Supplementary Information for:

"Shore Power for Vessels Calling at US Ports – Benefits and Costs"

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Contents

S1 MATERIALS AND METHODS S-4

S1.1 Cleaning the vessel call history S-4

S1.2 Port information S-7

S1.3 Cruise vessel information S-9

S1.4 Problem definition S-9

S2 RESULTS AND DISCUSSION S-14

S2.1 Requiring all container ships calling at major California ports to use shore power S-14

S2.2 Requiring all ships at California ports to use shore power S-14

S2.3 Requiring all ships calling at major US ports to use shore power S-14

S2.4 Sensitivity analysis S-15

S2.5 Discussion S-17

S3 REFERENCES S-20

List of figures

Figure S-1: 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 derived from (1) EASIUR, and (2) APEEP. If retrofitted berths at each port were scheduled 20% more efficiently than the mean for that port, the result would be to increase the net benefit of retrofit, though this effect would be more prominent if the social costs were based on EASIUR than on APEEP. 16

Figure S-2: The optimal decision if the actual social costs of pollution were equal to the 5th, mean, or 95th percentile values in APEEP. An optimal decision based on the 5th percentile values would be to do nothing. If the true social cost was given by the 95th percentile value two to three times as many vessels would be retrofitted as in the case based on mean values, generating five to six times the total net benefit. 17

List of tables

Table S-1: For most vessel types, there is a small tail of very long port calls. These port calls, while few in number, could dominate the analysis if it were assumed that the vessel could be switched to shore power over this entire duration. To prevent this, call durations are replaced by the shorter of the actual call duration and the 90^{th} quantile value of call durations for vessels of a particular type. 5

Table S-2: Summary statistics for cargo vessel calls included in the analysis. The busiest ports are in Southern California and the Gulf of Mexico. The former are dominated by vessels that require gantry cranes to unload, and would therefore require a work barge to supply with electricity from the shore (primarily, container ships). The latter are dominated by vessels that could be supplied from a tower erected on shore (primarily, tankers). 6

Table S-3: Number of berths available for vessels in each of our sets, as well as the average rate of utilization of the berths. Alternatively, these can be thought of simply as the maximum number of ships that is likely to be in the port at any given time. If shore power infrastructure were built to cater to all such vessels, then the rate of utilization represents the percentage of time that the shore power infrastructure would be used on average. These ports were selected because a preliminary analysis indicated that they would have the highest energy use (and were therefore likely benefit the most from a shift to shore power).7

Table S-4: The 17 ports analyzed to determine the benefits and costs of using shore power for cruise vessels. Utilization and annual energy use are calculated assuming that each visit lasts 10 hours and that the vessel draws 5,400kW of power on average when in port. 9

Table S-5: Potential reduction in the quantity of electricity supplied by shore power by assuming that some vessels will not plug into shore power even if they are equipped to receive it and at least one berth is equipped to supply it 13

Table S-6: A summary of the results discussed in Sections S2.1-S2.3 suggests that - except for container ships in California - applying a blanket requirement that shore power be used is likely to produce a significant net societal loss 15

Table S-7: Comparing shore power (the solution to Problem (i) based on EASUR, applied to the Port of Long Beach) to the VSR program at that Port. The cost of shore power to the port is estimated to be the annualized cost of retrofitting and operating the required number of berths. 18

S1 MATERIALS AND METHODS

S1.1 Cleaning the vessel call history

To clean the data, we first extracted the records for calls to US ports. Only records in which the vessel had arrived in port after June 2013 were retained. A number of vessel types (e.g., tugs, yachts, pleasure boats, coast guard, law enforcement vessels etc.) that are not relevant to this analysis were removed. The California “At-berth” regulation applies only to vessels with a capacity of greater than 10,000 dead weight tons (DWT) and longer than 400 feet.[1] As such, in this analysis only vessels larger than this threshold were retained. The California regulation only applies to container, refrigerated cargo, and passenger vessels; however, we did not apply that restriction in assembling our dataset. Also, a capacity threshold of 10,000 DWT excludes virtually all passenger vessels, including cruise liners. In our analysis, cruise liners are analyzed separately, as they are unlikely to share shore power infrastructure with cargo vessels. We also identified and discarded duplicate records.

We discarded vessel calls of less than five hours’ duration for two reasons. First, we believed that a call of this duration might not be one in which a vessel actually docks in port to discharge cargo. In addition to the Fleetmon data, we obtained vessel call histories from the ports of Pascagoula, Houston, and Seattle. About 1% of the vessel calls (66/4,760 at Houston, 12/1,131 at Seattle, and none at Pascagoula) were of less than five hours’ duration. As such, our assumption was largely validated by independent data. Second, even if such a record represented a “genuine” port call, it would be too short for it to be economical for the vessel to be connected and disconnected to shore power. The Long Beach study[2] suggests that connecting a vessel to shore power would take between 20 minutes and two hours, and disconnecting it would take similarly long. At this point, the dataset consisted of about 46,000 unique calls by 3,300 unique ships to

187 unique US ports. Note that we purchased data on *all* vessel calls for only the twenty busiest ports in the United States. We have data for *some* vessel calls at a large number of US ports because many of the vessels in the dataset called at these smaller ports also. It was found that certain port calls, especially for tankers and liquefied gas carriers were extraordinarily long (>1000 hours). This may be due to errors in the raw data, or due to the fact that some tankers might have been used as floating storage for substantial periods of time (see, for example, Raval[3]). Similarly, ongoing industrial action at US west coast ports might have prolonged the stay of some other types of vessels.[4] It is unlikely that such vessels would be able to use shore power even if it were available, as they might have been anchored in or near the port area but not at a berth. AIS transmissions can be reliably received for 10-20 nautical miles., and the range may be up to 50 nautical miles.[5]

Table S-1: For most vessel types, there is a small tail of very long port calls. These port calls, while few in number, could dominate the analysis if it were assumed that the vessel could be switched to shore power over this entire duration. To prevent this, call durations are replaced by the shorter of the actual call duration and the 90^{th} quantile value of call durations for vessels of a particular type.

