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Reducing Greenhouse Gas Emissions from Ships through Analyzing of Marginal Abatement Cost (MAC) Curves

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I. INTRODUCTION

International shipping contributes with approximately 2.4% of global anthropogenic greenhouse gas (GHG) emissions, and its share is expected to increase in the future (International Maritime Organization, 2014), GHGs from shipping include mainly carbon dioxide (CO_2), methane (CH_4) and dinitrogen oxide (N_2O), of which CO_2 dominates the global warming potential. In addition, ships also emit other gasses with climate impact such as black carbon which has a warming potential and sulphate particles which have a cooling effect.

Energy efficiency measures are important to implement in order to decrease fuel use, but significant reduction in GHG emissions can be achieved only by the replacement of fossil fuels with renewable fuels. Energy efficiency can be defined by the relationship between the benefit or performance of a service and the energy input.

In fact, CO_2 emissions from the shipping sector rose substantially in recent decades as global trade and production continued to expand. Because ships are by far the most energy-efficient means of moving goods, shipping-sector emissions are expected to continue to grow even as rising oil prices encumber growth in other transportation modes.

In recent years, social interest on global warming issues has grown increasingly in recent years and topics related to energy conservation and reduction in CO_2 emissions is omnipresent. International efforts to reduce the impact of climate change started primarily in Rio in 1992 where the framework for sustainable development was agreed by more than 150 governments. This was followed by adoption of the Kyoto Protocol in 1997 which bound the Annex I nations to reduce GHG emissions to an average of 5.2% below 1990 levels, by 2012. Although ships are the most fuel efficient mode of mass transport, the Second International Maritime Organization (IMO) GHG Study 2009 identified a significant potential for further improvements in energy efficiency mainly by the use of already existing technologies. Due to its international nature, marine transportation could not be directly handled through the Kyoto Protocol by Annex I countries. Instead, they are tasked to work through IMO. Political and public pressures have therefore been mounting on IMO, being a reasonable organisation for international shipping under climate change conventions, to act, see IMO publications in the references.

Marginal abatement cost (MAC) curves are a staple of policy discussions where there is a need to illustrate the incremental contributions of parts to a whole. In the instance, they provide a simple and elegant way to illustrate greenhouse gas emission (GHG) reductions from design standards, retrofit technologies, and operational measures that improve ship energy efficiency relative to their costs.

The first generation of MAC curves for marine GHG reductions effectively stimulated discussion about measures and standards but lacked detail. Development of more tailored policies for the industry requires MAC values with greater resolution, so that they are more applicable to specific ship types in the context of future trends. Such policies are critical to creating appropriate incentives and market signals in a diverse and competitive industry. Policies based on more general, low-resolution data are more likely to lead to unintended inequities and poorly matched incentives.

This article is divided into these sections: Section 1, Introduction; Section 2, Greenhouse gas emission from ships; Section 3, Applying the MAC curves for ship types and technical measures; Section 4, Results and Section 5, Conclusion.

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II. Greenhouse Gas Emission from Ships

MEPC 67 (Marine Environment Protection Committee) approved the Third IMO GHG Study 2014, providing updated emission estimates for greenhouse gasses from ships. According to estimates presented in this study, international shipping emitted 796 million tonnes of CO_2 in 2012, that is, about 2.2% of the total global CO_2 emissions for that year. By contrast, in 2007, before the global economic downturn, international shipping is estimated to have emitted 885 million tonnes of CO_2, that is, 2.8% of the total global CO_2 emissions for that year.

IMO's Marine Environment Protection Committee (MEPC) has given extensive consideration to control of GHG emissions from ships and finalized in July 2009 a package of specific technical and operational reduction measures. In March 2010 MEPC started the consideration of making the technical and operational measures mandatory for all ships irrespective of flag and ownership. This work was completed in July 2011 with the breakthrough adoption of technical measures for new ships and operational reduction measures for all ships, which are consequent, the first ever mandatory global GHG reduction regime for an entire industry sector. The adopted measures add to MARPOL Annex VI a new Chapter 4 entitled "Regulations on energy efficiency for ships' making mandatory the Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Plan (SEEMP) for all ships. The regulations entered into force through the tacit acceptance procedure on 1 January 2013 and apply to all ships over 400 gross tonnages and above.

