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Evaluating Strategies to Reduce the Environmental Impact of Commercial Maritime Vessels for the Port of Houston

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ACRONYMS AND ABBREVIATIONS

AIS	Automatic Identification System
BSFC	brake specific fuel consumption
CASP	clean air strategy plan
CH2	compressed hydrogen
CH4	methane
CMV	commercial maritime vessel
CO, CO2	carbon monoxide, carbon dioxide
DWT	deadweight tons
ECA	emission control area
EF	emission factor
EI	emission inventory
EPA	Environmental Protection Agency
FAME	fatty acid methyl ester
GMEI	Goods Movement Emission Inventory
HBC	harbor craft
HC	hydrocarbon
HFO	heavy fuel oil
HSC	Houston Ship Channel
IMO	International Maritime Organization
LH2	liquid hydrogen
LF	load factor
LLAF	low load adjustment factor
LNG	liquefied natural gas
MDO	marine diesel oil
MGO	marine gas oil
MMSI	Maritime Mobile Service Identity
N2O	nitrous oxide
NO, NO2	nitric oxide, nitrogen oxides

NOx	oxides of nitrogen
OGV	ocean-going vessel
PHA	Port of Houston Authority
PM	particulate matter
POH	Port of Houston
RM	residual marine
RORO	roll-on/roll-off
SCR	selective catalytic reactor
SO2	sulfur dioxide
SOx	oxides of sulfur
SM	sea margin
TEU	twenty-foot equivalent unit
TTI	Texas A&M Transportation Institute
VOC	volatile organic compound
VA	virtual arrival
VLCC	very large crude carrier
VSRIP	vessel speed reduction incentive program
VSRP	vessel speed reduction program

EXECUTIVE SUMMARY

The Port of Houston (POH), one of the busiest and most strategic maritime gateways in the United States, faces growing pressure to reduce emissions from maritime activities. To address this issue, this project focuses on evaluating emission reduction strategies for activities of both Ocean-going Vessels (OGVs) and Harbor Craft (HBC) along the Houston Ship Channel (HSC). Recognizing the complexity of these activities and the need for a structured approach, the effort has been designed in two phases:

Phase 1: Baseline Emission Inventory

The first phase (Chapters 1–5 of the report) developed a framework to estimate the vessel-level emissions inventory. Emission results were cross-validated with the POH's Goods Movement Emissions Inventory (GMEI). The framework is used to estimate the emission inventories of the baseline scenario and emission reduction strategies.

Table ES-1 presents the total baseline emissions in 2022 of OGVs and HBC, and Table ES-2 summarizes emissions by PHA terminals.

Table ES-1. 2022 Total Emissions of OGVs and HBC

Entity		NOx Tons	PM10 Tons	PM2.5 Tons	HC Tons	CO Tons	SO2 Tons	CO2 Tonnes
OGV	PHA	4,893	102	94	233	530	252	360,376
	Non-PHA	7,706	170	156	367	829	418	606,337
	Total	12,599	272	250	599	1,359	670	966,712
	Percent PHA	39%	38%	38%	39%	39%	38%	37%
HBC	PHA	1,782	41	40	50	312	1	123,150
	Non-PHA	3,863	91	88	112	643	2	245,508
	Total	5,645	133	128	162	955	4	368,658
	Percent PHA	32%	31%	31%	31%	33%	33%	33%

Note: NOx = oxides of nitrogen; PM = particulate matter; HC = hydrocarbon; CO = carbon monoxide; SO2 = sulfur dioxide; CO2 = carbon dioxide.

Table ES-2. 2022 PHA Total Emissions by Terminal

Terminal	NOx Tons	PM10 Tons	PM2.5 Tons	HC Tons	CO Tons	SO2 Tons	CO2 Tonnes
Bayport Terminal	2,076	46	42	95	261	81	148,754
Barbours Cut Terminal	1,247	28	26	62	165	57	95,112
Turning Basin	1,049	21	19	41	115	43	71,195
CARE Terminal	644	15	14	22	93	18	51,650
Jacintoport Terminal	332	7	7	11	49	7	24,096
Southside Wharves	435	10	8	17	51	17	30,784
Manchester Wharves	211	4	4	8	25	7	14,083
Woodhouse	244	5	5	10	26	10	16,454
Bulk Materials Handling	136	2	2	5	18	3	8,833
Sims Bayou	211	5	5	8	31	6	16,953
Industrial Park East	91	2	1	4	9	4	5,608

Key findings from Phase 1 are as follows:

- OGV activities at the POH are primarily composed of tankers, container ships, general cargo ships, and bulk carriers, while HBC activities are dominated by tugboats and towboats.
- PHA terminals account for approximately 30–40% of total vessel-related emissions at the port, with Bayport Terminal generating the highest share among all terminals.
- Container ships are the largest contributors to PHA-related emissions, while tankers dominate emissions at non-PHA terminals. Within HBC, towboats are the leading contributors due to their large fleet size and extensive engine operating hours.
- When compared to the 2019 emissions estimated in the GMEI, the estimated OGV emissions at both PHA and non-PHA terminals are generally consistent. However, this study found significantly higher HBC emissions at PHA terminals. One of the reasons for the discrepancy is that the activity estimate of tugboats and towboats in this study is higher than that of the GMEI.

Phase 2: Emission Control Strategy Evaluation

The second phase (Chapters 6–8 of the report) evaluated the effectiveness of various emission control strategies and included a benefit–cost analysis using 2022 emissions as the baseline. Because several proposed strategies are not yet widely adopted, the research team developed assumptions regarding operational practices, technologies, and associated costs as necessary based on publicly available data sources. The strategies included:

- **Shore Power.** Shore power allows vessels to connect to the land-based electrical grid while at berth, shutting down onboard auxiliary engines to reduce emissions. The research team evaluated the emission reductions of both OGVs and HBC, with the following key assumptions:
    - Infrastructure Availability: All terminals and applicable berths can be fully equipped with shore power infrastructure.
    - Electricity Source: Power is supplied from the Texas electricity grid. There are no transmission losses during shore power usage.
    - Connection Threshold: Shore power usage begins after the first 30 minutes of hoteling time to account for crew setup and system activation.
- **Engine Upgrade.** This strategy was used to model the emissions benefits of retrofitting existing marine engines to comply with higher U.S. EPA tier standards. Tiers range from Tier 0 (least stringent) to Tier 3 or 4 (most stringent), with progressively stricter limits on emissions like NOx and PM. The project examined the following strategies:
    - Tier 1 (T1): Upgrade Tier 0 engines to Tier 1 (OGVs and HBC).
    - Tier 2 (T2): Upgrade Tier 0 and Tier 1 engines to Tier 2 (OGVs and HBC).
    - Tier 3 (T3): Upgrade Tier 0, Tier 1, and Tier 2 engines to Tier 3 (OGVs and HBC).
    - Tier 3/Tier 4 (T3/T4): Upgrade all engines to Tier 4 for HBC only; OGVs remain at Tier 3 (since Tier 3 is considered the highest level for OGVs).
- **Biodiesel Adoption.** Biodiesel is a renewable fuel derived from waste oils and agricultural feedstocks. It contains lower sulfur content and offers a life-cycle carbon offset, leading to moderate emission reductions in CO2, SO2, and PM. However, it may not lead to a significant change in NOx emissions. The analysis had the following key assumptions:

- Biodiesel (B20) Option: For analysis, a B20 blend (20% biodiesel, 80% petroleum diesel) is commonly used since it is more cost-effective and serves as a drop-in replacement, requiring minimal engine modifications.
- Scope: Existing diesel-powered vessels can adopt B20 with minimal retrofitting. Vessels that do not rely on diesel engines are excluded from the analysis.

- **Liquefied Natural Gas (LNG) Adoption.** LNG is a cleaner-burning fuel that emits significantly less SO2, NOx, and PM than diesel, and moderately less CO2 due to higher gravimetric energy efficiency. However, converting to LNG requires substantial investment in both vessel retrofitting and terminal bunkering infrastructure. The analysis was based on the following assumptions:
  - Scope: All existing diesel-powered vessels are considered eligible for LNG conversion.
  - Terminal Infrastructure: All terminals are equipped with LNG bunkering facilities, so vessels can refuel without modifying their current operation patterns.
- **Hydrogen (Full and Hybrid).** Hydrogen propulsion includes both full fuel-cell systems and hybrid configurations that combine hydrogen with diesel. Due to current design limitations in onboard hydrogen storage capacity, the research team examined the feasibility of hydrogen use for HBC based on the following key assumptions:
  - Green Hydrogen: Hydrogen can be produced via renewable sources like wind and solar. It was treated as a zero-emission fuel in this analysis.
  - Vessel Specification:
    - Fuel-Cell Strategy: Modeled after the HyZET tugboat, featuring a liquid hydrogen storage capacity of 4,000 kg and a 1-hour refueling time.
    - Hybrid Strategy: Based on the Hydrotug 1, which is powered by dual-fuel engines capable of co-combusting up to 85% hydrogen and 15% diesel by mass. The vessel includes 415 kg of compressed hydrogen onboard, with a 30-minute refueling time.
- **Electrification (Full and Hybrid).** Electrification, either full or hybrid, replaces conventional marine engines with battery-electric propulsion. This eliminates onboard emissions and transfers the emissions to the power plants. The

electrification strategy was evaluated for HBC based on the following key assumptions:

- Infrastructure Assumption: All terminals and applicable berths have charging facilities.
- Vessel Specification:
  - Full Electric Strategy: Modeled after the eWolf, which features a 6,200 kWh battery capacity and requires approximately 4.5 hours for a full recharge.
  - Hybrid Strategy: Based on the hybrid eTug, equipped with a 4,520 kWh battery. The vessel operates on battery power until depletion and requires approximately 3 hours to fully recharge.

- **Vessel Speed Control.** Emissions increase exponentially with speed due to increased fuel consumption. This strategy was to identify the optimal transit-mode speeds to reduce emissions within the HSC, based on the assumption that vessels can freely adjust speeds without affecting their total hotelling duration at terminals.

- **Inefficient Operation Identification.** This strategy was employed to identify periods of unnecessary idling, defined as vessel speeds of 1 knot or less along the HSC. By pinpointing vessels that frequently operate inefficiently, policymakers can target these vessels for operational improvements, such as addressing scheduling bottlenecks and reducing traffic congestion.

After quantifying the emission reductions from various strategies, the research team conducted a benefit-cost analysis focused on emission reductions for NOx, PM2.5, CO2, and SO2. The associated implementation costs included ship retrofits, terminal infrastructure upgrades, and changes in fuel expenses.

While cost specifications vary from vessel to vessel, the research team assumed a unified cost for ships of the same type and consistent terminal costs across all facilities. The emission reductions per million dollars invested of the main ship types under various strategies are summarized in Table ES-3 and

Table ES-4.