Vessel type	Unique vessels	Calls	Total hours	Call durations (in hours)				
				q99	q90	q50	q10	q1
Bulk carrier	638	5,300	460,000	540	190	48	7	5
Oil tanker	512	8,400	610,000	780	140	33	7	5
Liquefied gas carrier	57	400	65,000	1,700	360	65	18	6
Container ship	1084	18,200	650,000	230	69	21	10	6
General cargo vessel	159	1,300	100,000	610	150	47	11	5
Chemical carrier	174	2,300	130,000	550	110	28	8	5
Vehicle carrier	255	3,400	140,000	410	43	17	8	5
Oil Products Tanker	285	3,600	190,000	460	100	30	8	5
RoRo ship	44	800	26,000	200	64	20	8	5
Tanker	50	800	60,000	690	130	36	9	5
Heavy Lift Vessel	10	100	16,000	1,900	230	42	16	9
Forest-product carrier	22	200	15,000	430	170	50	9	6

To prevent such outliers from distorting our analysis, we calculated the 90^{th} percentile value of call durations for each type of ship (Table S-1) For calls that lasted longer than the 90^{th} percentile value of calls for that vessel type, we replaced the call duration with the 90^{th} percentile value.

Table S-2: Summary statistics for cargo vessel calls included in the analysis. The busiest ports are in Southern California and the Gulf of Mexico. The former are dominated by vessels that require gantry cranes to unload, and would therefore require a work barge to supply with electricity from the shore (primarily, container ships). The latter are dominated by vessels that could be supplied from a tower erected on shore (primarily, tankers).

Vessel type	Average power at berth	Number of ships	Los Angeles	Houston	Newark	Seattle	Los Angeles	Houston	Newark	Seattle	Los Angeles	Houston	Newark	Seattle
	kW		number of visits				average duration of calls (hours)				total energy use (MWh)			
Container - 1000	720	10	33	25	9	0	45	51	13	-	1,068	925	85	-
Container - 2000	1,039	78	184	160	103	59	33	47	18	25	6,359	7,876	1,881	1,541
Container - 3000	641	79	188	174	29	21	30	28	18	25	3,565	3,102	334	340
Container - 4000	1,136	150	288	255	281	63	41	29	26	24	13,430	8,379	8,441	1,731
Container - 5000	1,128	201	511	208	846	75	35	24	21	32	19,988	5,730	20,036	2,700
Container - 6000	804	261	473	226	529	212	34	25	25	27	12,761	4,533	10,789	4,645
Container - 7000	845	65	176	78	56	41	65	28	27	20	9,620	1,856	1,293	688
Container - 7000	845	28	175	6	111	17	60	30	22	30	8,901	150	2,036	430
Container - 8000	1,008	18	37	0	5	14	68	-	48	41	2,529	-	241	574
Container - 9000	1,030	118	267	2	109	153	65	32	42	43	17,941	65	4,664	6,840
Container - 10000	1,075	50	200	0	37	28	68	-	39	25	14,526	-	1,563	748
Container - 11000	1,500	12	62	0	0	6	69	-	-	23	6,406	-	-	211
Container - 12000	2,000	11	36	0	0	0	66	-	-	-	4,749	-	-	-
Container - 13000	1,700	3	4	0	0	0	69	-	-	-	470	-	-	-
Bulk carrier	208	638	237	600	80	55	60	82	100	124	2,936	10,252	1,660	1,419
Heavy Lift Vessel	467	10	5	17	5	1	67	71	33	21	157	564	76	10
Cargo ship	575	25	28	35	7	0	61	81	91	-	977	1,635	367	-
General cargo vessel	575	159	41	334	8	32	59	87	29	31	1,396	16,618	132	562
Forest-product carrier	208	22	14	16	1	4	57	61	82	116	167	202	17	96
Dry cargo	575	2	0	6	0	0	-	77	-	-	-	264	-	-
"Barge" vessels		**1,940**	**2,959**	**2,142**	**2,216**	**781**	**47**	**55**	**27**	**38**	**127,945**	**62,151**	**53,615**	**22,536**
Oil tanker	605	512	743	1,014	38	11	43	53	25	77	19,370	32,671	572	514
Tanker	605	50	74	205	18	6	49	59	72	79	2,200	7,374	785	286
Chemical carrier	738	173	22	773	51	1	48	49	28	17	781	27,711	1,051	13
Oil Products Tanker	605	285	140	896	45	1	41	48	26	44	3,502	25,889	708	27
Liquefied gas carrier	2,520	57	2	278	1	0	38	105	22	-	190	73,518	56	-
RoRo ship	229	44	0	46	72	1	-	49	13	9	-	515	220	2
Vehicle carrier	1,284	255	130	93	331	2	18	22	16	14	3,008	2,627	6,971	36
Ore-bulk-oil carrier	605	4	4	7	0	0	17	45	-	-	41	192	-	-
"Tower" vessels		**1,380**	**1,115**	**3,312**	**556**	**22**	**40**	**54**	**20**	**65**	**29,093**	**170,497**	**10,363**	**878**

Table S-2 provides a summary of the vessel call data for four key, geographically dispersed ports. The average power used when the vessel is in port was obtained from the Port of Los Angeles emissions inventory.[6] For container vessels, the average power use was given as a function of the vessel's size in terms of the maximum number of twenty-foot equivalent units (TEUs) the vessel could hold. Average power consumption values were provided for vessels with a capacity of between 1000 and 14,000 TEUs, in increments of 1000 TEUs. Our vessel data did not tell us the capacity of container ships in terms of their capacity in TEUs. However, this information was obtained for 270 vessels from their records with Fleetmon and regressed using ordinary least squares against the ship's capacity in deadweight tonnes (DWT).