The IMO predicts that tonne-miles of goods moved globally will increase 2% to 4% annually between now and 2050. This substantial industry growth translates to a near tripling of GHG emissions by 2050. It is estimated that GHG emissions from international shipping contribute to domestic and inland ships in 2007, for a total of 1050 mmt. At current rates of increase, shipping –sector CO_2 is expected to climb to between 2,500 mmt and 3,650 mmt by 2050. As of 2007, domestic and international shipping CO_2 emissions accounted for 3.3 percent of the global total. As the world economy's reliance on the global trade of goods, materials, and petroleum continues to rise, this figure is estimated to climb to between 2,500 mmt and 3,650 mmt by 2050.

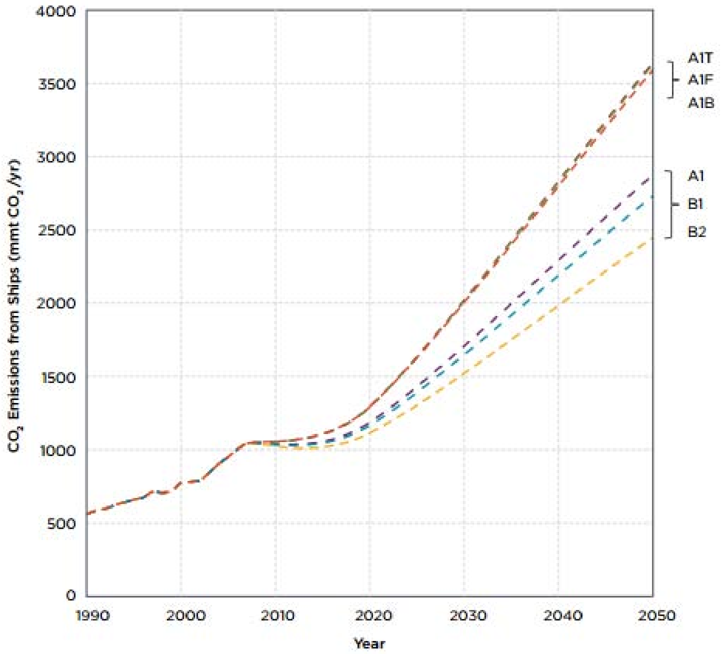

Figure 1: Projected growth of CO_2 emissions from shipping

A1F, A1B, A1T, A2, B1, and B2 are emission growth scenarios based on global differences in population, economy, land-use and agriculture. The six scenarios were used by the IMO Expert Group to form six growth scenarios for the shipping industry.

Figure 1 shows IMO projections of GHG growth based on six scenarios with varying assumptions for efficiency improvements, international trade growth, and GDP growth [5]. These estimates assume business as usual with little change to either economic growth rates or the composition and activity of the world's shipping fleet. Regulatory proposals before the IMO in 2011 could have significant impact on these projections, either by gradually increasing the overall efficiency of the shipping fleet or by increasing the tonne-mile cost of goods. But to meet ambitious CO_2 reduction goals, even more profound changes will be needed.

III. Applying the Marginal Abatement Costs (MAC) Curves for Ship Types and Technical Measures

The Marine Environment Protection Committee (MEPC) has been referred to a study of the greenhouse gas emissions from ships, first published in 2000 and updated in 2009 as the Second IMO GHG Study 2009, and presented at MEPC 59. The Second IMO GHG Study shows the social cost of some existing technical and operational measures. Policy makers and stakeholder have identified a range of abatement measures that are available or under development to slow the growth of energy consumption and CO_2 emissions from marine shipping. However the full cost accounting and assessment of effectiveness has been sparse. The cost-effectiveness of individual measures and of sets of measures is of increasing interest to policy makers, ship designers and builders, and existing ship owners.[6] Furthermore, some researches also indicated that estimate of CO_2 emissions reduction potential and associated marginal abatement costs for 14 types of new and existing ships as defined by the International Maritime Organization's (IMO) Greenhouse Gas (GHG) Experts Group. [7] Abatement cost is the cost of reducing environmental nagatives such as pollution. Marginal cost is an economic concept that measures the cost of an additional unit. The Marginal Abatement Cost (MAC) measures the cost of reducing one more unit of pollution. [11] Marginal Abatement Cost method includes six steps like as:

