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Reducing Greenhouse Gas Emissions from Ships

COST EFFECTIVENESS OF AVAILABLE OPTIONS

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EXECUTIVE SUMMARY

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 this instance, they provide a simple and elegant way to illustrate greenhouse gas (GHG) emission 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 discussions 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.

To improve the precision of marine MAC values, and specifically to support policies in development at the International Maritime Organization (IMO), the ICCT and its partners worked with the Society of Naval Architects and Marine Engineers (SNAME) to identify 50 potential ship efficiency measures. Of these, only 22 had sufficient performance data available to calculate the aggregated cost effectiveness and reduction potential associated with them. The study examined these measures against an unprecedented 53 ship types and sizes over 30 years. The marginal costs of this subset of measures were averaged across these ship types to produce a much more refined illustration of how by 2020 the industry's growing fleet could reduce annual CO_2 emissions by 436 million metric tons (mmt), or 33% of the projected annual total. Of that amount, 340 mmt (26% of the total) could be achieved for a net negative cost after fuel and other savings are accounted for.

This paper is a summary of work originally submitted to the IMO in a detailed technical report (Faber, Wang, Nelissen, Russell, & St Amand, 2011).

BACKGROUND

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.

As the United Nations organization responsible for reducing the intensity of growth in CO_2 emissions from shipping, the IMO is considering where reductions should come from, who will pay, and how to make the system as fair and effective as possible. At the core of many proposals under discussion are technical, operational, and design measures that could be applied to new or existing ships. De facto standards based on these measures may be the best short-term means of reducing greenhouse gas (GHG) emissions from the maritime sector.

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 870 mmt of CO_2 to the atmosphere, with an additional 180 mmt attributable 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.

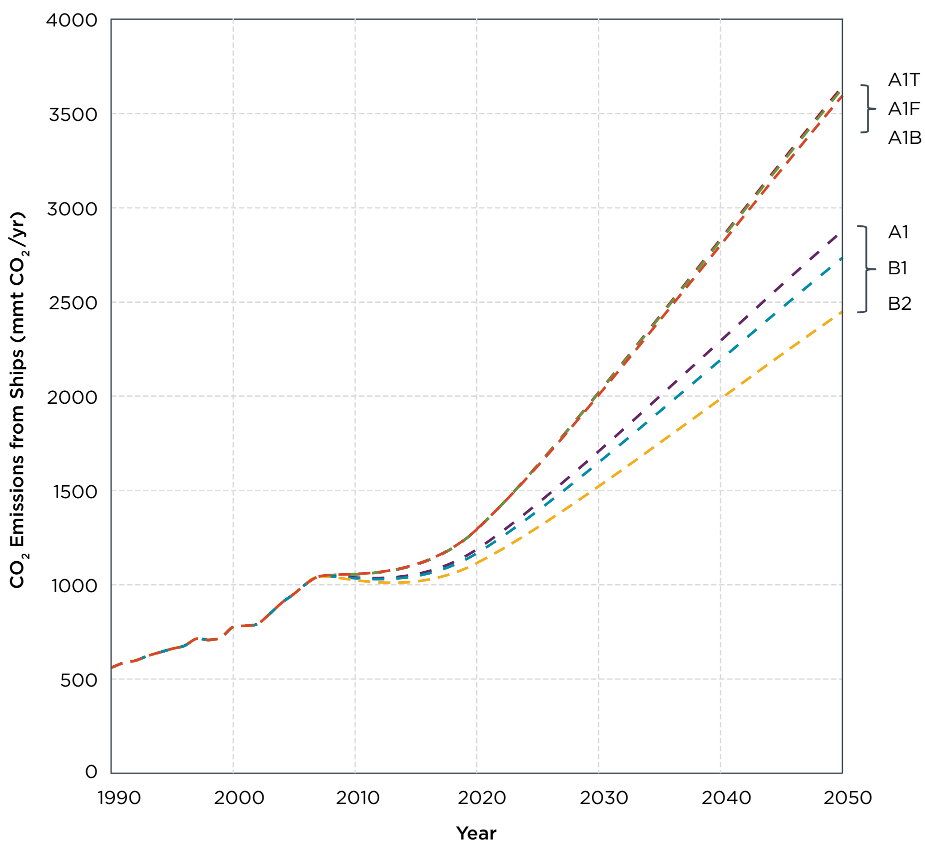


Figure 1. Projected growth of CO_2 emissions from shipping

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 (Buhaug et al, 2009). 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.

A major part of the solution will be taking advantage of the growing number of technologies and operational strategies aimed at increasing ship efficiency. Work that has been done on marginal abatement cost curves for efficiency technologies demonstrates the clear potential of these studies to inform policy and industry. But these have been broad-based estimates, lacking sufficient detail and transparency to function as more than a general guide for industry and policy makers. More granular MAC analysis, especially with respect to specific ship types and ages, will facilitate development of more tailored strategies by both regulators and industry. In particular, with current in-sector approaches to market-based mechanisms being considered at IMO, improving the MAC analysis requires aligning it better with how the maritime industry operates.