The relationship between capacity in DWT and number of TEUs was found to be linear and highly significant ($R^2 = 0.96$, $p \sim 0$), and was used to deduce the capacity in terms of TEUs for the remaining 800 container ships in the dataset.

Table S-2 shows the total energy use while the ship is in port. We also calculated the total energy use that would be displaced by shore power by assuming that a ship would be connected to shore power for 2.5 hours less than the total time it spent in port, as it would take some time to physically connect the necessary cables as well as to transfer the electrical load from on-board generators to the shore supply.

S1.2 Port information

Table S-3 summarizes the information extracted from the data for cargo vessels. Note that the relatively low level of utilization is a conservative assumption. We assume that the way vessels are scheduled to arrive and depart from a port that prevents utilization from being higher. If, in fact, utilization is low simply because some ports have spare capacity, then berths equipped to supply shore power could be used more efficiently. As a consequence, fewer berths would need to be retrofitted, which in turn would lower costs and make shore power more attractive. Based on data that we obtained directly from the ports, it is the case that some berths are used more efficiently than others. For example, the rates of utilization of some berths at the Barbour's Cut terminal in the port of Houston are well over 75%.

Table S-3: Number of berths available for vessels in each of our sets, as well as the average rate of utilization of the berths. Alternatively, these can be thought of simply as the maximum number of ships that is likely to be in the port at any given time. If shore power infrastructure were built to cater to all such vessels, then the rate of utilization represents the percentage of time that the shore power infrastructure would be used on average. These ports were selected because a preliminary analysis indicated that they would have the highest energy use (and were therefore likely benefit the most from a shift to shore power).

Port	**"Barge" vessels**		**"Tower" vessels**	
	Number of berths	Average berth utilization	Number of berths	Average berth utilization
Los Angeles	20	47%	11	31%
Houston	21	38%	40	34%
Long Beach	13	34%	15	30%
Tacoma	8	38%	4	12%
Port of Miami	4	20%	2	5%
Oakland	8	28%	3	16%
Galveston	6	16%	37	17%
Everglades	3	17%	8	13%
Port of Baltimore	6	30%	9	29%
Newark	9	31%	5	17%
Richmond, CA	2	16%	6	36%
Seattle	6	29%	2	5%
Port Angeles, WA	1	1%	5	21%
Corpus Christi	4	19%	11	19%
Yerbabuena Island	4	12%	5	15%
New Orleans	11	27%	5	16%
New York	3	20%	6	20%

S1.3 Cruise vessel information

Table S-4: The 17 ports analyzed to determine the benefits and costs of using shore power for cruise vessels. Utilization and annual energy use are calculated assuming that each visit lasts 10 hours and that the vessel draws 5,400kW of power on average when in port.

Name	Number of calls	Number of berths	Utilization	Total energy use (GWh)
Miami	726	7	12%	40
Port Canaveral	692	5	16%	38
Port Everglades	627	8	9%	34
New York	332	5	8%	18
Key West	331	5	8%	18
Tampa	210	3	8%	11
Seattle	198	4	6%	11
New Orleans	181	3	7%	10
Galveston	175	3	7%	10
Long Beach	160	2	9%	9
Boston	117	3	4%	6
Baltimore	108	2	6%	6
Los Angeles	102	3	4%	6
San Diego	90	4	3%	5
Charleston	84	1	10%	5
Bar Harbor	83	3	3%	5
Jacksonville	80	1	9%	4

Table S-4 summarizes port and vessel energy use information for cruise vessels.

S1.4 Problem definition

$$ben\_pvt_{i,j} = \left(m - e_j\right) \times ener_{i,j} \times o_{i,j} \qquad \textbf{Equation 1}$$

where

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

m is the cost of electric power generated from marine fuel on board the vessel, expressed in $ per kWh. This is calculated based on the price of marine fuel, and takes into account the efficiency of the diesel generator

e_j is the average price of electricity for industrial use in the state in which port j is located. This number is obtained from the Energy Information Administration.[7]

$ener_{i,j}$ is the amount of energy, expressed in kWh, that would go from being generated on board to being provided from shore. Note that this is not the total quantity of energy that the vessel would use while in port: the vessel would generate its own power while it was being connected to and disconnected from shore power (see Section S1.1) For cruise vessels, this would be given by the number of visits by vessel i to port j, multiplied by 10 hours per visit, multiplied by 5400kW.

$o_{i,j}$ is a binary decision variable. It is a dummy, which takes the value of one (1) if vessel i uses shore power at port j; and is zero (0) if it does not. $o_{i,j}$ helps determine the number of berths that must be retrofit at a port, j. The optimization problems below are written so that a new berth would have to be retrofit (and the cost of retrofit incurred) if accommodating an additional vessel at a port would cause the total annual number of hours that shore power is used at that port to exceed $k'_j \times \mu_j \times 8760$, where k'_j is the number of retrofitted berths at port j before the new vessel is accommodated, and μ_j is the average rate of utilization of berths at port j (see Equation 6 below). Some vessels – even if they were equipped to use shore power – might not generate a large enough benefit from plugging in at a particular port to justify the retrofit of an additional berth (e.g., if they did not spend much time there). Since μ_j is an average rate, in practice, it is possible that a vessel (i) that is equipped to use shore power (r_i =1) pulls into port and finds a retrofitted berth free, even if – when determining how many berths to retrofit – the decision maker had concluded that it was optimal to assume that that vessel (i) would not use shore power at port j ($o_{i,j} = 0$). If such a vessel were able to use shore power at port j, this would not be accounted for in the benefits calculated in Equation 1 and Equation 2. That is, the benefits would be underestimated. We estimated the maximum possible size of this gap by analyzing the solutions to each of the problems defined below to work out how much energy is consumed by vessels (i) that are equipped to use shore power (r_i=1), pull into a port (j) that has at least one retrofitted berth ($k_j \geq 1$), but for which $o_{i,j}$=0. We found that, for the busiest ports, this number was zero: any ship that was equipped to use shore power at Los Angeles or Houston would, in the optimal solution, use it. Across all 17 ports, this number was ~5%, which is therefore the upper limit of the amount of benefit that we are "leaving on the table" by making a decision based on an average. (See Table S-5 for port-by-port data).