- Identification of CO_2 abatement technology;
- Calculation of the cost-effectiveness of individual measures;
- Evaluation of the sensitivity to input parameters;
- Identification of constraints and barriers to implementation;
- Rank ordering technologies;
- Calculation of Marginal Abatement Cost Curve (MACC) as a function of ship type.

The first step identified CO_2 abatement technologies and operational measures. This was done through a comprehensive literature survey, a web-based survey and contacts with experts and technology users. The identification included collecting data on costs and abatement potential. [8]

The second step was the calculation of the cost-effectiveness of individual measures. Cost-effectiveness is by definition the quotient of costs and effect. This is also referred to as marginal abatement cost (MAC). CO_2 abatement technology often requires an investment in new technology. Generally, the technology requires maintenance and other operational costs. Since installing the technology may take time and cargo space, there may be opportunity costs involved (the time and space could have been used to generate revenue) due to loss of service. In addition, there are fuel savings which are a negative cost or a benefit. The cost-effectiveness is the total annual costs divided by the CO_2 abated per year. The discount rate used to annuitize capital costs reflects the cost of capital of the maritime industry. (8)

On the other hand, based on the description above, the model of the cost function is installed with new technology and indicated in Equation 1 below.

$$\Delta C_j = K_j + S_j - E_j + \sum O_j \tag{1}$$

In where:

ΔC_j is the change of annual cost of the technology j;

K_j is the capital cost of the technology j, discounted by the interest rate and written down over the service years of the technology or the remaining life time of the ship, which ever is shortest;

S_j is the service or operating costs related to use the technology;

ΣO_j is the opportunity cost related to lost service time and space due to the installation of the technology;

E_j is the fuel expenditure savings from that technology, which is a product of the price of fuel and the saving of fuel as described in Equation 2.

$$E_j = \alpha_j . F . P \tag{2}$$

Where

α_j is the fuel reduction rate of technology j;

F is the pre-installation or original fuel consumption for a ship;

P is the fuel price.

The original fuel consumption of a ship of a certain type, size and age is taken from the IMO 2009 GHG study. It is assumed to be constant over time so therefore the baseline does not need to make assumptions about which technologies would be used to achieve business-as-usual (BAU) energy –efficiency improvements.[8]

For each measure, costs associated with use of each identified ship type were determined. These included the cost of purchasing, installing, and operating, as well as any lots profits due to opportunity costs. Because these cost may vary significantly for ships of different types, sizes, and ages, a total of 53 ship type and size combinations were considered. These combinations were further applied to 6 different age bins spanning an assumed 30 year life. Altogether, we analyzed the marginal abatement costs associated with each measure for 318 ships types, sizes, and age combinations. The costs of each combination were then sorted and ranked. A simplified version of the calculation appears in equation (3):

$$MAC = \frac{\Delta C_j}{\infty_j . CO_2} = \frac{K_j + S_j - E_j + \sum O_j}{\infty . CO_2} \qquad (3)$$

In where: ΔC_j: Capital cost;

K_j = ΔC_j discounted by the interest rate and service years;
S_j: Service cost of the measure;
ΣO_j: Opportunity cost related to lost service time due to the installation of the energy-saving measure and the discounted costs related to alternative uses of capital;
E_j: Energy savings from that energy-saving measure, which is a product of the price of energy and the saving of energy;
∞_j: Energy reduction rate of energy-saving measure j;
CO_2: Original CO_2 emissions from a ship.

The third step was the evaluation of the sensitivity to input parameters. It is performed a sensitivity analysis for fuel prices and discount rates.

The fourth step was the identification of constraints and barriers to implementation. The technical barriers for each individual measures that based on information from manufacturers, users of the technology, and other experts. In addition to that several general barriers and constraints were identified.