Table ES-3. Emission Reductions per Million Dollars Invested ($/M) for OGVs

Strategy	Bulk Carrier	Vehicle Carrier	General Cargo	Container Ship	Chemical Tanker	Oil Tanker	Other Tanker
NOx (tons)							
Biodiesel	–	–	–	–	–	–	–
LNG	10.1	30.1	13.2	27.9	21.2	22.3	29.3
Shore Power	107.3	339.3	193.0	699.4	57.4	46.8	46.4
T1	34	112	129	181	225	276	81
T2	23	80	47	91	83	74	117
T3	5.2	15.4	8.8	18.6	13.4	14.4	17.2
PM2.5[1] (tons)							
Strategy	Bulk Carrier	Vehicle Carrier	General Cargo	Container Ship	Chemical Tanker	Oil Tanker	Other Tanker
Biodiesel	0.4	0.5	0.5	0.5	0.5	0.5	0.5
LNG	0.2	0.4	0.2	0.4	0.4	0.7	0.7
Shore Power	1.51	4.23	2.50	8.94	0.79	0.67	0.60
SO2[1] (tons)							
Strategy	Bulk Carrier	Vehicle Carrier	General Cargo	Container Ship	Chemical Tanker	Oil Tanker	Other Tanker
Biodiesel	1.2	1.4	1.3	1.6	1.3	1.6	1.7
LNG	0.5	1.3	0.6	1.4	1.0	2.2	2.3
Shore Power	2.77	7.77	4.59	16.42	1.44	1.23	1.06
CO2[1] (tonnes)							
Strategy	Bulk Carrier	Vehicle Carrier	General Cargo	Container Ship	Chemical Tanker	Oil Tanker	Other Tanker
Biodiesel	1,511	1,638	1,547	1,757	1,618	1,929	1,939
LNG	274.3	626.1	290.3	677.4	548.1	1,466.5	1,454.6
Shore Power	3,253	9,128	5,398	19,294	1,706	1,451	1,339

Note: A dash (–) means not applicable. 1: the tiers of the engines on OGV mainly affect NOx emissions.

Table ES-4. Emission Reductions per Million Dollars Invested ($/M) for HBC

NOx (tons)					
Strategy	**Tugboat**	**Towboat/ Pushboat**	**Fishing (C1/C2)**	**Misc.[2](C1/C2)**	**Excursion**
Biodiesel[1]	–	–	–	–	–
Hybrid Electric	4.079	4.251	0.127	1.078	0.388
Hybrid Hydrogen	1.138	1.246	0.047	0.364	0.125
Full Hydrogen	3.526	5.829	0.160	2.838	0.330
Shore Power	11.6	5.7	0.0	–	1.3
T1	297	258	7	90	0
T2	582	520	19	176	32
T3	251	225	9	78	15
T4	413	367	13	116	26
PM2.5 (tons)					
Strategy	**Tugboat**	**Towboat/ Pushboat**	**Fishing (C1/C2)**	**Misc. (C1/C2)**	**Excursion**
Biodiesel	0.584	0.599	0.457	0.971	0.388
Hybrid Electric	0.084	0.085	0.003	0.020	0.007
Hybrid Hydrogen	0.027	0.027	0.001	0.007	0.003
Full Hydrogen	0.079	0.128	0.005	0.102	0.007
Shore Power	0.40	0.22	0.00	–	0.03
T1	16.6	9.5	1.0	13.0	0
T2	13.6	10.8	0.6	6.3	0.5
T3	8.4	6.8	0.3	3.7	0.4
T4	10.2	8.3	0.4	4.4	0.5
SO2 (tons)					
Strategy	**Tugboat**	**Towboat/ Pushboat**	**Fishing (C1/C2)**	**Misc. (C1/C2)**	**Excursion**
Biodiesel	0.050	0.043	0.012	0.018	0.072
Hybrid Electric	−0.090	−0.060	−0.002	−0.012	−0.006
Hybrid Hydrogen	0.001	0.001	0.000	0.000	0.000
Full Hydrogen	0.003	0.004	0.000	0.002	0.000
Shore Power	−0.24	−0.09	0.00	–	−0.02
CO2 (tonnes)					
Strategy	**Tugboat**	**Towboat/ Pushboat**	**Fishing (C1/C2)**	**Misc. (C1/C2)**	**Excursion**
Biodiesel	1,604	1,595	900	1,491	1,182
Hybrid Electric	201	134	4	27	14
Hybrid Hydrogen	106	76	3	18	8

Full Hydrogen	291	362	10	166	22
Shore Power	539	193	0	–	45

1: Biodiesel is assumed to have little effect on NOx reduction. 2: Misc (C1/C2) has no eligible hoteling time based on 2022 activity data.

Key findings from Phase 2 are as follows:

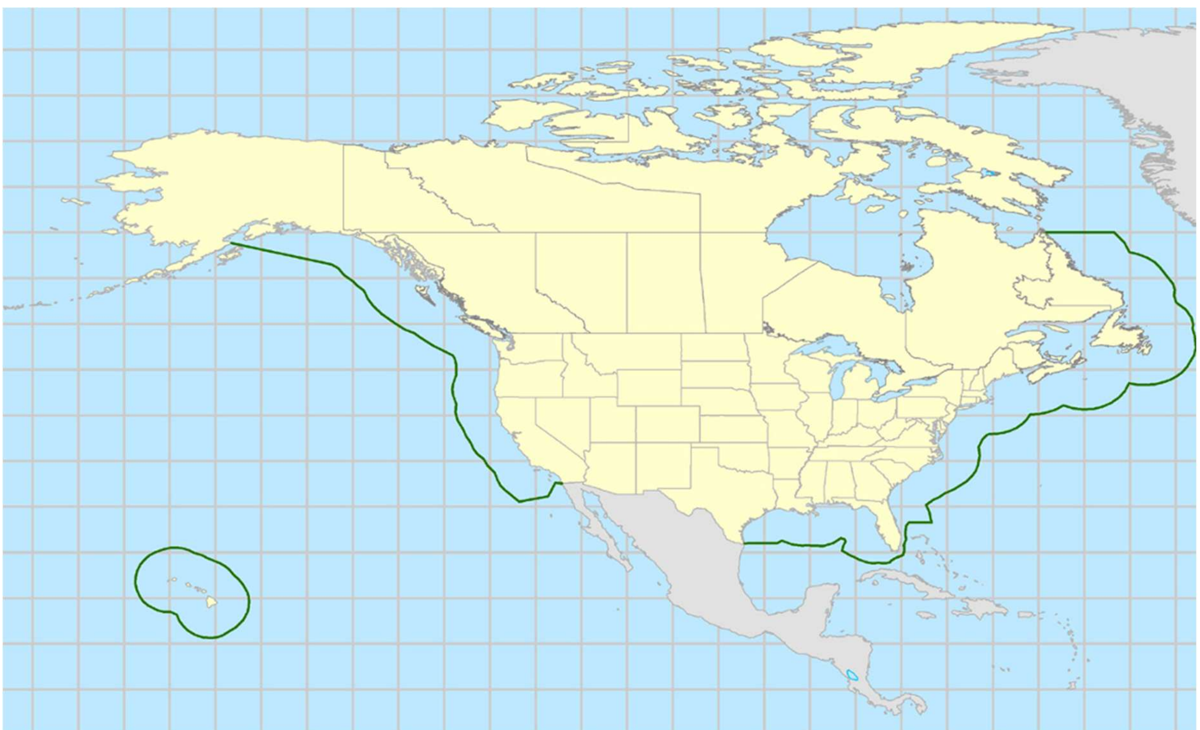
- **Alternative Fuels for OGVs:**
  - Biodiesel (B20) is the most cost-effective short-term solution, offering drop-in compatibility with existing engines and moderate reductions in PM2.5 and CO2.
  - LNG provides greater long-term benefits, with significant reductions in NOx, PM2.5, CO2, and SO2.
- **Alternative Fuels for HBC:**
  - Biodiesel remains a low-cost, widely applicable strategy for HBC vessels.
  - Hydrogen systems offer emission reductions but involve high retrofit and terminal infrastructure costs. The full hydrogen strategy, targeting specific vessel types, can achieve comparable emission reductions as hybrid hydrogen while minimizing retrofit costs.
  - Electric propulsion involves lower capital costs, but full electrification is generally unsuitable for HBC due to capacity constraints. Hybrid-electric systems are more practical and deliver better emission reductions per dollar spent compared to hydrogen. However, this strategy may increase SO2 emissions indirectly from the local power generation.
- **Shore Power.** This measure is more effective for OGVs to reduce emissions due to their long hoteling period and high auxiliary power demand. It is less impactful for HBC vessels as they usually have low-power auxiliary engines that produce fewer emissions.
- **Engine Tier Upgrades.** While upgrading to Tier 3 or Tier 4 engines yields the largest emission reductions, a more cost-effective strategy is (a) upgrading all OGVs to Tier 1, and (b) upgrading all HBC vessels to Tier 2. This approach balances emission benefits and implementation costs effectively.
- **Vessel Speed Control.** For OGVs, speed control can significantly reduce various emissions and fuel costs. Specifically, operating at 7–10 knots within the HSC minimizes NOx emissions the most while preserving operational efficiency.
- **Operational Efficiency and Idling.** Inefficient vessel behavior, defined as idling at ≤1 knot within the HSC, leads to unnecessary emissions. Among all categories,

"other tankers" exhibit the highest rate of inefficient operation, spending extended periods idling within the channel.

It should be recognized that the conclusions, results, and recommendations in this report are based on assumptions regarding vessel operations, technology adoption, and cost factors. These assumptions reflect the research team's best efforts based on information available from public sources. As a result, findings may vary under different assumptions, and future analyses with updated or more detailed data will be important to refine and validate these outcomes.

1. INTRODUCTION

The maritime industry plays a significant role in global trade and transportation, but because of its volume of activity, it is also a major contributor to air pollution. In response to growing environmental concerns and public health benefits, the International Maritime Organization (IMO) designated specific portions of U.S. and Canadian waters as an emission control area (ECA) on March 26, 2010, as shown in Figure 1, seeking to reduce oxides of nitrogen (NOx), sulfur oxides (SOx), and fine particulate matter (PM2.5) (U.S. Environmental Protection Agency [EPA], 2010). In 2023, IMO further established goals to reduce the environmental impact of maritime industry by 2050 (IMO, 2023) .



Source: EPA (2010)

Figure 1. Area of the North American ECA

In response to these global initiatives, ports and shipping operations have intensified efforts to implement and evaluate emission control strategies. This project focused on the Port of Houston (POH), one of the busiest ports in the United States and a key hub for petrochemical shipping and container traffic in the Gulf of America. The geographical domain for this study covered the Houston Ship Channel (HSC), Bolivar anchorage area, and 9-nautical-mile extensions from the Bolivar anchorage area, as illustrated in Figure 2 (National Oceanic and Atmospheric, 2025). The public terminals managed by the Port of Houston Authority (PHA) are displayed in Figure 3, encompassing 11 facilities.