$$ben\_env_{i,j} = ener_{i,j} \times o_{i,j} \times \sum_q \left(eim_q - \frac{eie_{q,j}}{1-t}\right) \times sc_{q,j} \times 10^{-6} \qquad \textbf{Equation 2}$$

where

$ben\_env_{i,j}$ is the net annual environmental benefit that would accrue from switching vessel i at port j to shore power

$ener_{i,j}$ and $o_{i,j}$ are defined as in Equation 1

eim_q is the emission index expressed in grams per kWh for pollutant k for marine diesel or gas oil. k = {NO_X, SO_2, $PM_{2.5}$, CO_2}. For NO_X, CO_2, and $PM_{2.5}$, we use the numbers given in the PoLA emissions inventory[6] for marine diesel or gas oil with 0.3% sulfur content, burned in IMO Tier 2 engines. For SO_2 - recognizing that Regulation 14 requires that only fuels with a maximum sulfur content of 0.1% be used in Emissions Control Areas (ECAs), including both US coasts – we use one third of the value given in PoLA emissions inventory.[8]

$eie_{q,j}$ is the emission index expressed in grams per kWh for pollutant k for the electricity that would be consumed in port j. This number is obtained by dividing the total emissions from fuel combustion from electric generation of each pollutant given in the National Emissions Inventory[9] for the state in which port j is located and dividing it by the net power generated in that state.[10]

t is the transmission and distribution loss, expressed as a percentage, and assumed to have a value of 10%. We include this term to take into account the fact that more electricity would have to be generated than is used by the ship.

$sc_{q,j}$ 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 this value from two models: Air Pollution Emission Experiments and Policy analysis[11] (APEEP), and the Estimating Air Pollution Impacts Using Regression[12] (EASIUR) method applied to the Comprehensive Air Quality Model with extensions[13] (CAMx). APEEP provides the mean, as well as 5th and 95th percentile values of the social cost of emitting one ton of a particular pollutant in each county in the continental United States. 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.

$$cst\_ship_i = r_i \times p_i \quad \textbf{Equation 3}$$

where

cst_ship_i is the annualized cost of retrofitting a ship to accept shore power.

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. For this analysis, we assume that such a retrofit would cost $500,000 for all ships. The number is a first order approximation of the average cost of retrofit of the twelve vessels studied in the PoLB study.[2] Clearly, this is a simplifying assumption: retrofit cost is likely to vary substantially from vessel to vessel. Due to the very large number of vessels considered in this analysis (>3,000), it is not practical to work out the cost of retrofitting each vessel. Nonetheless, an obvious way of improving on the present approach would be to derive a formula or heuristic to estimate retrofit costs based on vessel size, type, and vintage. This cost is amortized over 20 years, assuming a discount rate of 5%.

$$cst\_port_j = c \times k_j \quad \textbf{Equation 4}$$

where

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

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. When the analysis was done for the set of vessels that do not require a barge (including cruise vessels), we assumed (again, based on the numbers provided in the PoLB study[2] 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. These costs assume that a complete retrofit of existing port facilities would be needed, and are therefore conservative. The incremental cost of building new berths that are equipped for shore power would be smaller, as would the cost of retrofitting berths that were designed with future shore power implementation in mind (e.g., if the canalization is already in place.)

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

Objectives (i) and (ii) must both 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).

$$\forall j: k_j \leq n_j \qquad \textbf{Equation 5}$$

where

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

The total number of hours for which vessels occupied berths at a port cannot exceed the number of hours for which the berth would be available.

$$\forall j: \sum_i o_{i,j} \times h_{i,j} \leq k_j \times u_j \times 8760 \qquad \textbf{Equation 6}$$

where

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

$h_{i,j}$ is the number of hours that vessel i spent in port j in a year. Note that this is the total number of hours for which the vessel occupied the berth, and as such is greater than the number of hours for which the vessel uses shore power. For cruise vessels, $h_{i,j}$ would be calculated by multiplying the visits made by vessel i to port j by 10 hours per visit.

