Cost-Effectiveness of Reducing Sulfur Emissions from Ships

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We model cost-effectiveness of control strategies for reducing SO_2 emissions from U.S. foreign commerce ships traveling in existing European or hypothetical U.S. West Coast SO_x Emission Control Areas (SECAs) under international maritime regulations. Variation among marginal costs of control for individual ships choosing between fuel-switching and aftertreatment reveals cost-saving potential of economic incentive instruments. Compared to regulations prescribing low sulfur fuels, a performance-based policy can save up to $260 million for these ships with 80% more emission reductions than required because least-cost options on some individual ships outperform standards. Optimal simulation of a market-based SO_2 control policy for ∼4,700 U.S. foreign commerce ships traveling in the SECAs in 2002 shows that SECA emissions control targets can be achieved by scrubbing exhaust gas of one out of ten ships with annual savings up to $480 million over performance-based policy. A market-based policy could save the fleet ∼$63 million annually under our best-estimate scenario. Spatial evaluation of ship emissions reductions shows that market-based instruments can reduce more SO_2 closer to land while being more cost-effective for the fleet. Results suggest that combining performance requirements with market-based instruments can most effectively control SO_2 emissions from ships.

Introduction

Marine vessels can be a highly polluting mode of freight transportation. These vessels account for a non-negligible portion of local, regional, and global air emissions inventories (*1–12*) and contribute to air quality, human health, and climate change problems (*8, 12–19*). With regard to sulfur, ships release more sulfur emissions per ton-mile of cargo shipped than other transportation modes, due largely to dirty fuel and uncontrolled stacks (*20–24*). Studies estimate that the world cargo fleet accounts for 6–12% of the 55.2−68 million tons of sulfur emissions emanating from all global, anthropogenic sources (*5, 25, 26*).

Because of the uneven distribution of ship traffic and emissions, ships can make significant contributions to regional and local SO_2 emissions inventories (*9–12, 16–18, 27–29*). Moreover, regulating ship emissions might be more cost-effective in some regions for mitigating air pollution problems than controlling land-based sources, which are more regulated and face generally higher marginal control costs. Policymakers are increasingly considering controlling air emissions from ships (*30*).

Policy instruments for controlling air emissions can be categorized into two approaches: "command-and-control" and "market-based" (or "incentive-based"). A command-and-control approach achieves emissions reductions by setting standards with which all ships must comply. The most prevalent command-and-control instruments are prescriptive and performance-based standards (*31*). Prescriptive standards specify the method, and sometimes the actual equipment, that ships must use. Performance-based standards set a control target, allowing some latitude in how industry complies (*31*). A market-based approach achieves emissions reductions by encouraging behavior through market signals and economic incentives (*31–34*). Strengths and weaknesses of command-and-control and market-based approaches are provided in the Supporting Information.

The International Maritime Organziation (IMO) regulates ship air emissions through Annex VI of the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto (MARPOL 73/78). Specifically, Annex VI sets a global cap on sulfur content of marine fuels (not exceeding 4.5% mass/mass (m/m)) and provides that ships in SO_x Emission Control Areas (SECAs) have to burn low-sulfur (not exceed 1.5% m/m) marine fuel or use technologies with equivalent effects (*35*) to control sulfur emissions.

The Commission of European Communities adopted a European Union (EU) strategy in November 2002 to reduce emissions from seagoing ships (COM (2002) 595) which includes a new marine fuel Directive that will cut SO_2 and particulate matter (PM) emissions by reducing sulfur content of marine fuels (*23*). The U.S. Environmental Protection Agency (EPA) has adopted national emission standards for certain categories of marine diesel engines installed on U.S. flag vessels (*36–39*). No national sulfur limit to date has been set for marine fuels in the United States (*40*). The U.S., Canada, and Mexico are jointly evaluating the merits of an IMO application to designate one or more SECAs in North America.

In recent years, economic instruments have been introduced in some countries and ports around the world to encourage ships to reduce atmospheric emissions. These programs include environmentally differentiated fairway dues in Sweden, differentiated tonnage tax in Norway, incentive for ships to use shore power in Europe, a *Green Award* scheme in 35 ports around the world, voluntary speed reduction program and incentives to promote the Alternative Maritime Power (AMP) program in the Port of Los Angeles, and Carl Moyer Memorial Air Quality Standards Attainment Program in California (*23, 41–44*). Some programs have achieved reduction targets and been satisfactorily accepted by industry (*41*). The European Commission is investigating emissions trading schemes for marine vessels and tax regimes based on ships' environmental performance to benefit the least-polluting vessels (*23, 41*). A recent sulfur emissions pilot project in the North Sea SECA demonstrated that compliance through offsetting could reduce more sulfur emissions at significantly cheaper prices than if all vessels were to individually meet the 1.5% fuel sulfur content standard (*45*). Offsetting is a form of balancing between ships exceeding a prescribed limit while others achieve less reduction (*45*).

