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Electrifying ports to reduce diesel pollution from ships and trucks and benefit public health: Case studies of the Port of Seattle and the Port of New York and New Jersey

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Summary

The Port of Seattle and the Port of New York and New Jersey (NY/NJ) are key hubs serving international and domestic shipping in the United States. To reduce port emissions, both are investing in electrification, including by installing shore power and setting goals for 100% zero-emission harbor craft and trucks. By combining a series of simple, user-friendly tools, this study estimates how port electrification could reduce emissions and how that would benefit the surrounding regions in terms of air quality and public health.

We combined ICCT's global Port Emissions Inventory Tool (goPEIT) with our Systematic Assessment of Vessel Emissions (SAVE) model to estimate the emissions from ocean-going vessels (OGVs), harbor craft, and drayage trucks in 2019. We used the area of each port's jurisdiction as the boundaries and together these were the baseline results. We then modeled the emissions in a "full electrification" scenario that assumed 100% shore power connection for OGVs while at berth in ports and 100% electrification of harbor craft and trucks (the latter for NY/NJ only). The baseline and full electrification scenario results were then put into the Intervention model for Air Pollution (InMAP), an open-source, reduced-complexity model that estimates the air quality and health impacts of emissions on nearby regions.

We found that, at both ports, OGVs dominated total emissions and were more than 50% of carbon dioxide (CO_2), particulate matter ($PM_{2.5}$), and nitrogen oxides (NO_x) emissions from the sources we modeled in 2019. With full electrification, we estimated total

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$PM_{2.5}$ emissions reductions of 75% and 69% for Seattle and NY/NJ, respectively. Of all electrification technologies, electrifying harbor craft alone could reduce $PM_{2.5}$ emissions for Seattle and NY/NJ by 45% and 30%, respectively.

In the full electrification scenario, the annual average $PM_{2.5}$ concentration near the Port of Seattle would be reduced by 0.3–0.42 μg/m^3, a considerable amount in light of Seattle's annual average $PM_{2.5}$ concentration of 7.5 μg/m^3 in 2019. In addition, the total area affected by emissions from the Port of Seattle would be reduced from 292.1 km^2 to 54.5 km^2. With full electrification, the area near the Port of NY/NJ would also benefit greatly, with the City of Elizabeth seeing the highest air quality improvement of 0.82 μg/m^3 annual average $PM_{2.5}$ concentration reduction, and Jersey City achieving a 0.59 μg/m^3 annual average $PM_{2.5}$ concentration reduction. The total area affected by emissions from the Port of NY/NJ would be reduced from 2,172.3 km^2 to 504.5 km^2.

Air quality improvement near the Port of Seattle under the full electrification scenario is estimated to provide monetized health benefits of over $27 million annually. For the Port of NY/NJ, air quality improvement is expected to translate to at least $150 million of health benefits per year. This kind of quantification can help various ports apply for funding to support port electrification under programs like the U.S. Maritime Administration's Port Infrastructure Development Program and others that have received funding increases under the Bipartisan Infrastructure Law.

Background

The economic benefits of ports, which enable global trade, come at an environmental and social cost. Air pollution from port activities has been linked to higher rates of asthma, heart disease, cancer, and early death in those that live, work, and go to school in close proximity to them (Rutherford & Miller, 2019).

The Port of Seattle and the Port of New York and New Jersey (NY/NJ) play an important role in cargo and passenger transportation on the western and eastern coasts of the United States, respectively. The Northwest Seaport Alliance (NWSA), which is a marine cargo operating partnership of the ports of Seattle and Tacoma, is now the fourth largest container gateway in the United States, with throughput of 3.7 million twenty-foot equivalent units in 2019 (Swift, 2019).[1] The Port of NY/NJ is the largest port on the East Coast of the United States and the third largest in the nation; it moved 5.3 million twenty-foot equivalent units of cargo in 2019 (United States Department of Transportation, 2021).

Both ports have published emissions inventories. Seattle last published an emissions inventory for 2016, and it includes estimates of criteria pollutants, greenhouse gases (GHGs), and black carbon (BC; Starcrest Consulting Group, 2018). The Port of NY/NJ published an emissions inventory for 2019 and it covered criteria pollutants and GHGs, but not BC (Starcrest Consulting Group, 2020). Such inventories help understand port emissions and can support formulation of policies to reduce them.

The Port of Seattle has set a goal to be net-zero for port-owned emissions by 2040, and the Port of NY/NJ has committed to achieving net-zero carbon emissions by 2050 (Port of Seattle, 2020; The Port Authority of New York and New Jersey, 2021). To reduce port emissions, both ports are investing in electrification. The Port of NY/NJ has installed

1 The Port of Seattle handles only cruise ships and the North Harbor of the Northwest Seaport Alliance handles cargo. The Port of Tacoma is the South Harbor of the Northwest Seaport Alliance.

shore power at the Brooklyn Cruise Terminal (New York City Economic Development Corporation, 2016) and put its first electric truck into service in 2019 (Port of New York & New Jersey, 2019); 10 more heavy-duty battery electric yard tractors were unveiled in 2021 (Morley, 2021). The Port of Seattle is already equipped with shore power in the Smith Cove cruise terminal and Terminal 5, and is constructing shore power in the Bell Street cruise terminal (Port of Seattle, 2021). Additionally, the Port of Seattle set a goal in its clean air strategy that 100% of major cruise and container berths have shore power installed by 2030 (Port of Seattle, 2020). The same clean air strategy sets a goal to have sufficient infrastructure for zero-emission ready, including the fuel bunkering system and more, by 2030 and 100% zero-emission harbor craft and trucks by 2050.

There is support from the U.S. federal government, as well. In November 2021, Congress authorized an additional $450 million per year for the U.S. Department of Transportation Maritime Administration's Port Infrastructure Development Program (U.S. Department of Transportation, 2022). Applications for this program can be submitted each year by a public sponsor, such as a port authority, city, county, or state. Funds can be used for projects that reduce or eliminate port-related air pollution or GHG emissions, including port electrification or electrification master planning, harbor craft or equipment replacements or retrofits, microgrids, idling reduction infrastructure, ocean-going vessel (OGV) bunkering facilities, and electric recharging stations or hydrogen refueling stations for drayage trucks and other equipment.[2] This program and the Congestion Mitigation and Air Quality Improvement Program (CMAQ), the National Highway Freight Program (NHFP), and the Marine Highway Program all provide opportunities for ports and other entities to secure funding that can be used to build infrastructure to support port electrification.

To help understand the full potential of port electrification to reduce emissions, improve air quality, and benefit public health around ports, this paper estimates emissions from OGVs and harbor craft for the Port of Seattle and OGVs, harbor craft, and drayage trucks for the Port of NY/NJ for the year 2019, and then assesses the air quality and public health benefits of port electrification. The remainder of the paper is organized in three parts. First, we introduce the models used for quantifying emissions, air quality impacts, and public health impacts. We then present the results and discuss their implications before concluding with a brief discussion of future work that is needed.