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

Table S-5: Potential reduction in the quantity of electricity supplied by shore power by assuming that some vessels will not plug into shore power even if they are equipped to receive it and at least one berth is equipped to supply it

Problem (i) – Container and bulk cargo vessels - EASIUR

	Total	Los Angeles	Houston	Long Beach	Tacoma	Miami	Oakland	Galveston	Everglades	Baltimore	Newark	Richmond, CA	Seattle	Port Angeles	Corpus Christi	Yerba Buena Island	New Orleans	New York
Actual kWh used	353,876,865	116,569,724	38,189,069	47,446,286	26,123,927	6,688,237	31,993,852	-	4,007,352	11,825,982	35,708,994	-	19,444,166	-	-	5,854,188	2,355,367	7,669,720
Total kWh possible for retrofited ships	374,353,112	116,628,464	38,662,498	47,446,286	26,745,663	6,688,237	45,618,146	-	5,029,324	12,143,127	37,407,625	-	19,444,166	-	-	6,749,444	3,007,803	8,782,330
Maximum "leakage"	-5%	0%	-1%	0%	-2%	0%	-30%	-	-20%	-3%	-5%	-	0%	-	-	-13%	-22%	-13%

Problem (i) – Tankers and vehicle carriers - EASIUR

	Total	Los Angeles	Houston	Long Beach	Tacoma	Miami	Oakland	Galveston	Everglades	Baltimore	Newark	Richmond, CA	Seattle	Port Angeles	Corpus Christi	Yerba Buena Island	New Orleans	New York
Actual kWh used	404,917,609	30,367,351	154,896,178	41,749,391	6,019,839	-	3,367,178	62,351,237	7,375,429	26,191,258	8,899,344	18,399,010	876,488	9,622,298	13,940,188	5,801,866	4,861,263	10,199,289
Total kWh possible for retrofited ships	407,061,410	30,367,351	156,096,847	41,749,391	6,019,839	-	3,367,178	62,370,745	7,375,429	26,191,258	8,899,344	18,399,010	876,488	9,622,298	14,863,811	5,801,866	4,861,263	10,199,289
Maximum "leakage"	-1%	0%	-1%	0%	0%	-	0%	0%	0%	0%	0%	0%	0%	0%	-6%	0%	0%	0%

Problem (ii) – Container and bulk cargo vessels - EASIUR

	Total	Los Angeles	Houston	Long Beach	Tacoma	Miami	Oakland	Galveston	Everglades	Baltimore	Newark	Richmond, CA	Seattle	Port Angeles	Corpus Christi	Yerba Buena Island	New Orleans	New York
Actual kWh used	235,558,369	93,093,278	-	34,205,824	18,479,327	-	31,805,469	-	-	3,774,134	34,497,635	-	11,051,537	-	-	1,649,526	-	7,001,638
Total kWh possible for retrofited ships	246,289,908	93,093,278	-	34,205,824	18,661,152	-	36,814,850	-	-	5,495,510	34,497,635	-	11,184,354	-	-	5,235,335	-	7,101,971
Maximum "leakage"	-4%	0%	-	0%	-1%	-	-14%	-	-	-31%	0%	-	-1%	-	-	-68%	-	-1%

Problem (ii) – Tankers and vehicle carriers - EASIUR

	Total	Los Angeles	Houston	Long Beach	Tacoma	Miami	Oakland	Galveston	Everglades	Baltimore	Newark	Richmond, CA	Seattle	Port Angeles	Corpus Christi	Yerba Buena Island	New Orleans	New York
Actual kWh used	232,823,002	21,958,782	90,191,776	34,563,522	3,659,974	-	2,253,898	19,489,632	-	17,066,394	6,441,154	14,809,576	464,799	8,119,864	2,628,998	4,651,208	-	6,523,426
Total kWh possible for retrofited ships	239,280,381	22,029,817	90,427,810	34,563,522	3,659,974	-	2,253,898	24,896,460	-	17,071,707	6,441,154	14,809,576	639,227	8,407,860	2,904,742	4,651,208	-	6,523,426
Maximum "leakage"	-3%	0%	0%	0%	0%	-	0%	-22%	-	0%	0%	0%	-27%	-3%	-9%	0%	-	0%

Problem (i) – Container and bulk cargo vessels - APEEP

	Total	Los Angeles	Houston	Long Beach	Tacoma	Miami	Oakland	Galveston	Everglades	Baltimore	Newark	Richmond, CA	Seattle	Port Angeles	Corpus Christi	Yerba Buena Island	New Orleans	New York
Actual kWh used	141,293,539	75,746,645	-	34,518,033	-	-	31,028,861	-	-	-	-	-	-	-	-	-	-	-
Total kWh possible for retrofited ships	141,599,630	75,746,645	-	34,518,033	-	-	31,334,952	-	-	-	-	-	-	-	-	-	-	-
Maximum "leakage"	0%	0%	-	0%	-	-	-1%	-	-	-	-	-	-	-	-	-	-	-

Problem (i) – Tankers and vehicle carriers – APEEP

	Total	Los Angeles	Houston	Long Beach	Tacoma	Miami	Oakland	Galveston	Everglades	Baltimore	Newark	Richmond, CA	Seattle	Port Angeles	Corpus Christi	Yerba Buena Island	New Orleans	New York
Actual kWh used	147,400,518	17,118,546	71,593,667	28,921,980	-	-	1,130,720	16,392,101	-	3,010,873	-	9,232,631	-	-	-	-	-	-
Total kWh possible for retrofited ships	152,073,210	17,601,028	71,619,306	28,921,980	-	-	1,618,840	18,701,277	-	3,010,873	-	10,599,907	-	-	-	-	-	-
Maximum "leakage"	-3%	-3%	0%	0%	-	-	-30%	-12%	-	0%	-	-13%	-	-	-	-	-	-

Problem (ii) – Containers and bulk cargo vessels – APEEP

	Total	Los Angeles	Houston	Long Beach	Tacoma	Miami	Oakland	Galveston	Everglades	Baltimore	Newark	Richmond, CA	Seattle	Port Angeles	Corpus Christi	Yerba Buena Island	New Orleans	New York
Actual kWh used	216,751,897	110,636,954	5,013,992	45,310,611	14,182,436	-	31,947,516	-	-	-	-	-	7,215,767	-	-	-	-	2,444,620
Total kWh possible for retrofited ships	230,359,104	110,636,954	5,083,826	45,310,611	16,247,800	-	42,030,954	-	-	-	-	-	8,604,339	-	-	-	-	2,444,620
Maximum "leakage"	-6%	0%	-1%	0%	-13%	-	-24%	-	-	-	-	-	-16%	-	-	-	-	0%

