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Shore Power for Vessels Calling at U.S. Ports: Benefits and Costs

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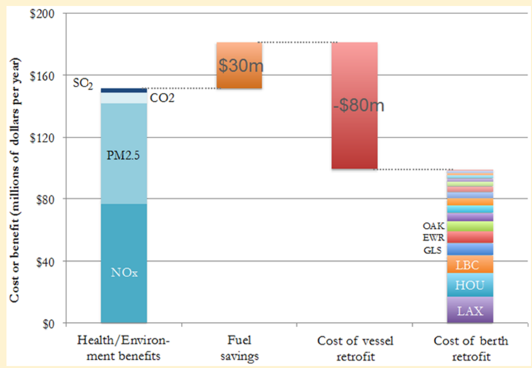
Supporting Information

ABSTRACT: When in port, ships burn marine diesel in on-board generators to produce electricity and are significant contributors to poor local and regional air quality. Supplying ships with grid electricity can reduce these emissions. We use two integrated assessment models to quantify the benefits of reducing the emissions of NO_X, SO_2, $PM_{2.5}$, and CO_2 that would occur if shore power were used. Using historical vessel call data, we identify combinations of vessels and berths at U.S. ports that could be switched to shore power to yield the largest gains for society. Our results indicate that, depending on the social costs of pollution assumed, an air quality benefit of \$70–150 million per year could be achieved by retrofitting a quarter to two-thirds of all vessels that call at U.S. ports. Such a benefit could be produced at no net cost to society (health and environmental benefits would be balanced by the cost of ship and port retrofit) but would require many ships to be equipped to receive shore power, even if doing so would result in a private loss for the operator. Policy makers could produce a net societal gain by implementing incentives and mandates to encourage a shift toward shore power.



1. INTRODUCTION

Shore power or "cold ironing" is the use of electricity from the shore to power a ship's systems when it is in port. When it is cruising, a ship's main engines drive an auxiliary power generator. As the ship begins maneuvering to enter a port, the main engines slow down and no longer drive the generator. An auxiliary generator is then switched on to supply electricity. Once the ship docks, the main engines are switched off, and the auxiliary generator continues to power it.[1] The electricity needed by a vessel in port, called the hoteling load, can range from a few hundred kilowatts to several megawatts, depending on the vessel's size and purpose.[2]

Although there is an ongoing move toward the use of cleaner, low-sulfur, fuels by ships in port, hoteling emissions are a significant contributor to poor local air quality. In 2012, hoteling emissions were 72% of all the SO_2 emissions and 11% of primary $PM_{2.5}$ and diesel PM (DPM) emissions released within the Ports of Los Angeles and Long Beach. Hoteling accounted for 18% of all SO_2 emissions in Los Angeles County, where both ports are located, and about 1% of the county's $PM_{2.5}$ and DPM emissions.[3−5]

Starting in 2014, the California Air Resources Board[6] (CARB) has required that at least 50% of a fleet's visits to major California ports either use shore power for most of their time in port or reduce their use of onboard auxiliary power generation by at least 50% compared to a historical baseline. This requirement will rise to 70% of all visits or baseline power by 2017 and 80% by 2020. CARB's regulations apply to container vessels, passenger vessels, and refrigerated cargo vessels.[7] This regulation is controversial,[8] and some leeway may be granted in its implementation. Our analysis assesses whether a switch to shore power would produce net benefits to society if implemented in other parts of the United States.

2. PRIOR WORK

The Port of Rotterdam conducted an analysis[1] to decide whether to equip its new terminal at Maasvlakte with cold-ironing facilities. It found that "the effects on the air quality on nearby urban [i.e., Rotterdam, 30 miles away] areas will be minimal, at high design and annual costs." A study of the economics of shore power at the Port of Goteborg[9] in Sweden concluded that the cost of port and ship retrofit would exceed fuel cost savings. Winkel et al.[10] conclude that the potential health benefits of a shift to shore power in Europe would be €2.94 billion in 2020. Korn et al.[11] outline the engineering required to retrofit vessels and berths. They also performed a high-level analysis to estimate the reductions in emissions associated with cold ironing. The most comprehensive publicly available study of shore power was conducted for the Port of Long Beach (PoLB) in 2004.[2]This study has several limitations in terms of current policy insight.

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First, current conditions have changed both the costs and the benefits of shore power that make the 2004 study findings out of date. Petroleum prices have changed significantly since the study was done. Furthermore, International Maritime Organization (IMO) regulations now require ships calling at U.S. ports to use cleaner, low-sulfur marine, gas or diesel oil, which can be up to 60% more expensive.[12]

Second, the Port of Long Beach's 2004 study implicitly assumes that these pollutants are equally harmful, and that they all cost the same to abate. Cost-effectiveness calculations divided the annualized cost of implementing cold ironing by the total mass of hydrocarbons, carbon monoxide, NO_X, PM_{10} and SO_2 emissions that would have been avoided. Retrofits were considered cost-effective if the net cost was below the $13 600[13] per ton of (total) emissions avoided that California's Carl Moyer program would have paid in 2002 to retrofit diesel engines to reduce their NO_X emissions. Moreover, a key component of diesel exhaust is $PM_{2.5}$,[14] which is more detrimental to human health than PM_{10}.[15] Sulfur dioxide, in addition to being harmful to human health, contributes to the formation of secondary particulate matter.[16] The 2004 study did not quantify the complex impact of these pollutants.

Third, the study was limited to a small sample of vessels that called at Long Beach and assumed that all benefits and costs of the retrofit would be felt only at Long Beach.

