Supporting Information for

Long-run Environmental and Economic Impacts of Electrifying Water-borne Shipping in the United States

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This document contains the supporting information for the paper titled as "Long-run Environmental and Economic Impacts of Electrifying Water-borne Shipping in the United States." In total, there are 23 pages, 17 figures, 6 tables.

1 Yale-NEMS Modeling

Yale-NEMS is a large-scale general equilibrium model for the U.S. energy markets. The model consists of the supply sectors of main energy sources (crude oil, natural gas, coal, and renewables), energy demand sectors (industrial, commercial, transportation, and residential), intermediate energy markets (electricity and liquid fuels), macroeconomy, and a link to international energy markets.[1] Yale-NEMS varies in its regional disaggregation across the modules. Most modules are disaggregated into Census divisions. One key exception is the Electricity Market Module (EMM), which is at the North American Reliability Corporation (NERC) region level, a much richer level of disaggregation.

Yale-NEMS projects the energy market equilibrium from the present to 2050 and incorporates relevant economic, technology, resource, policy, and demographic constraints. The projections include energy consumption, production, trade, and market prices. The baseline projection incorporates all current federal and state policies until their sunset dates, such as the Regional Greenhouse Gas Initiative (RGGI), Cross State Air Pollution Rule (CSAPR), California Assembly Bill 32: California Global Warming Solutions Act of 2006 (AB32), Mercury and Air Toxics Standards (MATS), and the Corporate Average Fuel Economy (CAFE) standards set by the Obama Administration. The waterborne transportation submodule (which includes inland waterborne transportation, such as on rivers) is linked to EMM in Yale-NEMS. EMM covers a variety of electricity-generating technologies, such as coal, natural gas, fuel oil, nuclear, and renewables (wind, solar, hydro, and municipal solid waste) in various locations. Given available capacity, purchased-power agreements, environmental regulations, and fuel prices, power plants generate electricity through minimizing variable costs to meet demand in each period and region.

To keep our overview concise, we first illustrate how Yale-NEMS forecasts energy consumption of the waterborne transportation sector and then discuss how we estimate the associated emissions. For other Yale-NEMS modules, there are detailed descriptions available on EIA's website (see https://www.eia.gov/outlooks/aeo/nems/documentation/).

1.1 Waterborne transportation energy consumption

Waterborne transportation is explicitly modeled in the Transportation Sector Demand Module (TDM) of Yale-NEMS.[2] The waterborne transportation submodule within the TDM of Yale-NEMS projects energy consumption by three types of waterborne transportation: (1) domestic waterborne (U.S.-flagged vessels); (2) international waterborne (foreign-flagged vessels) within the North American Emission Control Area (ECA); and (3) international waterborne (foreign-flagged vessels) outside of the North American ECA. The North American ECA consists of all oceanic areas within 200 nautical miles from the shoreline, in which all vessels are required to use low-sulfur fuels (1% mass by mass before January 1, 2015, and 0.1% mass by mass after that) or to invest in abatement technologies. In Yale-NEMS, waterborne energy consumption is mainly driven by endogenous variables (e.g., industrial output and international trade) and exogenously determined parameters (e.g., energy efficiency improvements and the vessel turnover rate, which captures the introduction of new vessels moving through U.S. waters). The final energy consumption forecast in Yale-NEMS is split by fuel type (distillate fuel oil, residual fuel oil, and natural gas), Census division, and vessel engine type (main engine and auxiliary engine).

Figure S1 presents the key steps involved in forecasting energy consumption of the waterborne transportation sector in Yale-NEMS. The detailed equations and descriptions are presented in EIA's documentation for the TDM.[2] The description of the detailed steps is in the pages 125-129 of EIA's documentation.[2] Figure S1.A shows the energy consumption forecast for the domestic waterborne transportation. Yale-NEMS first estimates total ton-miles traveled, which is mainly driven by the projections of industrial output (endogenously forecasted in Industrial Demand Module of Yale-NEMS). Then, the model maps ton-mile estimates to total energy demand using specific energy efficiency parameters (thousand Btu per ton-mile). Lastly, aggregate energy demand is then split into three fuel types—distillate fuel oil, residual fuel oil, and natural gas—based on the fuel share coefficients. The energy efficiency parameter and the fuel share coefficients are based on the judgment of energy experts at EIA.

Figure S1.B displays the main steps for estimating the international non-ECA energy consumption. Yale-NEMS first projects the total energy demand for the international non-ECA waterborne transportation based on the level of international trade (output from the Macroeconomic Activity Module). The aggregate energy demand is then disaggregated into fuel types and Census divisions, according to the exogenously determined share coefficients.

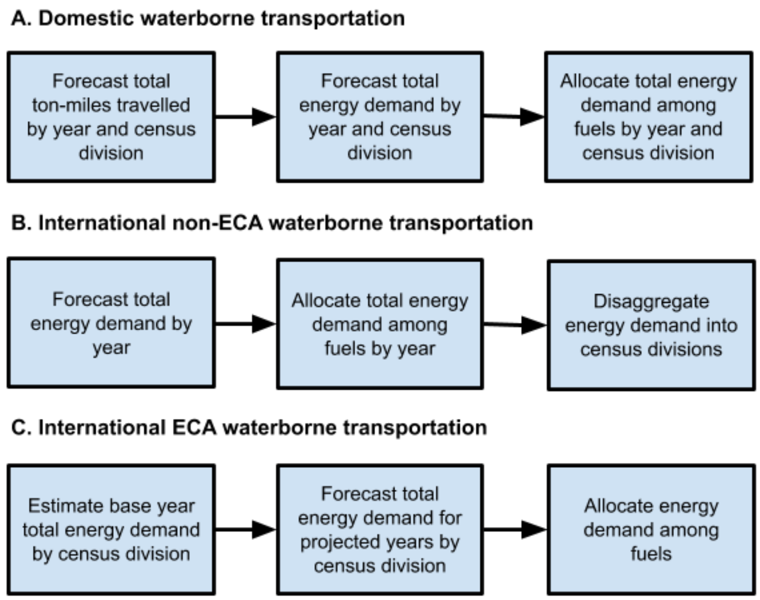

Figure S1: Key steps in determining energy consumption for waterborne transportation in Yale-NEMS

Figure S1.C shows the steps for the international ECA energy consumption forecast. Yale-NEMS first estimates the base year (2012) total energy demand. Then, the model projects the total energy consumption starting from the base year based on several factors, including international trade, energy efficiency improvements, and vessel turnover rate (representing the introduction of new vessels moving through the U.S. water areas). Lastly, Yale-NEMS allocates the total energy consumption among the fuel types based on the projected fuel prices using a logit function.

1.2 Modeling waterborne vessel electricity consumption in AEO2017

This section presents the steps of including waterborne vessel electricity consumption in Yale-NEMS. For each historical year up to 2016, we first calculate the percentage of total vessels that berthed at a U.S. port and plugged into the onshore grid in the year. We assume that this percentage remains constant in all years going forward. For the West Coast Census division, we account for the 'California Shore Power Regulation' in our estimates of the percentage of vessel visits that are powered by onshore electricity. The

Shore Power Regulation is a California regulation that mandates vessels (i.e., container ships, reefer vessels, and cruise ships) visiting each California port to shut down their auxiliary engines and plug into the onshore grid. From 2014 to 2016, 50% of vessel visits are required to be powered by electricity, followed by 70% of visits plugged in the electric grid in 2017-2019. Starting in 2020, 80% of vessel visits must plug in. In our modeling, we multiply the mandated proportion levels over time by the fuel consumption by marine vessels visiting Californian ports to estimate the marine electricity consumption.

We then multiply this percentage by the projected total auxiliary energy consumption by vessels at berth in Yale-NEMS. To prevent double-counting of electricity consumption in the U.S. energy system, we subtract the added electricity consumption of shore power from the commercial electricity demand, which is the most logical place to adjust to ensure consistency in the modeling.

1.3 Emissions estimation

Yale-NEMS itself does not generate emissions estimates of air pollutants from the waterborne transportation sector. Thus, we use a post-processing approach for emissions estimation. We estimate the emissions of SO_2, NO_x, $PM_{2.5}$, PM_{10}, and VOCs, using emission factors that map energy consumption to emissions. The emission factors used for the analysis are reported in Table S1.