To improve the resolution and utility of the MAC approach, in 2010 the ICCT collaborated on a major study with CE Delft, Navigistics, and JS&A Environmental Service, working under the auspices of SNAME. The project identified 53 different ship types to which efficiency technologies could be applied and for each evaluated the potential benefits of 22 existing technical and operational measures that could be deployed immediately or in the near future and had sufficient operational data to analyze. The measures that were considered are grouped into 15 general categories (Table 1) and have been analyzed for their overall cost and potential to reduce GHG emissions when applied to all vessel types. (See Appendix A for more detailed descriptions of these measures.)

Note that these 22 measures represent just under half of the potential existing measures identified by the analysis team. Others lacked sufficient performance data for rigorous analysis or other key analytical criteria. For example, fuel consumption meters were left out because they did not directly lead to efficiency gains and therefore could not be evaluated in the same manner as other measures. Similarly, the effect of economy of scale was not included because it lacked specificity. These types of measures were difficult to analyze for a global fleet and could not be reasonably compared to the types of specific measures that comprise the MAC.

Table 1: Technologies and operations strategies to reduce GHG emissions from ships

Propeller Polishing	Hull Cleaning	Speed Reduction
Autopilot Upgrade	Air Lubrication	Main Engine Retrofits
Water Flow Optimization	Hull Coating	Speed Controlled Pumps and Fans
Weather Routing	Wind Power	High-Efficiency Lighting
Propeller Upgrade	Waste Heat Reduction	Solar Panels

METHODOLOGY

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 lost profits due to opportunity costs. Because these costs 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 ship types, sizes, and age combinations. The costs of each combination were then sorted and ranked. A simplified version of the calculation appears in equation (1).

(1)
$$\mathrm{MAC} = \frac{\Delta C_j}{\propto_j \times \mathrm{CO_2}} = \frac{K_j + S_j - E_j + \sum O_j}{\propto \times \mathrm{CO_2}}$$

Where:

ΔC_j = Capital cost

K_j = ΔC_j discounted by the interest rate and service years

S_j = Service cost of the measure

$\sum O_j$ = 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

α_j = Energy reduction rate of energy-saving measure *j*

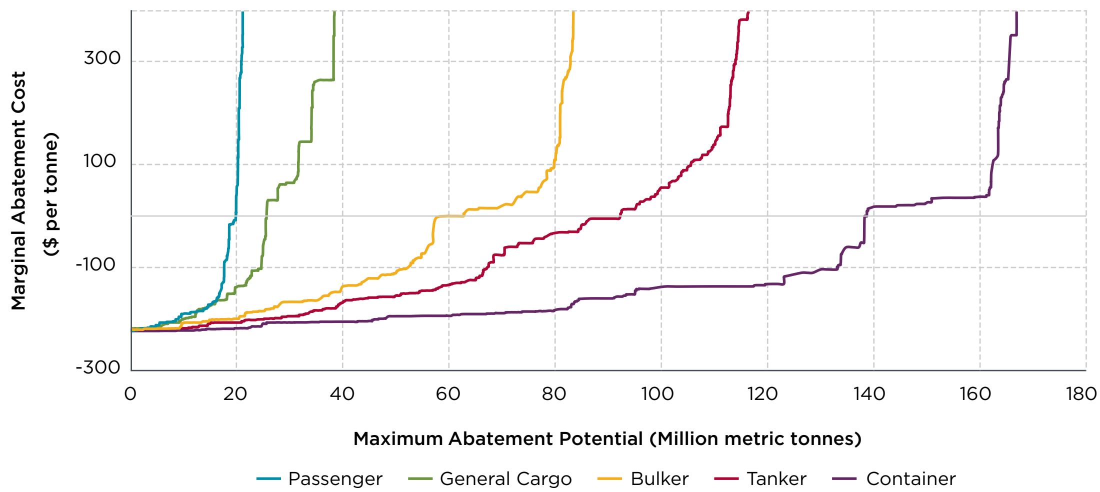
CO_2 = Original CO_2 emissions from a ship

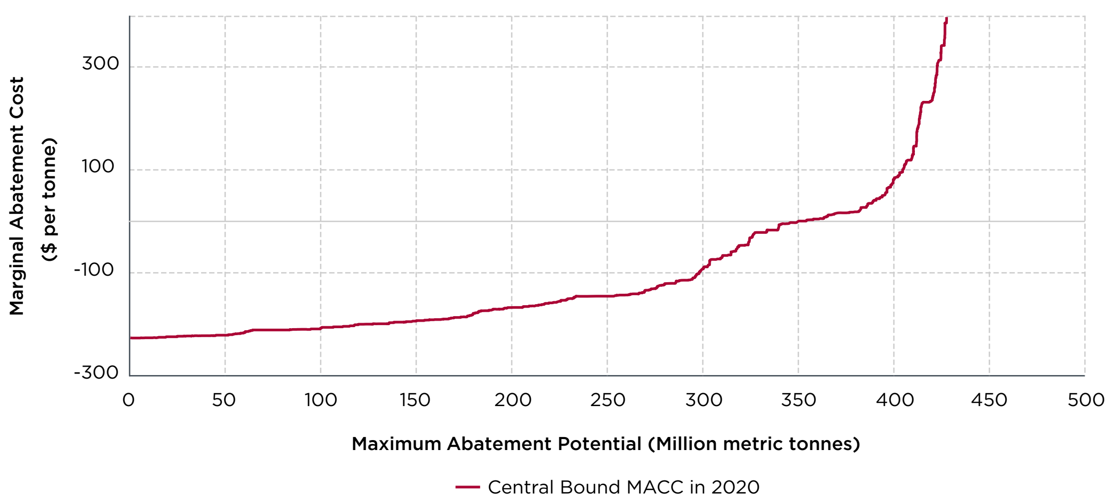
CE Delft and SNAME provided detailed purchasing and operational costs and energy-savings data for each measure. These details can be found in Faber et al. (2011), MEPC61-INF 7. Although most of the data originally came from suppliers, they were adjusted downward as appropriate to be conservative and rigorously validated using published studies and peer review by experts from industry, NGOs, and government who reviewed all of the spreadsheets, analytical methods, and supporting material that went into this work. The following sections briefly discuss the most significant variables examined during the course of this work.