Our study addresses these shortcomings, and extends the 2004 study to include other US ports, as well as all of the 3300 vessels that called at U.S. ports in the 18 months between July 2013 and December 2014. We seek to determine whether and where to deploy shore power in a way that better accounts for the benefits it confers and costs it imposes on society.

3. MATERIALS AND METHODS

Cargo Vessel Information. This analysis is underpinned by a large data set of vessel port calls purchased from Fleetmon,[17] a German firm that collects and archives vessel-position data. These data were collected using land-based stations that receive transmissions from the automatic identification system (AIS) on ships. AIS systems continuously transmit the ship's unique identifier and position. We obtained a list of all cargo-carrying vessels that had departed at least once from the 20 busiest international ports (by cargo volume) in the 18 months from July 2013 to December 2014. For each of these vessels, we obtained a list of every port call the vessel had made anywhere during that time. Each vessel call record consisted of the identity of the vessel, the name of the port, the time at which the vessel arrived at the port, and the time at which it departed. For each vessel, we also obtained the Maritime Mobile Service Identity (MMSI), a unique nine-digit number associated with the AIS station carried by the ship, the ship's IMO registration number, as well as some information about vessel dimensions (length, width, and capacity in dead weight tons (DWT)). The raw data set consisted of 7600 vessels and 870 000 global port calls. The process by which these data were cleaned to prepare them for analysis is described in detail in the Supporting Information. We analyzed a clean data set that consisted of about 46 000 unique calls by 3300 unique ships to 187 unique U.S. ports.

The Long Beach report on shore power[2] discusses ways in which electricity could be delivered to vessels. Vessels that do not require the use of a gantry crane to load and unload cargo could be supplied by means of a tower constructed on the shore, from which cables can be lowered on to the ship. Vessels that do require the use of gantry cranes for loading and unloading cannot be supplied in this way because a tower would interfere with the movement of gantry cranes, which are designed to move along the full length of the wharf. Such vessels would need to be connected to shore power using a barge. These two types of vessels (those that require barges for shore power and those that do not) are likely to use different parts of the port; i.e., dock at different terminals and berths.

In recognition of this, we split the data for cargo vessels into two sets. Vessel types (including container, general cargo, and bulk cargo) that would be connected by barge were placed in one set. Tankers and vehicle carriers, which would not require work barges, were placed in another. There were 1910 vessels that would need to be supplied by barge and 1373 vessels that could be supplied using a gantry tower. These two sets were analyzed separately.

The average power used when a particular type and size of vessel is in port was obtained from the Port of Los Angeles (PoLA) emissions inventory.[18]

Port Information for Cargo Vessels. The vessel call data were also used to deduce the number of berths at each port for each of the two sets of vessels. We counted the number of vessels from each set that were in port on each of the approximately 500 days for which we have data. We assumed that the 90th percentile value of this distribution represented an estimate of the number of berths available to the types of vessels belonging to that set. This is to account for the fact that not all stationary ships within AIS range of a port were necessarily at berth: some may have been moored offshore, perhaps acting as floating storage.[19] We calculated the average utilization of berths at each port by dividing the total duration for which the ships were in port by the product of the total number of berths available and the total number of hours that had passed between the earliest arrival date and the latest departure date for vessels at that port. This number was needed to ensure that, when we calculated the number of berths that ought to be retrofit at each port, the total number of hours for which ships could expect to obtain shore power was limited by the availability of a berth that was equipped to supply it. We assume that the current average levels of utilization are a good approximation of this availability.

Cruise Ship and Port Data. Cruise ships often call at a different set of ports (e.g., Port Canaveral) than do cargo vessels. To analyze cruise ship activity, we obtained a nearly complete record of arrivals and departures that was maintained by the U.S. Army Corps of Engineers' Navigation Data Center until 2012, which is the last year for which data are available. We selected the 17 busiest cruise ports in the continental United States and the 132 cruise ships that visited them in 2012 for analysis. The integrated assessment models that we use to quantify the benefits of a shift to shore power do not extend to Hawaii, Alaska, or U.S. overseas territories such as the Virgin Islands, all of which see significant cruise activity.

The cruise ship data only told us on what day ships arrived and departed but not the times. We assumed that each berth could handle only one departure per day: as such, the maximum number of departures on a single day was used as a proxy for the number of berths at each port. We assumed that all cruise ships stay in port for 10 h on each visit. This number is based on results from Moffat and Nichols,[20] which suggest that cruise ships stay an average of 12 h in the Port of Charleston. Cruise operators are under pressure to reduce this duration to improve cost efficiency, as well as for environmental

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reasons. Assuming that vessels stay in port for 10 h is conservative: longer stays would make shore power more attractive. We assumed that, on average, cruise ships use 5400 kW of power when in port.[4]

Problem Definition. We now define the benefits and costs of using shore power. We consider two kinds of benefits. The first is the monetary benefit that accrues to the ship owner. At 2015 fuel prices, it is cheaper to buy one kWh of electricity from the grid than to produce it using the vessel's diesel-fired auxiliary generator. We assumed that vessels would use marine diesel oil or marine gas oil with 0.1% sulfur as required by Regulation 14 of the IMO and that engines would conform to the IMO's Tier 2 NO_X standard.[21] This second assumption is conservative: Tier 2 applies to vessels constructed after January 2011. For dirtier engines, the environmental benefit of switching to shore power would be greater. We assumed that such fuel was priced at $680 per ton, the spot price in Houston in March 2015. The second benefit is environmental: emissions per kilowatt hour from grid electricity are generally lower than those from electricity produced by burning marine diesel oil. This benefit accrues to society, mostly in the form of an improvement in air quality and corresponding improvements in health. This benefit can be monetized (e.g., in $ per ton of emissions avoided) by using integrated assessment models.[22−26]

We also consider two kinds of costs. The first is the cost to the ship owner of retrofitting the vessel so that it may accept shore power. The second is the cost to the port of extending or expanding the power distribution network, as well as of putting in place the electrical equipment (transformers, cables, etc.) required. In addition, the port would have to acquire, maintain, and operate a work barge for each berth that was already equipped with gantry cranes. For berths that did not require gantry cranes to unload vessels, the port would need to build a tower to lower power supply cables on to the ship.