Table S1: The emission factors for pollution estimates

	Distillate oil		Natural gas		Residual oil	
	Auxiliary	Main	Auxiliary	Main	Auxiliary	Main
NO_x	13.90	14.10	1.40	1.40	14.70	15.00
PM_{10}	0.25	0.25	0.10	0.10	1.50	1.50
$PM_{2.5}$	0.35	0.35	0.10	0.10	1.46	1.46
SO_2	0.40	0.38	0.00	0.00	11.10	11.25
VOC	0.52	0.72	0.00	0.00	0.46	0.50

Notes: The unit is g/kWh. The data is from the California Air Resources Board (https://www.arb.ca.gov/regact/2008/fuelogv08/appdfuel.pdf).

Because onshore electricity is generated by power plants, we are also interested in emissions from these plants. Yale-NEMS directly provides SO_2 and NO_x emissions estimates from the electricity generating sector. We estimate the emission of $PM_{2.5}$, PM_{10}, and VOCs, following a similar approach to the one taken in Gillingham and Huang.[3] For each future year, we calculate the percentage change in projected power plant fuel consumption in that year relative to the consumption in 2014. Then we apply this percentage change to the EPA 2014 National Emissions Inventory (NEI). Note that this approach assumes constant emission factors over time, so it is a simplification. The simplification could imply that our local air pollutant emission results from the electricity sector are somewhat biased upwards to the extent that there are policies leading to reduced emission factors for fossil fuel generators. This could mean that the net benefits of shipping electrification are even greater than in our estimates because we would be overestimating the added emission from electricity to power the shipping. For CO_2 emissions, we take the estimates directly reported in Yale-NEMS, which accounts for the emissions for the entire U.S. energy system.

1.4 Fuel switch in the waterborne shipping electrification scenarios

In our electrification scenarios, we allow fossil fuels (e.g., distillate oil, residual oil, and natural gas) consumed by waterborne vessels to be gradually replaced with onshore electricity. The replacement from 2019 to 2025 follows the following linear adjustment,

$$Q_{f,t} = \left(1 - \frac{t - 2018}{2025 - 2018}\right) Q_{f,t}^{0},$$

$$Q_{e,t} = \frac{t - 2018}{2025 - 2018} \sum\nolimits_{f} Q_{f,t}^{0},$$

where $Q_{f,t}^{0}$ is the consumption by waterborne vessels for fuel f in year t ($t < 2025$) in the reference case, and $Q_{f,t}$ is the adjusted fuel consumption. $Q_{e,t}$ is the electricity consumption by waterborne vessels in year t. From 2025 onwards, the fuels are entirely replaced with electricity, as follows:

$$Q_{f,t} = 0,$$

$$Q_{e,t} = \sum\nolimits_{f} Q_{f,t}^{0}.$$

2 Estimating social costs of local air pollutant emissions

We use the estimates of marginal damages from Muller et al.[4] to calculate total social costs of local air pollutant emissions. Because the emissions results from Yale-NEMS and the marginal damages from Muller et al. have different granularity, we downscale the Census division-level emissions data to the county level to match the level of aggregation of the marginal damage estimates in Muller et al. For each county in a Census division, we first compute the share of waterborne shipping and power generating emissions based on the EPA National Emission Inventory (NEI) 2014 and assume that the same share continues to hold to 2050. Then we apply this share coefficient to the Census division-level total emissions reported by Yale-NEMS simulations.

We should acknowledge upfront that the marginal damages from this study come with large error bars if one were to consider alternative concentration-response functions, the confidence intervals of those functions, and possible different values of the value of statistical life. For example, see Dimanchev et al. for a quantification of the variability of these air pollution mitigation benefits.[5] In addition, we use the same marginal damage coefficients over time (not adjusted for population growth), which could also underestimate avoided social costs from emissions reductions.

3 Estimating the cost of replacing tugboats

The on-the-ground costs of electric tugboats are not publicly available due to confidentiality. We did attempt to contact one manufacturer, Damen Shipyards Group, that is among the few with the capacity to build electric tugboats. However, we were not successful because the shipyard told us that the cost was confidential. We, therefore, estimate the unit cost of replacing a conventional tugboat with an electric one based on the existing evidence we could find from numerous sources. Note that the horsepower of tugboats ranges from 100 to over 10,000, and thus the costs can vary significantly. Here we present the average cost of replacing a tugboat across the whole U.S. tugboat fleet, which is estimated following the steps:

1. Calculate the average horsepower per tugboat in the U.S. based on the USACE data, which is around 2,171 (https://usace.contentdm.oclc.org/digital/collection/p16021coll2/id/3709/rec/38).
2. USACE estimates a rule-of-thumb of $1,000 per horsepower for diesel tugboat replacement cost (https://planning.erdc.dren.mil/toolbox/library/EGMs/egm05-06.pdf).
3. Multiplying the above two numbers, the average replacement cost for a diesel tugboat is then around $2 million.
4. Port of Auckland in New Zealand reports that the cost of an electric tugboat is about *twice* the cost of a conventional diesel one, including the cost of port-side charging infrastructure (http://www.poal.co.nz/media/ports-of-auckland-buys-world-first-electric-tug). Thus, we estimate that the average cost of electric tugboat replacement is around $4 million.

5. Since the costs of building port-side infrastructure for tugboats are already counted in the port retrofitting cost category in our paper, which is assumed to be $1.5 million, we then come up with an average cost of purchasing an electric tugboat to be $2.5 million. We consider this an average estimate and recognize that there would be substantial heterogeneity in this value depending on the exact electric tugboat being built.

4 Supplementary tables and figures

Figure S2 presents energy consumption by domestic and international waterborne transportation.

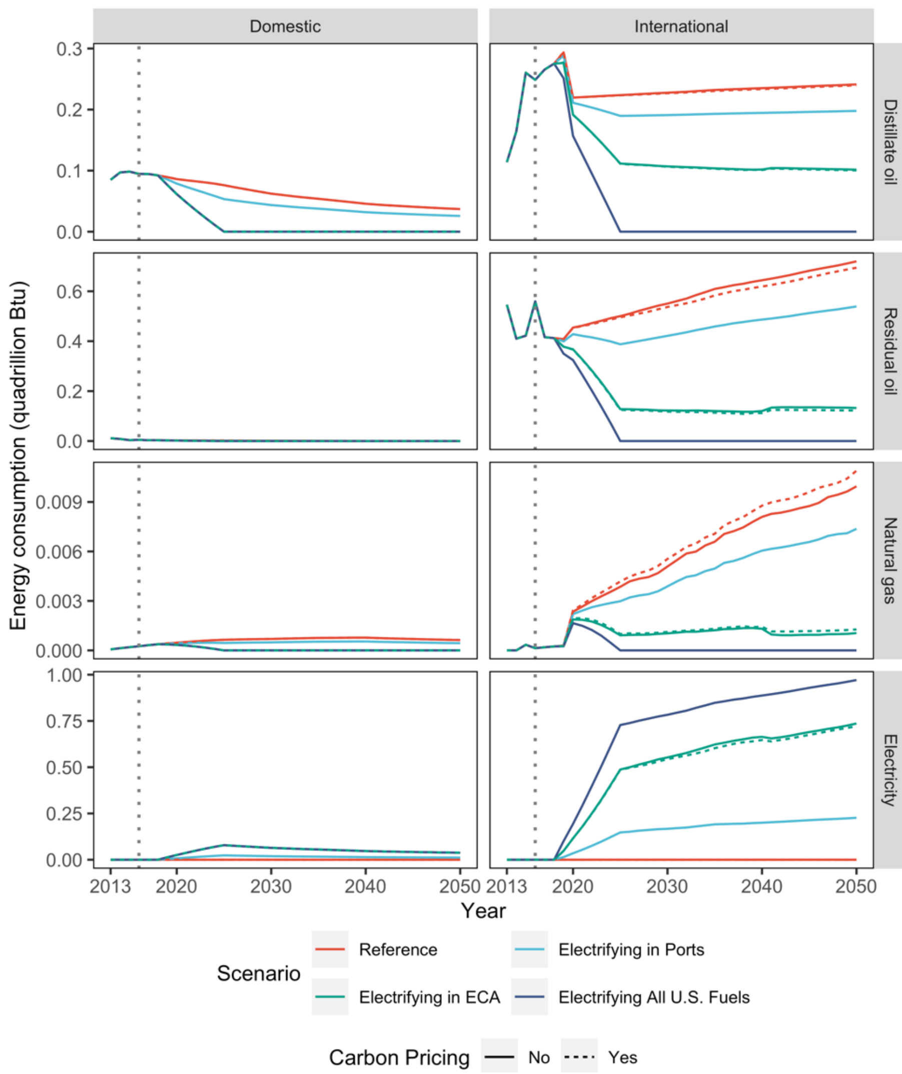

Figure S2: Energy consumption by domestic and international waterborne transportation in the United States

Notes: The vertical dotted line separates historical and projected data.