The fifth step was to rank order technologies based on their cost-effectiveness. The rank-ordering was done separately for each of the 318 different combinations of ship type, size, and age that were considered in our model. Of course, for each combination of ship type, size and age only those technologies were rank ordered that can be implemented on those ships. [8]

The sixth step was to develop Marginal Abatement Cost Curves (MACC). MACC are plots of the cost effectiveness of additional measures against the resulting cumulative reduction in CO_2 emissions. For each combination of ship type, size and age, there are a suite of technical and operational measures that can be applied together. In other words, the cost and effectiveness are not a simple summation. Moreover, if different measures are implemented on the same ship, the cost-effectiveness of the measures changes because the effect of each additional measure is reduced by the fuel savings realised by previous measures. The construction of a MACC assumed that the most cost effective option (which is the option with the highest net present value) would be implemented first, the next most cost effective option second, and so on. [8]

Once calculated, mutually exclusive measures were compared based on cost effectiveness for each ship category. To develop the MAC curve, the 15 categories are ranked based on their marginal abatement cost, with the least expensive option assumed to be implemented first, followed by the second-least expensive, and so on for all measures. Because some measures will have lower CO_2 abatement potential as they are applied after other measures, marginal costs of subsequent measures were adjusted where previous measures would dilute their effectiveness.

Charting the 15 categories of efficiency measures beginning with the least expensive yields the marginal abatement cost curve. Figure 2 and Figure 3 show the aggregate curve and the contributing curves for each ship type. Comparing the marginal abatement costs in this manner shows that the majority of potential emission reductions, 340 mmt out of a total 436 mmt, could be reduced at negative marginal cost. This is equivalent to a central bound value of 33% potential reductions from projected improvements versus business as usual by 2020. 26% of these improvements can be had with negative cost. The lower and higher bounds for total potential emission reductions are 20% and 46%.