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TABLE 1. SO_2 Emissions and Fuel Use in SECAs from U.S. Foreign Commerce

SECAs	unique ships[b]	fuel use (tons)	SO_2 emissions (tons)
Baltic Sea[a]	686	95,200	4,890
North Sea[a]	2,087	495,000	25,400
US West Coast	3,139	1,716,000	87,800
total	4,748	2,300,000	118,000

[a] Fuel use and emissions estimates represent vessels carrying U.S. foreign commerce in the 2002 Foreign Traffic Entrances and Clearances data set (*49*), and only during periods when they are operating in these European SECAs. [b] There are about 9,600 ships carrying U.S. foreign commerce in 2002; all the ships traveled in the Baltic Sea also traveled in the North Sea; about 478 ships traveled in both the North Sea and the US West Coast.

Due to the global nature of the shipping industry, international, uniform environmental regulations are favored by the industry to unilateral actions taken by national, regional, and local authorities. MARPOL Annex VI, however, which is command-and-control in nature and is the most important international treaty governing air emissions from ships, may not be the most cost-effective or timely strategy for controlling ship emissions. In this paper, we compare the cost-effectiveness of three environmental approaches: a prescriptive regulation, a performance-based regulation, and a market-based instrument, for controlling sulfur emissions from ships.

We apply the Waterway Network Ship Traffic, Energy and Environment Model (STEEM) to characterize ship traffic and SO_2 emissions from U.S. foreign commerce in 2002 within defined control areas (*46*). The Marine Emissions Optimization Model (MEOM), a mixed-integer linear programming model used first to optimize fleetwide emissions reductions for ~45 passenger ferries at a local scale in the New York−New Jersey Harbor, has been adapted to simulate the optimal SO_2 emissions reduction from ships in SECAs (*47*).

Characterizing Ship Traffic and Emissions in SECAs

We define three areas, including the Baltic Sea, the North Sea, and a U.S. West Coast 200 nautical mile zone (US West Coast), in which ships need to take special measures to reduce SO_2 emissions. MARPOL Annex VI has designated the Baltic Sea and the North Sea as SECAs. The US West Coast, which is a hypothetical SECA, resembles the area of the U.S. West Coast Exclusive Economic Zone (EEZ) under the 1982 United Nations Convention on the Law of the Sea (UNCLOS), in which the U.S. has jurisdiction regarding the protection and preservation of the marine environment should the U.S. ratify the UNCLOS (*48*). Figure SI1 in the Supporting Information shows geographic locations and shapes of these control areas.

Applying STEEM (*46*), we estimated fuel use and SO_2 emissions from individual ships carrying U.S. foreign commerce in the 2002 Foreign Traffic Entrances and Clearances data set (*49*). We created an empirical global waterway network based on historical ship positions and solved the routes in the 2002 Entrances and Clearances data set (*49*). Emissions were estimated based on trip length and vessel characteristics, such as engine power and speed, and were allocated spatially based on locations of the solved routes. Table 1 summarizes the number of unique ships, fuel use, and SO_2 emissions from ships in the three defined areas. There were about 9,600 ships carrying U.S. foreign commerce in 2002, 3,139 of which operate in the US West Coast zone. If this zone were designated as a SECA, then about one-third of cargo ship traffic serving U.S. ports would be affected. SO_2 emissions from U.S. foreign commerce ships in the US West Coast in 2002 are about 11% more than SO_2 emissions from all sources in California in 2000 (*50*).