Models used

Transport Canada developed the Port Emissions Inventory Tool (PEIT), a desktop tool for estimating emissions from ports (The Environment & Water business unit of SNC-Lavalin Inc., 2014). The ICCT has turned PEIT into the goPEIT model, a free, online tool, and made it applicable to any port in the world.[3] goPEIT requires inputs on activity data like hours of engine use, vehicle kilometers traveled, and fuel used for major port-related equipment. It outputs estimates of air pollution emissions and GHG emissions. The emissions factors in goPEIT are from the International Maritime Organization's Fourth GHG Study (Faber et al., 2020), the EPA MOVES 2010b model for the on-road vehicle sector (United States Environmental Protection Agency, 2012), the EPA NONROAD 2008 emissions model for the cargo handling equipment (CHE) sector (United States Environmental Protection Agency, 2010b), and emissions testing results

2 Harbor craft include ferries, fish boats, tugboats, other service craft except tugs, and yachts.

3 gopeit.org. Please contact xiaoli.mao@theicct.org to get an account and access permission. goPEIT is expected to be available circa spring 2023.

for rail sector that PEIT identifies. goPEIT enables users such as terminal operators and port authorities to develop port emissions inventories at a level of detail that varies depending on data availability.

The Systematic Assessment of Vessel Emissions (SAVE) model was described in detail in our previous work (Olmer et al., 2017) and has been updated to be consistent with the Fourth IMO GHG Study (Faber et al., 2020). In this study, we used SAVE to identify ships sailing within the ports of Seattle and NY/NJ based on satellite and terrestrial Automatic Identification System (AIS) data in 2019. (See Appendix A for the study regions for each port.) We also relied on SAVE for information about ship activity, including hours of navigation within the study region and average speed in different operational phases. However, if a goPEIT user has access to ship activity data, including hours and speeds transiting, anchoring, and berthing within a port's jurisdiction, goPEIT alone can estimate emissions from ships and the SAVE model is not required. For emissions from trucks, goPEIT requires inputs such as the number of truck visits annually, average speed, driving distance, and average per-visit idle time within port. In this study, input data for drayage truck activities in the Port of NY/NJ were from the aforementioned 2019 port emissions inventory report; data for drayage truck activities in the Port of Seattle were not available for 2019 and were therefore excluded from this modeling.

Once the baseline port emissions inventories were input for both ports, goPEIT provided detailed results including emission results for OGVs, harbor craft, and drayage trucks (for NY/NJ). For OGVs, results are disaggregated for different operational phases, namely normal cruising, at anchor, and at berth. Our "full electrification" scenario was constructed by simply making the emissions zero for harbor craft, drayage trucks, and for OGV auxiliary engines while at berth. We modeled direct emissions only and the upstream emissions from electricity production are beyond the scope of this study. Note that the electricity sources for Seattle are mainly carbon-free, including 86% hydroelectricity, 5% nuclear, and 5% wind power. Electricity sources for New Jersey are mainly (over 90%) natural gas and nuclear power, and in New York over 60% of the electricity comes from renewable sources.[4]

We used the Intervention model for Air Pollution (InMAP), an open-source, reduced-complexity model, to estimate the annual average concentrations change in fine particulate matter ($PM_{2.5}$) and the resulting mortality risk from port emissions from OGVs, harbor craft, and drayage trucks. InMAP can run on a personal computer and is more accessible to non-specialists than standard chemical transport models (Tessum et al., 2017). InMAP uses the output of WRF-Chem, a more comprehensive chemical transport model, to extract meteorological, chemical and physical parameters; no processing of the WRF-Chem output is needed and this makes InMAP faster and easier to use (Tessum et al., 2017). Although InMAP is generally less accurate than typical chemical transport models when compared to monitoring data, researchers have found that the modest reduction in accuracy is acceptable because primary $PM_{2.5}$ results from InMAP agree with WRF-Chem with an R^2 value of 0.98 (Tessum et al., 2017). Additionally, InMAP has been used in the examination of the health and economic impacts of $PM_{2.5}$ pollution from each economic sector in the United States (Goodkind et al., 2019). In this study, we applied the version of InMAP published in August 2021 and more details are in Appendix B.

Figure 1 illustrates our process. Once inputs on activity data for port-related activities, including vessels, trucks, cargo handling equipment, rail locomotives, and administration

4 Data from U.S. Energy Information Administration, https://www.eia.gov/state/

sectors were provided, goPEIT estimated and output emissions from those sources. Those were then used as the input to the InMAP model. The emissions results were first entered into the InMAP preprocessor, which simulates the physical and chemical processes of the emissions, including advection, turbulent mixing, atmospheric aerosol chemistry, dry deposition, and wet deposition. Then InMAP output annual average changes in $PM_{2.5}$ concentration in a flexible grid cell setting based on population density. That was then used by InMAP to calculate health impacts, and this is done using default census and mortality rate datasets that are already included in the model (the user can change these if they wish) to estimate premature mortality associated with $PM_{2.5}$ exposure from port-related activities. Together this gave a baseline of the impact of shipping emissions.

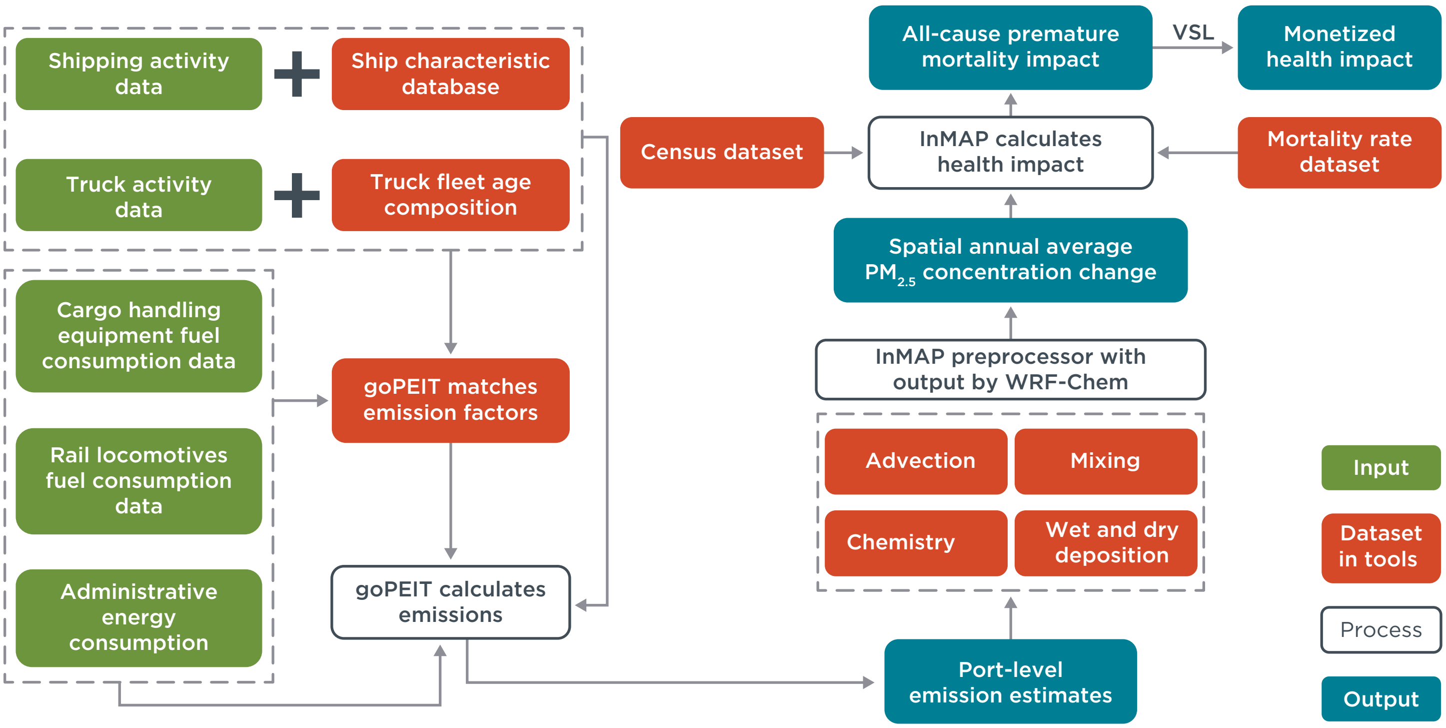

Figure 1. Schematic of using goPEIT and InMAP to estimate port emissions, changes in air pollution concentrations, and resultant health impacts.