Figure S3 contains the disaggregated results of energy consumption in the U.S. seaports and inland ports. We split the total energy consumption of waterborne transportation based on the summary statistics of shipping tonnage of seaports and inland ports in the United States (source: https://usace.contentdm.oclc.org/digital/collection/p16021coll2/id/2092).

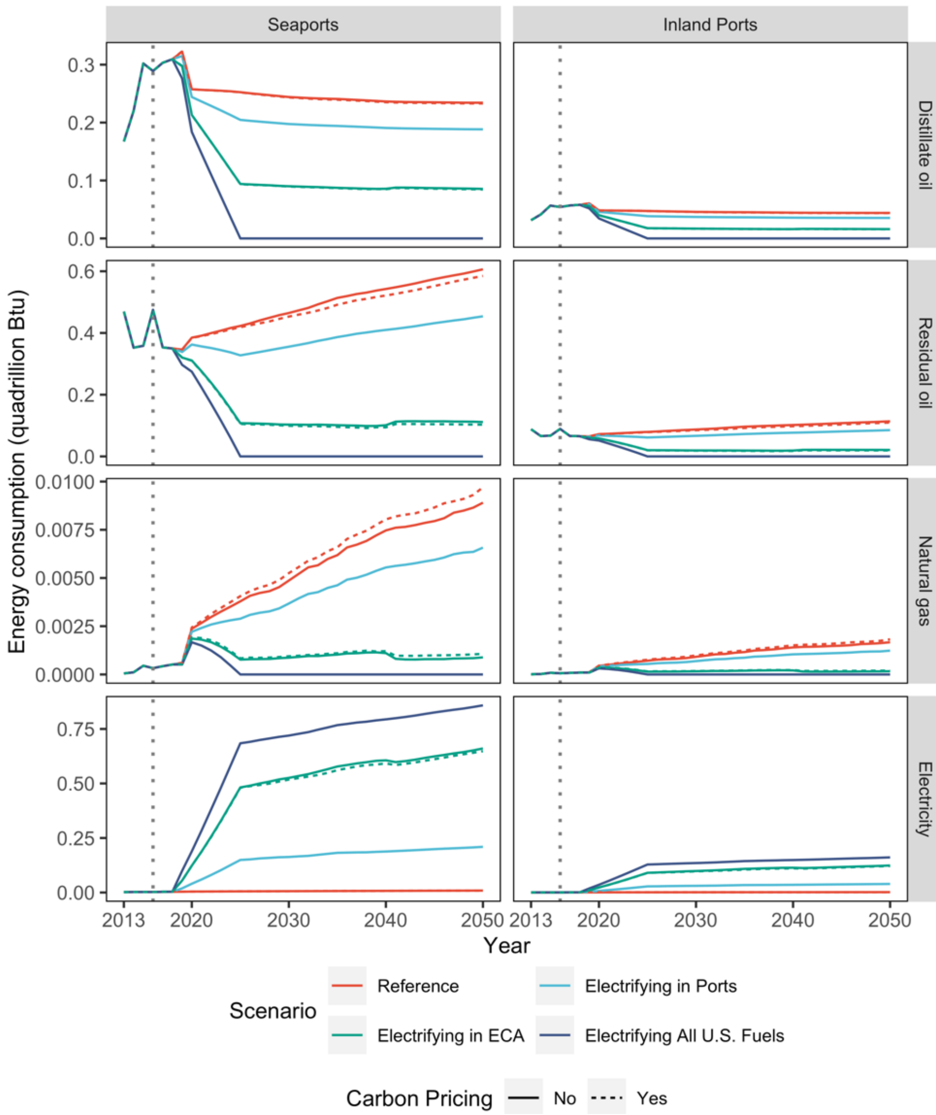

Figure S3: Energy consumption in the U.S. seaports and inland ports

Notes: The vertical dotted line separates historical and projected data.

Figure S4 presents the results of energy consumption from the electric power sector by fuel type. We observe that the increase in electricity demand due to electrification leads to more electricity generated by natural gas and renewables, which are relatively cleaner fuel sources.

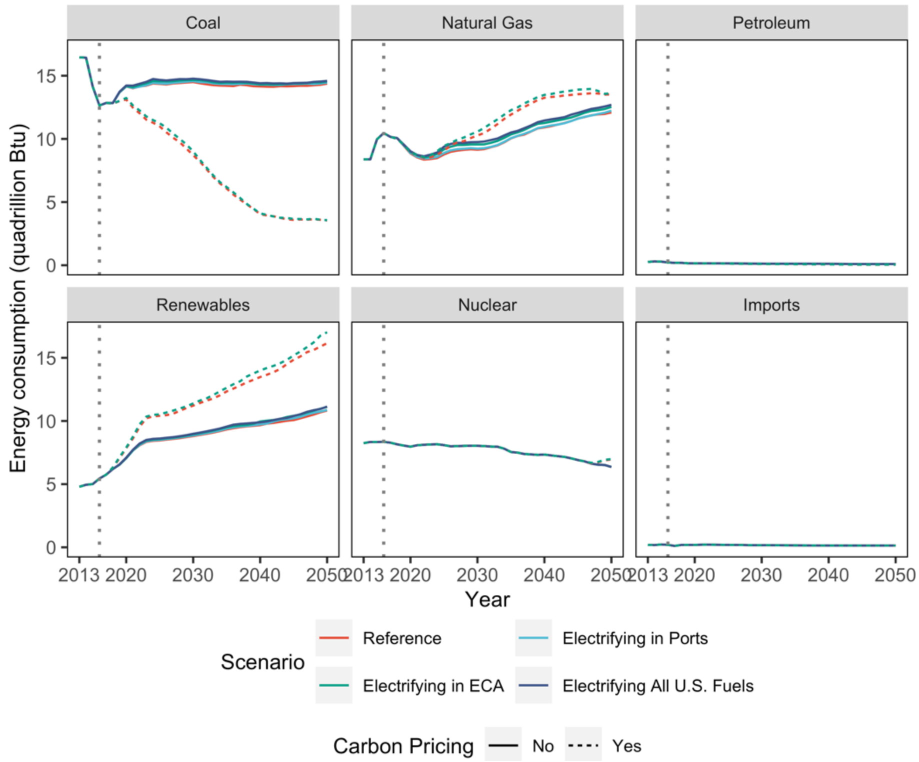

Figure S4: Energy consumption in the electric power sector by fuel type

Notes: The vertical dotted line separates historical and projected data.

Figure S5 shows the carbon dioxide emissions from fossil fuel combustion in the domestic and international waterborne sectors in the U.S.

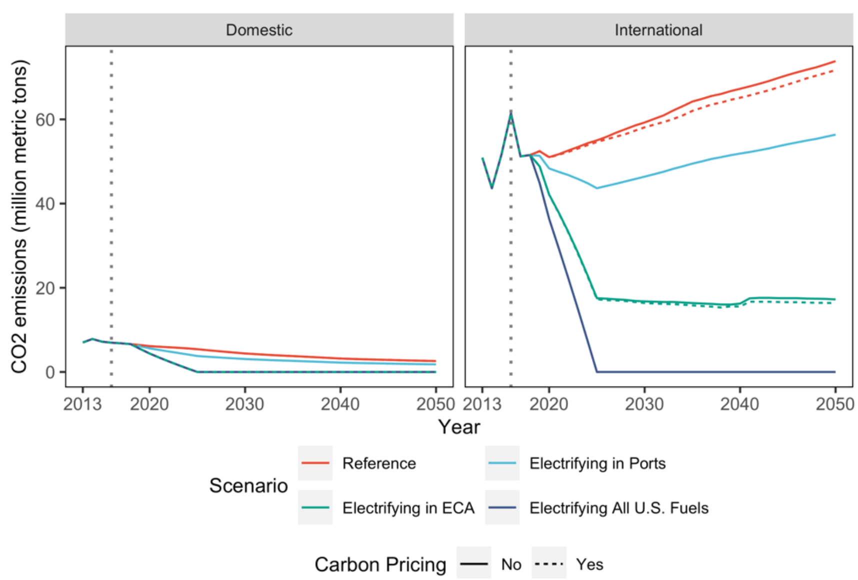

Figure S5: Energy-related CO_2 emissions by domestic and international waterborne transportation

Notes: The vertical dotted line separates historical and projected data.