Problem (ii) – Tankers and vehicle carriers – APEEP

	Total	Los Angeles	Houston	Long Beach	Tacoma	Miami	Oakland	Galveston	Everglades	Baltimore	Newark	Richmond, CA	Seattle	Port Angeles	Corpus Christi	Yerba Buena Island	New Orleans	New York
Actual kWh used	255,544,431	27,921,189	113,257,358	39,380,687	3,337,968	-	3,054,443	29,289,063	-	8,647,975	3,677,285	15,345,336	-	-	4,197,286	3,564,704	-	3,871,136
Total kWh possible for retrofited ships	268,113,633	27,921,189	113,823,933	39,380,687	3,337,968	-	3,054,443	36,167,792	-	10,368,701	3,732,129	16,185,157	-	-	4,879,746	5,091,326	-	4,170,562
Maximum "leakage"	-5%	0%	0%	0%	0%	-	0%	-19%	-	-17%	-1%	-5%	-	-	-14%	-30%	-	-7%

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

$$\forall i, j: o_{i,j} \leq r_i \qquad \textbf{Equation 7}$$

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

S2 RESULTS AND DISCUSSION

In addition to the cases discussed in the main text of the article, we analyzed various other subsets of the data. The results are reported below, and summarized in Table S-6.

S2.1 Requiring all container ships calling at major California ports to use shore power

Requiring all container ships calling at California ports to use shore power would produce close to zero net benefit (or loss). At current fuel prices, for more than half the 525 container vessels, using shore power produces a net loss even after taking into account environmental benefits. To the extent that this requirement is an approximation of California's "At-berth" regulation, it can be argued that the regulation produces the kind of optimum described by Problem (i): benefits are maximized; subject to the condition that total *net* benefit is positive.

S2.2 Requiring all ships at California ports to use shore power

The total cost of requiring all vessels calling at California ports would significantly exceed the benefits, regardless of which integrated air quality model was used.

S2.3 Requiring all ships calling at major US ports to use shore power

Mandating the use of shore power at all US ports and for all ships would result in a substantial net loss to society. Depending on which model was used to estimate the social cost of pollution, this loss would be between \$70 and \$140 million per year. APEEP generally produces a lower estimate for the environmental benefit of a switch to shore power. This is because – with the significant exception of the social cost of SO_X emissions in southern California and the Bay

Area, where EASIUR's estimate is about an order of magnitude lower than that obtained from APEEP – EASIUR generally arrives at a higher social cost of emissions than APEEP.

Table S-6: A summary of the results discussed in Sections S2.1-S2.3 suggests that - except for container ships in California - applying a blanket requirement that shore power be used is likely to produce a significant net societal loss

Objective	Use shore power for all (EASIUR)					Use shore power for all (APEEP)				
Applied to	Container ships Calling at California ports	Container and bulk cargo ships calling at California ports	Tankers and vessel carriers calling at California ports	All container andbulk cargo ships calling at major US ports	All tankers and vehicle carriers calling at major US ports	Container ships Calling at California ports	Container and bulk cargo ships calling at California ports	Tankers and vessel carriers calling at California ports	All container andbulk cargo ships calling at major US ports	All tankers and vehicle carriers calling at major US ports
Total number of vessels	525	808	531	1,910	1,373	525	808	531	1,910	1,373
Number of vessels retrofit	525	808	531	1,910	1,373				1,910	1,373
Container	*525*	*525*		*1,064*		*525*	*525*		*1,064*	
Other "barge" vessels		*283*		*846*			*283*		*846*	
Tankers			*397*		*1,077*			*397*		*1,077*
Of which liqified gas carriers					*57*					*57*
Ro-Ro and vehicle carriers			*134*		*296*			*134*		*296*
Other "tower" vessels										
Cost of vessel retrofit	$21	$32	$21	$77	$55	$21	$32	$21	$77	$55
Fuel savings	$4	$4	$2	$16	$20	$4	$4	$2	$16	$20
Net private benefit	-$17	-$28	-$19	-$61	-$36	-$17	-$28	-$19	-$61	-$36
Environmental benefit	$54	$57	$24	$108	$62	$47	$50	$19	$60	$32
NOx	*$27*	*$28*	*$12*	*$55*	*$33*	*$12*	*$12*	*$2*	*$14*	*$11*
SO2	*$3*	*$3*	*$10*	*$4*	*$27*	*$16*	*$17*	*$8*	*$18*	*$6*
PM2.5	*$22*	*$23*	*$1*	*$44*	*-$1*	*$17*	*$18*	*$8*	*$23*	*$12*
CO2	*$3*	*$3*	*$1*	*$5*	*$3*	*$3*	*$3*	*$1*	*$5*	*$3*
Number of berths retrofit	47	47	42	130	174	47	47	42	130	174
Los Angeles	*20*	*20*	*10*	*20*	*11*	*20*	*20*	*10*	*20*	*11*
Houston	*0*	*0*		*21*	*40*	*0*	*0*		*21*	*40*
Long Beach	*13*	*13*	*14*	*13*	*15*	*13*	*13*	*14*	*13*	*15*
Tacoma	*0*	*0*		*8*	*4*	*0*	*0*		*8*	*4*
Miami	*0*	*0*		*4*	*2*	*0*	*0*		*4*	*2*
Oakland	*8*	*8*	*6*	*8*	*3*	*8*	*8*	*6*	*8*	*3*
Galveston	*0*	*0*		*6*	*37*	*0*	*0*		*6*	*37*
Port Everglades	*0*	*0*		*3*	*8*	*0*	*0*		*3*	*8*
Baltimore	*0*	*0*		*6*	*9*	*0*	*0*		*6*	*9*
Newark_(New_York)	*0*	*0*		*9*	*5*	*0*	*0*		*9*	*5*
Port_of_Richmond	*2*	*2*	*7*	*2*	*6*	*2*	*2*	*7*	*2*	*6*
Seattle	*0*	*0*		*6*	*2*	*0*	*0*		*6*	*2*
Port_Angeles	*0*	*0*		*2*	*5*	*0*	*0*		*2*	*5*
Corpus_Christi	*0*	*0*		*4*	*11*	*0*	*0*		*4*	*11*
Yerbabuena_Island	*4*	*4*	*5*	*4*	*5*	*4*	*4*	*5*	*4*	*5*
New Orleans	*0*	*0*		*11*	*5*	*0*	*0*		*11*	*5*
New York	*0*	*0*		*3*	*6*	*0*	*0*		*3*	*6*
Cost of berth retrofit	$34	$34	$9	$95	$39	$34	$34	$9	$95	$39
Net social benefit	$20	$23	$16	$13	$23	$13	$16	$10	-$35	-$7
Total net benefit	**$3**	**-$5**	**-$4**	**-$48**	**-$12**	**-$4**	**-$13**	**-$9**	**-$96**	**-$43**