THE MARGINAL ABATEMENT COST CURVE

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. Figures 2a and 2b 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%.





Figures 2a and 2b: Central estimate of abatement potential by ship type and in aggregate

Figure 3 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.

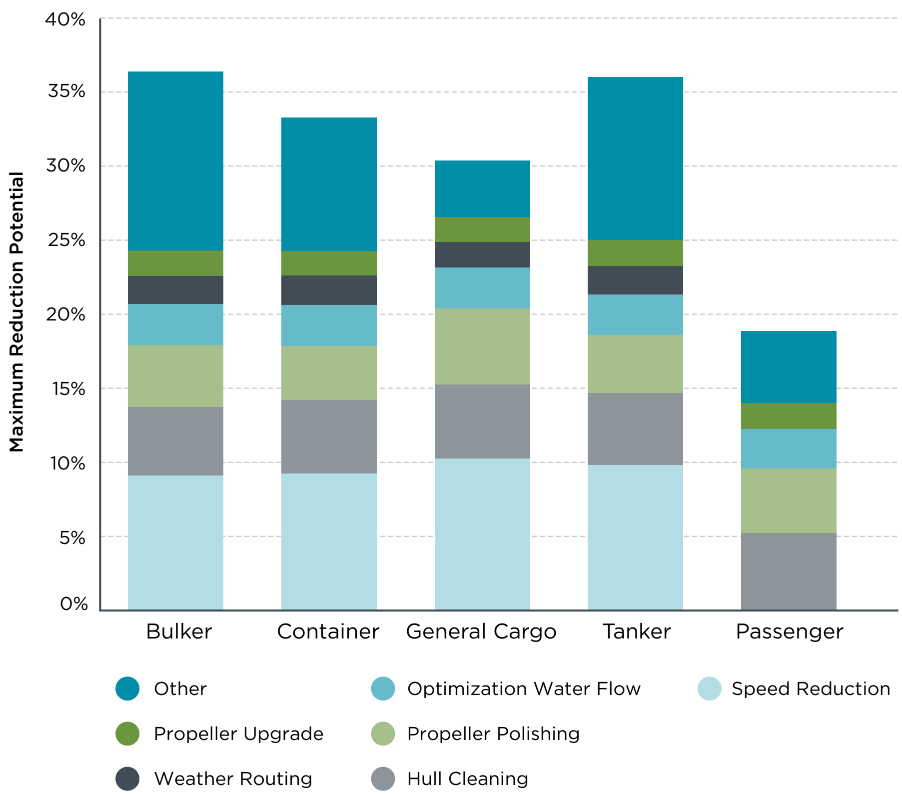


Figure 3: CO_2 reductions of technical and operational measures by ship types

Reorganizing the MAC curve and bundling CO_2 reductions by measure shows the relative cost and reduction potential of each measure. This is the classic step-wise MAC curve that has become a fixture of ship-efficiency discussions (Figure 4).

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. Speed reduction has the largest reduction potential, with moderate cost. Solar panels have the highest MAC, with limited CO_2 reduction potential. The total potential reductions apparent in Figure 4 do not line up with those in Figure 2 because of the lower resolution required to depict the measures in a stepwise form.