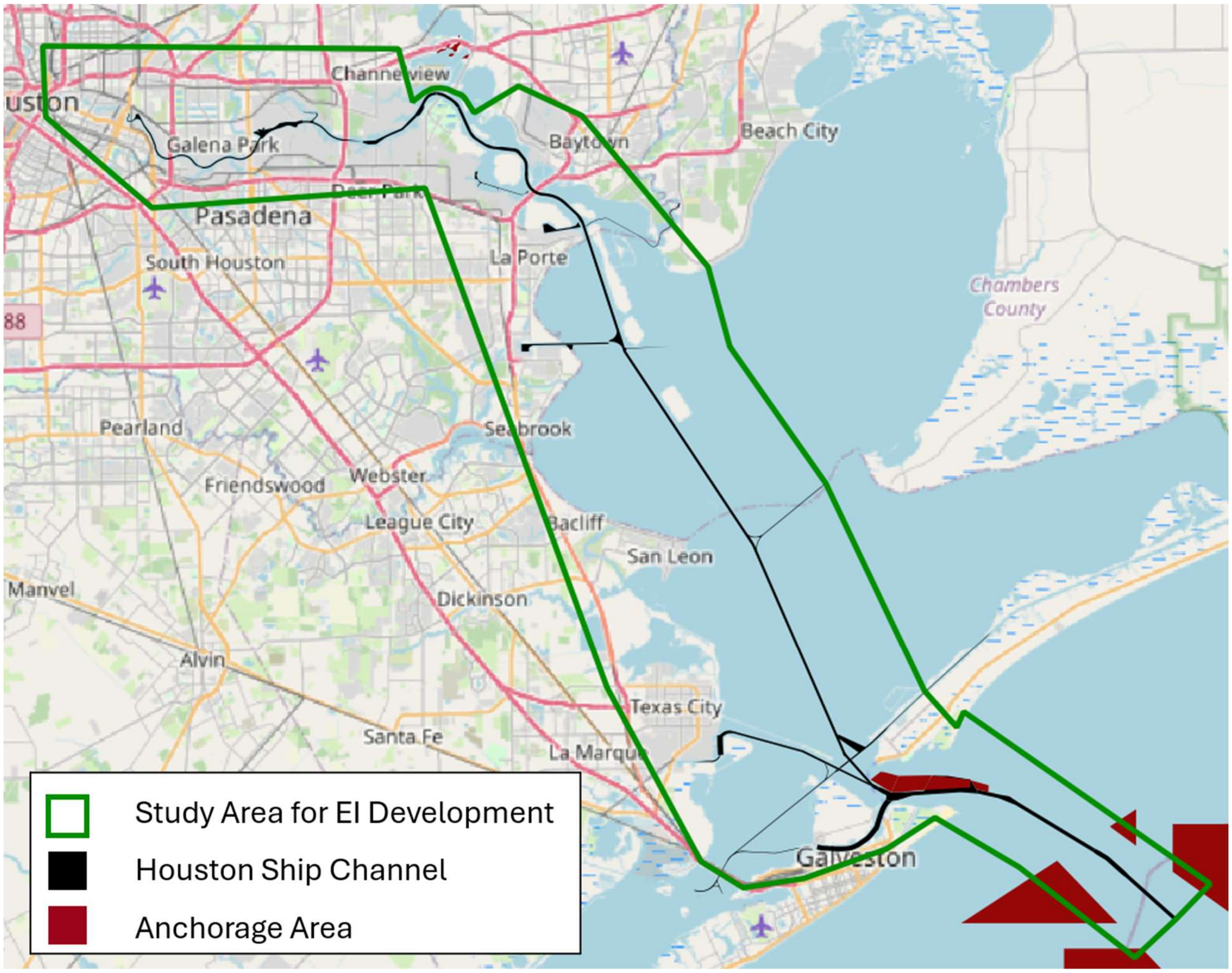


Figure 2. Study Area of the Port of Houston

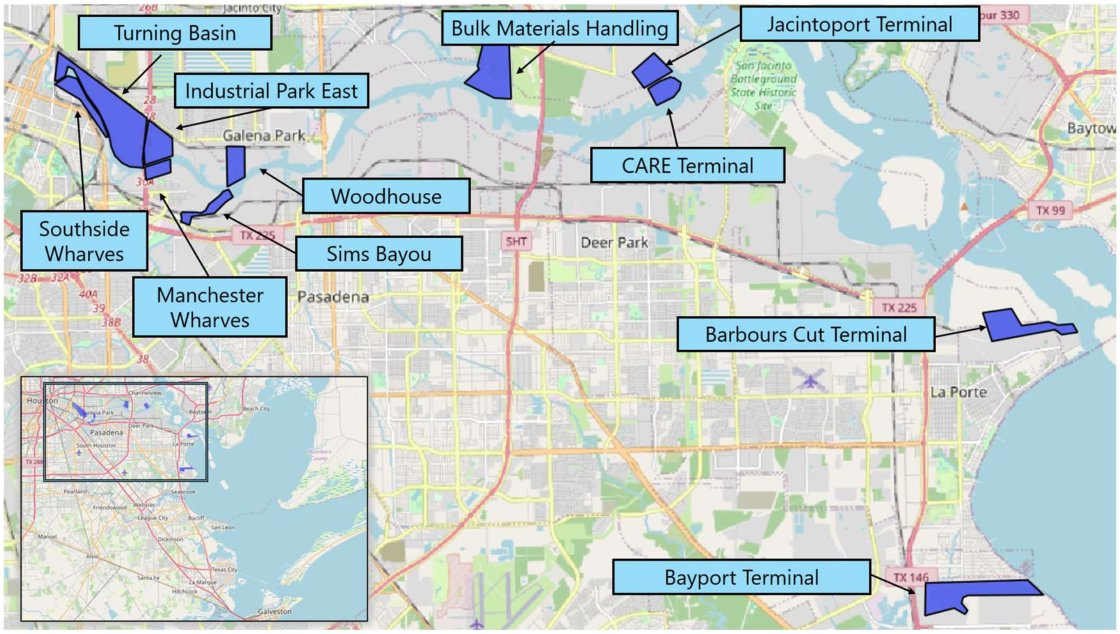


Figure 3. Public Terminals in the Port of Houston

The primary goals of this project were to:

- Develop a comprehensive estimation of emission inventories (EIs) for commercial maritime vessels (CMVs), including ocean-going vessels (OGVs) and harbor craft (HBC).
- Assess the potential impacts of various control measures. The CMV EI covers all vessel activities within the POH domain, distinguishing between PHA and non-PHA sources based on visits and stays at public terminals.

Using Automatic Identification System (AIS) data, vessel-level emissions were estimated based on formulas established by U.S. EPA. The methodology was verified against 2019 AIS data, with results showing consistency with the related Goods Movement Emission Inventory (GMEI) report (Kristiansson et al., 2021). Subsequently, the model was applied to 2022 AIS data as a baseline to evaluate several emission control strategies, including shore power, engine tier regulations, alternative fuels, electrification, and vessel speed reduction.

Based on the analysis of the practical implementation and effectiveness of these strategies, this report provides insights into how the POH can contribute to international emission reduction goals while improving air quality and promoting public health in surrounding communities.

2. REVIEW OF POH DOCUMENTS

2.1 Goods Movement Emissions Inventory

A 2021 GMEI report summarized the 2019 maritime-related emissions in the Greater Port of Houston (Kristiansson et al., 2021). Particularly, the report identified the emissions associated with the public terminals owned, operated, managed, or leased by PHA.

Regarding the study area, the Greater Port of Houston is a 25-mile-long complex of nearly 200 private and public industrial terminals along the 52-mile-long HSC. For the emission sources, the GMEI report covered the emissions from (a) ocean-going vessels, (b) commercial harbor craft, (c) cargo handling equipment, (d) locomotives, and (e) heavy-duty vehicles.

With respect to emission analysis, the GMEI report distinguished PHA emissions according to whether the vessels visited the public terminal. If a ship visited a private terminal only or entered the HSC without visiting public terminals, it was categorized as non-PHA emissions. The report compared emissions by (a) vessel type—analyzing PHA and non-PHA emissions for both OGVs and HBC; and (b) terminal-level activity—assessing total and at-berth emissions from OGVs and HBC at each public terminal.

The GMEI study comprehensively considered the emissions for vessel categories and terminals. Based on that information, the Texas A&M Transportation Institute (TTI) research team conducted an emission analysis comparison between OGVs and HBC. Table 1 displays the results, highlighting that OGVs are the dominant source of emissions at both PHA and non-PHA sources, particularly for NOx, SOx, and carbon dioxide (CO2).

Table 1. Emission Summary for OGVs and HBC in Terms of PHA and Non-PHA

2019 PHA Emissions	NOx Tons	PM10 Tons	PM2.5 Tons	VOC Tons	CO Tons	SOx Tons	CO2e Tonnes
OGV	4,120	69	63	132	348	171.3	259,134
HBC	496	12	12	12	113	0.4	39,805
2019 Non PHA Emissions	**NOx Tons**	**PM10 Tons**	**PM2.5 Tons**	**VOC Tons**	**CO Tons**	**SOx Tons**	**CO2e Tonnes**
OGV	7,939	172	159	247	716	448	678,387
HBC	3,816	88	85	93	847	3	302,443

Note: VOC = volatile organic compound; CO = carbon monoxide.

2.2 Port Houston Clean Air Strategy Plan

The Port Houston 2021 Clean Air Strategy Plan (CASP) aims to outline emission reduction strategies through industry best management practices, port-specific data, and partnerships, strengthening its environmental leadership (Port Houston, 2021b). The CASP has three main goals: (1) reduce pollutants significantly from 2019 levels, (2) promote technology adoption for emissions reduction, and (3) improve communication to address underlying factors in air pollution. The CASP proposes three vessel-related strategies:

- **Strategy 1: Upgrade Equipment and Technology.** This strategy focuses on modernizing equipment and technology to reduce emissions in port operations. By supporting the upgrade of fleets, particularly for tugboats and towboats, Port Houston aims to decrease pollutants like NOx and PM2.5, improving both environmental sustainability and operational efficiency.
- **Strategy 2: Implement Operational and Technological Efficiencies.** This strategy emphasizes the adoption of operational and technological improvements to minimize emissions. By coordinating partnerships for at-berth ship emission reductions, including the use of shore power and shipside emission capture systems, Port Houston seeks to significantly reduce air pollution from vessels while enhancing infrastructure and fostering industry commitment.
- **Strategy 3: Promote Partnering and Collaborative Alignment.** This strategy focuses on fostering partnerships and collaboration to advance emission reduction goals. Through initiatives like supporting area-wide vessel scheduling optimization and aligning emission reduction goals with stakeholders' sustainability objectives, Port Houston aims to drive collective action toward cleaner, more sustainable port operations.