With these costs and benefits in mind, a decision maker might have one of the following objectives.

(i) Maximizing the benefit (the sum of the private saving to ship owners or operators and the environmental benefit), subject to the condition that the total net benefit is non-negative.

(ii) Maximizing the total net benefit (the sum of environmental and private benefit less the cost of retrofitting the vessels and berths).

The benefits and costs are defined mathematically as follows.

$ben\_pvt_{i,j}$, the private benefit, expressed in dollars per year, that would accrue to the vessel operator if vessel i used shore power at port j, is given by

$$\mathrm{ben\_pvt}_{i,j} = (m - e_j) \times \mathrm{ener}_{i,j} \times o_{i,j} \tag{1}$$

where

m is the cost of electric power generated from marine fuel on board the vessel, in $ per kWh.

e_j is the average price of electricity for industrial use in the state in which port j is located.[27]

$ener_{i,j}$ is the amount of energy, in kWh, that would go from being generated on board to being provided from shore.

$o_{i,j}$ is a binary decision variable, which takes the value of one (1) if vessel i uses shore power at port j; and zero (0) otherwise.

$ben\_env_{i,j}$, the net annual environmental benefit of switching vessel i at port j to shore power, is given by

$$\mathrm{ben\_env}_{i,j} = \mathrm{ener}_{i,j} \times o_{i,j} \times \sum_q \left(\mathrm{eim}_q - \frac{\mathrm{eie}_{q,j}}{1-t}\right) \times \mathrm{sc}_{q,j} \times 10^{-6} \tag{2}$$

where

eim_q is the emission index, in grams per kWh, for pollutant k for marine diesel or gas oil. k = {NO_X, SO_2, $PM_{2.5}$, CO_2}.[18,4]

$\mathrm{eie}_{q,j}$ is the state-average emission index expressed in grams per kWh for pollutant k for the electricity that would be consumed in port j.[28,29]

t is the transmission and distribution loss, assumed to have a value of 10%.

$sc_{q,j}$ is the value, in dollars per ton, of emitting pollutant k at port j. For NO_X, SO_2, and $PM_{2.5}$, we obtain the value of $\mathrm{sc}_{q,j}$ from two models: AP2, the newest version of the Air Pollution Emission Experiments and Policy analysis[30,23] (APEEP), and the Estimating Air Pollution Impacts Using Regression[24] (EASIUR) method applied to the Comprehensive Air-Quality model with extensions (CAMx).[31]

As Heo et al.[25] describes, both models quantify "the societal impacts of air pollution...based on an impact pathway analysis that converts air pollutant emissions to ambient concentrations, estimates their societal effects (e.g., premature mortality and other health effects), and monetizes these outcomes using estimates of willingness-to-pay to avoid these effects". (p 4)

CAMx is "state-of-the-science" and operates at a higher spatial and temporal resolution than does AP2.[24] It is, however, computationally very demanding. EASIUR is a computationally tractable approximation of CAMx. Like Weis et al.,[32] we believe that performing our analysis with both models makes our results more robust and sheds additional light on the sources of uncertainty in environmental decision making. AP2 calculates marginal damages for sources that emit at stack height, as well as for area sources at ground level. We assume emissions from ships to be area sources. AP2 also provides damage values for 2002, 2005, 2008, and 2011. We use the 2005 values because these provide a confidence interval as well as an estimate of the mean social damage. The APEEP model calculates the marginal damages caused by various forms of pollution and includes "crops, trees, people, man-made materials, visibility resources, and sensitive ecosystems,"[23] (p 5) and concludes that mortality and morbidity account for close to 95% of the total damages.[23] (p 8) The EASIUR model[24,25] only accounts for damages resulting from increased mortality because these are a close approximation of the total damages.

We conduct the analysis and report results assuming social costs obtained from both models. For CO_2, we assume a social cost of $40 per ton (in 2015 U.S. dollars, assuming a 3% discount rate).[33]

We define cst_ship_i, the annualized cost of retrofitting a ship to accept shore power as

$$\mathrm{cst\_ship}_i = r_i \times p_i \tag{3}$$

where

r_i is a decision variable that takes the value of one (1) if a vessel is retrofit, and zero (0) if it is not

p_i is the annualized cost of retrofitting a ship for shore power. We assume that it would cost $500 000 to retrofit each ship, a first-order approximation of the average cost of retrofit of the 12 vessels studied in the PoLB study.[2] This cost is amortized over 20 years, assuming a discount rate of 5%.

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cst_port_j, the annualized cost of retrofitting a port to provide shore power to all the ships that require it, is given by

$$\text{cst\_port}_j = c \times k_j \tag{4}$$

where

k_j is a decision variable that takes the value of the number of berths that are retrofit at port j. k_j is a positive integer.

c is the sum of the annualized cost of retrofitting a single berth to provide shore power and the annual cost of operating and maintaining the required equipment.