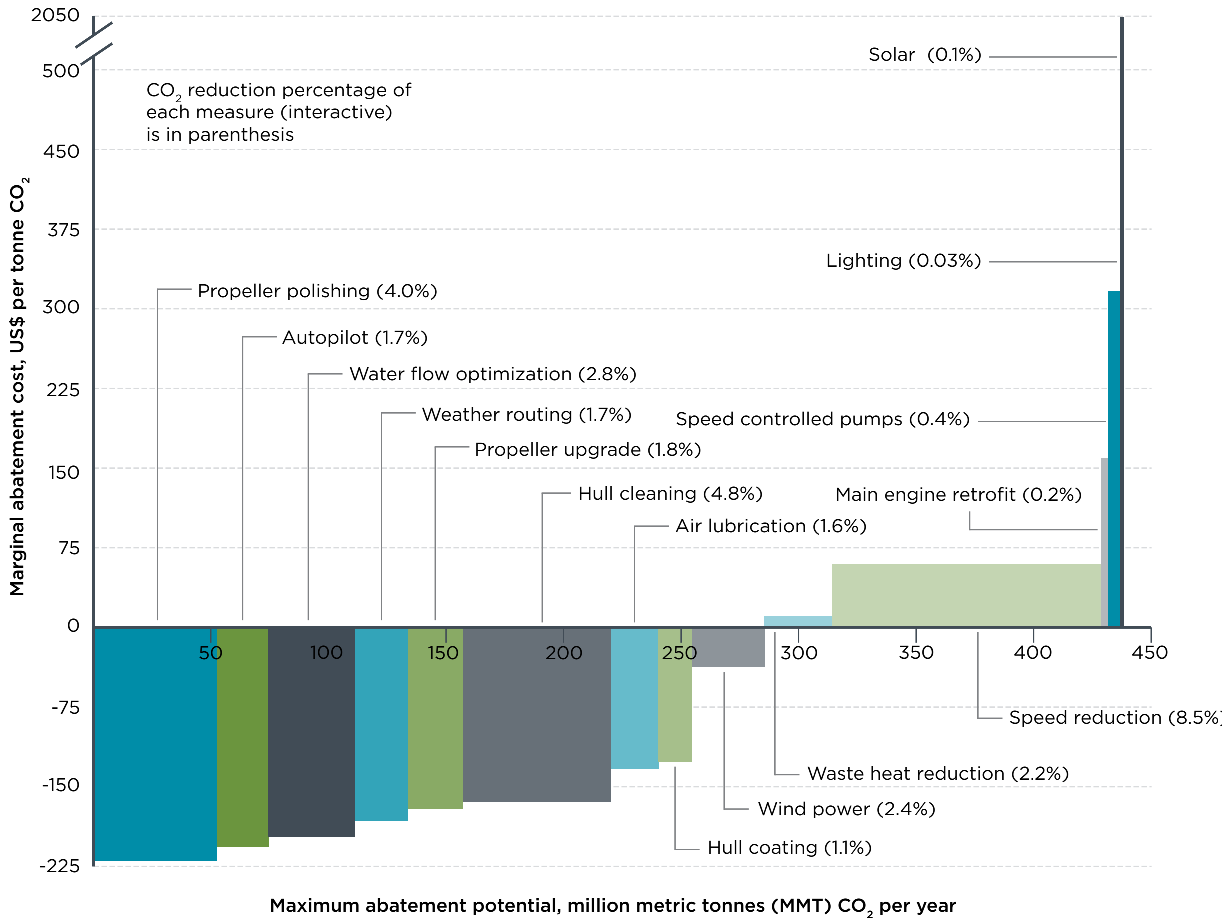


Figure 4: Marginal CO_2 abatement costs of analyzed technologies

KEY VARIABLES IN MAC DEVELOPMENT

While the simple presentation of the step-wise MAC's is elegant and easy to understand and communicate, these types of estimates require substantial assumptions about future conditions and can therefore be only fully understood within the context of these assumptions.

Fuel price

Fuel price is the single most important variable in determining the net cost effectiveness of CO_2 emission reduction measures. Though steadily rising, fuel price is volatile, creating a perception of risk that investments may not pay off optimally. The phase-in of low-sulfur fuel mandates adds additional price uncertainty first for emission control areas and later throughout the world.

A worldwide sulfur cap has been under extensive debate and will subject to a review in 2018 to determine viability. This analysis assumed that the sulfur cap would be implemented as planned. Considering increasing ship activity and relative scarcity of naturally occurring low-sulfur fuel, a $700 per tonne fuel price was projected for 2020 and used in this study. This fuel price is higher than other MAC studies but reflects a more conservative estimate and is consistent with the historic price from the U.S. Energy Information Administration (EIA) as well as International Energy Agency (IEA) projections (Figure 5). Future fuel prices may also include additional levies or carbon prices in the range of $20–$50 per ton, depending on the adopted measure. Any such carbon price is directly convertible to an equivalent increase in fuel price.

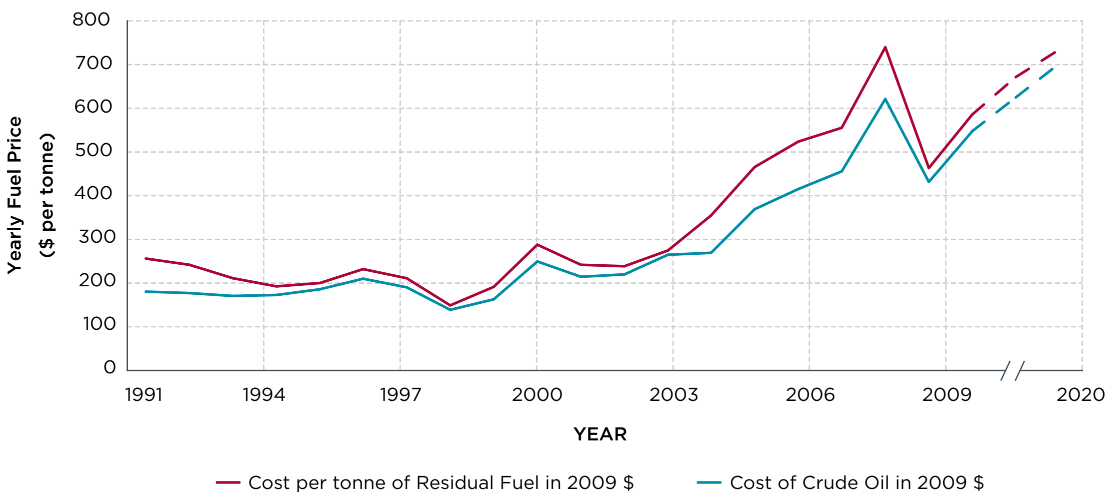


Figure 5: Historic and projected prices for residual fuel and crude oil.