TABLE 2. Summary of Costs and Performance of SO_2 Control Measures

	fuel switching[a]		seawater scrubbing		
scenarios	price premium	capital costs	SO_2 reduction	capital costs[b] ($/kW)	O&M of capital costs[c]
scenario 1	$30	$0	95%	$130	1.0%
scenario 2	$30	$0	95%	$195	1.8%
scenario 3	$30	$0	99%	$130	1.0%
scenario 4	$73	$36,000	98%	$137	1.5%
scenario 5	$336	$120,000	99%	$130	1.0%
scenario 6	$336	$0	99%	$130	1.0%
scenario 7	$30	$120,000	99%	$130	1.0%

[a] Fuel switching constantly reduces 44% of SO_2 emissions. [b] Capital costs include equipment purchase and installation costs. [c] Annual operation and maintenance costs as percent of total capital costs.

Performance and Costs of SO_2 Emissions Control Measures

The most straightforward way to control SO_2 emissions from ships is to switch from high-sulfur marine bunker fuel, of which the worldwide average sulfur content from 2000 to 2003 was 27,000 ppm (2.7%), to low-sulfur marine fuel with sulfur content not exceeding 15,000 ppm (1.5%) (*20, 51*). Fuel switching can reduce about 44% of SO_2 emissions, and is also the primary approach adopted by MARPOL Annex VI to reduce SO_2 emissions in SECAs (*52*). Alternatively, MARPOL Annex VI allows ships in SECAs to use an on-board exhaust gas cleaning system (EGCS), or any other technological method to reduce SO_2 emissions from both auxiliary and main propulsion engines to 6.0 g SO_2/kWh or less (*52*). We consider seawater scrubbing, a type of EGCS, to be a likely alternative to fuel switching, and evaluate it as such in this paper. The Supporting Information provides a more detailed discussion about the performance and costs of the control measures.

Cost-Effectiveness of Control Policies

Studies show that great uncertainties exist in the price premium of low-sulfur marine fuel, the performance of scrubbing, and the capital and operational costs (*53, 54*). These uncertainties were explicitly considered when we were evaluating the cost-effectiveness of three ship sulfur emissions control policies. Table 2 summarizes seven scenarios for SO_2 control measures by varying the costs and performance within uncertainty bounds. These scenarios are referred to in the following sections.

In Table 2, Scenarios 1, 2, and 3 represent the situation when low-sulfur marine fuel premium is low and constant while the performance and costs of seawater scrubbing vary within uncertainty bounds. Scenario 5 represents the situation when the costs of fuel switching are high, while seawater scrubbing has the highest reduction rate and the lowest cost. The comparison of Scenario 5 and Scenario 6 reveals the sensitivity to capital costs for fuel switching. The comparison of Scenario 5 and Scenario 7 can demonstrate the sensitivity to the premium of low-sulfur marine fuel. Scenario 4 represents our best estimates of the value of variables.

The three sulfur emissions control policies include: (1) a prescriptive standard that requires all ships within SECAs to switch to low-sulfur marine fuel; (2) a performance-based approach that requires all ships in SECAs to control SO_2 emissions but also allows them to either switch fuel or scrub

TABLE 3. Summary of Performance and Costs of Control Policies[a]

	prescriptive standard		performance-based			market-based	
scenarios[b]	fleet cost-effectiveness ($/ton SO_2)	fleetwide costs (million $)	SO_2 reduced[a] (ton)	fleet cost-effectiveness ($/ton SO_2)	fleetwide costs (million $)	fleet cost-effectiveness ($/ton SO_2)	fleetwide costs (million $)
scenario 1	$1,330	$69	53,408	$1,274	$68	$1,237	$64
scenario 2	$1,330	$69	53,286	$1,284	$68	$1,274	$66
scenario 3	$1,330	$69	53,520	$1,272	$68	$1,228	$64
scenario 4	$3,741	$194	56,977	$3,317	$189	$2,428	$126
scenario 5	$16,578	$862	93,509	$6,446	$603	$2,346	$122
scenario 6	$14,897	$774	92,434	$5,682	$525	$2,346	$122
scenario 7	$3,011	$156	53,648	$2,895	$155	$1,579	$82

[a] Prescriptive standard and market-based approach constantly reduce ~52,000 tons of SO_2 emissions; performance-based standard may produce greater reductions. [b] Scenarios defined in Table 2.

exhaust gas while minimizing private compliance costs; and (3) a market-based approach that allows ships in SECAs to either switch to low-sulfur marine fuel, or install EGCS, or purchase SO_2 emissions credits from other ships that can reduce SO_2 at a lower marginal cost. Therefore, we analyze seven scenarios under a set of three different policy approaches, thereby developing a set of 21 case results. Table 3 summarizes the performance and costs of control policies in the three control areas.