The user can then run what-if scenarios that reduce or eliminate pollution from particular sources to compare the avoided premature mortality. We converted that premature mortality to monetized health impacts by applying a value of a statistical life (VSL) assumption from the U.S. EPA, which was $7.9 million in 2008 U.S. dollars (United States Environmental Protection Agency, 2014). We adjusted that for inflation using the U.S. Consumer Price Index and arrived at $9.4 million in 2019 U.S. dollars. Other costs, such as those associated with increased hospitalizations and incidences of illnesses like asthma, heart disease, and lung disease, were not quantified.

Results

Port of Seattle

The emissions from each pollution source under different operational phases are shown in Table 1. For OGVs, emissions at berth were around 80% of all OGV emissions within the port jurisdiction, and some of these emissions can be eliminated using shore power.

Table 1. Emissions at the Port of Seattle in tonnes, 2019

Source	Count of units	Operational phase	NO_x	SO_x	PM_{10}	$PM_{2.5}$	VOC	BC	CO	CO_2
OGVs	198	Anchor	74	2.4	1.6	1.5	2.3	0.4	5.3	4456
		Berth	384.2	12.6	8.7	8	12.3	2	26.2	24,801
		Cruising	38.5	1.1	0.9	0.9	2.4	0.1	4.7	1,548
		Total	497	16	11	10	17	3	36	30,806
Harbor craft	181	Cruising	438	13.9	9.4	8.7	16.6	1.8	36.5	21,701
Total			**934.7**	**30**	**20.6**	**19.1**	**33.6**	**4.3**	**72.7**	**52,506**

Figure 2 shows the composition of $PM_{2.5}$ emissions from OGVs and harbor craft. For OGVs, container ships and cruise ships were the main contributors and for harbor craft, tugs and ferries were a combined 92% of all $PM_{2.5}$ emissions.

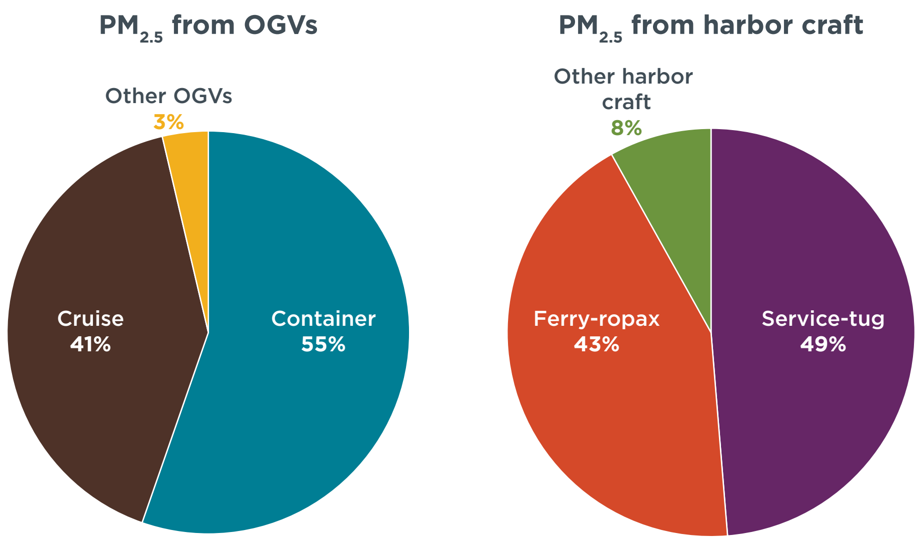

Figure 2. Share of $PM_{2.5}$ emissions from different OGVs and harbor craft types in the Port of Seattle, 2019.

Figure 3 illustrates the impact of the full electrification scenario on $PM_{2.5}$ emissions, which are reduced by 75% in total. Connecting ships to shore power would reduce direct $PM_{2.5}$ emissions by 29%, with cruise ships and containers accounting for 13% and 16% of these reductions, respectively. Although over 80% of OGV emissions took place while at berth, shore power connection still could not help with the remaining emissions while cruising and anchoring. In addition, even for at-berth shipping emissions, shore power only reduces emissions from auxiliary engines that are needed for onboard electrical systems, and emissions from boilers still exist (Wang et al., 2015). For harbor craft, full electrification would reduce 45% of the $PM_{2.5}$ emissions from all sources we modeled.

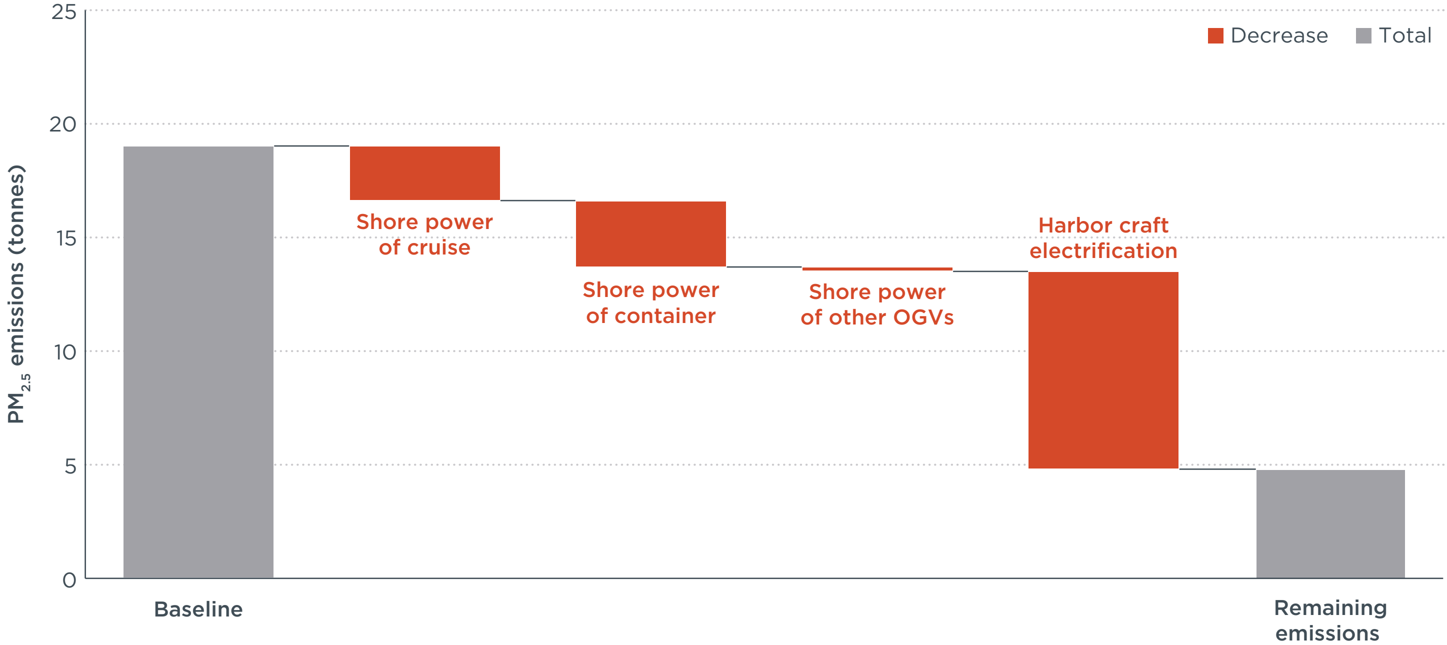

Figure 3. $PM_{2.5}$ emissions reduction potential under the full electrification scenario by source at the Port of Seattle in 2019.