Figure 6 shows the same step-wise MAC chart as before but with the fuel price removed. As in Figure 4, 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.

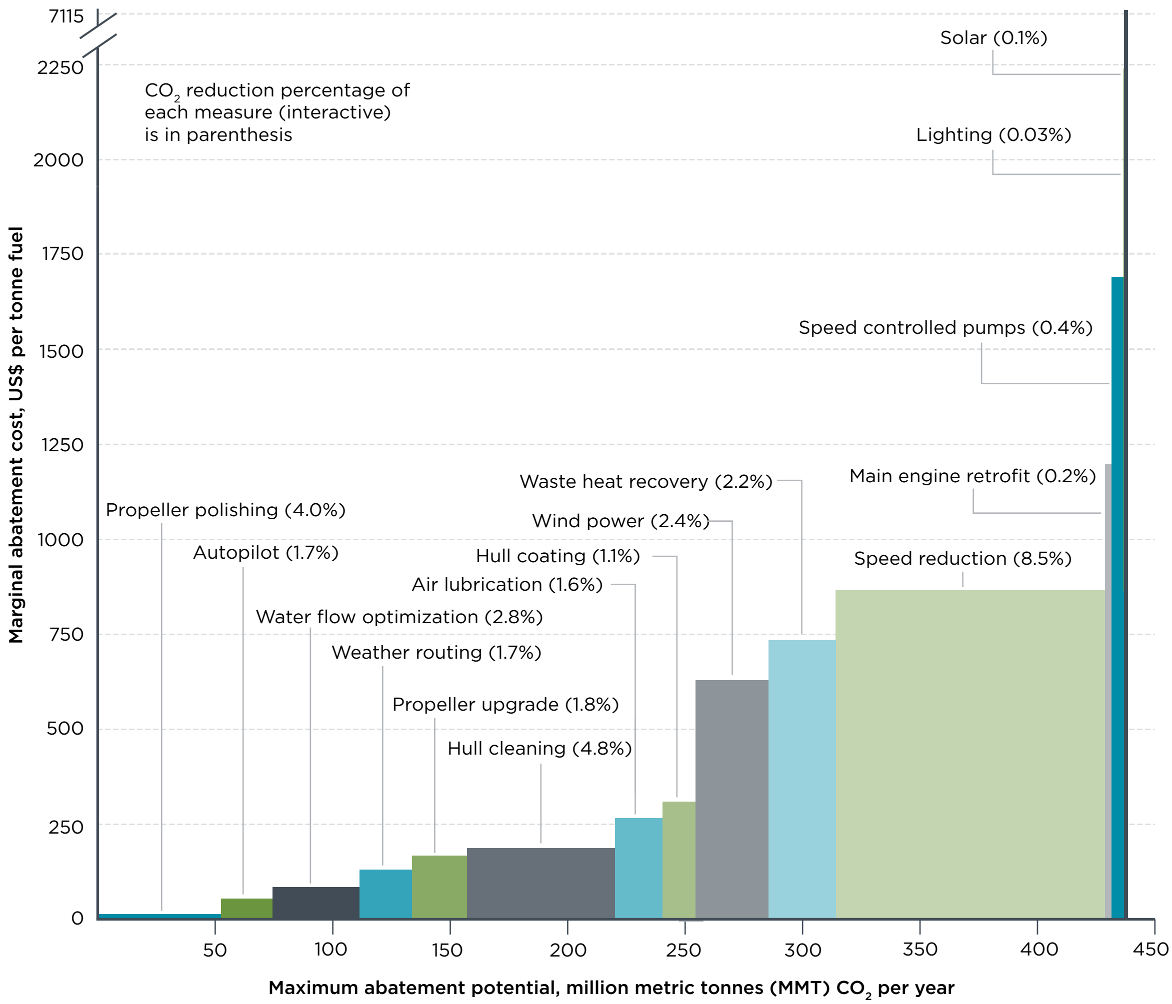


Figure 6: CO_2 emission abatement potential and cost of fuel saving

Technology progress and learning curves

As a new technology passes from prototype to pilot to market, the cost generally decreases substantially due to economies of scale. This market maturation effect occurs gradually and must be characterized for newer technologies that are included among well-established measures. This study captured the "learning curves" of new technologies by assuming that current implementation costs decrease over a set period of time. Specifically, a 10%–15% learning curve was assumed for air lubrication, wind engines/kites, solar power, and waste heat recovery because they are much newer technologies and have not achieved the same levels of market maturity and penetration as the other measures.

Discount rate

The discount rate of different shipping firms varies because it usually includes a large proportion of the risk premium. For this study a discount rate of 10% was used.

Implementation time

Some technical measures need to be retrofitted, and the time required to do so may exceed the dry-docking period. The costs incurred during this period of time were estimated based on operational costs from Drewry Consulting and historical charter rates.