2.3 ES^{2}G Environment, Social, Safety, and Governance

This Port Houston (2021a) report discusses the Maritime Traffic Efficiency Program, a vessel-relevant strategy developed in partnership with the Greater Houston Port Bureau and PortXchange. The program's digital platform, Asynchronizer, improves transparency around vessel movements and terminal schedules. By optimizing ship arrival and departure times, the initiative reduces port congestion, minimizes vessel idle time, and lowers emissions.

Additionally, in pursuit of enhanced efficiency, Port Houston is committed to upgrading operations at Bayport Terminal, with the specific goal of minimizing wait times for both trucks and vessels. Furthermore, Port Houston has applied for the Shore Power Grant to plan electrical capacity for shore power at Bayport Terminal (Port Houston, 2023).

3. EMISSION ESTIMATION METHOD

3.1 Overview

One of this project's objectives was to develop a comprehensive estimate of CMVs in the POH, calculating the emission baseline for the further development of emission reduction measures. To accomplish this goal, the TTI research team identified vessel activities using the AIS data and calculated the corresponding emissions by following the recommended practice of U.S. EPA (2022).

Section 3.2 explains how the AIS data were processed, while Section 3.3 matches the vessels with various databases. Since the estimation of EIs served as the direction for future measure development, it was necessary to distinguish the emissions associated with the public terminals or private terminals, as detailed in Section 3.4.

3.2 AIS Data Cleaning

AIS equipment plays a crucial role in maritime safety by providing real-time information about vessel movements and enabling vessels to communicate and cooperate to prevent collisions and ensure safe navigation. The AIS data published by MarineCadastre.gov is sourced from the Nationwide Automatic Identification System, operated by the U.S. Coast Guard. Within this dataset, users can access comprehensive vessel information such as position data, speed, vessel identification details, and other pertinent information (MarineCadastre.gov, 2022).

This project adhered to the practice recommended by U.S. EPA (2009, 2022), processing the AIS data in the following steps:

1. Data Subsetting: The AIS data were filtered to retain only the ship data within the study area. Activities that fell outside the predefined boundaries of the study area were omitted from further analysis and processing.
2. Data Cleaning: The AIS data were downloaded from Marine Cadastre. These data could include unnecessary information, such as buoys, floats, and non-propelled vessels, and such data were removed before calculating emissions. For instance, the following Maritime Mobile Service Identity (MMSI) codes were excluded:

   a. MMSI numbers beginning with 0 (i.e., 0xxxxxxxx), which are assigned to coast stations or groups of coast stations for maritime communication and traffic monitoring.
   b. MMSI numbers beginning with 1 (i.e., 1xxxxxxxx), which are typically used for search-and-rescue aircraft.
   c. MMSI numbers beginning with 9 (i.e., 9xxxxxxxx), which are generally assigned to search-and-rescue transmitters rather than conventional vessels.
   d. MMSI codes that are not exactly 9 digits long.
3. Voyage Determination: The AIS data were sorted so each of the vessel movements was ordered by date and time. This definition of a voyage generally allows for the classification of distinct inbound and outbound movements. The time delta between subsequent AIS records was calculated. A default threshold delta time of 30 minutes was used to delineate voyages for all vessels. If the timespan between two records with the same vessel identification number was greater than the threshold, a new voyage was defined.
4. Voyage Check: Despite the data filtering process in Step 1, a voyage that only visited the Port of Texas City and Port of Galveston was not desirable in this project. This step examined all voyages for each ship, removing any voyage not reaching the POH region, as presented in Figure 4 with diagonal stripes. Some examples of removed activities are shown in Figure 5.
5. Gap Filling for Draft Data. The AIS data provided the draft information for each message received. However, some vessels reported null, zero, or negative values, which posed difficulties for further analysis. To ensure complete data, this project used the vessels with complete drafts to assign draft values to vessels lacking drafts or having 0 values in drafts.

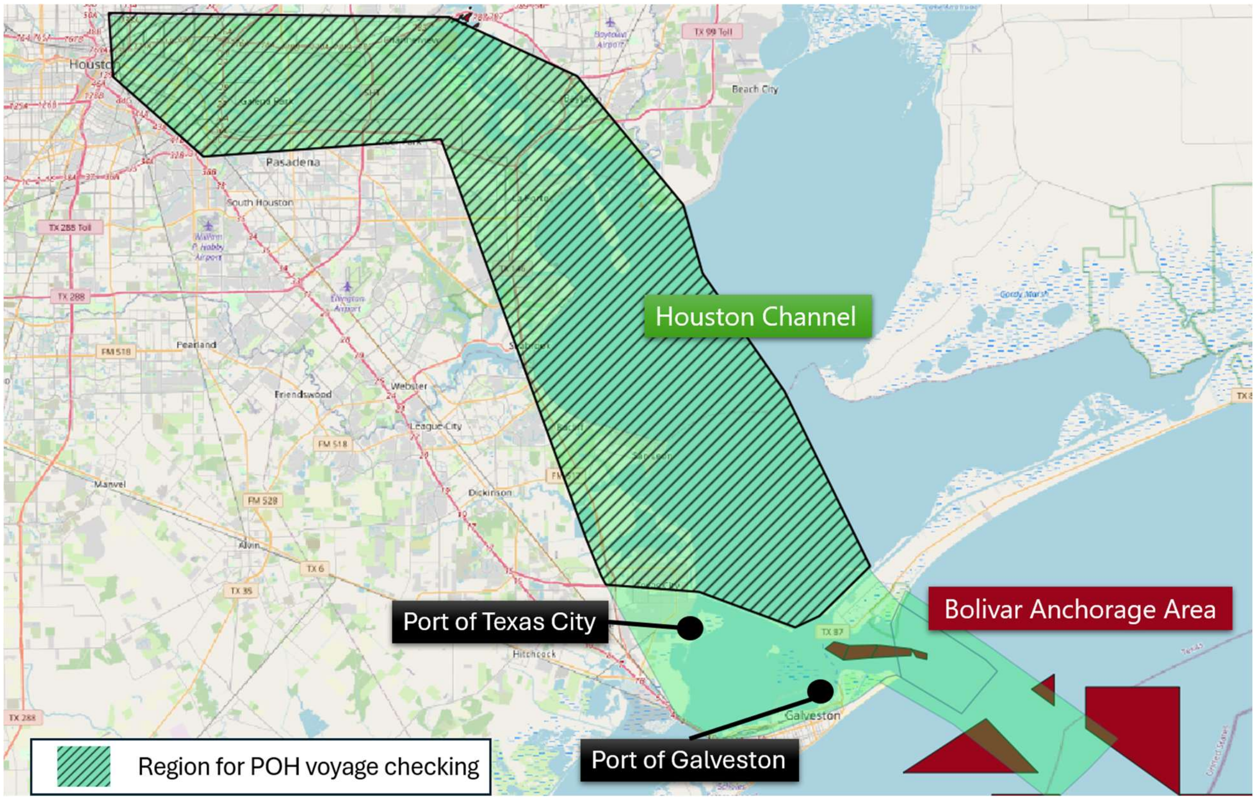


Figure 4. Region for POH Voyage Checking

Figure 5. Examples of Removed Voyages

Vessels with complete draft data were grouped by AIS category. For each vessel category, the average draft and length were calculated. A linear regression model was then used to establish the relationship between draft and length, expressed as follows:

$$draft = length * coefficient_{\text{vessel type}} + constant_{\text{vessel } type}$$

The draft-length curve is plotted in Figure 6, showing that larger vessels, which are generally heavier, require more draft. If the vessel data lacked the ship length information, the average ship length for each ship type was applied to specify the draft, as presented in Table 2.

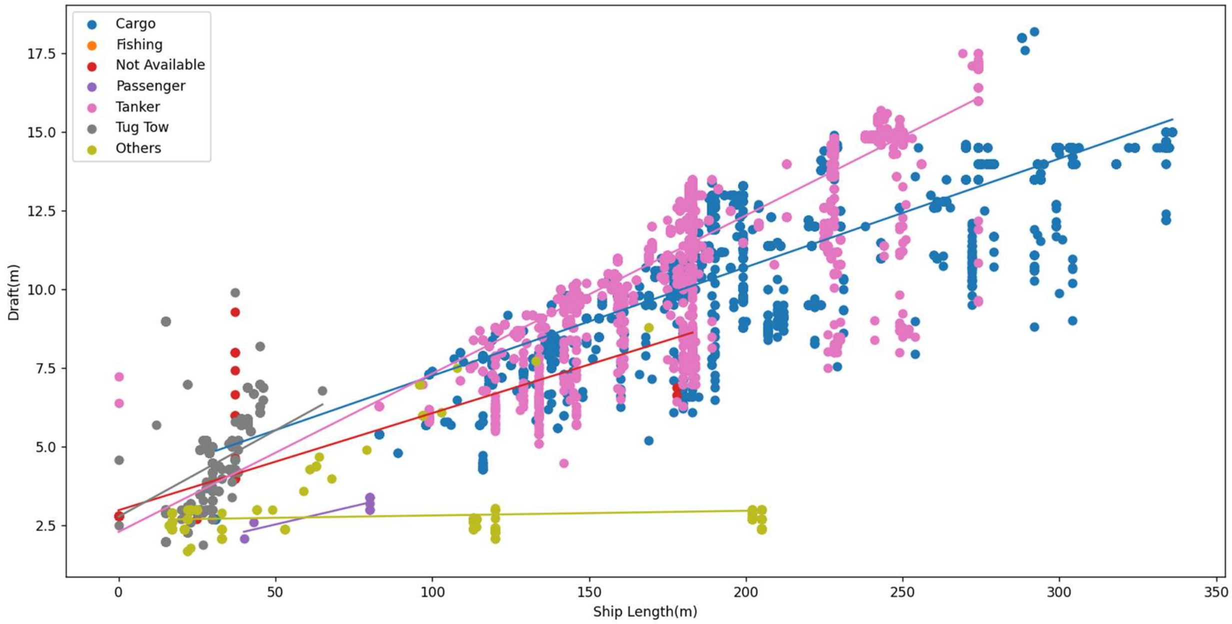


Figure 6. Linear Regression Models for Ship Lengths and Drafts

Table 2. Average Ship Length Using Vessels with Complete Draft and Length Data

AIS Ship Type	Draft (Meters) Model	Average Ship Length (Meters)
Cargo	Draft = Length ∗ 0.0354 + 3.1995	201
Fishing	Draft = Length ∗ 0.0267 + 2.1917	50
Not Available	Draft = Length ∗ 0.0275 + 2.8385	35
Passenger	Draft = Length ∗ 0.0227 + 1.3420	124
Tanker	Draft = Length ∗ 0.0407 + 2.6984	181
Tug Tow	Draft = Length ∗ 0.0170 + 3.3087	32
Others	Draft = Length ∗ 0.0014 + 3.2032	101

3.3 Source for Vessel Matching

According to the AIS data, the ships were classified into nine primary types by matching the AIS ship code (U.S. Coast Guard, 2018), as displayed below. Type 3 (military) and Type 7 (pleasure craft/sailing) were not examined further since they are not CMVs.