The other emissions at the Port of Seattle, including PM_{10}, CO_2, and NO_x, would also be reduced substantially, by 75%, 68%, and 85%, respectively. In absolute terms, this means 15 tonnes of PM_{10}, over 35,000 tonnes of CO_2, and 790 tonnes of NO_x reduction from port electrification in a year. While this is based on 2019 activity, a macroeconomic assessment submitted to the U.S. Maritime Administration projected that the cargo throughput in the Port of Seattle would increase over 100% from 2020 to 2050 (Schenk et al., 2020); that means we can expect bigger emissions reduction potential in the future.

In the baseline scenario, up to 0.53 µg/m^3 annual average $PM_{2.5}$ concentration was attributable to port emissions in the communities located near the port, as shown in Figure 4. That is considerable, as annual average $PM_{2.5}$ concentration from all sources in Seattle in 2019 was 7.5 /m^3 (IQAir, n.d.). As shown in the map, Seattle is the main area influenced; a small area of Bellevue is affected, also, but much less than Seattle. Under the full electrification scenario, air quality would be much improved from the baseline situation. The area that had the highest $PM_{2.5}$ concentration attributable to port emissions in the baseline scenario was estimated at 0.09 µg/m^3 in the full electrification scenario, an 83% reduction from the baseline of 0.53 µg/m^3. The area affected by port air pollution would also shrink from 292.1 km^2 to 54.5 km^2.

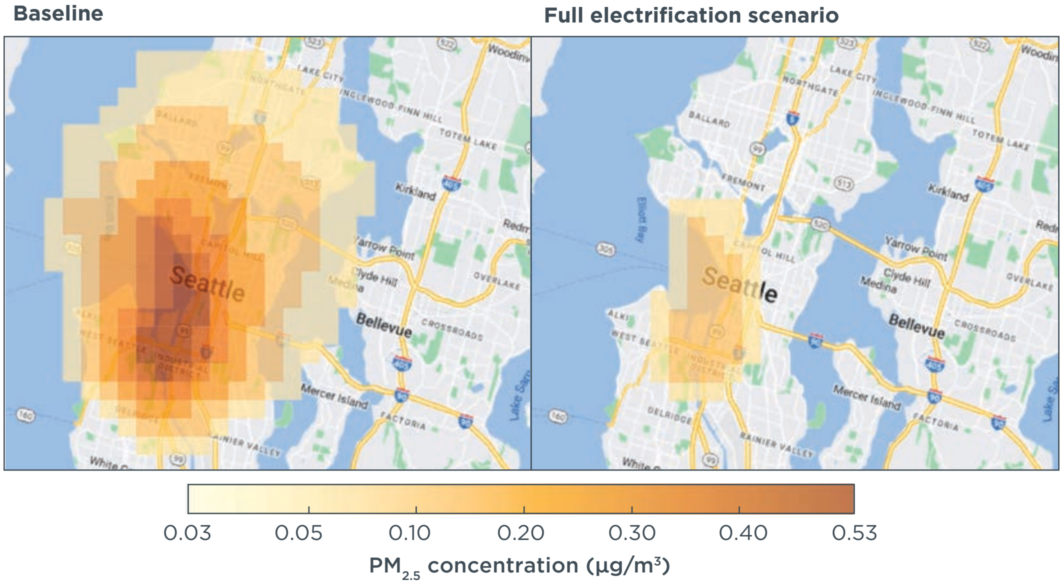

Figure 4. Annual average $PM_{2.5}$ concentration (µg/m³) attributable to Seattle port emissions, under the baseline (left) and full electrification (right) scenarios.

The reduced annual average $PM_{2.5}$ concentration and the benefit in terms of avoided premature deaths is shown in Figure 5. For the nearby region of the port, $PM_{2.5}$ concentration is reduced by 0.3–0.42 µg/m³, 4%–6% of the annual average $PM_{2.5}$ concentration from all sources in Seattle in 2019 (IQAir, 2022). This emissions reduction would avoid about 3 premature deaths per year in Seattle and represents over $27 million in public health benefits per year.

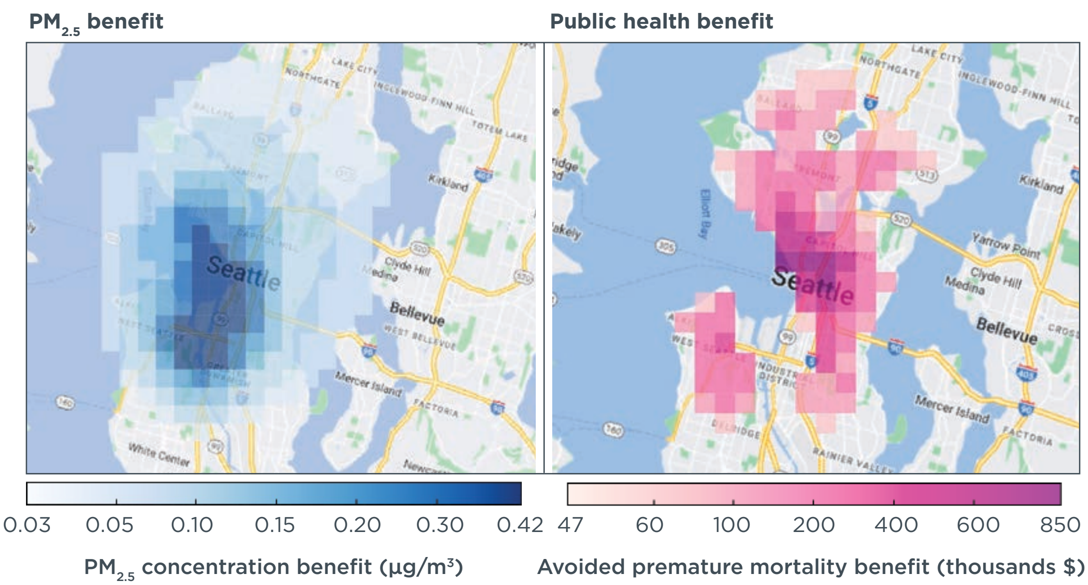

Figure 5. Benefit of reduced annual average $PM_{2.5}$ concentration (µg/m³) and monetized public health benefits (thousands $) in Seattle in electrification scenario, with a 0.01° x 0.01° grid cell, 2019

Port of NY/NJ

Table 2 shows the estimated emissions at the Port of NY/NJ in 2019. Generally, the emissions result was similar to that of the 2019 emissions inventory report published by the Port Authority (Starcrest Consulting Group, 2020) and a detailed comparison is in Appendix C. We included BC emissions in this study, and they were not in the Port Authority's report. Results show that OGVs were the biggest contributor, responsible for 52% of CO_2, 50% of $PM_{2.5}$, and 61% of NO_x emissions. Harbor craft contributed 24% of CO_2, 30% of $PM_{2.5}$, and 31% of NO_x emissions. Emissions at berth were around 50% of total OGVs emissions, and these can be reduced or eliminated by using shore power.