Policy 1: All Ships in SECAs Switch to Low-Sulfur Marine Fuel. In this case, the 4,748 ships carrying U.S. foreign commerce in the two European SECAs and/or the US West Coast SECA reduce ~52,000 tons of SO_2 emissions by switching to low-sulfur marine fuels. Both cost-effectiveness and the amount of SO_2 reductions of this policy are dominated by the performance-based policy. The results and discussion of this policy are presented in the Supporting Information.

Policy 2: Performance-Based Requirements in SECAs. The performance-based emission control policy gives ship operators more compliance flexibility. A performance-based approach may "over-control" pollution because least-cost options reduce more emissions for some individual sources (*55*). Table SI3 in the Supporting Information summarizes the costs of this control policy.

The number of ships scrubbing increases as fuel switching costs increase, as scrubbing performance increases, and as scrubbing costs decrease. Almost 20% of the vessels in SECAs will install scrubbing systems when the price premium of low-sulfur marine fuel is extremely high (Scenarios 5 and 6). Under these scenarios, total SO_2 reductions in SECAs are ~80% more than when no or only a few ships install scrubbing systems, and the fleet average costs of reducing one ton of SO_2 is ~40% of the control policy that requires all ships switch to low-sulfur marine fuel. This implies that performance-based control policy can significantly decrease the fleet average marginal costs of SO_2 reduction under Scenarios 5 and 6, and this could save the fleet ~$260 million a year. This is because where normal operation of a device produces "over-control" relative to compliance, we assume the operator will not make adjustments unless it saves money/labor to do so. In addition to generating emissions allowances, this produces 80% more emissions control than required because least-cost options reduce more emissions for some individual ships. Under Scenario 4, a performance-based policy reduces 10% more emissions with ~$5 million savings for the whole fleet.

The maximum and minimum costs for one ton of SO_2 reductions for individual ships also decrease under the performance-based regulation. Scenarios 4, 5, and 7 show that capital costs of fuel switching could result in some old ships pursuing allowance-purchase strategies, because they do not have dual-fuel capacity and only spend a very short time in SECAs; in other words, capital costs could increase marginal costs of SO_2 reduction in cases with a very short amortization time remaining in ship service life. Comparing Scenarios 6 and 1 shows that the fuel price premium also determines switchover between fuel switching, other SO_2 reduction strategies, and allowance purchase for some individual ships, but not as significantly as the capital costs of fuel switching. The comparison of Scenario 1 and 3 shows the impact of the performance of scrubbing systems. The minimum costs of reducing one ton of SO_2 range from ~$190 to ~$200 for individual ships when the performance of exhaust gas scrubbing system varies within the estimated upper and lower bounds.

Policy 3: Simulation of Market-Based Instruments. We simulated a market-based control policy with the objective to minimize the overall fleetwide SO_2 reduction costs for ships in SECAs, and with the constraint that total SO_2 reductions in SECAs are no less than the prescriptive regulation that all ships in SECAs have to burn low-sulfur marine fuel. We assumed that ships that do not control SO_2 emissions should be able to compensate the extra costs of those who reduce more than required by purchasing emissions credits. We also assumed that ship operators and/or ship owners have sufficient information to make their decisions to minimize private costs, and the impacts of emissions at different locations within SECAs are similar and thus can be exchanged equally, i.e., SO_2 reductions at one location produce benefits equivalent with reductions anywhere else in SECAs. This last assumption may be most important to environmental policy makers, and will require atmospheric modeling and health effects analysis to quantify. Evaluation of distributional effects in the following section shows that a market-based approach can reduce more ship SO_2 emissions closer to land with more benefits to the land-based receptors.

The SECA Marine Emissions Optimization Model (SECA-MEOM) is a mixed-integer linear programming model developed from the mixed-integer nonlinear Marine Emissions Optimization Model (MEOM) that was used to optimize fleet-wide emissions reductions for ~45 passenger ferries in the New York−New Jersey Harbor (*47*). The Supporting Information provides a detailed description of the model.