Figure S6 the carbon dioxide emissions from fossil fuel combustion in inland ports and seaports in the U.S., which are split based on the method similar to Figure S3.

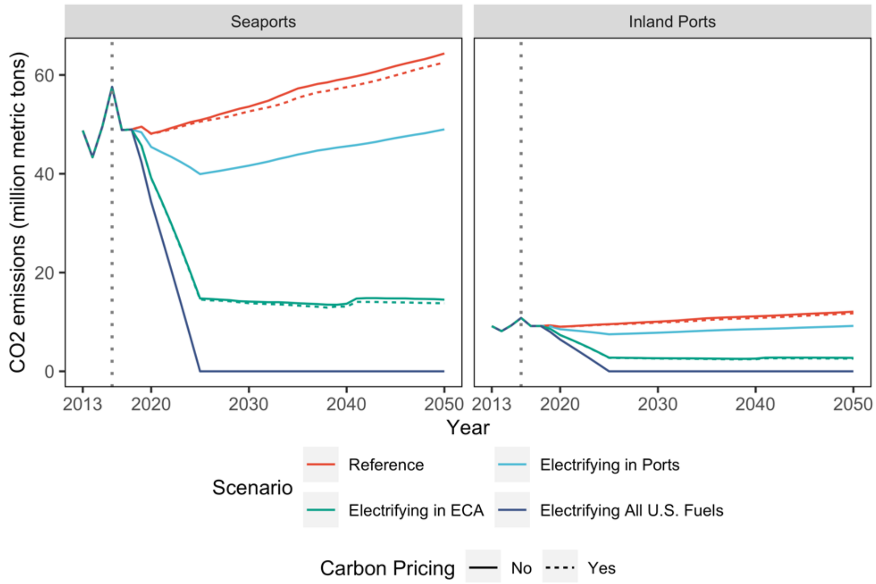

Figure S6: Energy-related CO_2 emissions by seaports and inland ports

Notes: The vertical dotted line separates historical and projected data.

Figure S7 presents comparisons of carbon emissions between the scenarios and reference case based on data from the waterborne shipping and electric power sectors.

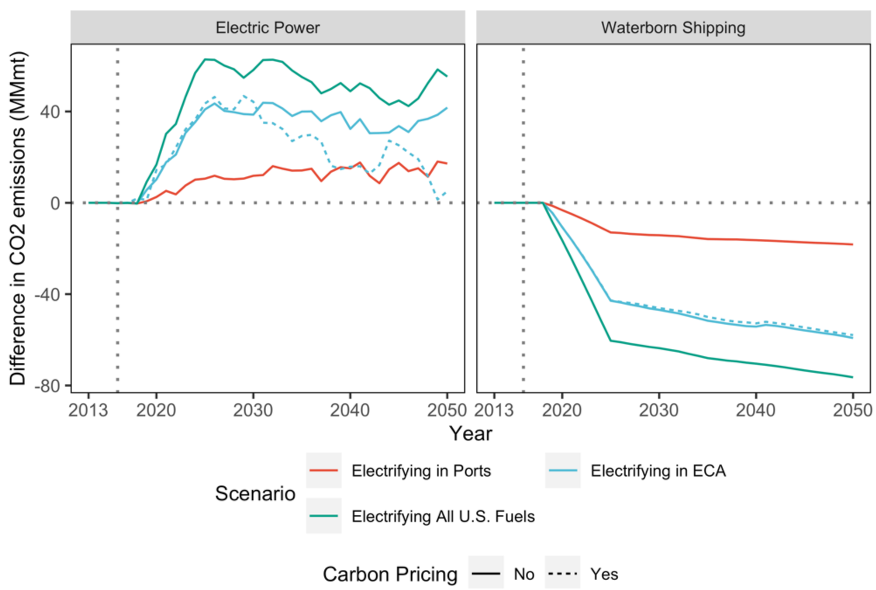

Figure S7: Differences in energy-related CO_2 emissions in the electric power and transportation sectors from the reference case

Notes: The vertical dotted line separates historical and projected data.

Figure S8 presents comparisons of local air pollutant emissions between the scenarios and reference case based on data from the waterborne shipping and electric power sectors. This figure provides a direct comparison with Figure 3 in the main text.

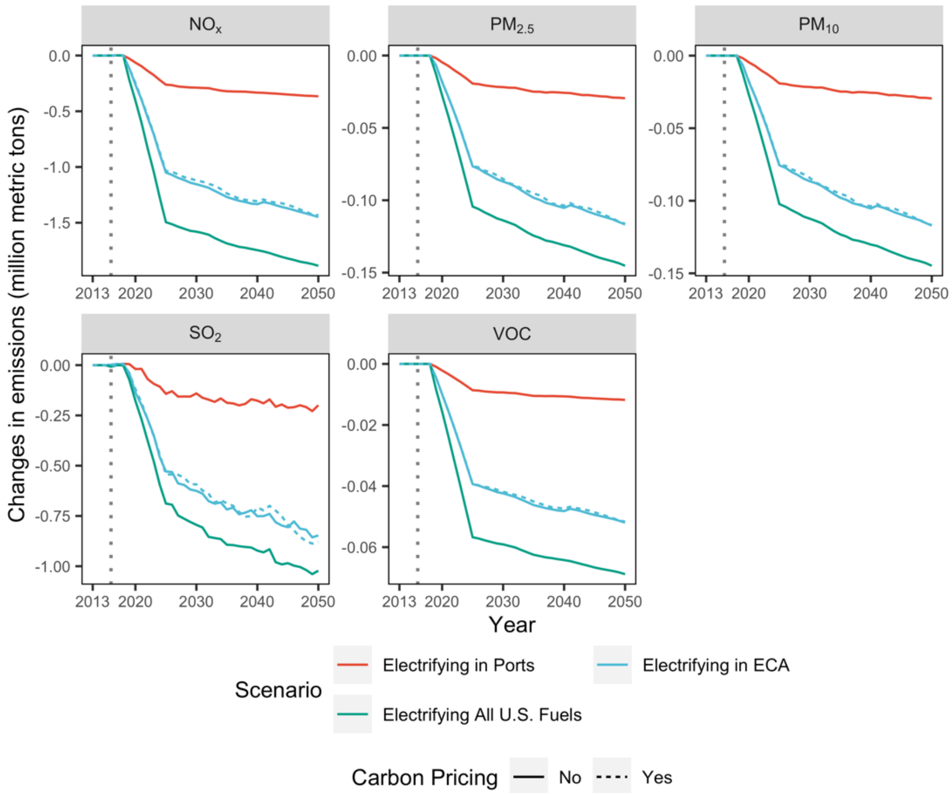

Figure S8: Differences in local air pollutant emissions in the electric power and transportation sectors from the reference case

Notes: The vertical dotted line separates historical and projected data.

Figure S9 contains the energy-related local air pollutant emissions by domestic and international waterborne transportation in the U.S. These results are estimated based on energy fuel consumption.