Table 2. Emissions at the Port of NY/NJ in tonnes, 2019

Source	Count of units	Operational phase	NO_x	SO_x	PM_{10}	$PM_{2.5}$	VOC	BC	CO	CO_2
OGVs	1,522	Anchor	588	19	12	11	18	3	42	35,128
		Berth	903	30	19	17	28	5	64	56,037
		Cruising	416	11	8	7	23	1	45	15,480
		Total	1,907	59	39	35	69	9	152	106,645
Harbor craft	267	Cruising	983	35	24	22	42	4	92	50,981
Drayage trucks	5,170,130 truck calls	Driving	53	0.1	5	3	6	—	19	11,470
		Idling	189	0.3	14	11	25	—	66	36,946
		Total	242	0.4	19	15	31	—	85	48,416
Total			**3,132**	**95**	**81**	**72**	**142**	**13**	**329**	**206,042**

Figure 6 shows $PM_{2.5}$ emissions from OGVs and harbor craft. For OGVs, container ships, tankers, and auto carriers were the main contributors of the emissions, accounting for 68%, 15%, and 6%, respectively. For harbor craft, tugs and ferries were a combined 97% of the $PM_{2.5}$ emissions.

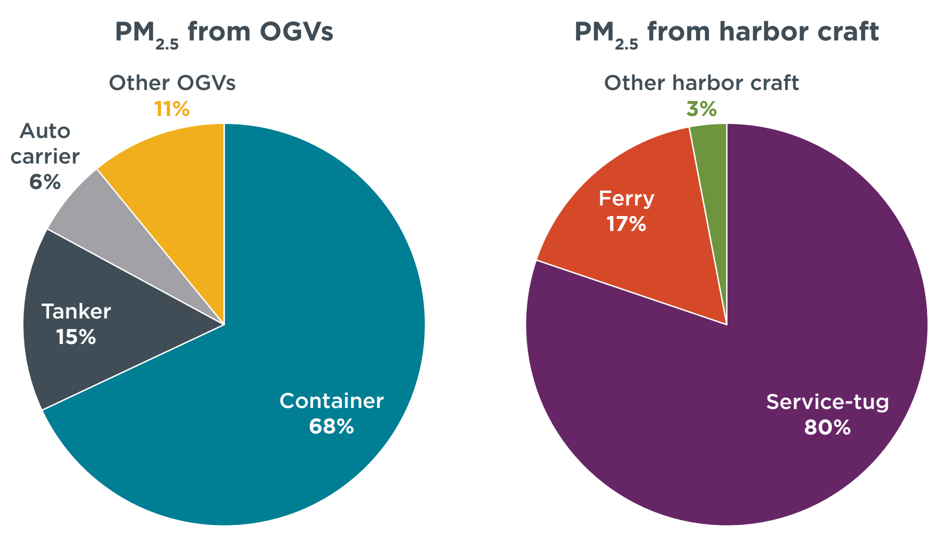

Figure 6. Share of $PM_{2.5}$ emissions from different OGVs and harbor craft types in the Port of NY/NJ, 2019.

Figure 7 illustrates the emissions reduction potential from port electrification by emission source. In total, the full electrification scenario could help to reduce over 68.5% of the 2019 $PM_{2.5}$ emissions. Connecting containers, tankers, and auto carriers to shore power would eliminate 12.7%, 1.9%, and 1.3% of $PM_{2.5}$ emissions, respectively. Electrification of harbor craft and drayage trucks could help to reduce over 51% of the $PM_{2.5}$ emissions. The reduction potential of shore power was not as high as the potential from electrifying harbor craft and drayage trucks. Recall that shore power only reduces auxiliary engines' emissions when ships are at berth, and thus only a portion of OGV emissions are cut down to zero with 100% shore power.

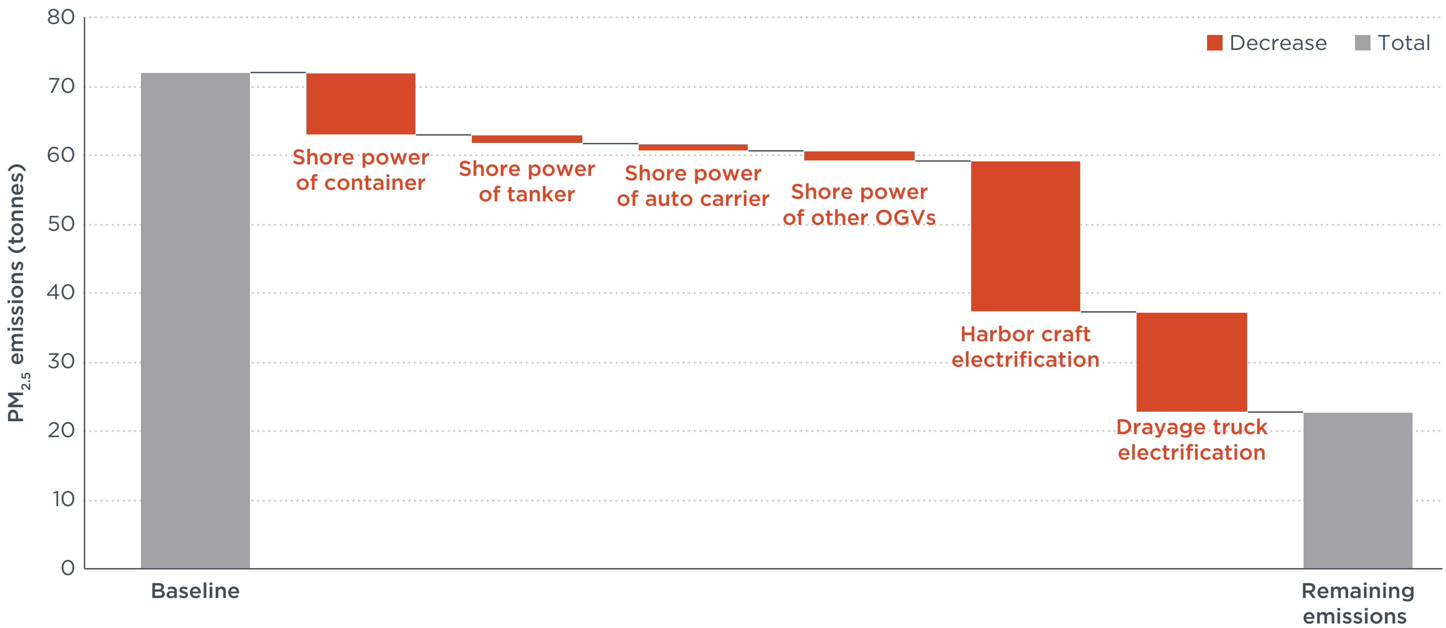

Figure 7. $PM_{2.5}$ emissions reduction potential with full electrification by emission sources for the Port of NY/NJ, 2019

Other emissions, including CO_2, PM_{10}, and NO_x, would also be reduced by 64%, 70%, and 66% in the full electrification scenario. In absolute terms, this represents over 130,000 tonnes of CO_2, 57 tonnes of PM_{10}, and 2,000 tonnes of NO_x reduced by port electrification in a year, based on the results for 2019.