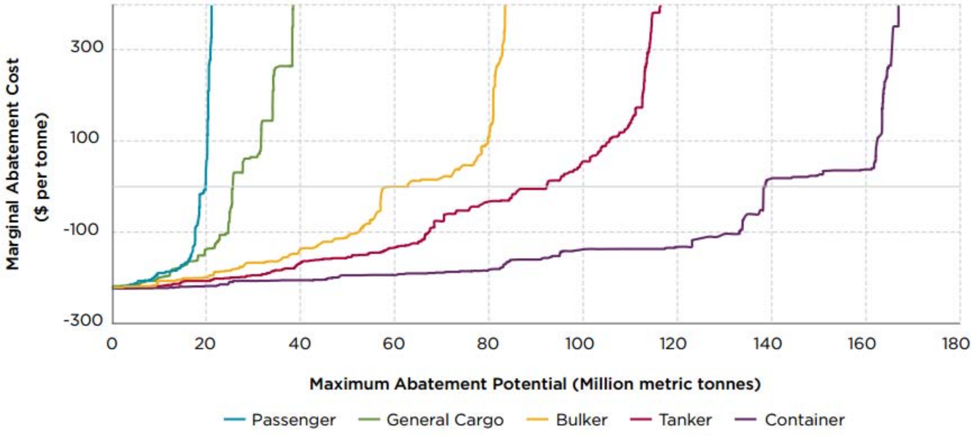

Figure 2: Central estimate of abatement potential by ship type

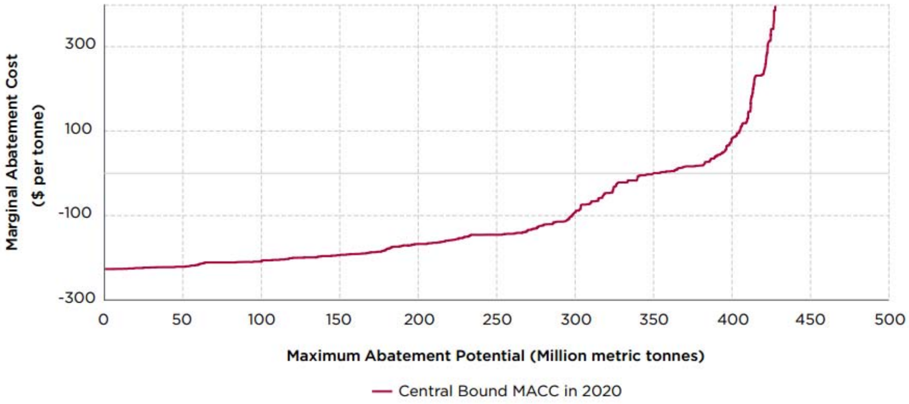

Figure 3: Central estimate of abatement potential in aggregate

Figure 4 further breaks down the reduction potential for the five major ship types. Each ship type, except for passenger ships, can achieve more than a 30% reduction. The lower reduction potential for passenger ships is mainly attributable to the assumption that speed reduction was not an option.

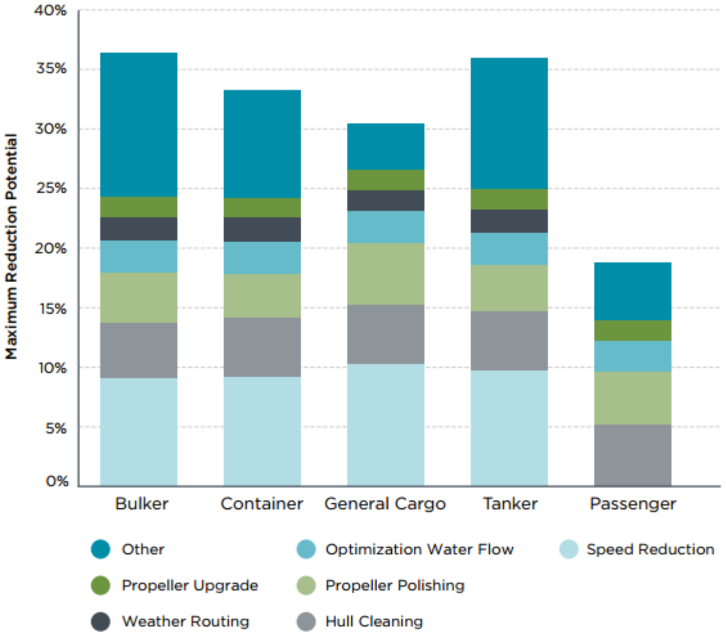

Figure 4: CO_2 reductions of technical and operational measures by ship types

Reorganizing the MAC curve and bundling CO_2 reductions by measure shows the relative cost and reduction potential of each measure.

IV. RESULTS

Mitigation measures on the MAC curves represent the urban sectors of GHG emissions that are compatible with those reported in the city's GHG inventory, and include technologies that reduce electricity and natural gas consumption in buildings, and gasoline and diesel for transportation options. A total of fifty mitigation measures are compiled to represent six technologies in energy supply (for renewable and non-renewable sources), 36 technologies in residential and commercial/institutional buildings (for space heating, space cooling, water heating, lighting, and appliances, in addition to options to reduce the demand on grid electricity), five measures in passenger vehicles and freight trucks, and three measures for waste from residential and commercial/institutional sources.

This is the classic step-wise MAC curve that has become a fixture of ship-efficiency discussions (Figure 5)