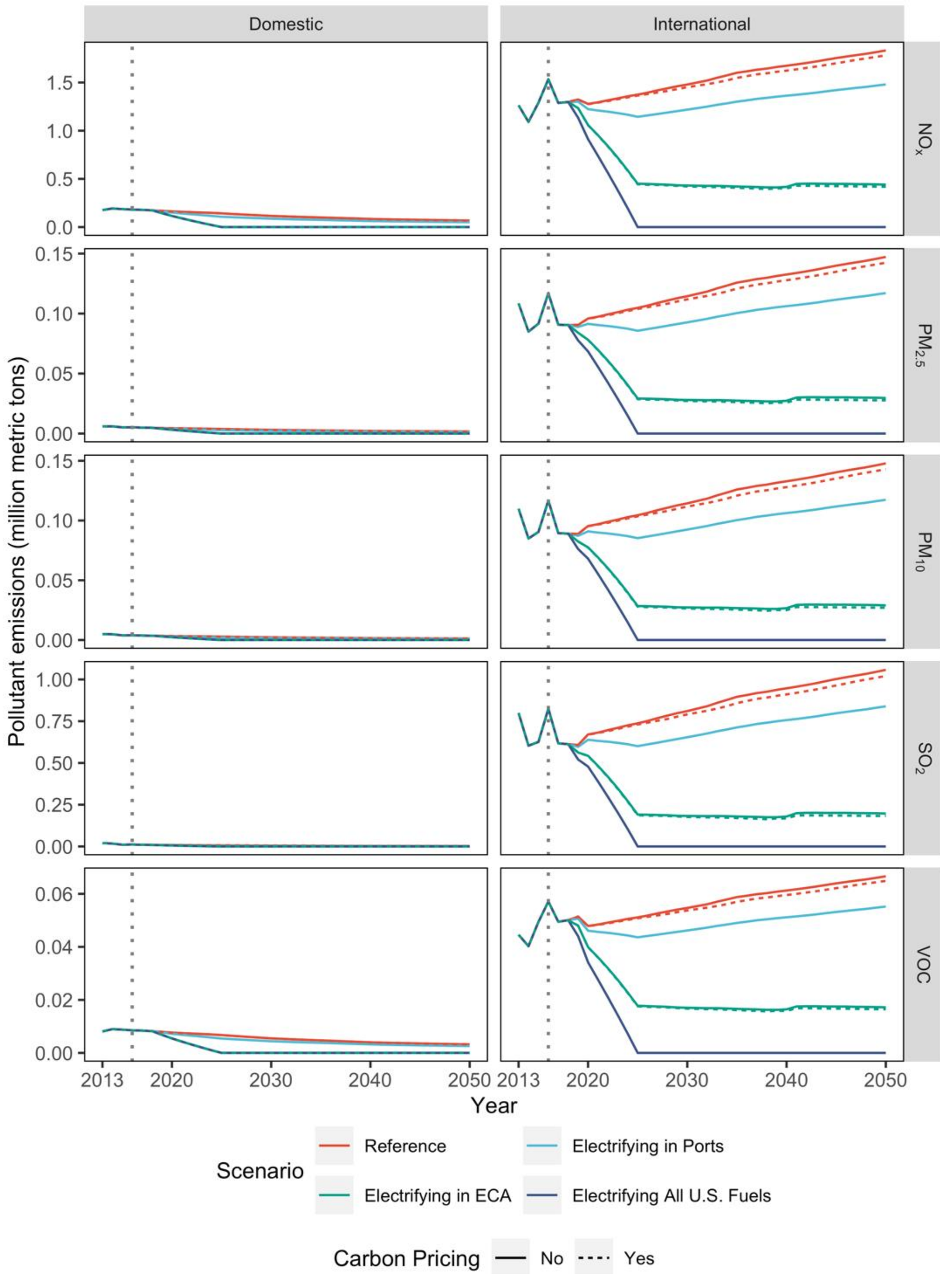

Figure S9: Energy-related local air pollutant emissions by domestic and international waterborne transportation

Notes: The emissions are from fossil fuel combustions in the waterborne transportation sector (distillate oil, residual oil, and natural gas). Other sources of local air pollution emissions are not counted. The vertical dotted line separates historical and projected data.

Figure S10 presents the results of local air pollutant emissions disaggregated by seaports and inland ports.

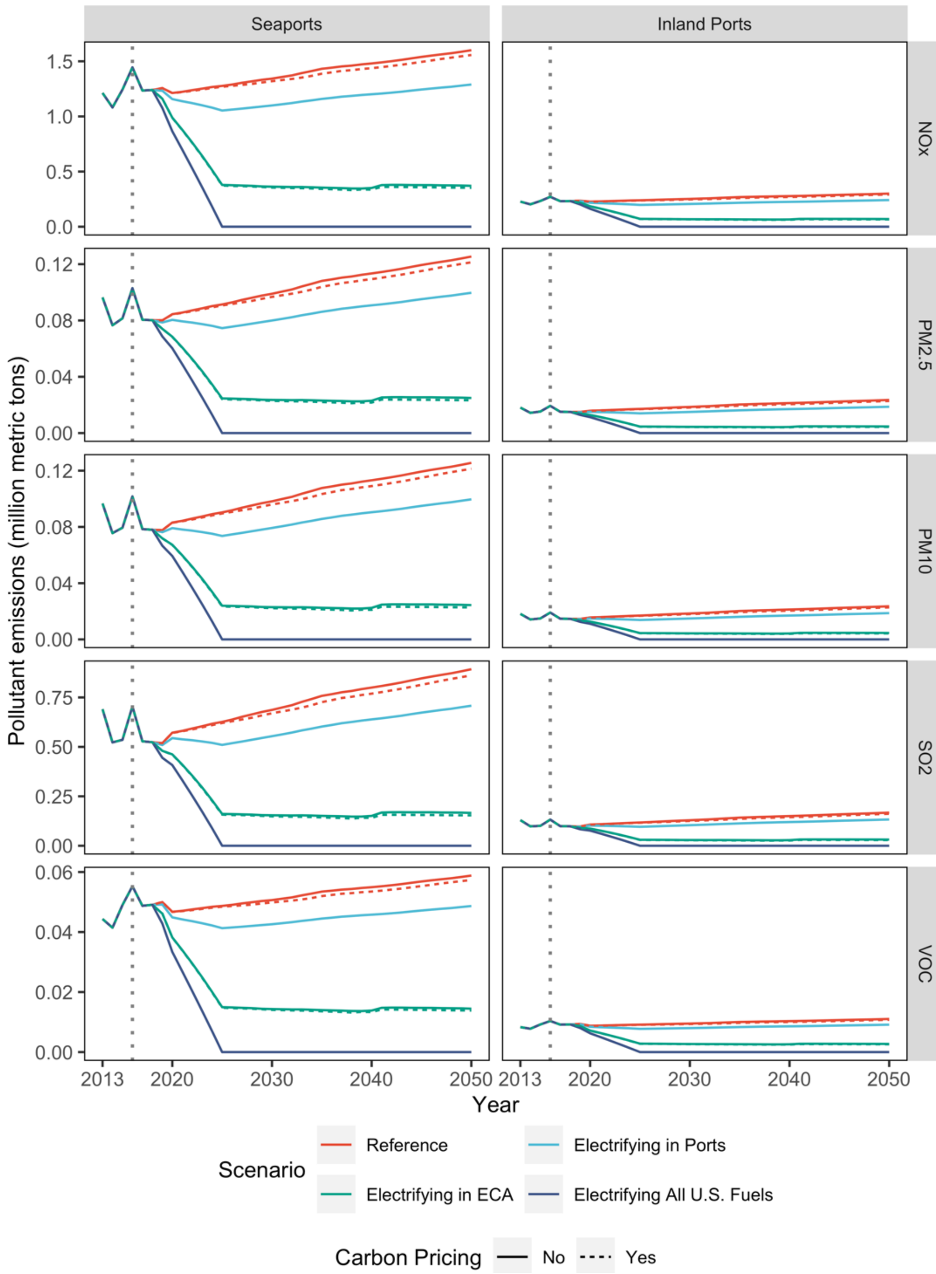

Figure S10: Energy-related local air pollutant emissions in seaports and inland ports

Notes: The emissions are from fossil fuel combustions in the waterborne transportation sector (distillate oil, residual oil, and natural gas). Other sources of local air pollution emissions are not counted. The vertical dotted line separates historical and projected data.

Figure S11 contains the results of local air pollutant emissions related to fossil fuel combustion in the electric power and transportation sectors in the U.S.