We base our costs assumptions on those given in the PoLB study.[2] For the set of vessels that do not require a supply barge, we assumed that putting in an electrical distribution network costs \$1 000 000 and that a terminal substation costs \$500 000. These capital costs are amortized over 20 years at a discount rate of 5%. We assume that terminal operating and maintenance (O & M) costs are \$100 000 per year. For the set of vessels for which a barge is required, an additional capital expense (amortized over 20 years and at 5%) of \$2 000 000 is assumed, as well as an additional O & M cost of \$350 000 per year.

Objectives (i) and (ii) must each be achieved subject to the following physical constraints.

The number of berths retrofitted at each port cannot exceed the total number of berths available for that set of vessels (i.e., "barge" or "tower" vessels).

$$\forall\ j\text{: } k_j \le n_j \tag{5}$$

where

n_j is the number of berths available for a particular set of vessels at port j and k_j, is as in eq 4.

The total number of hours for which vessels occupy berths at a port cannot exceed the number of hours for which the berth is available.

$$\forall\ \text{j: } \sum_{\text{i}} o_{\text{i,j}} \times h_{\text{i,j}} \le k_{\text{j}} \times u_{\text{j}} \times 8760 \tag{6}$$

where

$o_{i,j}$ and k_j are as defined in eq 1 and eq 4, respectively;

$h_{i,j}$ is the number of hours that vessel i spent in port j in a year;

u_j is the average rate of utilization of berths for a particular set of vessels at port j; and

finally, a ship must be retrofit for it to be able to use shore power anywhere.

$$\forall\ \text{i, j: } o_{\text{i,j}} \le r_{\text{i}} \tag{7}$$

where $o_{i,j}$ and r_i are as defined in eq 1 and eq 3, respectively.

The condition that the total net benefit be greater than or equal to zero may be written as follows.

$$\left(\sum_{\text{i,j}} \text{ben\_pvt}_{\text{i,j}} + \sum_{\text{i,j}} \text{ben\_env}_{\text{i,j}} - \sum_{\text{i}} \text{cst\_ship}_{\text{i}} - \sum_{\text{j}} \text{cst\_port}_{\text{j}}\right) \ge 0 \tag{8}$$

Therefore, Problem (i) may be written as follows.

Maximize $(\Sigma_{i,j}\text{ben\_pvt}_{i,j} + \Sigma_{i,j}\text{ben\_env}_{i,j})$, subject to the constraints given in eqs 5−8.

Finally, Problem (ii) may be written as follows.

Maximize $(\Sigma_{i,j}\text{ben\_pvt}_{i,j} + \Sigma_{i,j}\text{ben\_env}_{i,j} - \Sigma_i\text{cst\_ship}_i - \Sigma_j\text{cst\_port}_j)$, subject to the constraints given in eqs 5−7.

We solved each of these mixed-integer linear problems twice for each type of vessel, assuming the social cost of pollutants derived from APEEP[30] and those from EASIUR.[24] The problems were written in the General Algebraic Modeling System (GAMS) and solved using the Gurobi solver.[34]

4. RESULTS AND DISCUSSION

Results for Cruise Ships. Solving Problem (i) for cruise ships results in the corner solution, regardless of air-quality model used. A policy that seeks to maximize benefits subject to the condition that net total benefit is at least zero would switch all ships and berths to shore power. On the basis of EASIUR, doing so would generate an annual environmental benefit of \$45 million and a fuel saving of \$16 million, about 40% of what we estimate the cruise ships in our database currently spend on fuel in port. This would be partially offset by \$8 million in annualized vessel retrofit costs and \$20 million in berth retrofit costs. On the basis of APEEP, the total environmental benefit would be \$15 million per year. All other costs and benefits would be the same as those with EASIUR.

Problem (ii) asks what a policy whose goal is to maximize net benefits, total benefits less total costs, ought to prescribe. Depending on the air-quality model used, between half (APEEP) and two-thirds (EASIUR) of cruise vessels ought to be retrofit. The total environmental benefit would be \$40 million, determined on the basis of EASIUR, and \$11 million, determined on the basis of APEEP. Determined on the basis of EASIUR, the benefits would be evenly split between reductions in NO_X emissions and $PM_{2.5}$ emissions. Determined on the basis of APEEP, about half the benefit would come from reductions in $PM_{2.5}$, a quarter from a reduction in NO_X, a sixth from reductions in SO_2, and the rest from CO_2 emissions reductions.

There has been significant progress both in the United States (e.g., California is phasing in a requirement that all cruse ships calling at its ports use shore power) and elsewhere (see, for example, Wahlquist[35]) in moving cruise vessels to shore power. This is partially because each vessel represents a large and visible source of pollution and partially because there is a commercial incentive for vessel operators to make the switch. Our results indicate that society might benefit from an even broader (perhaps universal) move toward shore power for cruise ships.

Results for Cargo-Carrying Ships. The use of shore power for cargo ships is still in its early stages. If marginal social costs of pollution from EASIUR are used, the optimal solution to Problem (i) is to retrofit nearly two-thirds of the cargo vessels considered and 250 of 300 berths. Doing so would produce \$150 million in annual environmental benefits and \$30 million in fuel savings (20% of the estimated current cost of fuel burned in port), which would be completely offset by \$80 million in vessel retrofit costs and \$100 million in berth retrofit costs. If the calculations were based on APEEP, the annual total benefit would be \$85 million, of which \$15 million would come from fuel cost savings and the rest from improved air quality. Determined on the basis of APEEP, it would be optimal to retrofit about a quarter of the vessels and 120 berths.