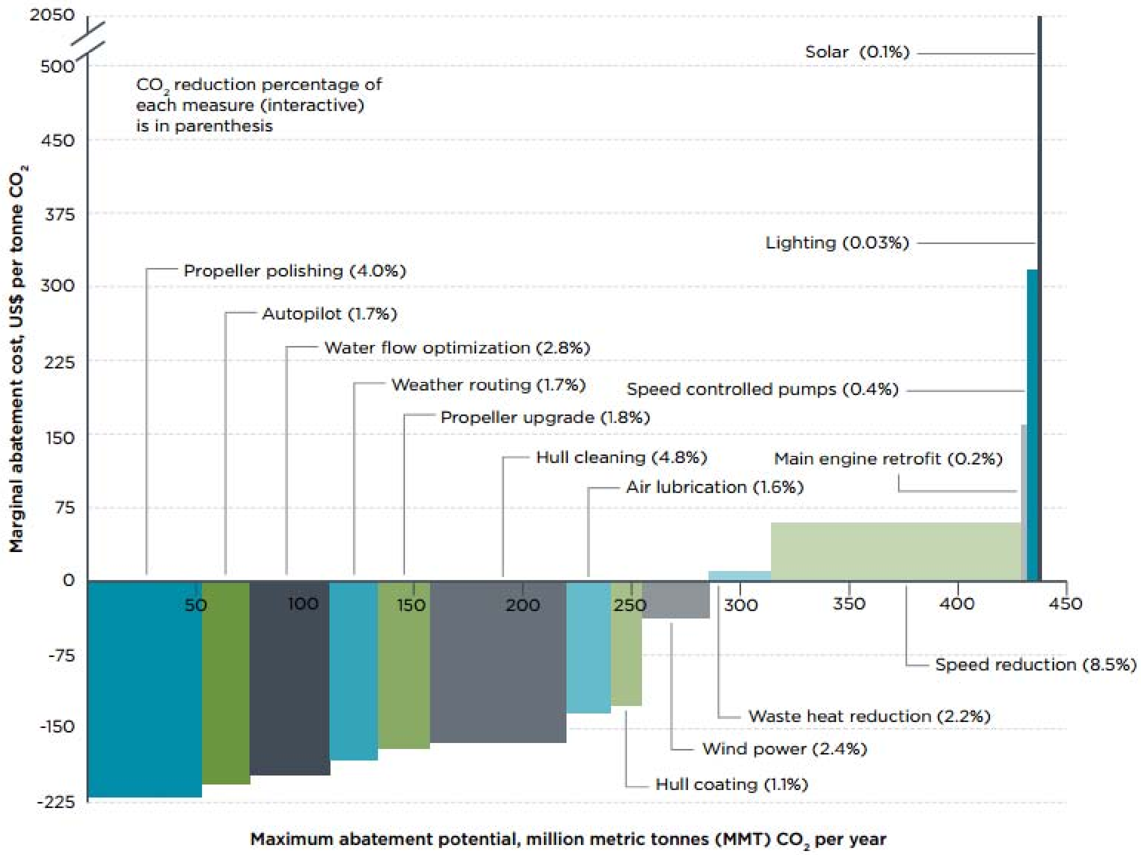

Figure 5: Marginal CO_2 abatement costs of analyzed technologies

Reading from left to right, efficiency measures are arranged according to increasing cost per tonne of CO_2 averted. It was assumed that the measure with the lowest marginal abatement cost would be adopted first, followed by the one with the second lowest MAC, etc. The emission reduction potential of the remaining measures decreases and the cost increases as each additional measure is implemented.

The width of each bar represents the potential of the measure to reduce CO_2 emissions from the world fleet. The height of each bar represents weighted average marginal cost of avoiding one tonne of CO_2 emissions through that measure, assuming that all measures to the left are already applied. Propeller polishing has the lowest average MAC, with moderate CO_2 reduction potential. The total potential reductions apparent in Figure 5 do not line up with those in Figure 3,4 because of the lower resolution required to depict the measures in a stepwise form.