The air quality impacts are shown in Figure 8. For the baseline scenario, with no additional port electrification policies, up to 1.22 µg/m^3 annual average $PM_{2.5}$ concentration was attributable to port emissions in the communities located near the port, especially around the area of Elizabeth, NJ, Newark, NJ, and Brooklyn, NY, with Elizabeth suffering the most impact. Under the full electrification scenario, with over 56% reduction of $PM_{2.5}$, SO_x, and NO_x emissions, the annual average $PM_{2.5}$ concentration attributable to port emissions would decrease by more than 65%. Additionally, the area affected by port air pollution would shrink from 2,172.3 km^2 to 504.5 km^2.

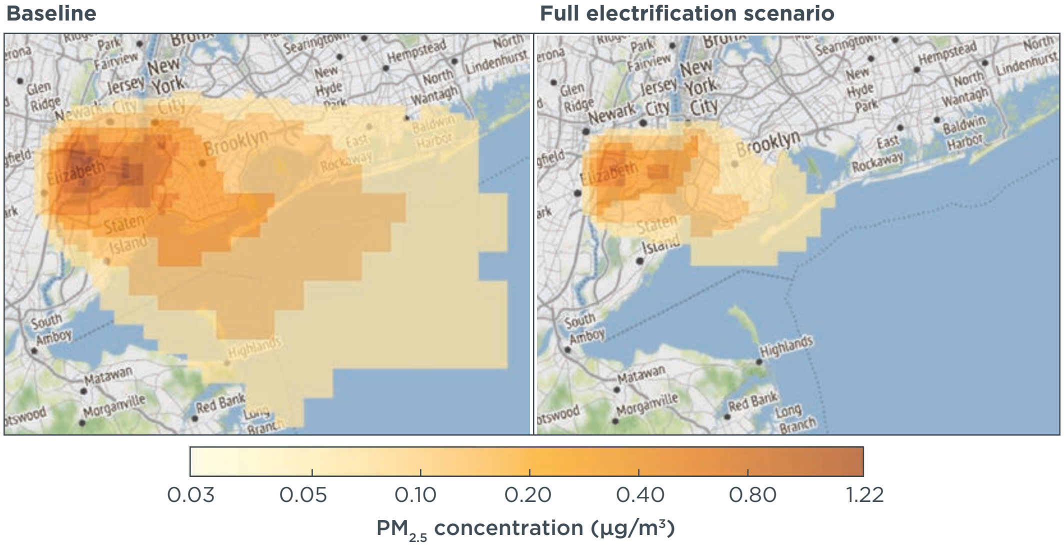

Figure 8. Annual average $PM_{2.5}$ concentration (µg/m³) attributable to NY/NJ port emissions, 2019.

Figure 9 shows the air quality and public health benefits of port electrification. The nearby region of Elizabeth, NJ would get the most air quality benefit, with its annual average $PM_{2.5}$ concentration reduced by 0.82 µg/m³. Another key region to benefit would be Jersey City, NJ with a 0.59 µg/m³ reduction in $PM_{2.5}$ concentration.

Under the full electrification scenario, we estimated 16 avoided premature deaths per year just from reduced $PM_{2.5}$ exposure. This translates to at least $150 million in public health benefits, the VSL calculation showed. To give some perspective, the public health benefits would be equal to around 10% of the annual budget of the New York City Department of Health and Mental Hygiene (New York City Department of Health and Mental Hygiene, n.d.). Brooklyn would receive the largest public health benefits. Although the reduced annual average $PM_{2.5}$ concentration in Brooklyn would be below 0.2 µg/m³, with over 2.5 million people living there, the public health benefits would be over $60 million per year.

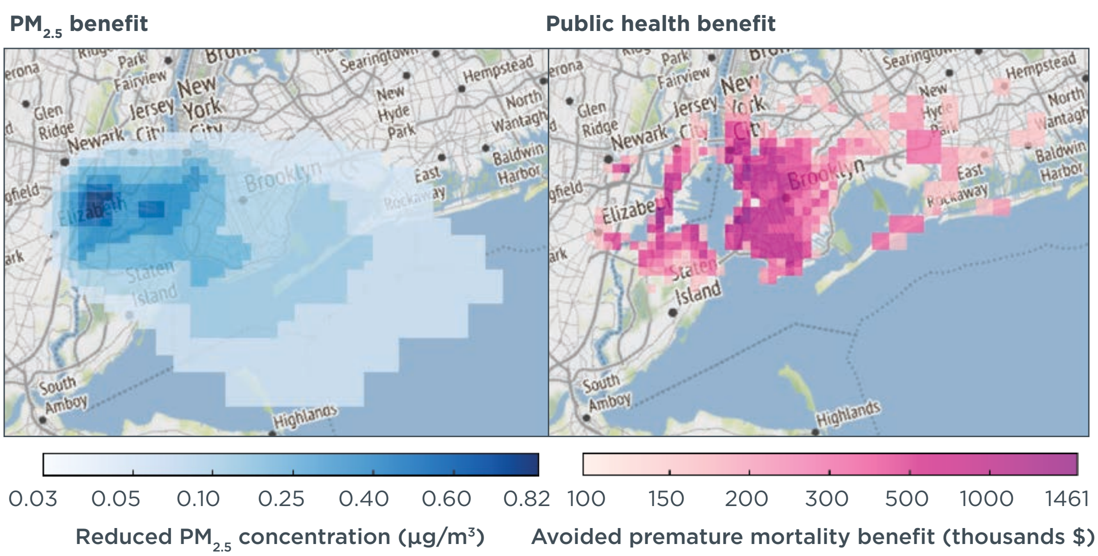

Figure 9. Benefit of reduced annual average $PM_{2.5}$ concentration (µg/m³) and monetized public health benefits (thousands $) in NY/NJ in the full electrification scenario, with a 0.01° x 0.01° grid cell, 2019.

Comparison to prior work

A previous global study found 50 premature mortalities related to shipping emissions for Seattle and 150 for New York, both in 2015 (Anenberg et al., 2019). That is much higher than the results in this study, which analyzed port emissions and found 3 avoided permature mortalities for Seattle and 16 for NY/NJ, down from 4 and 24 premature deaths, respectively, without port electrification; these numbers drop by around half if we only consider shipping emissions. There are several reasons for the difference. The main reason is that our results are based on port-level emissions and we did not include emissions from ships that were nearby but never called on the ports. For example, Seattle is part of the NWSA region and is impacted by airshed emissions over five times higher than the port-level shipping emissions from our results (Starcrest Consulting Group, 2018). Further, more of the regions in Seattle and NY/NJ, and thus more people, would be impacted if we had considered more of the ships sailing around the regions.

Another reason for the difference is that in 2015, the ship engine standards for the North American Emission Control Area were Tier II. Beginning in 2016, the standard was Tier III, and that would reduce NO_x emissions by 75% from ships built after 2016 (United States Environmental Protection Agency, 2010a). For Anenberg et al. (2019), the modeling year was 2015, so some ships would emit higher NO_x emissions than they would in 2019, the year of focus in our study. As NO_x is an important precursor of $PM_{2.5}$, the higher NO_x emissions would lead to higher $PM_{2.5}$ concentration and increased mortality (Hodan & Barnard, 2004). Further, we mainly focus on the mortality from $PM_{2.5}$, but Anenberg et al. (2019) considered not only $PM_{2.5}$ but also ozone, and that would be expected to lead to around 8%–10% additional mortality (Anenberg et al., 2019).