1. Cargo
2. Fishing
3. Military
4. Not Available
5. Other
6. Passenger
7. Pleasure Craft/Sailing
8. Tanker
9. Tug Tow

To apply the U.S. EPA emission inventory guidance (U.S. EPA, 2022), the researchers needed to match the ship types with the U.S. EPA ship categories. Three databases were used for this matching process, as displayed in Figure 7 and summarized in the subsequent list.

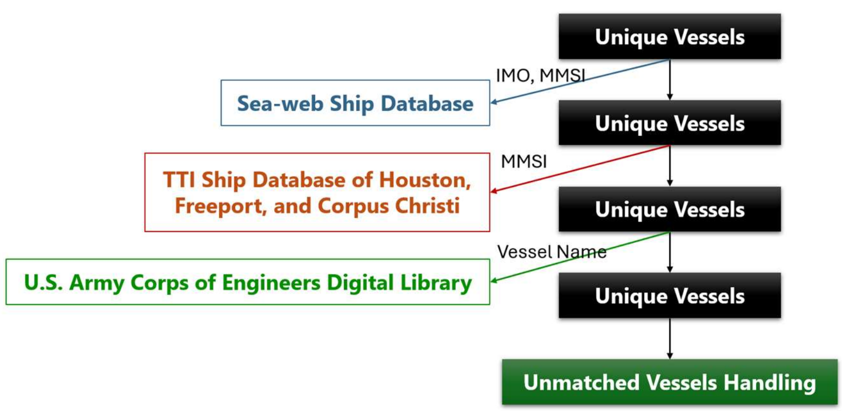


Figure 7. Ship Database Sources

1. Sea-Web Database. The research team utilized the Sea-Web Ships Database, matching vessels using MMSI and IMO numbers.
2. TTI Ship Database of Houston, Freeport, and Corpus Christi. For vessels not matched in the Sea-Web database, the team used the TTI database for the

Houston, Freeport, and Corpus Christi areas to match vessels using MMSI numbers.

3. U.S. Army Corps of Engineers Digital Library. For vessels still unmatched, the team accessed the U.S. Army Corps of Engineers Digital Library, using vessel names to match the remaining ships.

Despite using multiple databases, some vessels remained unmatched. This project followed U.S. EPA guidance by averaging engine parameters and emission factors from matched vessels to estimate emissions for unmatched vessels.

The ship-type matching criteria are detailed in Appendix A. Still, a few unmatched vessels lacked vessel type codes, making it difficult to determine their general ship types. This project used manual searching for vessel information according to the MMSI numbers to specify each vessel's details.

3.4 Emission Formulas

The TTI research team referred to the U.S. EPA emission inventory guidance to estimate the emission inventory (U.S. EPA, 2022). Typically, three types of emission sources are associated with OGVs—propulsion engines, auxiliary engines, and boilers. In contrast, HBC only have propulsion and auxiliary engines as their emission sources. The functions of these emission sources are summarized below:

- Propulsion engines, also referred to as main engines, supply power to move the vessel.
- Auxiliary engines supply power for non-propulsion loads, such as generating electricity.
- Boilers are responsible for heating fuel and water.

3.4.1 OGV: Emissions of Propulsion Engines

The OGV emissions from propulsion engines can be estimated using Equation 3.1.

$$E_p = P_p \times A \times EF_p \times LLAF \qquad \textit{Equation 3.1}$$

where:
E_p: Vessel emissions (grams) for propulsion engines.=
P_p: Operating power (kW) for propulsion engines.=A:
Activity duration (hours).
EF_P: Emission factor for a target pollutant (g/kWh).

$LLAF$: Low load adjustment factor (unitless).

The activity (A) means the duration of an observed activity (hours), while the rest of the emission parameters can vary between vessels. The determination of emission factors (EFs) is introduced in Section 3.4.4.

The engine operating power (P_p) of the propulsion engine is determined by Equation 3.2, where the installed power (P_{ref}), maximum speed (V_{ref}), and draft (D_{ref})=are subject to ship types, engine categories, and engine types (see U.S. EPA Table C.2[1]). The parameter sea margin (SM) is related to the weather condition of the vessel's current position.

$$P_p = P_{ref} \times \left(\frac{V}{V_{ref}}\right)^3 \times \left(\frac{D}{D_{ref}}\right)^{\frac{2}{3}} \times SM \qquad \text{Equation 3.2}$$

where:
P_ref: Installed propulsion power (kw).
V: Average speed of the activity segment (kn).
V_ref: Maximum speed of a certain ship type (kn).
D: Average draft of the activity segment (m).
D_ref: Maximum draft of a certain ship type (m).
SM: Sea margin, which accounts for average weather conditions, assumed to be 1.10 for coastal operations and 1.15 for at-sea operations.

The low load adjustment factor (LLAF) is applied to OGVs when the propulsion engines are operating at less than 20% load. This is because diesel engines are less efficient at low loads, resulting in an increase in emissions per unit of energy consumption. The load factor (LF) for OGVs can be estimated using Equation 3.3.

$$LF = \frac{P_P}{P_{ref}} \qquad \text{Equation 3.3}$$

LF: Load factor of propulsion engines.
P_P: Propulsion engine operating power estimated by Equation 3.2.
P_{ref}: Propulsion engine installed power.

With the estimated LF, one can acquire the LLAF for a target pollutant, as illustrated in Table 3 (see U.S. EPA Table 3.10).

[1] In this section, references to "Table X.X" refer to tables within this report, while references formatted as "U.S. EPA Table C.X" refer to tables in *U.S. EPA (2022)*.

Table 3. Low Load Adjustment Factors for OGVs with Diesel Engines

Propulsion Engine LF	NOx	HC	CO	PM	CO2	SO2
≤ 2%	4.63	21.18	9.68	7.29	3.28	9.54
3%	2.92	11.68	6.46	4.33	2.44	6.38
4%	2.21	7.71	4.86	3.09	2.01	4.79
5%	1.83	5.61	3.89	2.44	1.76	3.85
6%	1.6	4.35	3.25	2.04	1.59	3.21
7%	1.45	3.52	2.79	1.79	1.47	2.76
8%	1.35	2.95	2.45	1.61	1.38	2.42
9%	1.27	2.52	2.18	1.48	1.31	2.16
10%	1.22	2.2	1.96	1.38	1.25	1.95
11%	1.17	1.96	1.79	1.3	1.21	1.78
12%	1.14	1.76	1.64	1.24	1.17	1.63
13%	1.11	1.6	1.52	1.19	1.14	1.51
14%	1.08	1.47	1.41	1.15	1.11	1.41
15%	1.06	1.36	1.32	1.11	1.08	1.32
16%	1.05	1.26	1.24	1.08	1.06	1.24
17%	1.03	1.18	1.17	1.06	1.04	1.17
18%	1.02	1.11	1.11	1.04	1.03	1.11
19%	1.01	1.05	1.05	1.02	1.01	1.05
≥ 20%	1	1	1	1	1	1

Note: HC = hydrocarbon; SO2 = sulfur dioxide.

The SM parameter is used to capture the general weather conditions, assumed to be 1.10 for coastal operations and 1.15 for at-sea operations (unitless). At-sea operations have a higher average value since they are expected to experience more extreme environmental conditions, and waves and wind at sea can put additional load on the propeller. The coastline is defined according to the United States Government's open data site (Data.gov, 2019).

3.4.2 OGV: Power of Auxiliary Engines and Boilers

The calculation for emission sources of auxiliary engines and boilers is similar to the propulsion engines, whereas the LLAFs are not involved in the formula, as presented in Equations 3.4 and 3.5.

$$E_a = P_a \times A \times EF_a \quad \textit{Equation 3.4}$$

$$E_b = P_b \times A \times EF_b \quad \textit{Equation 3.5}$$

where:
E_a, E_b: Vessel emissions (grams) for the auxiliary engine/boiler emissions.
P_a, P_b: Auxiliary engine/boiler operating power (kW).
A: Activity duration (in hours).
EF_a, EF_b: Emission factors for a target pollutant (g/kWh).

The operating power for auxiliary engines and boilers (P_a, P_b) depends on ship types and operating modes (see U.S. EPA Tables E.1 and E.2). The emission factors (EF_a, EF_b) are determined in Section 3.4.4, and the operating mode determination is discussed in Section 3.4.6.

3.4.3 HBC: Power of Propulsion and Auxiliary Engines

HBC have two emission sources—propulsion engines and auxiliary engines. The calculation for the two emissions involves the consideration of LFs, and the emission formulas are listed in Equations 3.6 and 3.7.

$$E_p = P_p \times A \times EF_p \times LF_p \quad \textit{Equation 3.6}$$

$$E_a = P_a \times A \times EF_a \times LF_a \quad \textit{Equation 3.7}$$

where:
E_p, E_a: Vessel emissions (grams) for propulsion/auxiliary engines.
P_p, P_a: Operating power (kW) for propulsion/boiler engines.
A: Activity (hours).
EF_p, EF_a: Emission factors for a target pollutant (g/kWh).
LF_p, LF_a: Engine load factors (unitless).

The propulsion and auxiliary engine power (E_p, E_a) and the LF are associated with the HBC ship types (see U.S. EPA Tables G.1 and 4.4). These values are organized in Table 4. Note that barges typically do not have a propulsion or auxiliary engine since they are usually not self-propelled. An auxiliary engine LF of 0.43 can be assumed for all ship types.

Table 4. Engine Powers and Load Factor for HBC

Ship Type	Average Installed Propulsion Power (kW)	Average Installed Auxiliary Power (kW)	Propulsion Engine Load Factor	Auxiliary Engine Load Factor
Barge	0	0	0	0
Crew and Supply	1,037	50	0.45	0.43
Excursion	513	24	0.42	0.43
Fishing (C1/C2)	909	186	0.52	0.43
Government	1,343	389	0.45	0.43
Harbor Ferry (C1/C2)	3,658	419	0.42	0.43
Miscellaneous (C1/C2)	1,309	205	0.52	0.43
Pilot	1,211	28	0.51	0.43
Towboat/Pushboat	1,559	97	0.68	0.43
Tugboat	3,512	285	0.5	0.43
Work Boat	464	36	0.45	0.43

3.4.4 OGV and HBC: Emission Factors

Emission factors transform energy consumption into emissions, and the values vary across ship types, engine tiers, engine types, and fuel types. Table 5 summarizes the U.S. EPA tables of EFs.