FUTURE PROJECTIONS AND COMPARISON TO OTHER STUDIES

Other recent studies have considered the marginal abatement costs of energy-efficiency improvements and presented results in a visually similar form. The authoritative IMO GHG study (Buhaug et al, 2009) concluded that ship emissions could be reduced 20% to 40%, depending on the measures used, the cost of fuel, and growth in ship activity. In a report to the European Commission on GHG reduction from ships, CE Delft presented a cost-effectiveness analysis for 29 measures and 14 different ship types, calculating a 35% abatement reduction in 2030 (Faber et al., 2009). Det Norske Veritas (DNV), with a more optimistic analysis of low-carbon measures for the shipping industry, investigated 28 energy-saving options and forecast a reduction of more than 50% by 2030 (Alvik, Eide, Endresen, Hoffmann, & Longva, 2010).

Figure 7 compares the IMO, CE Delft, and DNV studies. The ICCT study estimates that the CO_2 reduction potential is 90 mmt more the IMO study estimated for 2020 and 140 mmt less than the DNV study forecast for 2030. This is mainly because the number of measures considered varies among the studies. For instance, four measures considered in the DNV study, such as “fixed sails and wings,” were not included in the ICCT and CE-Delft 2009 studies because they were not considered likely to be market-ready in the timeframe covered. In addition, the IMO study assumed that ships whose remaining useful life was less than the useful life of a given energy-saving measure would not use such a measure. Our study assumes ships will use the measure no matter how old the ships are. While we relied on many of the same data as CE Delft, we did not consider some auxiliary measures that they did because such measures (e.g., fuel consumption meters or propeller monitoring), if used independently, may not yield any emission reduction. Details of the DNV analysis were unavailable for use in forming specific distinctions.

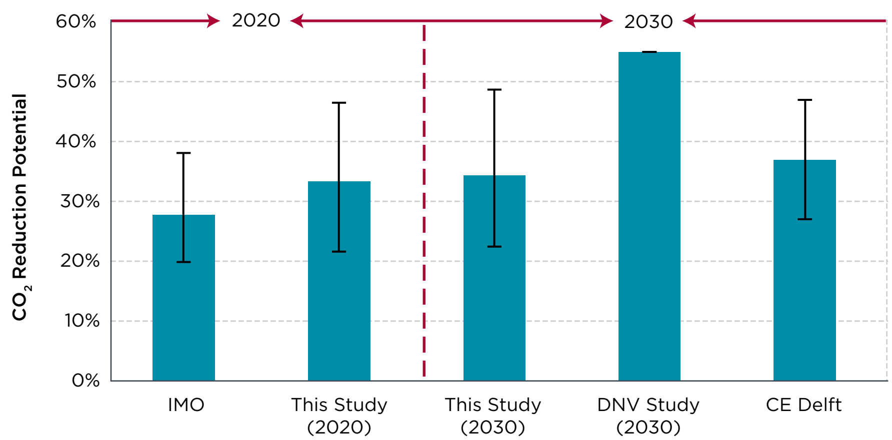


Figure 7: Comparison of available studies

Despite this study's close attention to detail and desire to capture the best available data, the amount of data and knowledge of these issues is continually growing. This type of MAC analysis should also be revised regularly to incorporate such new developments. Examples of new developments since the original MAC analysis include: Maersk gave a large share of credit of CO_2 reduction and fuel conservation to slow steaming; Propulsion Dynamics illustrated the importance of hull and propeller cleaning and monitoring both in terms of fuel savings and CO_2 reduction; Green Ship of the Future scrutinized the fuel savings and the payback of waste heat recovery, variable nozzle rings, and speed control pumps, among other things. The magnitude of the emission reductions and the estimate of the marginal costs reported by these sources would provide an additional means of verifying and refining the MAC analysis.

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

Initial efforts to describe the marginal abatement costs of ship efficiency measures used relatively broad assumptions. The report 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.

As with any analysis that is heavily data-dependent, the resolution and accuracy of the source data can be refined. This study looks at 53 different ship categories, but there are many more divisions that could be relevant. They could also be further subdivided and analyzed in categories relevant to new technologies, such as ship size, hull shape, or installed power. Future analyses would also benefit from including some of the 28 known measures that did not have sufficient performance data to be included in this analysis. Beyond data improvement, both technical and economic variables can be investigated in more depth.

For improving technical analyses, several refinements are necessary to capture real-life conditions. First, off-design performance is common for even standard technologies. This variation of performance among ships with otherwise similar efficiency design values needs to be further researched and documented to provide additional inputs for uncertainty and variability. Likewise, inclusion of non-performance effects such as installation space and operability changes can improve applicability of results for the industry. Also, even though this analysis included such considerations, the representation of interactions and interference among technologies can be further refined as industry experience comes to light. Similarly, the accounting of potential risk from factors such as off-spec performance or unanticipated operational problems can be refined with actual data to better improve opportunity cost estimates.