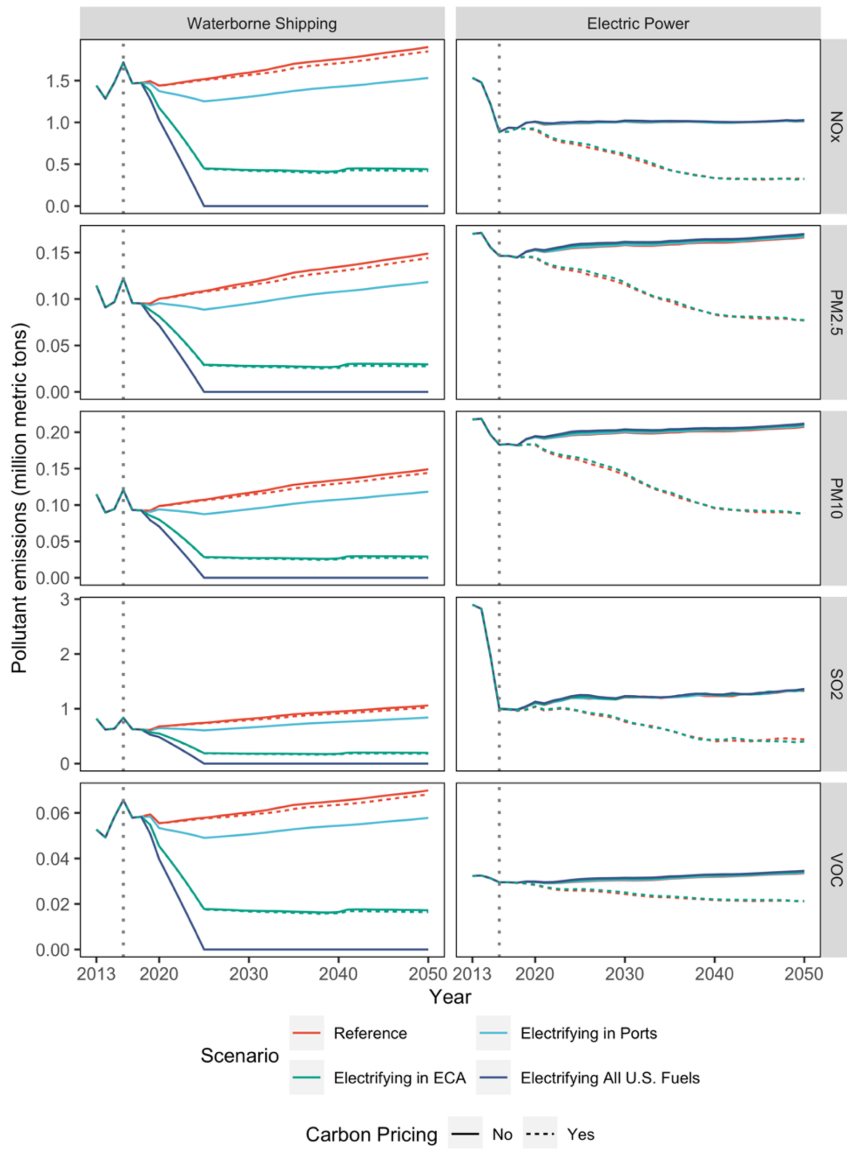

Figure S11: Energy-related local air pollutant emissions in the electric power and transportation sectors

Notes: The emissions are from fossil fuel combustions in the waterborne transportation sector (distillate oil, residual oil, and natural gas) and the power sector (coal, oil, and natural gas). Other sources of local air pollution emissions are not counted. The vertical dotted line separates historical and projected data.

Figure S12 contains the average electricity prices in the United States projected in Yale-NEMS. We see that electrifying waterborne transportation does not significantly change electricity prices, while carbon pricing substantially increases electricity prices.

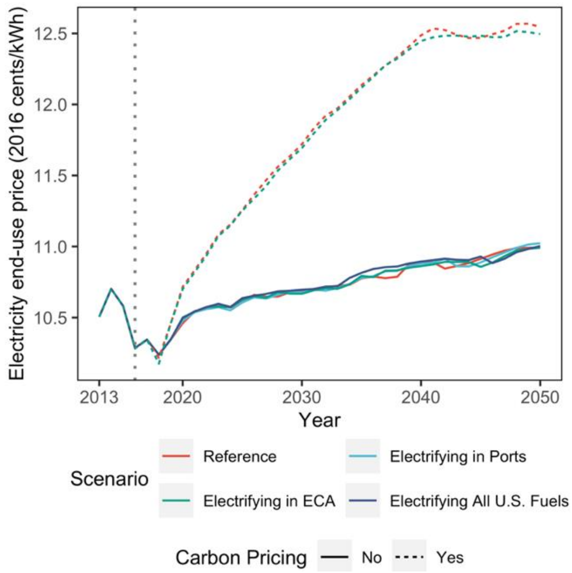

Figure S12: Average end-use electricity price in the United States

Notes: The vertical dotted line separates historical and projected data.

Figure S13 presents cumulative discounted avoided social costs in relevant locations across the United States with and without the social costs from emissions from power generation included. The results do not show significant differences when we include emissions from power generation.

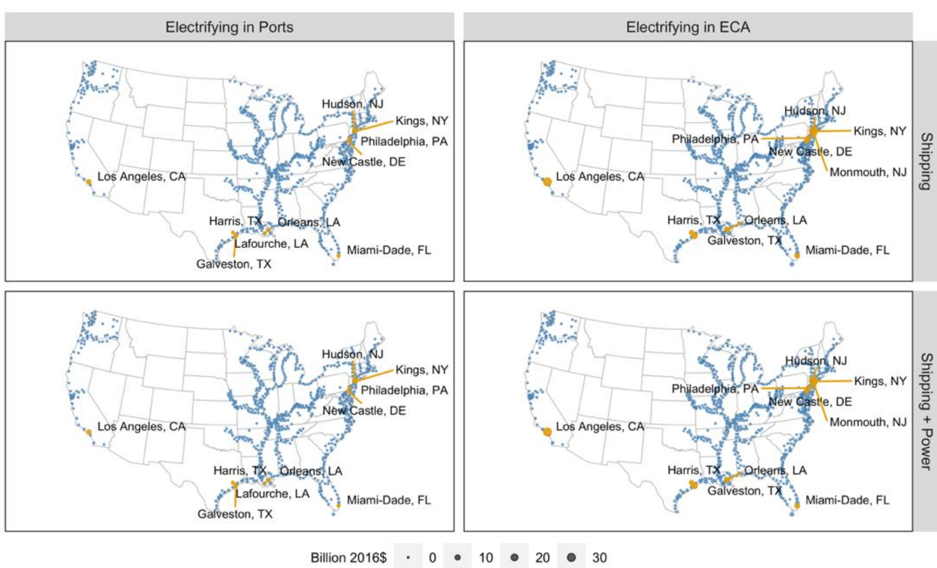

Figure S13: Cumulative discounted avoided social costs from reduced carbon and local air pollutant emissions from waterborne shipping and power generation

Notes: The local air pollutants included in the social cost estimations are SO_2, NO_x, $PM_{2.5}$, PM_{10}, and VOC. Carbon costs shown in Table 1 are included as well, and assumed to be equally spread across all U.S. counties. The discount rate is assumed to be 3%. The cash flow includes the years from 2019 to 2050. The size of the dots represents the level of avoided social costs, in which the yellow dots and texts indicate the ten counties with the largest values.

Table S2 presents the comparisons of carbon and local air pollutant emissions between scenarios in 2050, which are visually displayed in Figures 2 and 3 in the main text.

Table S2: Comparisons of emissions between scenarios in 2050

Pollutant	Electrifying in Ports vs Reference	Electrifying in ECA vs Reference	Electrifying All U.S. Fuels vs Reference	Carbon Pricing vs Reference	Electrifying in ECA & Carbon Pricing vs Reference	Electrifying in ECA & Carbon Pricing vs Carbon Pricing
CO_2	-2.71	-16.33	-21.38	-1021.11	-1071.65	-50.54
NO_x	-0.37	-1.45	-1.89	-0.74	-2.17	-1.43
$PM_{2.5}$	-0.03	-0.12	-0.15	-0.09	-0.21	-0.12
PM_{10}	-0.03	-0.12	-0.14	-0.12	-0.24	-0.12
SO_2	-0.20	-0.85	-1.02	-0.92	-1.80	-0.88
VOC	-0.01	-0.05	-0.07	-0.01	-0.07	-0.05

Notes: the unit in this table is Mt.

Table S3 summarizes the primary findings regarding energy consumption, generation, carbon emissions, and local air pollutant emissions between the waterborne shipping and electric power sectors.

5 Sensitivity analysis

5.1 Varying phase-in periods of electrification

Figure S14 shows the net CO_2 emissions from the waterborne shipping and power generation sectors combined with various phase-in periods. In general, the results appear to be insensitive to varying assumptions across the years. With extended phase-in periods (2030 and 2035), we see that the CO_2 emissions are slightly higher than those in the *Electrifying in ECA* scenario or the *Electrifying All U.S. Fuels* scenario in the early projection years.