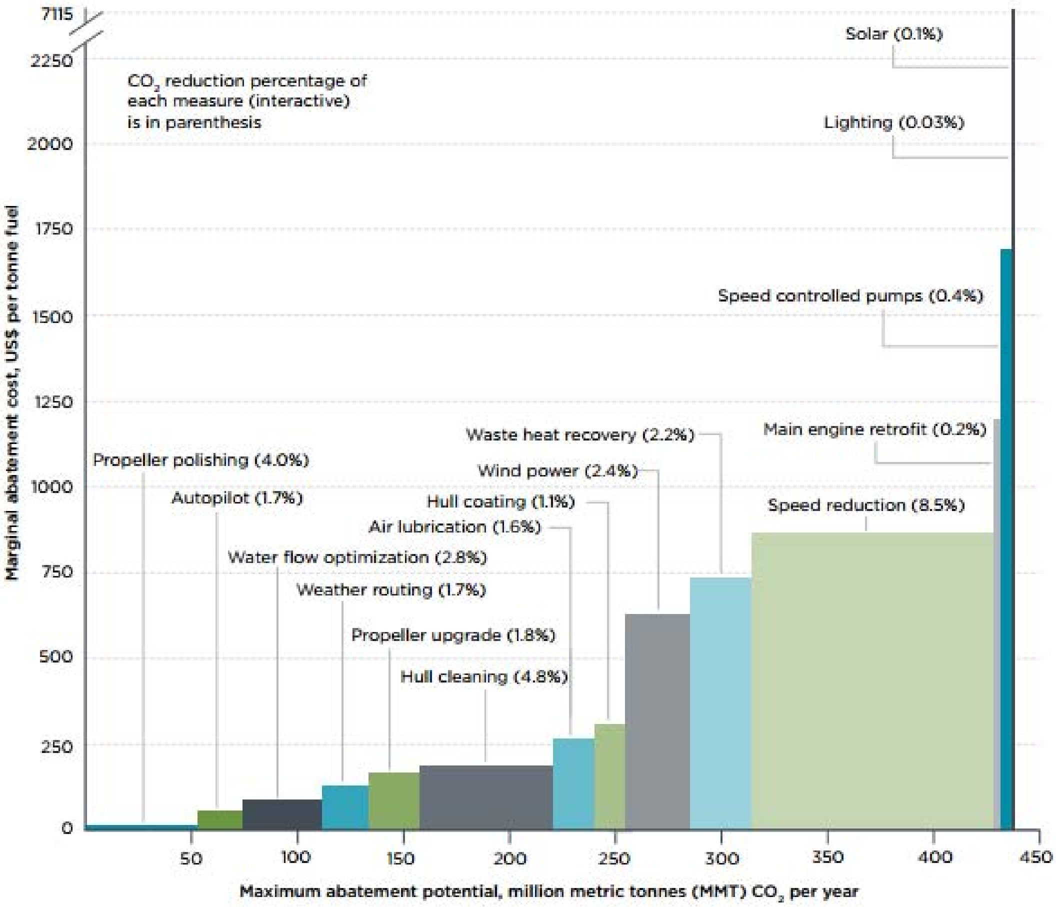

Figure 6: CO$_2$ emission abatement potential and cost of fuel saving

Figure 6 shows the same step-wise MAC chart as before but with the fuel price removed. As Figure 5, the width of each bar represents the potential of a measure to reduce CO$_2$ emissions from the world fleet. The difference is that the height of each bar represents weighted average marginal cost of saved fuel. With this visualization, the cost of fuel-saving technologies can be simply compared with fuel price. For example, the cost of saving one tonne of fuel using propeller polishing is $13, and the CO$_2$ reduction potential is approximately 50 mmt across the entire fleet. If fuel prices are higher than $13 per tonne, it makes economical sense to apply propeller polishing.

V. CONCLUSION

Initial efforts to describe the Marginal Abatement Cost (MAC) of ship efficiency measures used relatively broad assumptions. This article summarized here breaks down the fleet in much more detail and focuses on a limited set of available efficiency measures that can be analyzed rigorously. It provides the best policy tool currently available for describing and projecting fleet efficiency potential, but future work can refine understanding even further, as better performance data for existing and future measures becomes available.

For economic improvements, this study notes many market barries for technologies that both inhibit deployment of the measures and inject uncertainty into the analysis of benefits. Broadly speaking, these market barries can be categorized as either split incentives or uncertainty and need to be better elaborated in future MAC studies.

In particular, the issues of split incentives, where the cost of ship efficiency improvements are not directly related to end user benefits, needs dedicated attention. The split incentive concern arises between the vessel owner, who controls capital spending and energy conservation efforts, and the operator, who is responsible for fuel cost. This primarily occurs when vessel especially bulk carriers, tankers, and container ships – are under time charter or bareboat charter. Uncertainty about energy savings is intrinsic and influenced by external factors such as weather, shipping route, etc. Fuel cost, the most important return source from using these measures, is a particularly potent source of uncertainty when considering efficiency measures.

VI. ACKNOWLEDGEMENT

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