Optimal Solutions of SO_2 Emissions Reductions. Results of Policy 3 can be compared to Policy 2, which conforms more closely with IMO SECA regulations (see Tables SI3 and SI4). Importantly, the fleet can achieve least-cost emissions reduction targets for the SECA by allowing vessels with the lowest marginal control costs to control most emissions. For example, in Scenario 4 (representing our best estimates of costs and performance of the control measures) 219 ships scrub and less than 485 ships switch to low-sulfur fuel. By comparison, only 24 ships adopt scrubbing technology in Scenario 4 for Policy 2 (see Table SI3). Moreover, with fleet-wide versus vessel-by-vessel targets, the cost of reducing one

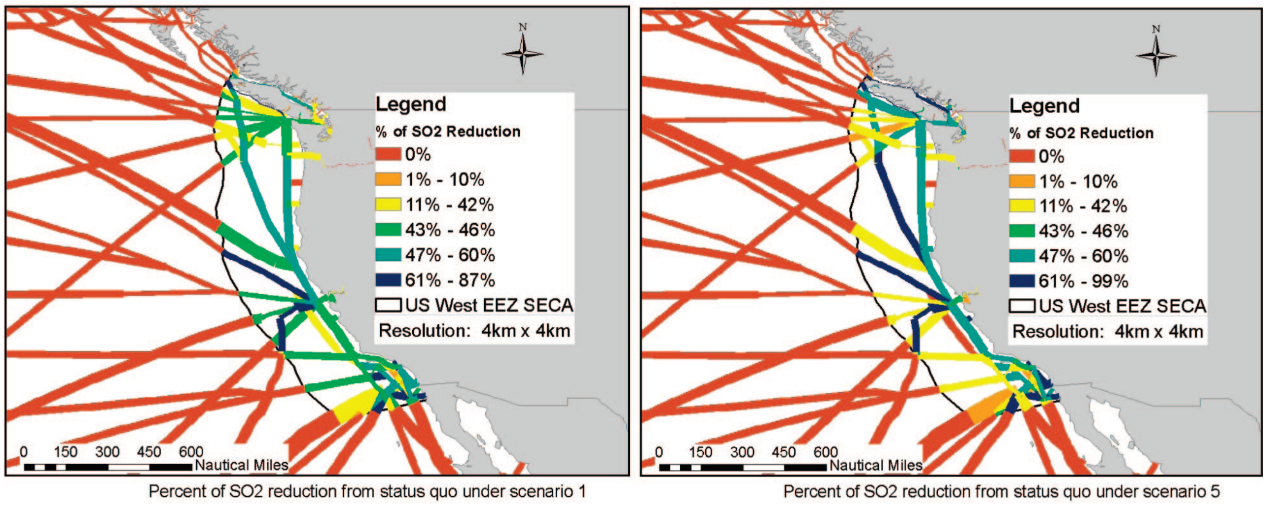

FIGURE 1. Percent of SO_2 reductions for a market-based approach under (a) Scenario 1 and (b) Scenario 5.

ton of SO_2 is ~\$900 lower, although ships in Policy 2 might reduce SO_2 beyond the SECA target. Therefore, a market-based approach could save ~\$63 million annually for the SECA fleet. These cost-savings increase dramatically under assumptions of high fuel switching costs. Other interesting examples are Scenarios 5 and 6. When the low-sulfur marine fuel price premium is extremely high, the SECA SO_2 reduction goal can be achieved with 426 of the 4,748 ships scrubbing exhaust gas while other SECA vessels purchase allowances.

Distributional Impacts of Market-Based Instruments. The cost-effectiveness evaluation of our three policies shows the cost-saving potential of a market-based approach for reducing SO_2 emissions from ships. The market-based instrument, however, would less suit the ship emissions control problem if stakeholders are treated inequitably, i.e. some locations within the SECA would see more reductions than others (geographic inequity), and some stakeholders would carry heavier cost burdens than others (cost inequity). We evaluated the geographic inequity and the cost inequity among ships by type and by flag under the two extreme scenarios: Scenario 1 under which ships more likely choose to switch to low sulfur marine fuel, and Scenario 5 under which ships more likely choose to install EGCS. Figure 1 a and b show the percentage of reduction at each location for our market-based approach under Scenarios 1 and 5, respectively (Figures SI2 and SI3 in the Supporting Information show the spatially resolved reduction of SO_2 in the US West Coast under the two scenarios).

The amount of SO_2 reduction at each location is a function of the amount of SO_2 emissions without control and the performance of SO_2 control measures. Overall, ~40,000 tons or ~46% of SO_2 emissions can be reduced from the US West Coast under Scenario 1. Figure 1a shows that most segments achieve reductions within 42−46%, and only few segments achieve higher reductions from scrubbing. It also shows that uncontrolled vessels mostly operate on segments near the fringes of the SECA (yellow in Figure 1a), where segments have less than 42% SO_2 reduction. Therefore, geographic and cost inequities do not seem to be significant in this case.