Table 5. EF Tables in the U.S. EPA Guidance

OGV	
Pollutant	**EPA Tables and Equations**
NOx	Table 3.5
BSFC	Table 3.6
PM	Table 3.7, Equation 3.3
VOC, HC, CO, and CH4	Table 3.8
N2O	Table 3.9
CO2	Equation 3.4
SO2	Equation 3.5
HBC	
Pollutant	**EPA Tables and Equations**
NOx	Table H.1
BSFC	Table 4.3
PM	Table H.2
VOC, HC, and CH4	Table H.4
CO	Table H.5
N2O	Equation 4.3
CO2	Equation 4.5
SO2	Equation 4.4

Note: BSFC = brake specific fuel consumption; N2O = nitrous oxide.

Additional details and the relevant formulas for OGVs and HBC are as follows:

1. Nitrogen Oxides: For OGVs, NOx emission factors vary by engine group, engine type, fuel type, and engine tier (as determined by keel-laid year), as presented in U.S. EPA Table 3.5. For HBC, the factors vary by engine group, engine category, cylinder displacement, and model year, as shown in U.S. EPA Table H.1.

2. Brake Specific Fuel Consumption: BSFC is a measure of fuel efficiency in engines. For OGVs, BSFC rates vary by engine group, fuel type, and engine type, influencing the emission factor of PM, carbon dioxide, and sulfur dioxide. For HBC, BSFC rates vary by engine power range, affecting the EF of NOx, CO2, and SO2.

3. Particulate Matter: For OGVs, the PM emission factor is calculated for slow-speed-diesel and middle-speed-diesel propulsion engines, auxiliary engines, and boilers, according to Equation 3.8. The emission factor for steam turbine and gas turbine engines can be found in U.S. EPA Table 3.7.

$$EP_{PM10} = PM_{base} + (S_{act} \times BSFC \times FSC \times MWR) \quad \textit{Equation 3.8}$$

where:
EF_{PM10}: PM emission factor adjusted for fuel sulfur (g/kWh).
PM_{PM10}: Base emission factor assuming zero fuel sulfur (0.1545 g/kWh for marine diesel oil [MDO]/marine gas oil [MGO] and 0.5761 g/kWh for residual marine [RM] fuel/heavy fuel oil [HFO]).
S_{act}: Actual fuel sulfur level (weight ratio), set as 0.001 since most vessel activities are within the ECA in 2015 and beyond.
$BSFC$: Brake specific fuel consumption.
FSC: Fraction of sulfur in fuel that is converted to direct sulfate PM, defaulted as 0.02247.
MWR: Molecular weight ratio of sulfate PM to sulfur, which is 224 / 32 = 7.

For HBC, the PM emission factor is associated with the engine category, group (propulsion or auxiliary), cylinder displacement, engine power, and model year, as displayed in U.S. EPA Table H.2.

4. Volatile Organic Compounds, Hydrocarbon, Carbon Monoxide, and Methane: For OGVs, the EF of HC and CO for vessels with C3 propulsion engines varies by engine group and type. VOC emission factors are calculated as 1.053 times the HC emission factors, while CH4 emission factors are calculated as 2% of the HC emission factors.

5. For HBC, the EF of VOC, HC, and CH4 can be found in U.S. EPA Table H.4, and the CO in Table H.5. These factors are associated with the engine category, group (propulsion or auxiliary), cylinder displacement, engine power, and model year.

6. Nitrous Oxide: For OGVs, the EF of N2O for vessels with C3 propulsion engines varies by engine group and type, and these factors are presented in U.S. EPA Table 3.9. By contrast, the emission factor for HBC depends on BSFC, as suggested by Equation 3.9.

$$EF_{N2O} = BSFC \times NCF \quad \textit{Equation 3.9}$$

where:
EF_{N2O}: N2O emission factor (g/kWh).
$BSFC$: Brake specific fuel consumption.
NCF: N2O conversion factor, assumed to be 0.000156.

7. Carbon Dioxide: For both OGVs and HBC, the CO2 emission factor depends on BSFC rates and fuel type, which is calculated according to Equation 3.10.

$$EF_{CO} \quad = BSFC \times CCF \qquad \textit{Equation 3.10}$$

where:
EF_{CO2}: CO2 emission factor (g/kWh).
$BSFC$: Brake specific fuel consumption.
CCF: Carbon content factor, which varies by fuel type (g CO2/g fuel). For OGVs, use 3.206 for MDO/MGO, 3.114 for RM/HFO, and 2.75 for liquefied natural gas (LNG). For HBC, use 3.19.

8. Sulfur Dioxide: For both OGVs and HBC, the EF of SO2 is calculated according to Equation 3.11:

$$EF_{SO2} = BSFC \times S_{act} \times FSC \times MWR \qquad \textit{Equation 3.11}$$

where:
EF_{SO2}: SO2 emission factor (g/kWh).
$BSFC$: Brake specific fuel consumption.
S_{act}: Actual fuel sulfur level (weight ratio), set as 0.001 for OGVs and 0.000015 for HBC.
FSC: Fraction of sulfur in fuel that is converted to SO2, defaulted as 0.97753.
MWR: Molecular weight ratio of SO2, which is 64 / 32 = 2.

3.4.5 Engine Tier Determination

Marine engine emissions in the United States are regulated by U.S. EPA under 40 CFR Part 1042 (Federal Register, 2020). Emission standards differ by engine category: OGVs typically use Category 3 (C3) engines, while HBC primarily use Category 1 (C1) and Category 2 (C2) engines. The criteria for determining emission tiers vary accordingly. For OGVs, the tier is based on the keel-laid year of the vessel. For HBC, tier classification depends on cylinder displacement, engine power, and model year, as defined by U.S. EPA regulations. These standards are summarized in Table 6. Note that Tier 4 applies only to C1 and C2 engines and is not applicable to C3 engines used by OGVs.

Table 6. Engine Tier Determination

Tier	OGV	HBC
Uncontrolled (T0)	Keel-laid year 1999 and earlier	C1 and C2 engine tiers vary by cylinder displacement, engine power, and model year (see U.S. EPA Table B.1)
Tier 1 (T1)	2000–2010	
Tier 2 (T2)	2011–2015	
Tier 3 (T3)	2016 and later	
Tier 4 (T4)	–	

3.4.6 Operating Mode Assignment

Identifying a vessel's operating mode is crucial for accurately determining power and emission sources, particularly for OGV auxiliary engines and boilers. U.S. EPA provides the general considerations for operating modes, as shown in Table 7.

Table 7. General Operating Mode Considerations

Operating Mode	General Speed Considerations	Geospatial Considerations	General Propulsion Engine Load Factor Considerations
Transit	> 3 kn	Outside the breakwater or restricted speed zone	> 20%
Maneuvering	> 1 kn	Between the breakwater and pier/wharf/dock or anchorage zone	≤ 20%
Hotelling	≤ 1 kn	At a pier/wharf/dock	–
Anchorage	≤ 3 kn	In an anchorage zone	–

OGVs operate in four modes: (1) transit, (2) maneuvering, (3) hotelling, and (4) anchorage. For HBC, only two modes—(1) hotelling and (2) non-hotelling—are needed to assess the use of propulsion engines. The research team developed an algorithm to determine the mode based on U.S. EPA general considerations, as presented in Figure 8, which takes the current speed and positions into account.

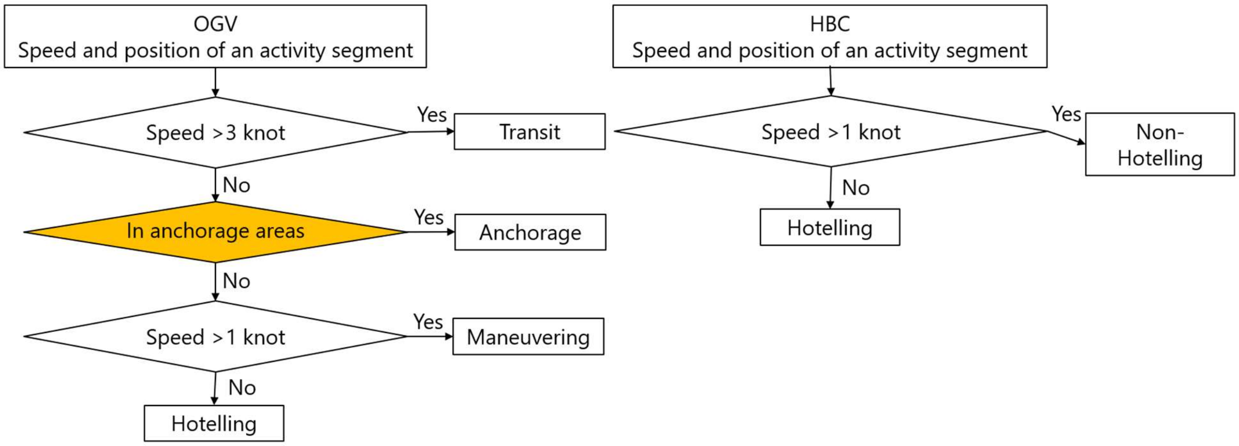


Figure 8. Logic of Operating Mode Determinations

The operating mode determines the auxiliary engine power and boiler power for OGVs. Additionally, it is related to the use of propulsion engines. In hotelling or anchorage modes, the propulsion engine is not used because the vessel is not moving. The engine use under operating modes is shown in Table 8.

Table 8. Engine Use under Different Operating Modes

Vessel Category	Operating Mode	Primary Engine	Auxiliary Engine	Boiler
OGV	Transit	v	v	depends on ship type
OGV	Maneuvering	v	v	v
OGV	Hotelling	x	v	v
OGV	Anchorage	x	v	v
HBC	Non-Hotelling	v	v	-
HBC	Hotelling	x	v	-

Note: v = operate; x = stop operating.

3.4.7 Summary

Table 9 summarizes the emission formulas for OGVs and HBC. These parameters were derived from AIS data and ship mapping. By analyzing AIS data, the research team obtained the activity duration. Additionally, the MMSI, IMO, or ship name from AIS data was used to map the vessel to its U.S. EPA ship type, allowing the team to determine its power. The emission factor depended on several variables, including fuel type, engine type, engine category, and engine tier, necessitating a more comprehensive database.