Conclusions and future work

This study assessed the emissions reduction potential and health benefits of port electrification, with the major U.S. ports of Seattle and NY/NJ as case studies. We used reduced complexity tools—goPEIT as the emissions inventory tool and InMAP as the air quality and health impacts estimation tool—to demonstrate a user-friendly way to estimate port emissions and emissions reduction benefits. Considering OGVs and harbor craft at the Port of Seattle, we found that OGVs were the main emissions contributor, accounting for 58% of CO_2, 52% of $PM_{2.5}$, and 53% of NO_x emissions. For the Port of NY/NJ, OGVs were also the biggest contributor, responsible for 52% of CO_2, 50% of $PM_{2.5}$, and 61% of NO_x emissions. Under the full electrification scenario, however, we estimated that 75% of port $PM_{2.5}$ emissions could be reduced in Seattle and 69% could be reduced NY/NJ by applying shore power and electrifying harbor craft and drayage trucks; harbor craft electrification alone accounted for 40% of the $PM_{2.5}$ reduction in Seattle and 25% of the $PM_{2.5}$ reduction in NY/NJ.

With no additional emissions control policies, we estimated that up to 0.53 µg/m^3 annual average $PM_{2.5}$ concentration in the region of the Port of Seattle was attributable to port emissions, and up to 1.22 µg/m^3 of annual average $PM_{2.5}$ concentration in the region of the Port of NY/NJ was attributable to port emissions. With shore power connection of OGVs while at berth and electrification of harbor craft, the annual average $PM_{2.5}$ concentration near the Port of Seattle would be reduced by 0.3–0.42 µg/m^3, which would be considerable considering Seattle's annual average $PM_{2.5}$ concentration of 7.5 µg/m^3 in 2019; additionally, the area affected by port emissions would be reduced from 292.1 km^2 to 54.5 km^2. For the Port of NY/NJ, Elizabeth, NJ would achieve highest air quality benefit, reducing 0.82 µg/m^3 annual average $PM_{2.5}$ concentration, and Jersey City, NJ would achieve 0.59 μg/m^3 annual average $PM_{2.5}$ concentration reduction benefit. The air quality improvement near the Port of Seattle could prevent 3 premature deaths per year, or a public health benefit of over $27 million. For the Port of NY/NJ, air quality improvement is expected to avoid 16 premature deaths per year, which translates to at least $150 million of health benefits per year.

Note that the public health benefits results in this study are conservative because the results of morbidity are not included due to InMAP model limitations. That said, a global-level estimation of the economic consequences of air pollution suggested that morbidity costs would be around 10% of the mortality costs (Organization for Economic Cooperation and Development, 2016).

The tools and methods used in this study are all user-friendly and easily accessible. They can be used by a variety of stakeholders who want to establish their own emission inventories and identify the benefits of different kinds of emissions reduction policy packages. In this work, we focused on estimating the potential benefits of port electrification projects. Work examining the cost of port electrification, including the capital cost of equipment, operation and maintenance costs, and the cost of developing port infrastructure, would be another important way to support policymakers. Further, cost-benefit analyses of different potential policy interventions are also needed, as these would provide a potential roadmap of port electrification.

With more ports seeking to decarbonize, creating emissions inventories and estimating the emissions reduction potential of different abatement technologies will become increasingly important. As emission control policies globally and regionally evolve, we will also continuously update our goPEIT tool to allow users to generate up-to-date assessments of their port emissions. Finally, besides the air quality improvement and mortality avoidance, morbidity improvement is another area of concern for public health. Although the InMAP model does not currently include a morbidity estimation module, the ICCT intends to develop an estimation method using InMAP's output in the future.

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Appendix A. Study regions of the ports

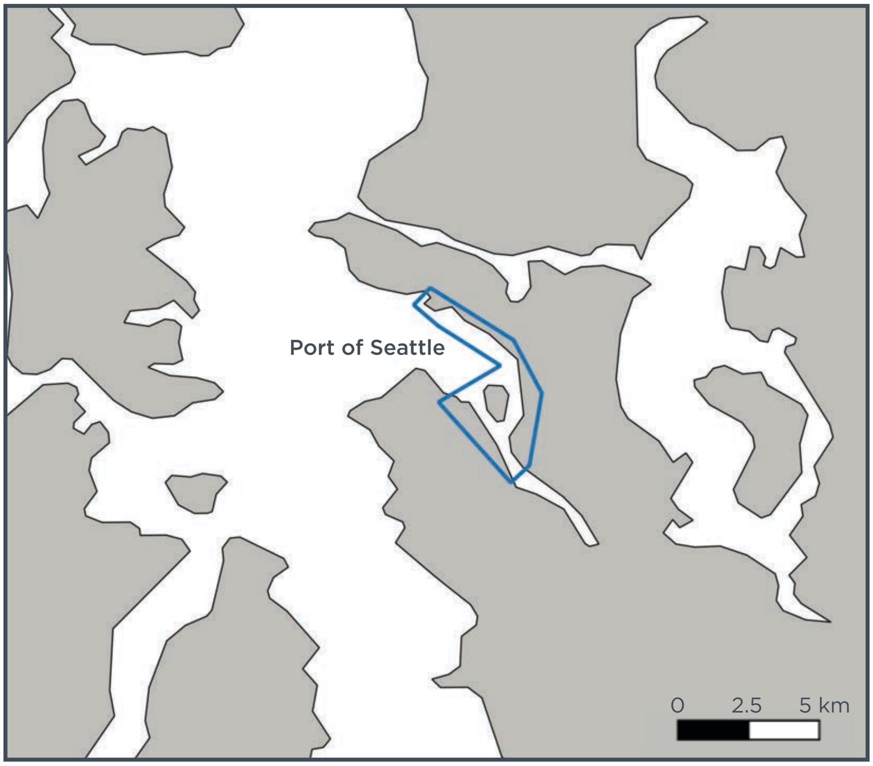

Figure A1. Study region of the Port of Seattle.

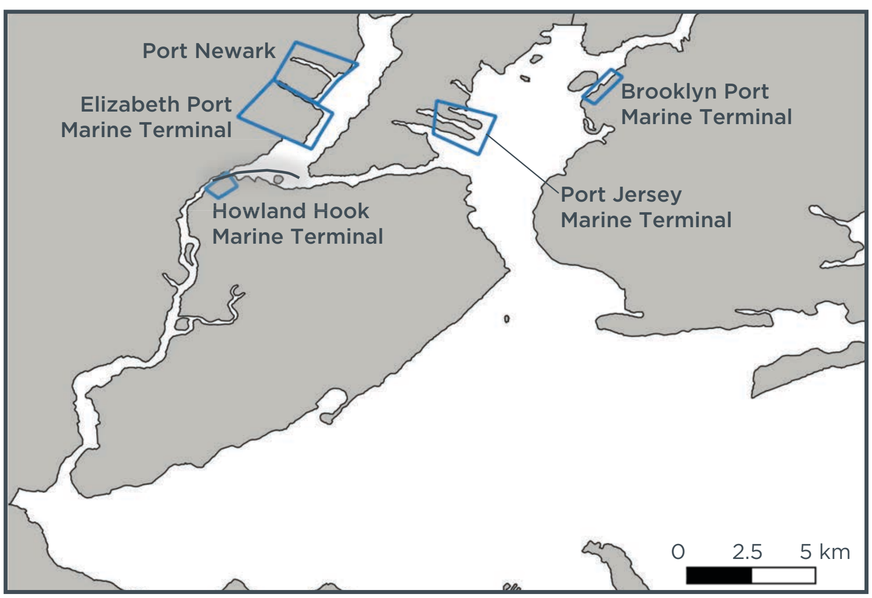

Figure A2. Study region of the Port of NY/NJ.