Table S3: Summary results of major findings by waterborne shipping and electric power sectors

	Waterborne Shipping Sector	Electric Power Sector
Electrifying in Ports	a. In 2050, 0.25 quads of fossil fuels consumed by waterborne vessels are replaced by electricity in a year. b. In 2050, CO_2 emissions decrease by 18 Mt. c. In 2050, NO_x emissions decrease by 0.37 Mt; PM_{10} emissions decrease by 0.03 Mt; $PM_{2.5}$ emissions decrease by 0.03 Mt; SO_2 emissions decrease by 0.22; VOC emission decrease by 0.01 Mt.	a. In 2050, the increased electricity consumption is generated by natural gas (0.14 quads), coal (0.08 quads) and renewables (0.04 quads), which accounts for electricity transmission losses. b. In 2050, CO_2 emissions increase by 17 Mt. c. In 2050, NO_x emissions increase by 0.004 Mt; PM_{10} emissions increase by 0.001 Mt; $PM_{2.5}$ emissions increase by 0.001 Mt; SO_2 emissions increase by 0.02; VOC emission increase by 0.0003 Mt.
Electrifying in ECA	a. In 2050, 0.78 quadrillion Btu of fossil fuels consumed by waterborne vessels are replaced by electricity in a year. b. In 2050, CO_2 emissions decrease by 59 Mt. c. In 2050, NO_x emissions decrease by 1.46 Mt; PM_{10} emissions decrease by 0.12 Mt; $PM_{2.5}$ emissions decrease by 0.12 Mt; SO_2 emissions decrease by 0.86; VOC emission decrease by 0.05 Mt.	a. In 2050, the increased electricity consumption is generated by natural gas (0.43 quads), coal (0.17 quads) and renewables (0.28 quads), which accounts for electricity transmission losses. b. In 2050, CO_2 emissions increase by 42 Mt. c. In 2050, NO_x emissions increase by 0.01 Mt; PM_{10} emissions increase by 0.003 Mt; $PM_{2.5}$ emissions increase by 0.003 Mt; SO_2 emissions increase by 0.02; VOC emission increase by 0.0007 Mt.
Electrifying All U.S. Fuels	a. In 2050, 1.02 quadrillion Btu of fossil fuels consumed by waterborne vessels are replaced by electricity in a year. b. In 2050, CO_2 emissions decrease by 76 Mt. c. In 2050, NO_x emissions decrease by 1.9 Mt; PM_{10} emissions decrease by 0.15 Mt; $PM_{2.5}$ emissions decrease by 0.15 Mt; SO_2 emissions decrease by 1.06; VOC emission decrease by 0.07 Mt.	a. In 2050, the increased electricity consumption is generated by natural gas (0.6 quads), coal (0.21 quads) and renewables (0.31 quads), which accounts for electricity transmission losses. b. In 2050, CO_2 emissions increase by 55 Mt. c. In 2050, NO_x emissions increase by 0.01 Mt; PM_{10} emissions increase by 0.004 Mt; $PM_{2.5}$ emissions increase by 0.004 Mt; SO_2 emissions increase by 0.04; VOC emission increase by 0.001 Mt.
Carbon Pricing	a. In 2050, 0.1 quadrillion Btu of fossil fuels consumed by waterborne vessels are replaced by electricity in a year. b. In 2050, CO_2 emissions decrease by 2 Mt. c. In 2050, NO_x emissions decrease by 0.05 Mt; PM_{10} emissions decrease by 0.005 Mt; $PM_{2.5}$ emissions decrease by 0.005 Mt; SO_2 emissions decrease by 0.04; VOC emission decrease by 0.002 Mt.	a. In 2050, electricity generation by natural gas increases 1.4 quads, by coal decreases 11 quads, by renewables increases 5.3 quads. b. In 2050, CO_2 emissions decreases by 962 Mt. c. In 2050, NO_x emissions decrease by 0.69 Mt; PM_{10} emissions decrease by 0.12 Mt; $PM_{2.5}$ emissions decrease by 0.09 Mt; SO_2 emissions decrease by 0.88; VOC emission decrease by 0.012 Mt.
Electrifying in ECA & Carbon Pricing	a. In 2050, 0.77 quadrillion Btu of fossil fuels consumed by waterborne vessels are replaced by electricity in a year. b. In 2050, CO_2 emissions decrease by 60 Mt. c. In 2050, NO_x emissions decrease by 1.48 Mt; PM_{10} emissions decrease by 0.12 Mt; $PM_{2.5}$ emissions decrease by 0.12 Mt; SO_2 emissions decrease by 0.88; VOC emission decrease by 0.05 Mt.	a. In 2050, electricity generation by natural gas increases 1.45quads, by coal decreases 11 quads, by renewables increases 6.2 quads. b. In 2050, CO_2 emissions decreases by 957 Mt. c. In 2050, NO_x emissions decrease by 0.69 Mt; PM_{10} emissions decrease by 0.12 Mt; $PM_{2.5}$ emissions decrease by 0.09 Mt; SO_2 emissions decrease by 0.92; VOC emission decrease by 0.012 Mt.

Notes: All results are compared to the reference case.

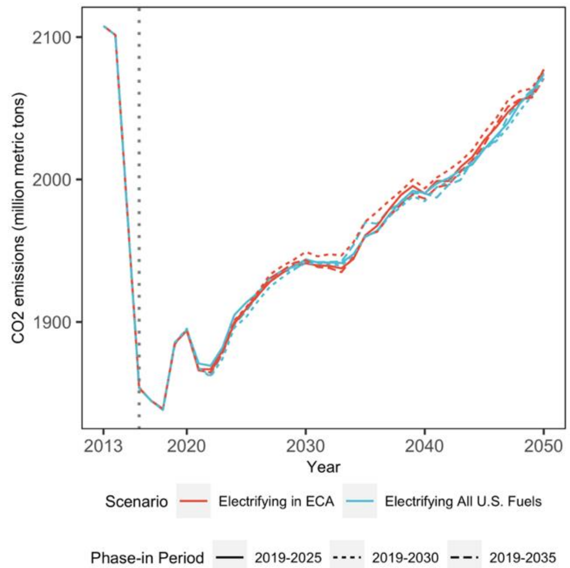

Figure S14: Energy-related CO_2 emissions from the waterborne shipping and power generation sectors with varying phase-in periods

Notes: The vertical dotted line separates historical and projected data.

Figure S15 presents the local air pollution emissions for five pollutants. Not surprisingly, the extended periods for full implementation of electrification slow down the rate of pollution reductions in the early projected years for the *Electrifying in ECA* and *Electrifying All U.S. Fuels* scenarios.

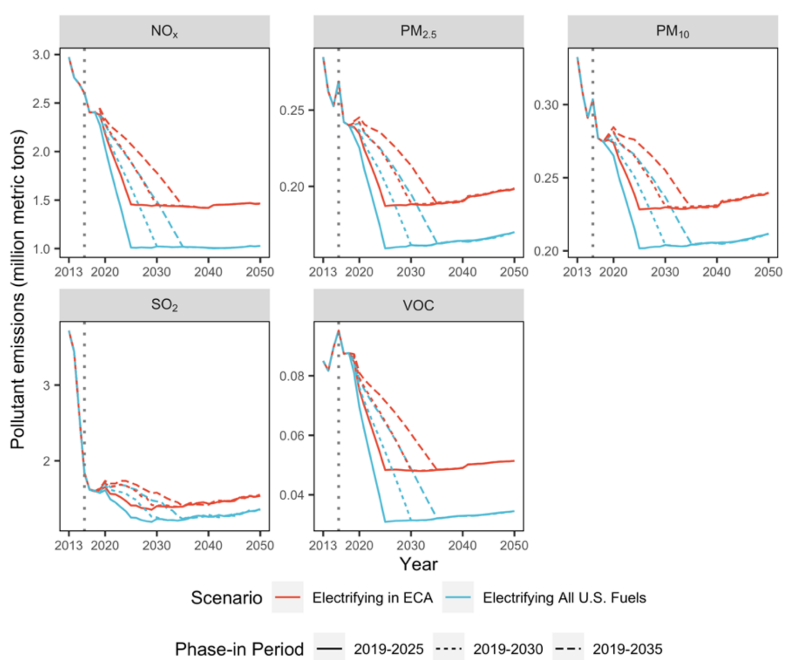

Figure S15: Energy-related local air pollution emissions with varying phase-in periods

Notes: The emissions are from fossil fuel combustions in the waterborne transportation sector (distillate oil, residual oil, and natural gas) and the power sector (coal, oil, and natural gas). Other sources of local air pollution emissions are not counted. The vertical dotted line separates historical and projected data.