S2.4 Sensitivity analysis

This analysis assumes that ports are currently scheduled as efficiently as they can be; that is, every berth at port j can be occupied for only a total of (μ_j x 8760) hours each year. Having invested in retrofitting a berth, it may be assumed that a port would schedule this valuable asset with great care and therefore extract a higher rate of utilization from it. Such a move would lower the cost of using shore power, make its adoption more widespread in the optimal solution. We tested the sensitivity of the optimal solution to the assumption of a higher rate of utilization for each berth (see Figure S-1). The solution based on EASIUR is very sensitive to what we assume about the rate of utilization; the solution based on APEEP is not. In both cases, the direction of the sensitivity is as we would expect it to be: scheduling berths more efficiently increases the total net benefit.

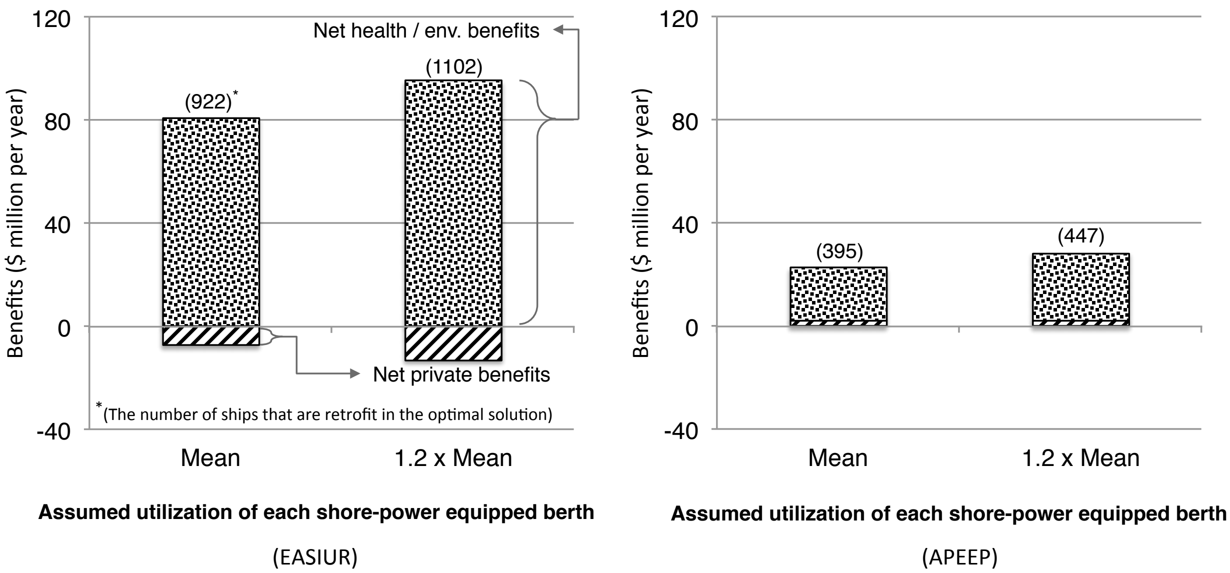

Figure S-1: Sensitivity of the solution to Problem (ii) to an increase in the rate of utilization of retrofitted berths for cargo and cruise vessels assuming social costs of pollution derived from (left) EASIUR, and (right) APEEP. If retrofitted berths at each port were scheduled 20% more efficiently than the mean for that port, the result would be to increase the net benefit of retrofit, though this effect would be more prominent if the social costs were based on EASIUR than on APEEP.

Finally, we recognize that the social cost of pollution produced either by the EASIUR or APEEP models is itself uncertain. The APEEP model quantifies this uncertainty by reporting the 5th and 95th percentile values of the social cost of each pollutant, in addition to the mean. We analyze the impact of this uncertainty on the decision to retrofit in two ways. We re-run our optimization models assuming the 5th and 95th percentile. The results are shown in Figure S-2 if the decision maker based their decision on the 5th percentile values, they would decide not to retrofit a single ship or port. Based on the 95th percentile value, the decision maker would retrofit nearly a quarter of all container and bulk cargo vessels, and nearly a third of all tankers and vehicle carriers (recall that when the mean value of social cost was assumed, the optimal solution based on APEEP was to retrofit 10% of all vessels).