Table 9. Emission Formulas for OGVs and HBC

Vessel Category	Corresponding Formulas
OGV	• Propulsion engine $$E_p^{OGV} = P_p^{OGV} \times A \times EF_p^{OGV} \times LLAF$$ • Auxiliary engine $$E_a^{OGV} = P_a^{OGV} \times A \times EF_a^{OGV}$$ • Boiler $$E_b^{OGV} = P_b^{OGV} \times A \times EF_b^{OGV}$$
HBC	• Propulsion engine $$E_p^{HBC} = P_p^{HBC} \times A \times EF_p^{HBC} \times LF_p^{HBC}$$ • Auxiliary engine $$E_a^{HBC} = P_a^{HBC} \times A \times EF_a^{HBC} \times LF_a^{HBC}$$

Notes:

- E_p, E_a, E_b: Vessel emissions (g) for propulsion engines, auxiliary engines, and boilers.
- P_p, P_a, P_b: Operating power (kW) for propulsion engines, auxiliary engines, and boilers.
- A: Activity duration (in hours).
- EF_p, EF_a, EF_b: Emission factor for a target pollutant (g/kWh).
- $LLAF$: Low load adjustment factor (for propulsion engine of OGVs).
- LF_p, LF_a: Load factor.

3.5 Port Call Definition

The goal of this project was to estimate the emissions associated with the PHA activities. A ship voyage was classified as PHA emissions if it called at a public terminal; otherwise, it was classified as non-PHA emissions. This project developed a port-call algorithm to determine whether each activity visited certain terminals. Each activity voyage was examined interval by interval, where an interval was the time between two successive AIS signals. The algorithm was as follows:

(1) Initialize a terminal matrix – Construct a matrix used for recording the cumulative inside time and outside time for each terminal, as well as the port-call number and total time. Then go to Step (2).

(2) Assign activity intervals – Check the activity segment if it is within a terminal. If yes, add this activity interval to the inside time of that terminal; otherwise, add it to the outside time for all terminals. If an examined point belongs to a terminal, its outside time should be reset to 0. Go to Step (3).

(3) Check departure conditions – If the outside time exceeds the leaving threshold ($threshold_{out}$), the vessel is considered to have left the port. At this point, verify whether the cumulative inside time meets the port-call threshold ($threshold_{in}$). If it does, record the port call and cumulative residence time;

otherwise, no port calls are recorded. Since the vessel is now considered to have left the terminal, reset its outside time to 0. If this is the last interval, go to Step (4); otherwise, go back to Step (2).

(4) Handle final interval – In the final activity segment, there is no need to check if the outside time exceeds $threshold_{out}$ to confirm a port call. Instead, determine whether inside time exceeds $threshold_{in}$; if so, record the port call. This ensures that calls are captured even if the vessel has not yet left the terminal by the end of the voyage. Then go to Step (5).

(5) Generate results – The final output matrix contains the port-call number and cumulative residence time of a voyage in different terminals. If the ship visits more than two terminals within a voyage, the voyage emission can be allocated to the terminals in proportion to port residence time.

This procedure is summarized in Figure 9, and the main public terminals were displayed previously in Figure 3. The algorithm evaluates the continuous time spent within the terminal area. If the cumulative time exceeds the port-call threshold, it is counted as a port call.

By using the proposed algorithm, this project screened the voyages in one year. Two thresholds—one to define the minimum time of a port call and one to define the maximum time for a short leave from a port—were set to 40 minutes and 3 minutes, respectively. A vessel had to stay in the port for at least 40 minutes to count as a port call. If it left the port for more than 3 minutes, the in-port time was reset.

To validate the 40-minute threshold, this study analyzed NOx emissions across different voyages, categorizing them based on their duration of stay in the terminals, considering only those longer than 10 minutes. The results indicate that there is no significant difference in total NOx estimates whether the threshold is set at 1 hour or 2 hours. This finding can be attributed to the fact that the majority of PHA emissions come from vessels that berth for several hours, as illustrated in Figure 10. Therefore, a 40-minute threshold is deemed sufficient for estimating PHA-related emissions without introducing substantial bias. A sensitivity analysis regarding the in-port time threshold is presented in Section 4.4.

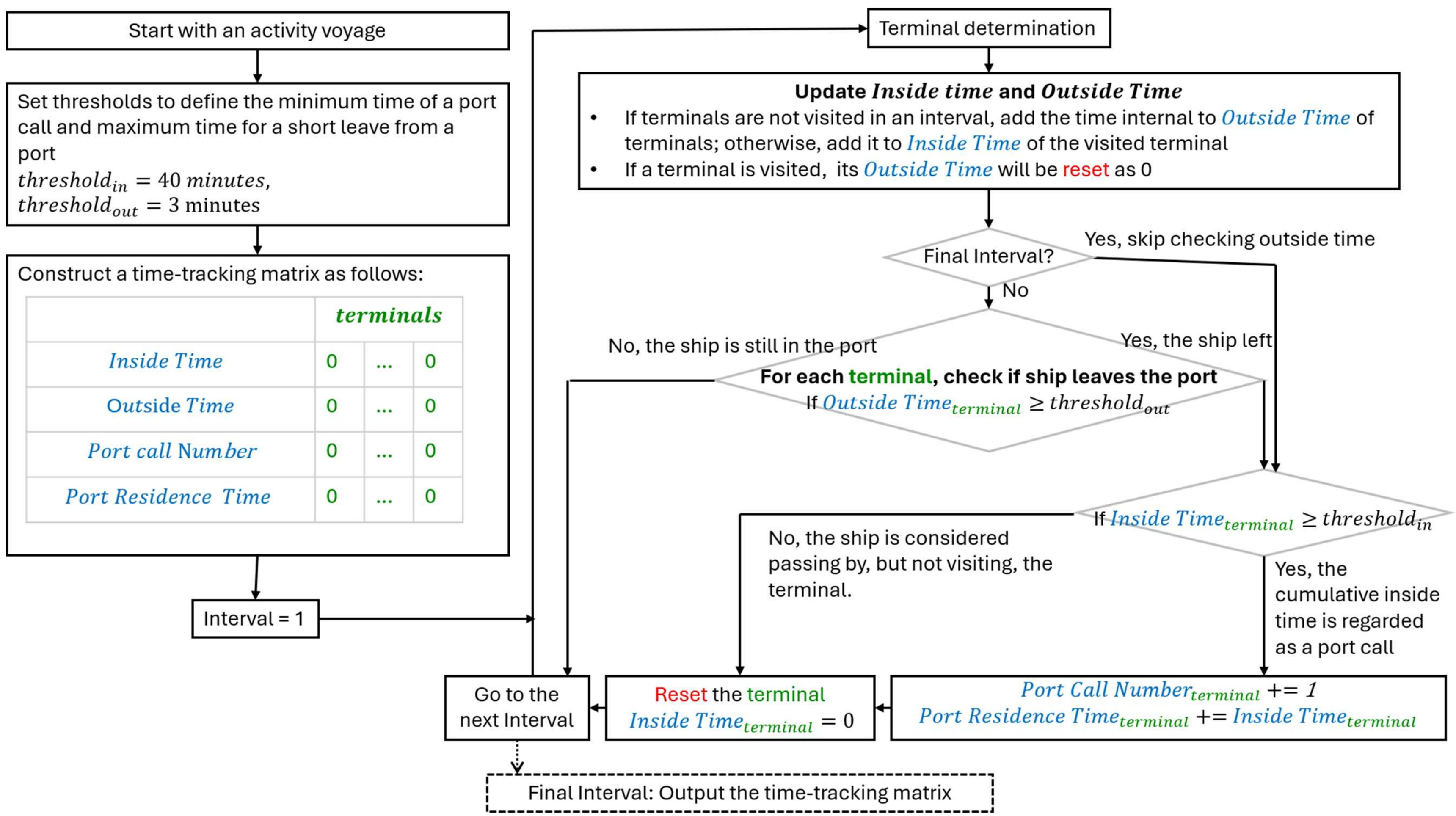


Figure 9. Port-Call Algorithm Summary

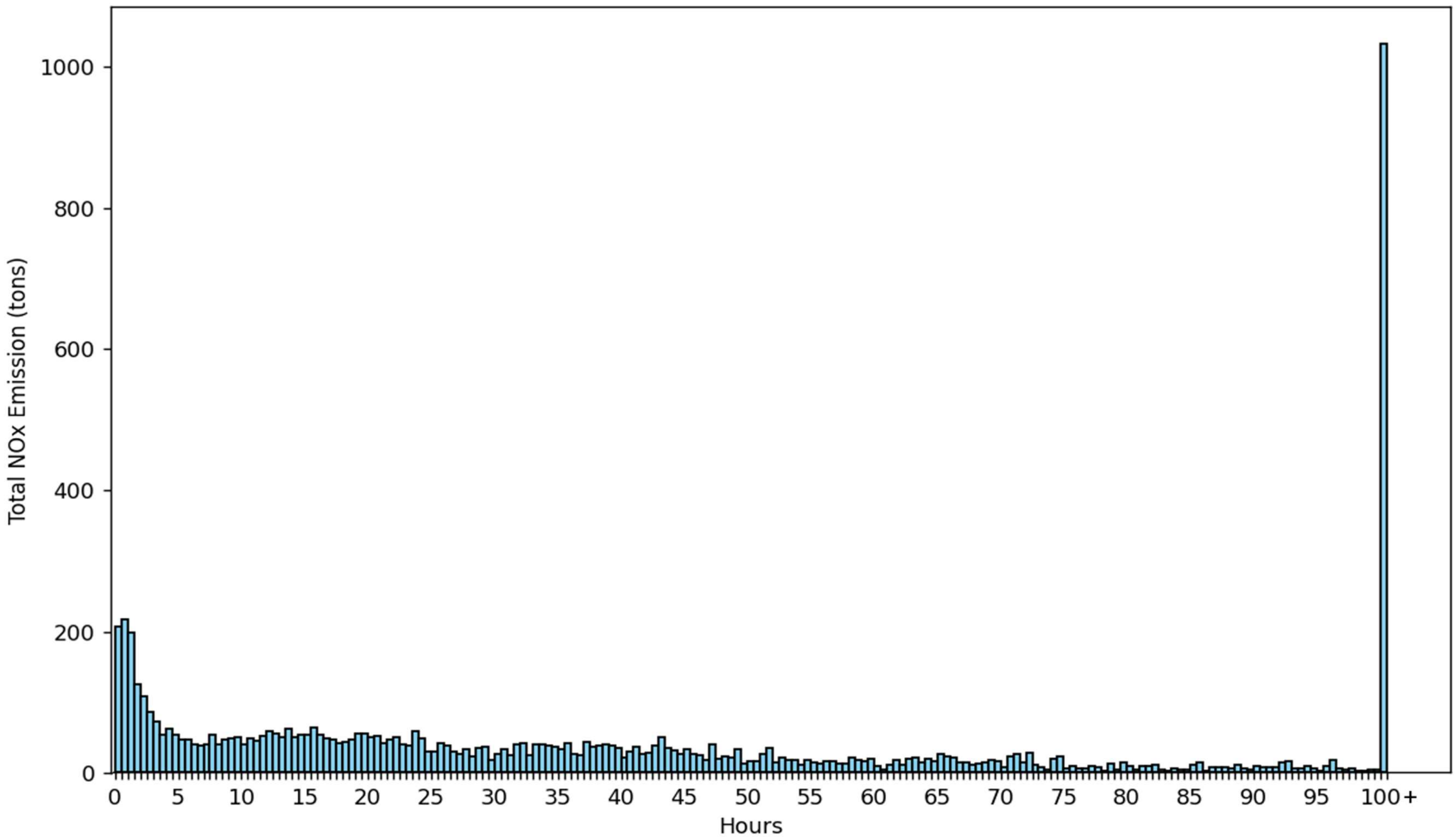


Figure 10. Emission Distributions for Maximum In-Port Time of Voyages

4. VERIFICATION OF EMISSION ESTIMATION METHOD USING 2019 EMISSIONS

To validate the emission estimation method introduced in Section 3, the TTI research team applied the methodology to 2019 AIS data and compared the estimated emissions with those reported in the GMEI. This verification step increased confidence in the robustness of the method and its applicability for establishing the 2022 emissions baseline.