Furthermore, we also perform the same illustrative cost-benefit analysis for the two sensitivity scenarios. Table S4 presents the estimated costs and benefits by category and in total. We see that the net benefits of waterborne shipping electrification with various phase-in periods are positive, which are slightly lower than the corresponding baseline results in the second column of Table 1 in the main text.

Table S4: Cumulative net present values of waterborne shipping electrification compared to the reference with varying phase-in periods

	Electrifying in ECA (Phase-in to 2030)	Electrifying in ECA (Phase-in to 2035)
Fuel Costs	-124.08	-111.43
Port Retrofit Costs	-9.22	-8.33
Vessel Retrofit Costs	-2.38	-2.26
Social Costs of Carbon	7.67	14.77
Social Costs of Local Air Pollution	227.44	206.80
Tugboat Costs	-12.39	-11.57
Total	87.03	88.00

Notes: The unit is billion U.S. 2016$. The discount rate is assumed to be 3%. The cash flow includes the years from 2019 to 2050.

5.2 Varying social cost of carbon

Table S5 presents the illustrative results of cost-benefit analysis with varying values for the SCC. For the high SCC case, we assume \$100/ton CO_2, while for the low SCC case, we assume \$7/ton CO_2 (matching the value used by the Trump Administration).[6] We see that results are close to the baseline results, which are insensitive to SCC assumptions.

Table S5: Cumulative net present values of waterborne shipping electrification compared to the reference with varying SCC

	High SCC (\$100/ton CO_2)		Low SCC (\$7/ton CO_2)	
	Electrifying in Ports	Electrifying in ECA	Electrifying in Ports	Electrifying in ECA
Fuel Costs	-53.76	-137.56	-53.76	-137.56
Port Retrofit Costs	-10.21	-10.21	-10.21	-10.21
Vessel Retrofit Costs	-2.52	-2.52	-2.52	-2.52
Social Costs of Carbon	4.06	19.12	0.28	1.34
Social Costs of Local Air Pollution	61.89	252.02	61.89	252.02
Tugboat Costs	-	-13.29	-	-13.29
Total	-0.54	107.56	-4.32	89.77

Notes: The unit is billion U.S. 2016$. The discount rate is assumed to be 3%. The cash flow includes the years from 2019 to 2050.

5.3 Varying economic costs of electrification

Table S6 displays the cost-benefit analysis results with varying costs of electrification, one case with 20% higher costs and another case with 20% lower costs than the baseline assumptions. We see that the results under these two sensitivity cases are close to the baseline results in Table 1.

Table S6: Cumulative net present values of waterborne shipping electrification compared to the reference with varying costs of electrification

	High costs (20% higher than baseline)		Low costs (20% lower than baseline)	
	Electrifying in Ports	Electrifying in ECA	Electrifying in Ports	Electrifying in ECA
Fuel Costs	-53.76	-137.56	-53.76	-137.56
Port Retrofit Costs	-11.09	-11.09	-9.33	-9.33
Vessel Retrofit Costs	-3.03	-3.03	-2.02	-2.02
Social Costs of Carbon	2.56	13.24	2.56	13.24
Social Costs of Local Air Pollution	61.89	252.02	61.89	252.02
Tugboat Costs	-	-15.95	-	-10.63
Total	-3.43	97.63	-0.66	105.72

Notes: The unit is billion U.S. 2016$. The discount rate is assumed to be 3%. The cash flow includes the years from 2019 to 2050. The altered electrification costs include port retrofit, vessel retrofit, and tugboat replacement.

5.4 Spatial heterogeneity in reduced social costs of emissions

Figure S16 presents the map with the changes in social costs from reducing air pollution in the year 2020 in the two electrification scenarios (without carbon pricing) compared to the reference case.

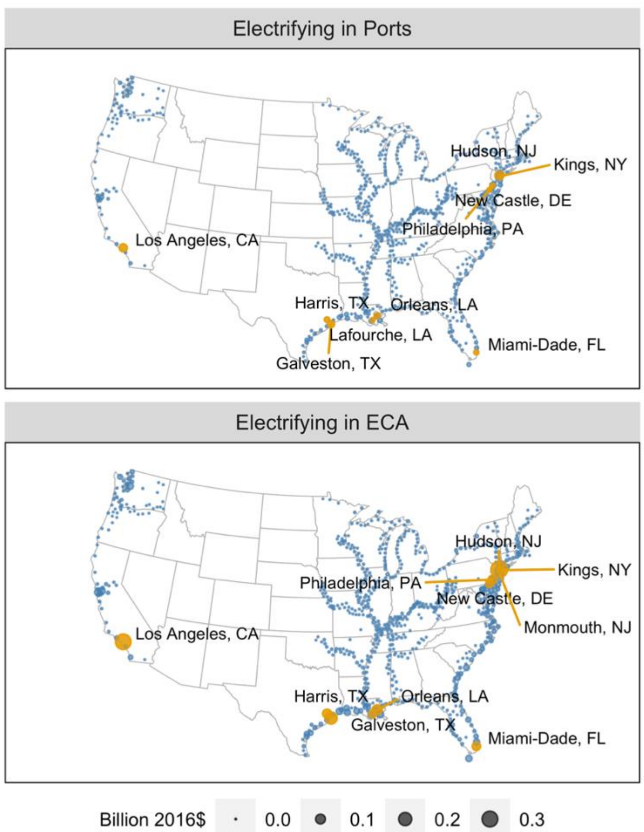

Figure S16: Avoided social costs from reducing pollution from waterborne transportation in 2020

Notes: The local air pollutants included in the social cost estimations are SO_2, NO_x, $PM_{2.5}$, PM_{10}, and VOC. The results are not undiscounted. The size of the dots represents the level of avoided social costs, in which the yellow dots and texts label the ten counties with the largest values.

5.5 Alternative approaches for estimating carbon emissions

Figure S17 presents CO_2 emissions directly reported in Yale-NEMS and estimated using the EN16268 European Standard as a sensitivity check. The EN16268 European Standard covers a methodology for estimating energy consumption and greenhouse gas emissions of transportation services and has been used by many logistics companies.[7] The major difference between the EN16268 European Standard and Yale-NEMS for estimating greenhouse gas emissions is the assumed emission factors. Here we present this sensitivity analysis as an alternative method to CO_2 emissions reported in Yale-NEMS. The sensitivity results do no show significant changes from our primary results.

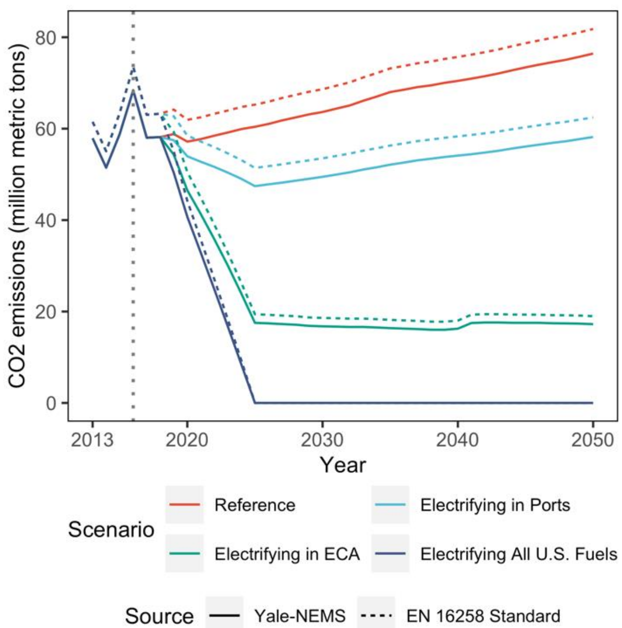

Figure S17: Energy-related CO_2 emissions from waterborne transportation using the EN 16268 European Standard

Notes: The EN 16268 European Standard represents a methodology for estimating energy-related GHG emissions from transport services (freight and passengers) published by the European Committee for Standardization.

References

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