In the EASIUR-derived solution, half of the total environmental benefit stems from a reduction in NO_X and half from a reduction in $PM_{2.5}$ emissions. In the APEEP-based solution,

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Table 1. Summary of the Optimal Solutions to Problems (i) and (ii)[a]

	EASIUR						APEEP					
Objective	**Maximize net total benefit**			**Maximize total benefit,**			**Maximize net total benefit**			**Maximize total benefit,**		
Applied to	Container and Bulk Cargo Vessels	Tankers and Vehicle Carriers	Cruise Vessels	Container and bulk Cargo Vessels	Tankers and Vehicle Carriers	Cruise Vessels	Container and Bulk Cargo Vessels	Tankers and Vehicle Carriers	Cruise Vessels	Container and bulk Cargo Vessels	Tankers and Vehicle Carriers	Cruise Vessels
Total number of vessels	1,910	1,373	132	1,910	1,373	132	1,910	1,373	132	1,910	1,373	132
Number of vessels retrofit	453	367	102	946	1,151	132	190	149	57	423	504	132
Cost of vessel retrofit	$18	$15	$6	$38	$44	$8	$8	$6	$3	$17	$18	$8
Fuel savings	$7	$10	$16	$12	$18	$16	$3	$6	$11	$5	$11	$16
Net private benefit	-$12	-$5	$9	-$26	-$26	$8	-$5	$0	$7	-$12	-$7	$8
Environmental benefit	$69	$41	$42	$90	$61		$32	$15	$11	$44	$25	$15
NOx	*$35*	*$21*	$22	*$45*	*$32*	$23	*$8*	*$4*	$2	*$9*	*$7*	$2
SO2	*$3*	*$0*	$0	*$3*	*$0*	$1	*$11*	*$4*	$2	*$16*	*$6*	$3
PM2.5	*$29*	*$17*	$18	*$38*	*$27*	$18	*$12*	*$6*	$6	*$17*	*$10*	$8
CO2	*$3*	*$2*	$2	*$4*	*$3*	$2	*$2*	*$1*	$1	*$3*	*$2*	$2
Number of berths retrofit	51	69	55	87	161	62	27	32	35	44	80	62
Canaveral			*5*			*5*			*5*			*5*
Los Angeles	*15*	*8*	*3*	*20*	*11*	*3*	*12*	*6*	*2*	*19*	*10*	*3*
Houston	*0*	*13*		*10*	*36*	*0*		*7*	*0*	*1*	*21*	*0*
Long Beach	*7*	*12*	*2*	*11*	*15*	*2*	*7*	*10*	*2*	*10*	*14*	*2*
Tacoma	*4*	*3*		*6*	*4*	*0*		*0*	*0*	*3*	*1*	*0*
Miami	*0*	*0*	*7*	*3*	*0*	*7*		*0*	*6*	*0*	*0*	*7*
Oakland	*8*	*2*		*8*	*3*	*0*	*8*	*1*	*0*	*8*	*3*	*0*
Galveston	*0*	*4*	*3*	*0*	*35*	*3*		*3*	*3*	*0*	*14*	*3*
Port Everglades	*0*	*0*	*8*	*2*	*7*	*8*		*0*	*4*	*0*	*0*	*8*
Baltimore	*1*	*4*	*2*	*4*	*8*	*2*		*1*	*1*	*0*	*2*	*2*
Newark	*9*	*4*		*9*	*5*	*0*		*1*	*0*	*1*	*2*	*0*
Richmond, CA	*0*	*5*		*0*	*6*	*0*		*3*	*0*	*0*	*5*	*0*
Seattle	*3*	*1*	*4*	*6*	*2*	*4*		*0*	*3*	*2*	*0*	*4*
Port Angeles	*0*	*4*		*0*	*5*	*0*		*0*	*0*	*0*	*0*	*0*
Corpus Christi	*0*	*1*		*0*	*9*	*0*		*0*	*0*	*0*	*2*	*0*
Yerbabuena Island	*1*	*4*		*4*	*5*	*0*		*0*	*0*	*0*	*4*	*0*
New Orleans	*0*	*0*	*3*	*1*	*4*	*3*		*0*	*0*	*0*	*0*	*3*
New York	*3*	*4*	*5*	*3*	*6*	*5*		*0*	*4*	*0*	*2*	*5*
Tampa			*3*			*3*			*3*			*3*
Boston			*3*			*3*			*0*			*3*
San Diego			*0*			*4*			*0*			*4*
Charleston			*1*			*1*			*1*			*1*
Bar Harbor			*0*			*3*			*0*			*3*
Jacksonville			*1*			*1*			*1*			*1*
Key West			*5*			*5*			*0*			*5*
Cost of berth retrofit	$37	$15	$18	$64	$35	$20	$20	$7	$12	$32	$18	$20
Net social benefit	$32	$25	$24	$26	$26	$24	$13	$8	-$1	$12	$7	-$6
Total net benefit	**$20**	**$20**	**$33**	**$0**	**$0**	**$32**	**$7**	**$8**	**$7**	**$0**	**$0**	**$2**

[a]Compared to EASIUR, APEEP generally produces lower estimates of environmental benefits and results in optimal solutions that involve a more limited application of shore power. All monetary estimates are in millions of dollars per year.

about two-fifths of the benefits come from reducing $PM_{2.5}$ and approximately a third each from SO_2 and NO_X reduction.

The geographical distribution of both benefits and optimal locations for berth retrofits for cargo ships varies considerably on the basis of the air-quality model used. APEEP produces a solution where proportionally more berths in California are retrofitted than in other parts of the country.