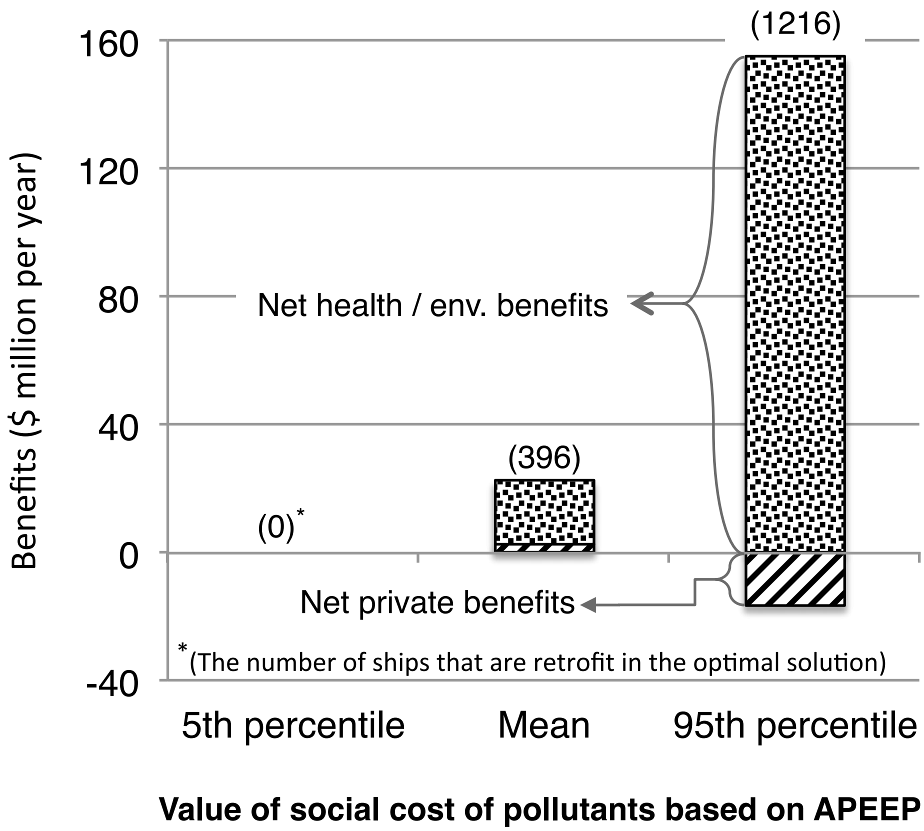

Figure S-2: The optimal decision if the actual social costs of pollution were equal to the 5th, mean, or 95th percentile values in APEEP. An optimal decision based on the 5th percentile values would be to do nothing. If the true social cost was given by the 95th percentile value two to three times as many vessels would be retrofitted as in the case based on mean values, generating five to six times the total net benefit.

S2.5 Discussion

The fact that California requires that container, cruise, and reefer vessels calling at its ports cut their in-port emissions by as much as 80% by 2020 might change the incentives for the use of shore power at other ports. In order to quantify this effect, we solved Problem (i) assuming that all container ships calling at Oakland, Long Beach, Los Angeles, and San Francisco were already equipped to receive shore power (i.e., the cost of retrofit, p_i, for these ships was zero) and that all the berths equipped for container ships were also retrofit (i.e., c = 0 for such berths). Assuming social costs from APEEP, the optimal solution involved retrofitting 42 container and cargo vessel berths in ports outside California, versus seven in our original analysis, which implicitly assumed that no berths or vessels were currently equipped to supply or receive shore power. Assuming EASIUR social costs, the number of berths to retrofit in the optimal solution would be 80, nearly twice as many in the original solution.

The analysis also demonstrates that shore power is an inefficient way of reducing CO_2 emissions. The solution to Problem (i) involves the most widespread deployment of shore power. Implementing this solution would reduce CO_2 emissions about 0.2 million tons per year. The cost of berth retrofit would be $100 million and the cost (net of fuel savings) of vessel retrofit would be $50 million. If the co-benefits in terms of improved air quality were ignored, this would translate to a cost of $750 per tonne of CO_2 emissions abated. Put differently, the solution would reduce fuel use by about 60,000 tonnes per year. Smith et al.[5] estimate that, between 2007-12, vessels reduced their steaming speed by 12% and produced a 24% reduction in fuel use. This translates to a reduction in fuel use of 100 million tonnes per year.

Table S-7: Comparing shore power (the solution to Problem (i) based on EASUR, applied to the Port of Long Beach) to the VSR program at that Port. The cost of shore power to the port is estimated to be the annualized cost of retrofitting and operating the required number of berths.

Pollutant	VSR (2008) at the Port of Long Beach	Shore power
	reduction in tons per year	
NO_x	680	937
SO_2	450	39
$PM_{2.5}$	60	26
CO_2	26,000	45,000
Cost	$1.6 million	$11 million

Shore power may also be compared to the voluntary speed reduction program (VSR) in which some ports in California offer a reduction in port fees to vessels that cut their speed to 12 knots within a 40 nautical mile zone around the port (Table S-7). Note that the numbers for the

VSR scheme are from 2008,[14] when vessels were allowed to use fuel with a sulfur content 15 times higher than what is permitted now: shore power produces a much smaller benefit from SO_X emissions reduction because the fuel now contains much less sulfur. Table S-7 shows that, even as a method of improving air quality, paying vessels to slow down is more cost effective than shore power. Clearly, there are limits to how much a vessel can be slowed down and what benefits such a slowdown can produce. A selective deployment of shore power can ensure that benefits always exceed costs. The benefit cost ratio of the solution to Problem (i) is one (1) by design. The optimal solution to Problem (ii) produces a benefit cost ratio of between 2 (based on APEEP) and 3 (based on EASIUR). Gains from deploying shore power can therefore be additional to those made by the VSR program.

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