In Scenario 5, ~44,000 tons or ~50% of SO_2 emissions can be reduced from ships in the US West Coast. Figure 1b and Figure SI3 in the Supporting Information show that many of the shipping lanes that get greater reductions are closer to the shore, e.g. the South Coast of California, than the lanes that get less reduction. The 426 ships that install scrubbing equipment operate on segments where SO_2 reductions are greater than 44% (see Figure 1b); greater emissions reductions due to scrubbing are closer to land than in Scenario 1. This implies that one ton of SO_2 emissions reductions in Scenario 5 can likely yield more benefits (e.g., mitigate more landside impacts) than one ton of SO_2 emissions reductions in Scenario 1.

In Scenario 5, most vessels (4,322) remain uncontrolled (yellow and orange in Figure 1b); this accounts for many more at-sea segments than in Scenario 1, where segments have less than 42% SO_2 reduction. With more SO_2 emissions reductions closer to land, the market-based instruments can likely yield more benefits with lower overall costs than the command-and-control regulations and should be favored by both environmental interests and the shipping industry.

Our results show that it can be more cost-effective to control some types of ships than to control others, and that a market-based mechanism may achieve this. In fact, container ships and cruise ships were found to carry more than their share of the burden, because it is more cost-effective to install scrubbers on individual vessels with more powerful engines. In Scenario 1, container and passenger ships account for 48% and 11% of the total fleetwide costs while they account for ~38% and ~4% of the engine installed power, respectively. These vessels are responsible for ~65% of the 40,000 tons of SO_2 emission reductions in the US West Coast. In contrast, Scenario 1 also showed that bulk carriers and tankers are responsible for 13% and 11% of the costs while they account for ~22% and ~15% of the engine installed power in SECAs, respectively. These vessels are responsible for ~18% of the SO_2 emission reductions in the US West Coast. Miscellaneous, general cargo, and reefer ships jointly account for ~97% of uncontrolled engine installed power, while they account for less than 15% of the total main engine power of the SECA fleet. These vessels are responsible for ~10% of the SO_2 emission reductions in the U.S West Coast and 8% of the costs. The analysis of Scenario 1 shows that container and passenger vessels tend to reduce more emissions and bear more costs than other types of vessels under a market-based approach. A credit trading mechanism would enable non-controlling tankers and bulkers to assist higher polluting vessels to clean up sooner (i.e., ships with high power ratings, more frequent U.S. West Coast voyages, and more time in transit along coastwise lanes near shore). Similar results were obtained in Scenario 5.

Discussion

The cost-effectiveness evaluation shows that low-sulfur fuel price premium is the most important factor driving fleetwide average costs of SO_2 reduction, especially under the prescriptive policy when all ships have to switch to low-sulfur marine fuel. For individual ships, the capital costs of control are critical and can drive cost-effectiveness of SO_2 reduction when ships are old and spend very short time in SECAs but have to invest in equipment either for fuel switching or for scrubbing exhaust gas.

Performance-based control policy can significantly decrease the fleet average marginal costs of SO_2 reduction compared to policy prescribing fuel switching, especially when the low-sulfur marine fuel premium is very high. The total savings for the whole fleet can be up to \$260 million per year with 80% more reductions when more ships choose to minimize private costs by installing exhaust scrubbing systems (Scenario 5). The maximum and minimum cost effectiveness (\$/ton) of SO_2 reductions for individual ships also decrease with performance-based regulation. The analysis shows significant differences among cost-effectiveness for individual ships. Some ships can reduce emissions at ~\$190/ton while at least one ship would pay over \$4 million/ton for reducing one ton of SO_2; the lower value is within the range of current allowances for the Acid Rain Program and much lower than the Regional Clean Air Incentives Market Trading Credits for 2010 in California. The great variation between the marginal costs of individual ships implies strong cost-saving potential of an economic incentive instrument like emissions trading among ships, and perhaps among ships and land-based sources. Our analysis shows that EGCS can play an important role in least-cost emissions control strategies.