Appendix B. Details of InMAP model

InMAP needs an input with emissions for five primary pollutants: $PM_{2.5}$, NH_3, NO_x, SO_2, and VOC. The outputs then reflect the annual average and do not account for seasonal variations in emissions rates and meteorology. By calculation of pollutant transportation, chemical reaction in the atmosphere, InMAP outputs the change in $PM_{2.5}$ concentration.

For the premature death estimation, InMAP nested a linear concentration-response (C-R) function for adult all-cause mortality in the model. It was used to link $PM_{2.5}$ exposure and premature mortality. The estimation procedure can be divided to several steps as the following equations show:

$$\Delta M_i\,(C_i) = M_i(C_i) - M_i(C_i^o) = Pop_i \times \lambda_i^o \times \left[\frac{\lambda_i(C_i)}{\lambda_i^o} - 1\right] \qquad (1)$$

Where:

- $\Delta M_i C_i$: mortality change when concentration level change from baseline C_i^o to C_i, in grid $_i$;
- $M_i\,(C_i)$: mortality under $PM_{2.5}$ concentration C_i in grid $_i$;
- $M_i(C_i^o)$: mortality under $PM_{2.5}$ concentration C_i^o in grid $_i$;
- Pop_i: population in grid $_i$;
- λ_i^o: mortality rate under $PM_{2.5}$ concentration C_i^o in grid $_i$;
- $\lambda_i(C_i)$: mortality rate under $PM_{2.5}$ concentration C_i in grid $_i$;

The ratio $\lambda_i(C_i)/\ \lambda_i^o$ is called the relative-risk of mortality: $RR_i\,(C_i)$. Then the equation (1) can be expressed with equation (2):

$$\Delta M_i(C_i) = Pop_i \times \lambda 0_i \times [RR_i\,(C_i) - 1] \qquad (2)$$

With about 6% greater risk from each 10 μg m^{-3} increase in $PM_{2.5}$, the function for relative risk is from Krewsk et al., (2009):

$$RR_i\,(C_i) = exp[\ln(1.06)/10 \times (C_i - C_i^o)] \qquad (3)$$

InMAP model is installed with mortality rate data from National Center for Health Statistics[5], and average population data from 2008 to 2012 from Minnesota Population Center.[6] With equations mentioned above, we estimated the premature death caused by port emissions.

5 https://wonder.cdc.gov/Deaths-by-Underlying-Cause.html

6 https://www.ipums.org/projects/ipums-nhgis

Appendix C. Comparison between goPEIT results and results from Seattle and NY/NJ reports

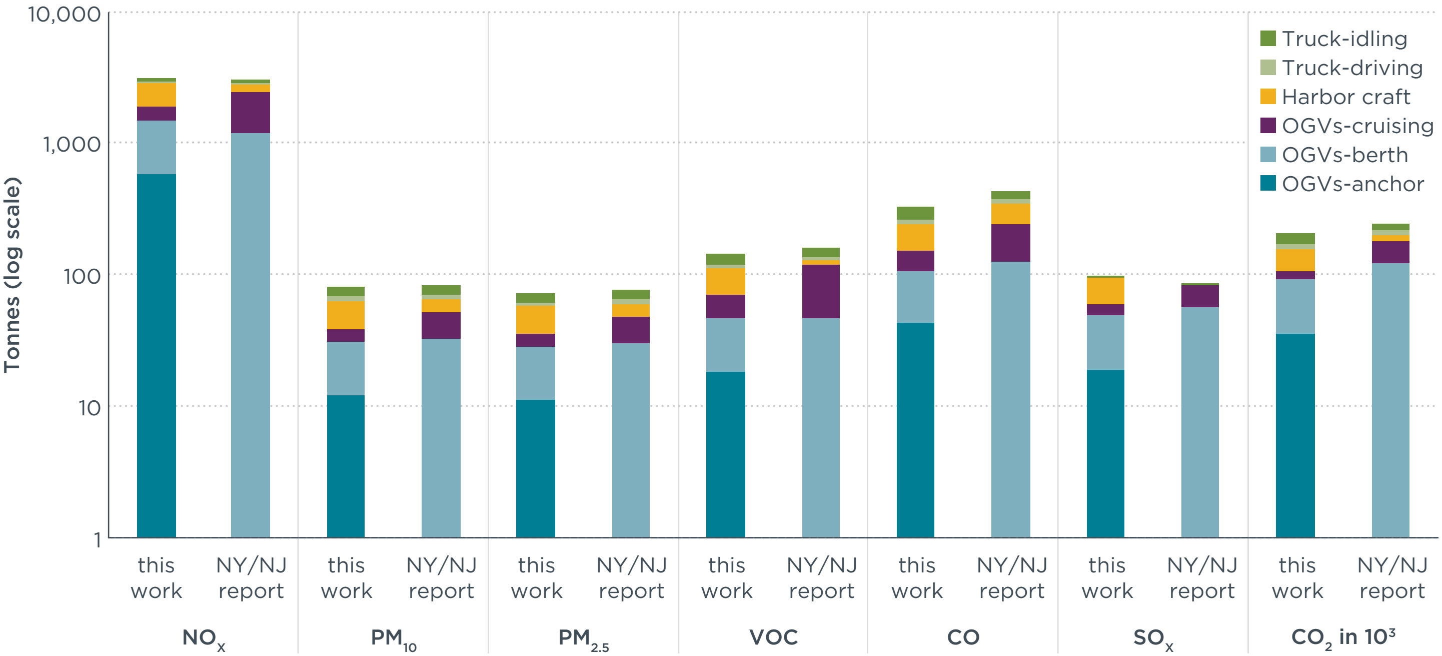

Figure C1. Comparison between goPEIT results and NY/NJ report results

Figure C1 shows the difference between results in this study and NY/NJ's report and overall, the emissions were similar. However, the emissions from each source were different. For OGVs, we estimated more emissions under anchor phase and less emissions under cruising phase. This might be a result of the activity data difference. Our activity data was from AIS data, for which anchor mode is indicated as speed over ground of OGVs of 1 to 3 knots; this is close to maneuvering mode, and thus part of maneuvering emissions might be assigned to anchor mode. Further, goPEIT mainly focused on port-level emissions, but the study area of NY/NJ's report also included areas around typical routes other than area immediately near the port. This could also contribute to the difference. Additionally, we estimated more harbor craft emissions than NY/NJ's report. One reason is that the NY/NJ report only included towboats/pushboats and assist tugs, while we also included others such as fishing boats, ferries, and yachts. Further, we may count craft passing through the port region which may not serve any port activity, and it will lead to overestimation results.

Figure C2. Comparison between goPEIT results and Seattle report results

Figure C2 shows the difference between results in this study and Seattle's report. We can find a big difference of harbor craft emissions. One main reason for the difference is the results for Seattle from Puget Sound Maritime Air Emissions Inventory report includes only non-NWSA activities, while our study includes all the activity within the Seattle port region. Another reason is similar to one mentioned above: we may count harbor craft passing through the port region which may not serve any port activity, and it will lead to overestimation results.