The solution to Problem (i) produces a large environmental benefit while ensuring that society is no worse off when all costs are accounted for (i.e., non-negative total net benefits). This requires the retrofit of a large number of cargo vessels, more than 80% of which would not be able to recover the cost of vessel retrofit from fuel savings. As such, left to themselves, the owners of these vessels would not switch to shore power. Society generates a large enough surplus from the reduced pollution for it to make economic sense to compensate these vessel owners for their net loss. It could, however, be argued that the vessel owners have hitherto been allowed to pollute without bearing the costs of the deterioration in air quality. Requiring them to retrofit the vessels, and perhaps even bear part of the cost of berth retrofit, ensures that they are no longer allowed to impose this externality on society.

In solving Problem (ii), we assume that the policy seeks to maximize total net benefit. Implementing the optimal solution to this problem would result in a significant total net benefit: $40 million annually, assuming the social costs produced by EASIUR, and $15 million, assuming the social costs in APEEP. The total environmental benefit in the optimal solution based on EASIUR is $110 million annually, which is split almost evenly between reduction in NO_X and $PM_{2.5}$. This benefit is offset by a net private loss of $20 million to ship operators and a cost of $50 million for port retrofit. Given our assumption

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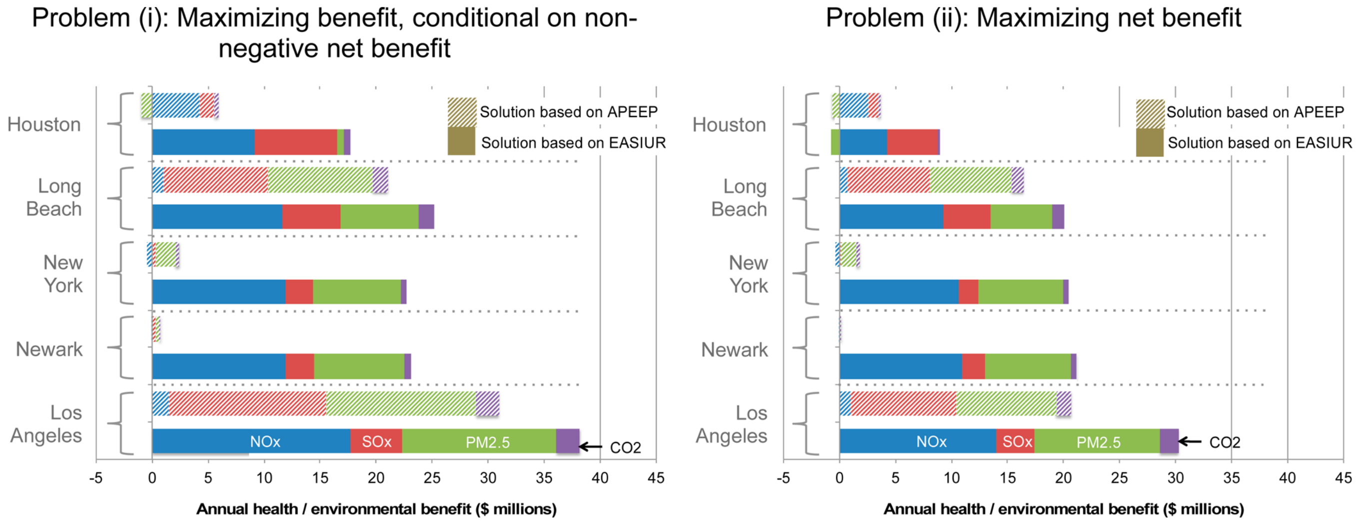

Figure 1. Distribution of the health and environmental benefits, in millions of dollars per year, of shore power in the optimal solutions to (left) Problem (i) and (right) Problem (ii) at select ports. Solutions based on EASIUR (flat colors) and APEEP (patterned colors) are shown.

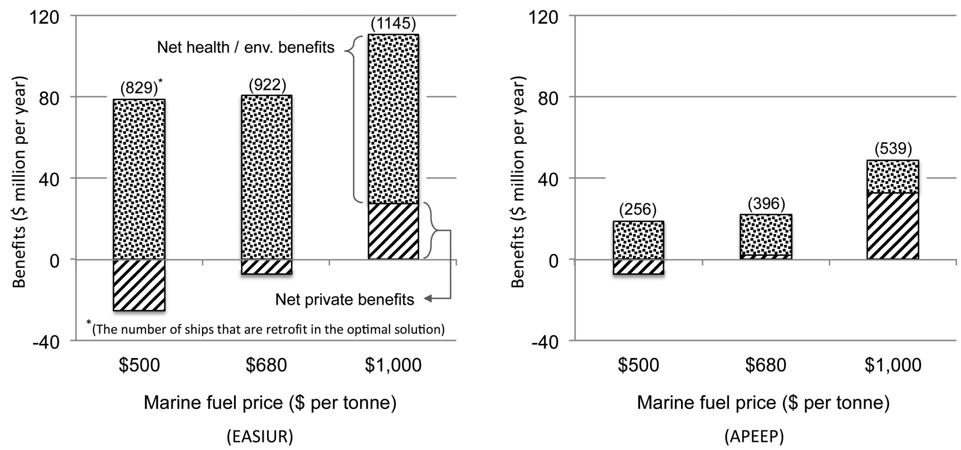

Figure 2. Sensitivity of the solution to Problem (ii) to changes in the price of marine fuel for cargo vessels and cruise ships on the basis of (left) EASIUR and (right) APEEP. At low fuel prices, the benefits of shore power are dominated by environmental benefits, which (for any given vessel) do not diminish with rising fuel costs. However, because of falling private benefits, it may become uneconomical to retrofit a few vessels or a few ports for which the environmental benefits of shore power are not large (e.g., ports where grid electricity is dirtier than average). This would not only diminish the environmental benefits somewhat but also result in a solution where fewer berths need to be retrofitted. As such, the net environmental benefit falls somewhat less steeply than the net private benefit. However, a high fuel price creates an incentive for more ships to be retrofitted. Both environmental and private net benefits rise (the former less steeply than the latter) to produce a nonlinear increase in total net benefit.