Simulation of optimal SO_2 emissions reduction shows that SECA emissions control goals can be achieved by scrubbing exhaust gas of only one out of ten ships, at fleet marginal control costs lower than performance-based regulation. A market-based control policy could save up to \$480 million annually over performance-based Policy; this achieves the SECA reduction target of 52,000 tons of SO_2 emissions although the performance-based policy reduces 80% more emissions than required (Scenario 5). If the market-based approach were required to reduce the same amount of the SO_2 emissions as the performance-based approach, up to ~\$180 million could be saved for the fleet (see Table SI5 in the Supporting Information).

Evaluation of distributional impacts shows that with more SO_2 emissions reductions in the US West Coast and with more reductions closer to land, market-based instruments may yield more benefits with lower overall costs than command-and-control regulations, and could be favored by both environmental interests and the shipping industry. The analysis also shows that it might be more cost-effective to control some types of ships than to control others, and that a market-based mechanism may achieve this.

The limitations of market-based instruments need to be addressed when selecting and designing such an instrument. To make the instrument work, ship operators should have sufficient information, including costs and performance of control measures, to make their decisions. An administrative mechanism is needed to collect, process, analyze, and distribute such information. The market-based instrument should try to keep transaction costs as low as possible. Uncertainty of compliance costs and uncertainty of environmental outcomes of these instruments need to be addressed to ensure the SO_2 reductions goal is achieved. The exchangeability of emissions at different locations should be investigated further to see whether emissions reductions at different locations need to be weighted for trading.

Monitoring and verification will be critical when implementing an emissions trading system. Fuel testing, documenting fueling process, certifying and inspecting EGCS, and documenting operation of such a system will be needed no matter whether using a command-and-control policy requiring low-sulfur marine fuel or other strategies allowing the use of aftertreatment technologies. To conservatively evaluate the benefits of performance-based or market-based control policies, we assume on-board continuous emissions monitoring systems are installed only on ships claiming more reductions than required by the SECA regulation, usually by installing an EGCS. We estimate that total annual costs of such a monitoring system are ~\$172,000 per unit based on the information from existing SO_2 trading programs (*56, 57*). Results show that under Scenario 4 in Table 2, our best estimate of the value of the variables, total annual savings for the performance-based policy over prescriptive policy 1 are ~\$1 million and are ~\$30 million for market-based policy over performance-based policy. These savings would increase substantially to hundreds of millions with the increase of low-sulfur fuel price premium.

Our focus on sulfur emissions in this paper responds to significant current efforts to reduce sulfur emissions from ships in the U.S. West Coast to mitigate particulate matter (PM) related health problems in California and visibility problems of the Class I areas of the western United States and the ongoing policymaking process of designating SECAs in North America (*58–60*).

Since low-sulfur fuel is not a requirement for reducing other pollutants (e.g., NO_x emissions can be reduced using selective catalytic reduction (SCR) systems designed for heavy fuel oil with sulfur content up to 3% and there are diesel particulate filters (DPF) systems that have very high sulfur tolerance with literally no sulfur limit), we understand that strategies allowing ships to burn regular heavy fuel oil and use aftertreatment technologies to reduce sulfur emissions will not compromise their capabilities to control other pollutants (*61–65*). We also understand that such strategies could serve as a transition mechanism to reduce sulfur emissions from ships in a timely and more cost-effective manner before requiring all ships to burn low-sulfur fuel may be chosen and implemented by policymakers.

We recognize the value of clear regulatory signals in environmental policy, which the IMO regulatory instrument for designating SECAs under MARPOL Annex VI represents. Our results suggest that both SECA-like regulations and market-based instruments are needed to control SO_2 emissions from ships for the U.S. West Coast. A market-based instrument (e.g., a marine-based emissions credit trading program) can complement the SECA regulation and would help keep control costs lower—especially when the price premium of low-sulfur marine fuel becomes high. Market-based instruments also can help mitigate the economic disadvantages of those ships that reduce emissions while minimizing potential economic advantages of those ships that do not control emissions. Market-based instruments such as cap and trade programs can be used as a means of setting long-term emissions allocations that adjust for expected strong growth in shipping and ship emissions. These instruments may offer greater certainty that industry measures will achieve ambient air quality goals, and also provide ship owners/operators better knowledge to plan long-term ship building and operating investment.

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Supporting Information Available

Additional discussion on “command-and-control” vs market-based instruments, performance and costs of fuel switching and seawater scrubbing, results and discussion of the prescriptive control policy, the SECA Marine Emissions Optimization Model (SECA-MEOM); three figures; four tables.

This material is available free of charge via the Internet at http://pubs.acs.org.

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