For economic improvements, this study notes many market barriers for technologies that both inhibit deployment of the measures and inject uncertainty into the analysis of benefits. Broadly speaking, these market barriers 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 vessels—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. The lack of certainty that fluctuating fuel prices implies for overall cost savings makes it more difficult for banks to finance these investments and defray substantial capital costs. Addressing market barriers, developing fair and pragmatic market mechanisms, and providing for the rapid development of new technologies will ensure maximum progress toward out collective goals and improve our ability to predict potential benefits.

As a complement to MAC analyses, a model-based tool that can be run with specified scenarios may be a useful policy instrument. Many of the temporal and highly variable inputs to the MAC, such as market conditions, learning curves, and discount rates may be better analyzed and tailored to specific parts of the fleet using a model. It would also allow for easy incorporation of additional variables that may be more variable among different fleets and applications, such as deterioration rates, utilization rates, and implementation times.

Critical to any advanced analytical efforts will be a better source of technical and experiential data from the industry. Currently, much of the data that could help refine these types of analysis is the domain of shipping companies and ship owners. Creating a more open-source repository for this type of data would create mutual benefits for industry and policy makers. Likewise, a system for verification and certification of new ship-efficiency measures (perhaps combined with a data repository) could be extraordinarily useful in streamlining the otherwise tedious process of assessing and delineating benefits and applicability of measures.

APPENDIX A: LIST OF ENERGY-SAVING MEASURES

This appendix provides a fuller, but still brief, description of the 15 energy-saving measures listed in Table 1. It describes the abatement potential of each, summarizes assumptions regarding market penetration, and identifies perceived market barriers to implementing each measure.

Autopilot upgrade/adjustment

Advanced adaptive autopilot systems can optimize rudder position. The system considers wind, currents, and ship yawing on a given route and minimizes vessel resistance. Rudder induced drag has a big influence on the course-keeping ability and vessel resistance. Such a system can optimize routing and fuel use.

Abatement potential: 0.5–3%

Market penetration: A significant portion of the world's fleet already employs this technology. Therefore, the actual abatement potential is much lower.

Market barrier: The major barrier is the split interest. Ship owners are responsible for investing in these technologies, and ship operators are those who pay for the fuel consumption and benefit from such technologies.

Propeller upgrade

The propeller is one of the most important components on a ship and its condition is critical to fuel-efficient operation. The propeller transmits power by converting rotational motion into thrust and, when operating most efficiently, will generate the least amount of turbulence. When propellers become scuffed or damaged during the course of normal operation, they do not move as smoothly. This additional friction can substantially reduce overall efficiency. Propeller upgrading is a measure that mainly involves replacing the propeller and/or optimizing the pitch of controllable pitch propellers.

Abatement potential: 0.5–3% for propeller upgrade (nozzle and tip winglets); 1–3% for propeller boss cap with fins; 2–6% for complete propeller-rudder replacement.

Market penetration: All technologies are available in the market. In general the industry has been slow to adopt propeller upgrades as it is waiting to see what the long-term impacts are (AEA, 2008).

Market barriers: The major barrier is the split interest. Ship owners are responsible for investing in these technologies, and ship operators are those who pay for the fuel consumption and benefit from such technologies.

Water flow optimization

The bow (transverse) thruster is an auxiliary propeller located in a large tube that transects the hull below the waterline in the front of the ship. The bow thruster is critical to controlling the ship during maneuvering, but the thruster tube opening creates a point of turbulence as the ship moves through the water. A thruster design incorporating the smallest possible tunnel diameter could minimize the turbulence created by the opening and increase hull efficiency. Adapting the propeller design to the tunnel diameter could also optimize the flow towards the propeller. Standard blades of backward skewed design with rounded tips will result in optimum thrust efficiency.

Abatement potential: 1%–4%

Market penetration: A significant portion of the world's fleet already employs this technology. Therefore, the actual abatement potential may be lower.

Market barriers: The major barrier is the split interest. Ship owners are responsible for investing in these technologies, and ship operators are the ones who pay for the fuel consumption and benefit from such technologies.

Weather routing

Weather routing takes into account currents and weather forecasts as well as real-time sea conditions to determine the most fuel-efficient route for long-distance voyages.

Abatement potential: 0.1–4%.

Market penetration: A significant portion of the world's fleet already employs this technology. Therefore, the actual abatement potential may be lower.

Market barriers: Fuel consumption is significantly affected by sea conditions; hence, a charterer is unlikely to pay a premium without a fuel-saving guarantee.

Hull cleaning

After a ship has been in service for a long period, its hull becomes fouled. Hull cleaning (usually through mechanical brushing, by divers or automated systems) effectively removes marine biological growth between dry-dockings. This reduces frictional resistance and, therefore, increases energy efficiency.

Abatement potential: 1–10%

Market penetration: A significant portion of the world's fleet already employs this measure. Therefore, the actual abatement potential may be lower.

Market barriers: Fuel consumption is significantly affected by sea conditions; hence, a charterer is unlikely to pay a premium without a fuel-saving guarantee.

Propeller polishing

Cleaning and polishing propeller surfaces can reduce roughness and get rid of accumulated organic materials, which reduces trailing turbulence on ships and the frictional loss of the propeller.

Abatement potential: 2–5% when done on a regular periodic basis; 2.5–8% when performed intermittently as required.

Market penetration: A significant portion of world's fleet employs this measure. Therefore, the actual abatement potential may be lower.

