawler 47 would need to significantly reduce its performance and speed to become more ecological than the MV Deo Volente.

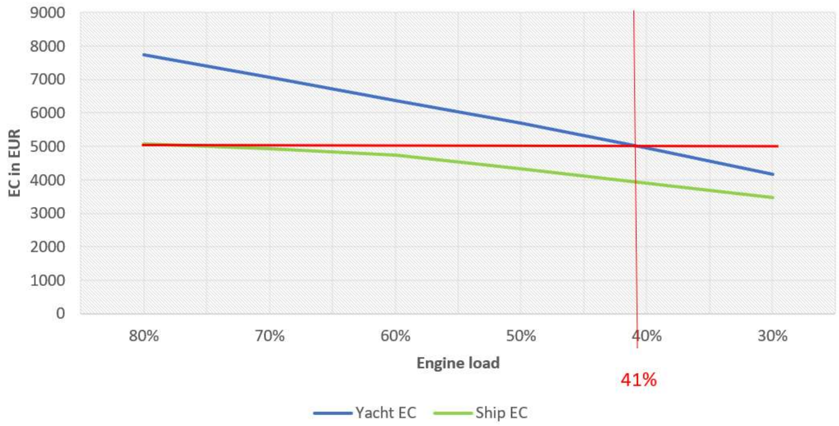

Fig. 3 - *External costs of ship and yacht for different engine loads.*

At this point, even with a reduction in power to 41% of the main engine load, the Beneteau Swift Trawler 47 would still be faster than the MV Deo Volente at 80% of the main engine load (16.2kn versus 13kn). Other economic factors would not favour this type of transport either, as [18] pointed out.

4. Conclusion

The decarbonization of the maritime sector is taking place worldwide, with the IMO and its body MEPC acting as key players. The EU is the most faithful observer of MEPC recommendations. EU legislation, such as MRV and the EU Emissions Trading Scheme, directly impacts ship owners, ships, and ports in the EU. For example, the greener transport of yachts from Northern Europe to Southern Europe during the summer months can be seen as a small step towards decarbonizing the maritime sector in the EU. This article focuses on operational measures (such as speed reduction) for decarbonizing yacht transport. In the long term, technological advances can only achieve full decarbonization, especially with alternative fuels such as methanol, ammonia, and hydrogen. Additionally, integrating digital technologies, such as AI and Big Data, offers promising potential to optimize routes and improve fuel efficiency, significantly reducing emissions. However, moving forward will also require robust regulatory frameworks that encourage innovation and ensure compliance. Collaboration among nations, industries, and scientific communities is essential for driving research, sharing knowledge, and developing solutions that pave the way to a more sustainable maritime future.

By addressing these challenges, the maritime industry contributes to the global fight against climate change and ensures its sustainability in the face of evolving environmental standards and expectations. The path ahead is complex and full of challenges, but with continued commitment and innovation, the maritime sector can progress toward a greener, more sustainable horizon.

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