that marine fuel with 0.1% sulfur content is used, the benefit from a reduction in SO_2 emissions is small. Determined on the basis of APEEP, the total environmental benefit would be $50 million annually, with approximately a third each coming from reductions in NO_X, SO_2, and $PM_{2.5}$ emissions. This is offset by a net private loss of $5 million to vessel owners and an annualized port retrofit cost of $30 million. Regardless of the air-quality model employed, virtually all of the "barge" vessels that it is optimal to retrofit are container vessels. Among the "tower" vessels, the optimal solution based on EASIUR is to retrofit tankers (the plurality of which are liquefied gas carriers) and many vehicle carriers and RoRo vessels. The optimal solution for "tower" vessels based on APEEP is to retrofit only tankers.

As was the case in Problem (i), over 80% of the vessels that would be retrofit in the optimal solution to Problem (ii) would not produce a saving in fuel cost large enough to compensate their owners. Once again, they could be compensated or required to compensate society for the damage that their pollution causes.

Table 1 summarizes our findings. It suggests that, depending on which air-quality model is applied, a quarter to two-thirds of all vessels can be switched to shore power to generate an environmental benefit sufficient to offset the cost of putting in place the necessary infrastructure on shore and on ships. A more limited deployment of shore power (a tenth to a quarter of vessels, depending on air-quality model) would produce a significant societal benefit net of the costs of installing shore power equipment.

Figure 1 shows that the distribution of environmental benefits, in terms of where they accrue and the gains from reducing the emissions of different pollutants, is extremely sensitive to the choice of air-quality model.

Sensitivity Analysis. We performed a sensitivity analysis on the results of Problems (ii), where we maximize the total net benefit. Figure 2 demonstrates that a 2-fold increase in marine fuel prices, with a fixed price for shore supplied electricity,

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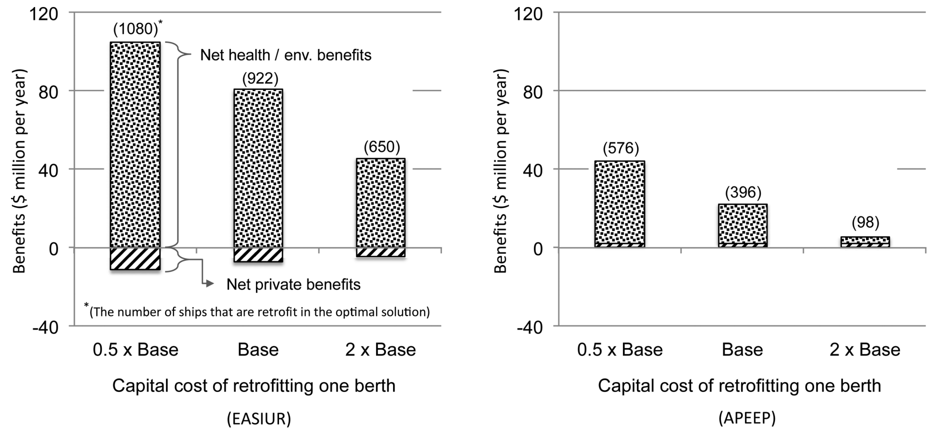

Figure 3. Sensitivity of the solution to Problem (ii) to changes in capital cost associated with retrofitting a single berth for cargo vessels and cruise ships, assuming social costs of pollution derived from (left) EASIUR and (right) APEEP. Results are somewhat less sensitive to the capital cost than they are to changes in the price of fuel. This is because operations and maintenance costs are as large, or larger than, the annualized cost of berth retrofit.

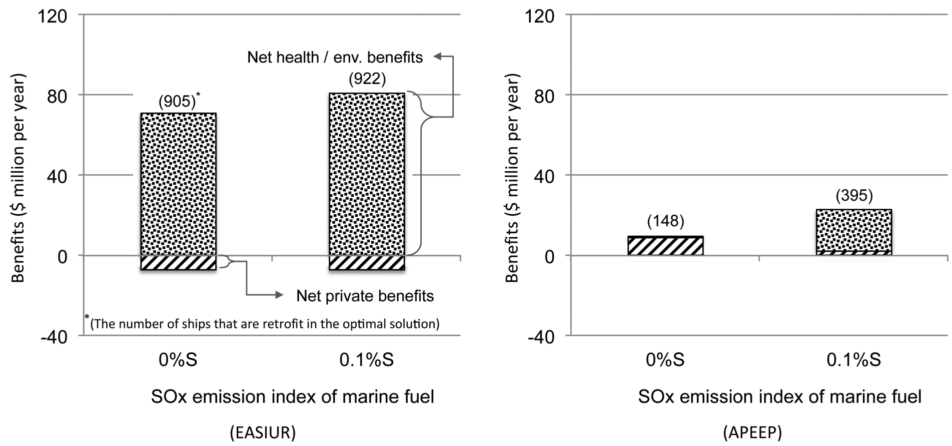

Figure 4. Sensitivity of the solution to Problem (ii) to changes in the sulfur content of the fuel that may be burnt off the U.S. coast for cargo and cruise vessels, assuming the social costs of pollution derived from (left) EASIUR and (right) APEEP. The optimal solution based on APEEP, which is dominated by the high social cost of SO_2 emissions in southern California, is far more sensitive to a change in the sulfur content of marine fuel than is the solution based on EASIUR.