Market barriers: Fuel consumption is significantly affected by sea conditions; hence, a charterer is unlikely to pay a premium without a fuel-saving guarantee.

Hull coating

Hull coatings can lower frictional resistance and limit fouling by aquatic organisms, reducing bunker fuel consumption and CO_2 emissions.

Abatement potential: 0.5–5%.

Market penetration: Roughly 5% of newly painted ships are painted with one of the two advanced coating systems presently available.

Market barriers: The major barrier is the split interest. Ship owners are responsible for investing in these technologies, and ship operators are those who pay for the fuel consumption and benefit from such technologies.

Wind power

Wind engines are available that can develop enough thrust to provide at least some propulsion. Computer-controled kites attached to the bow of a ship can harness wind power and substitute power for forward propulsion.

Abatement potential: 3.5–12% for wind engines; 2–20% for kites.

Market penetration: A number of cargo ships have been equipped with wind engines, including two vessels fitted with wingsails in Japan (a 1,600 deadweight ton (dwt) tanker and a 26,000 dwt bulk carrier) and a 50,000 dwt product carrier developed by Demark. The U.S.-based Kiteship and the German based Skysails have equipped more than ten cargo ships with wind kites to reduce demands from diesel engines.

Market barriers: These technologies are not mature and uncertainties remain, so banks are reluctant to provide financing. Another barrier is the split interest.

Waste heat recovery

Waste heat recovery equipment can pass exhaust gases from a ship's engines through a heat exchanger to generate steam for a turbine-driven generator. The thermal energy from the exhaust gas is captured and converted into electrical energy to reduce direct engine-fuel requirements for the propulsion system or reduce auxiliary engine requirements.

Abatement potential: 6–8%.

Market penetration: WHR can be employed on ships with main engine average performance is higher than 20,000 kW and auxiliary engine average performance higher than 1,000 kW. This size requirements limit the number of ships using this technology.

Market barriers: Large capital investment requirements, and split interests between ship owners and ship operators.

Air lubrication

This refers to a technique by which compressed air is pumped into a recess in the bottom of the ship's hull over the length; the entrained air reduces the frictional resistance between the water and the hull, and reduces the propulsion power demand. An injection system delivers air to recessed area of the hull through a system of automated compressors and valves, while a control system monitors the volume and pressure of air and maintains the optimal air level in the air cavity.

Abatement potential: 10–15% for tankers and bulker carriers, 5–9% for container vessels.

Market penetration: There are no vessels operating commercially that currently use this system. Sea trials have been conducted with a small demonstration vessel.

Market barriers: Large capital investment requirements, and the split interest.

Speed reduction

The main engine power output requirements approximate a cubic function between the ship service speed and ship design speed. The reduction of the service speed from the design speed will substantially reduce the required power output. A small reduction in speed can deliver important savings in fuel consumption.

Abatement potential: 15%–19% for 10% speed reduction and 36–39% for 20% speed reduction, if extra ships are not considered.

Market penetration: This has been observed for some ship routes.

Market barriers: The main concern is disruption of the supply chain. Importers complain about longer times for goods in transit. Another concern is that the engine may be less efficient at lower speeds.

Main engine retrofit

This includes main engine tuning and common rail engine upgrade. In main engine tuning, the most commonly used load range is determined and then the engine is optimized for operation at that load. This requires a different engine mapping and entails changes in injection timing. Using the common rail engine, combustion can be optimized over the entire engine operating range to improve energy efficiency.

Abatement potential: 0.1–0.8% for main engine tuning and 0.1-0.5% for common rail.

Market penetration: Both technologies are available.

Market barriers: The major barrier is the split interest. Ship owners are responsible for investing in these technologies, and ship operators are the ones who pay for the fuel consumption and benefit from such technologies.

Speed controlled pumps and fans

Pumps can circulate large amounts of water through engine cooling systems to cool the engine and save energy.

Abatement potential: 0.2%–0.8%

Market penetration: A significant portion of the world's fleet already employs this technology. Therefore, the actual abatement potential may be lower.

Market barriers: The major barrier is the split interest. Ship owners are responsible for investing in these technologies, and ship operators are those who pay for the fuel consumption and benefit from such technologies.

High-efficiency lighting

Using low-energy/low-heat lighting and optimizing the use of lighting where possible reduces demand for electricity and air conditioning. This measure leads to a lower hotel load and reduced auxiliary power needs.

Abatement potential: 0.1%–0. 8%

Market penetration: The technology is available in the market, but limited numbers of ships use it.

Market barriers: The major barrier is the split interest. Ship owners are responsible for investing in these technologies, and ship operators are the ones who pay for the fuel consumption and benefit from such technologies.

Solar power

Electricity and heat can be generated using solar panels installed on deck. Solar power can be combined with conventional engines to maximize performance as a hybrid.

Abatement potential: 0.2–3.75%.

Market penetration: Around 150 solar powered passenger ships are currently in use in Germany, Italy, Austria, Switzerland and the UK. The *Auriga Leader*, a car carrier owned by Nippon Yusen Kaisha, is the only commercially operated ship that uses solar panels to generate power and reduce demand on the diesel engines.

Market barriers: The technology is still under development. Capital requirements are significant, and abatement potential is limited.

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