results in a 2-fold increase in net benefit in the solution based on EASIUR but a 3-fold increase in the solution based on APEEP. This is not surprising because APEEP results in an optimal solution with smaller environmental benefits; as such, private benefits (which are highly sensitive to fuel price) play a greater role. Figure 3 demonstrates that the response to changes in the capital cost of berth retrofit is nonlinear. In general, quadrupling the capital costs causes benefits to fall to between one-third and half, depending on the air-quality model.

The 0.1% sulfur content we assume, and which represents the most stringent current IMO standard, translates to 1000 ppm (ppm), almost 2 orders of magnitude higher than what is permitted in road vehicles. Burning this fuel in ports could cause substantial harm to human health. As such, we consider the possibility that in the future, IMO could mandate an even lower sulfur content. Figure 4 suggests that, if estimates of benefits were based on the APEEP air-quality model, such a change would essentially destroy the case for shore power. If the EASIUR model were used, the optimal solution would be an only slightly less widespread adoption of shore power.

Although the results of the optimization are sensitive to fuel and capital costs, the biggest sensitivity is to the choice of air-quality model. The social costs in APEEP are obtained by running a reduced-form air-quality model called Climatological Regional Dispersion Model (CRDM), which was developed in 1996.[24] The model makes significant compromises to ensure that it is computationally tractable: for example, it uses "annual-average meteorological input and emissions".[24,25] It also does not account adequately for recent advances in the understanding of the atmospheric chemistry of key pollutants: for example, that organic particulate matter (PM) is composed primarily of secondary (rather than primary) PM.[24,25,36] EASIUR is based on CAMx, a comprehensive air-quality model that is developed and used for major regulatory impact analysis.[37,38] CAMx is "state-of-the-science"[24,25] and can operate at a much higher spatial and temporal resolution than does CRDM and APEEP; for example, it can "estimate the concentrations of key air pollutants and their precursors at a high temporal resolution typically of 15 min or less."[24] This fidelity comes at a high computational price; Heo[24] estimates that producing county by county estimates of the social costs of pollution (as APEEP does) using CAMx would take 6000 CPU years. To address this, Heo imposed a 148 × 112 square grid on the continental United States and adjacent Mexico and Canada and took a stratified random sample of 100 36 km × 36 km cells. This results in a higher resolution, especially in the western United States, than is available in CRDM, which operates at the resolution of individual counties. For example, Los Angeles County is about 100 km across and 150 km from north to south. CRDM and APEEP treat it as a homogeneous block; CAMx and EASIUR does not. Heo then ran a CAMx simulation for these cells to calculate the marginal social cost of emissions in those counties, and fitted a regression model with high goodness of fit ($R^2 > 0.9$). This regression model was then used to estimate the social cost of pollution at the other cells in the grid. Although the EASIUR model is arguably based on an air-quality model with greater fidelity to the atmospheric chemistry, the fact that a regression is used to extrapolate from relatively few sample runs introduces uncertainties of its own (e.g., the standard errors of the regression coefficients), which remain to be characterized.

Discussion. Our analysis makes the case for policy intervention: requiring vessel operators to switch to shore power will produce a net benefit to society that they do not have an incentive to provide in the absence of such a requirement.

The analysis is performed as if it were possible to implement a single, nationally applicable policy. The actual number of stakeholders is large and their different motivations are complex.

This argues for a method of regulation that involves state or federal agencies either phasing in a requirement for shore power or providing incentives (e.g., matching funds for port retrofit) for its uptake. Requirements imposed by a small group of states could ripple through the fleet and lead to broader adoption. For example, vessel operators who are required to retrofit their vessels to meet California's regulations would save money by plugging into shore power at other ports at no additional cost to them.

Given our finding that in some cases the policy decision could change significantly if a different air-quality model were used, it may be useful to test the sensitivity of other studies,[39−43] which also use reduced-form models, to the choice of model.

Finally, the current analysis is limited to ports in the continental United States, partly because no good integrated air-quality models exist to help us calculate the social cost of pollution in non-U.S. ports. It would be useful if estimates of these costs could be generated, especially for ports in Asia, where ships are permitted to use fuel with a significantly higher sulfur content when in port and where it is likely that large populations are exposed to pollution from vessels in port. However, such "damage is difficult to quantify given the other sources of contaminants and the complexities of tracking health".[44]

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b04860.

> Additional details on cleaning the vessel call history, port information, cruise vessel information, problem definition, container ship shore power requirements, sensitivity analysis, and discussion. Figures showing the sensitivity of the solution to Problem (ii) to an increase in the rate of utilization of retrofitted berths for cargo and cruise vessels assuming social costs of pollution and The optimal decision if the actual social costs of pollution were equal to the 5th, mean, or 95th percentile values in APEEP. Tables showing port calls, summary statistics for cargo vessel calls, the number of berths available for vessels, the 17 ports analyzed, potential reductions in the quantity of electricity supplied by shore power, a summary of results for earlier Supporting Information material, and a comparison of shore power to VSR. (PDF)

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Notes

The authors declare no competing financial interest.

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