4.1 Vessel Compositions

The number of unique vessels in 2019 is shown in Figure 11. A total of 2,900 OGVs were identified, with the majority being tankers and container ships. In contrast, 1,291 HBC were recorded, mostly consisting of tugboats and pushboats.

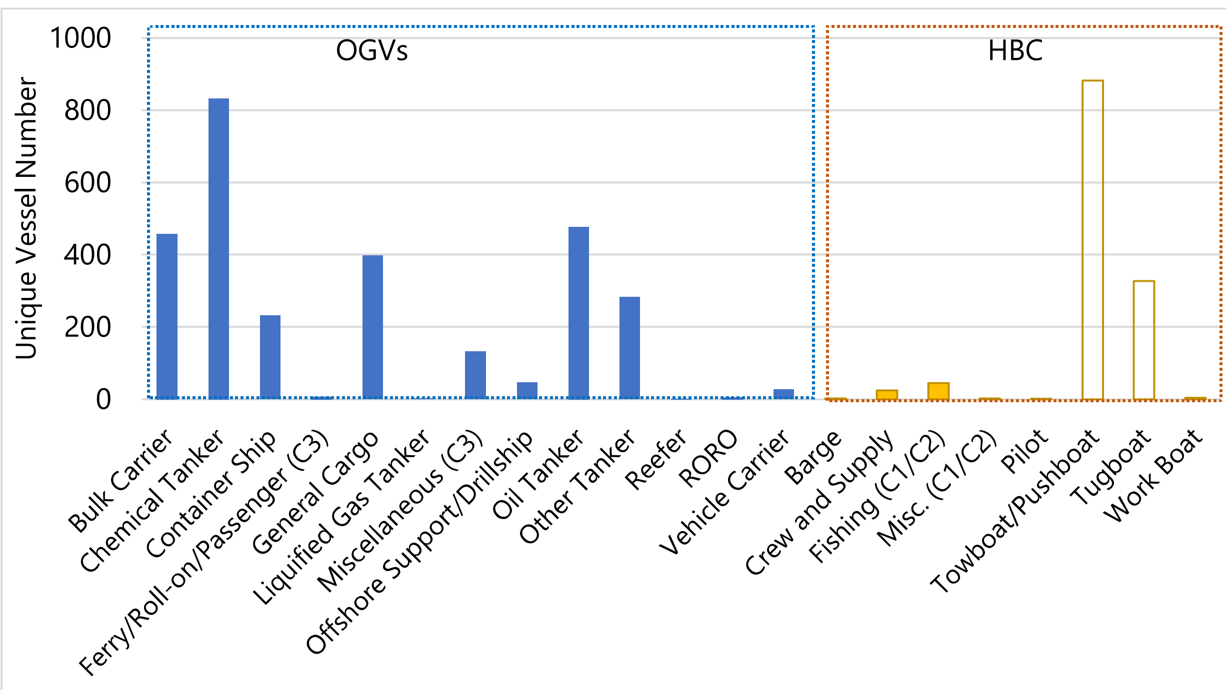


Figure 11. Number of Matched Vessel Types in 2019

Table 10 presents the distribution of engine emission tiers for OGVs, showing that the majority of vessels fall into Tier 1 (59%) and Tier 2 (35%), with only 1% meeting the latest Tier 3 standards. This finding indicates that most OGVs still rely on earlier-generation engines.

The tier distribution for HBC (Table 11) is heavily skewed toward Tier 0. Towboats and tugboats fall overwhelmingly into this uncontrolled category. Only a small fraction of the HBC fleet operates with Tier 3 (1%) or Tier 4 (1%) engines.

The GMEI estimates are also provided in each table for comparison. The GMEI distribution aligns closely with the observed values for OGVs because the database for OGVs is generally more complete and detailed. However, the GMEI exhibits a more advanced tier profile for HBC, characterized by a notably lower share of Tier 0 engines (63%) and higher adoption of Tier 1 (12%) and Tier 2 (13%) technologies. This discrepancy may be a result of data limitations or missing information in the vessel registry, which necessitates assumptions when assigning tiers.

Table 10. 2019 OGV Propulsion Engine Tier by Vessel Type, %

Ship Type	T0	T1	T2	T3
Bulk Carrier	2%	48%	50%	0%
Chemical Tanker	5%	49%	45%	1%
Container Ship	4%	83%	13%	0%
Ferry/Roll-On/Passenger (C3)	86%	14%	0%	0%
General Cargo	9%	72%	19%	0%
Liquefied Gas Tanker	100%	0%	0%	0%
Miscellaneous (C3)	0%	100%	0%	0%
Offshore Support/Drillship	39%	48%	11%	2%
Oil Tanker	1%	75%	22%	1%
Other Tanker	5%	31%	61%	4%
Reefer	100%	0%	0%	0%
Roll-On/Roll-Off (RORO)	0%	0%	100%	0%
Vehicle Carrier	15%	56%	30%	0%
Total	5%	59%	35%	1%
GMEI	6%	56%	37%	1%

Table 11. 2019 HBC Propulsion Engine Tier by Vessel Type, %

Ship Type	T0	T1	T2	T3	T4
Crew and Supply	32%	8%	20%	36%	4%
Fishing (C1/C2)	58%	39%	0%	0%	3%
Misc. (C1/C2)	33%	67%	0%	0%	0%
Pilot	0%	0%	0%	50%	50%
Towboat/Pushboat	94%	3%	3%	0%	0%
Tugboat	88%	5%	4%	1%	2%
Work Boat	100%	0%	0%	0%	0%

Table 12 summarizes the port-call statistics by OGV ship type. A "single visit" refers to a voyage in which a vessel called at only one terminal, whereas "multiple visits" indicates visits to more than one terminal during a single voyage. Figure 12 compares the distribution of port calls from the TTI classification with that reported in the GMEI. While the TTI dataset provides more detailed differentiation within the tanker category, both datasets consistently identify container ships and tankers as the primary contributors to port activity.

Table 12. 2019 PHA Arrivals/Departures and Shifts of OGVs

Ship Type	Single Visit	Multiple Visits
Bulk Carrier	370	24
Vehicle Carrier	81	0
General Cargo	398	31
Container Ship	1104	6
Chemical Tanker	980	88
Oil Tanker	240	0
Liquefied Gas Tanker	0	0
Other Tanker	214	6
Miscellaneous (C3)	0	1
Offshore Support/Drillship	55	98
Ferry/Roll-On/Passenger (C3)	3	0
Cruise	0	0
RORO	17	0

Note: Single visit: the vessel visits only one terminal in a voyage; multiple visits: the vessel visits multiple terminals in a voyage.

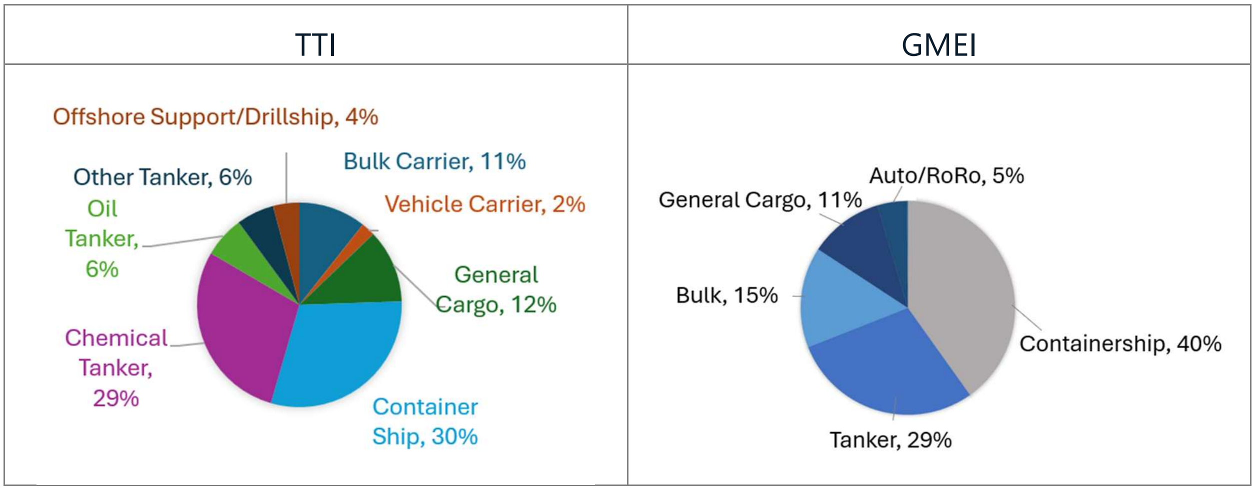


Figure 12. Comparison of PHA Port Calls with the GMEI

4.2 Comparison of Emission Inventory by Ship Type

Table 13 presents the estimated emissions for OGVs by ship type, distinguishing between PHA and non-PHA areas. The results show that while chemical tankers and container ships contribute the most NOx emissions within the PHA terminals, chemical and oil tankers dominate the non-PHA emissions. This pattern reflects POH's industrial profile, with strong petrochemical activity driving frequent visits from chemical and oil tankers. Its role as a major container hub also explains the high emissions from container ships. Overall, OGVs in PHA areas contribute approximately 40% of the total OGV-related emissions.

Table 13. 2019 PHA and Non-PHA OGV Emissions by Ship Type

Entity	Ship Type	NOx Tons	PM10 Tons	PM2.5 Tons	HC Tons	CO Tons	SO2 Tons	CO2 Tonnes
PHA	Bulk Carrier	355	6	6	15	36	14	20,708
	Vehicle Carrier	74	1	1	4	8	3	3,794
	General Cargo	611	10	9	25	58	23	32,927
	Container Ship	1,137	19	18	62	126	48	61,969
	Chemical Tanker	1,175	21	19	47	111	49	71,133
	Oil Tanker	253	7	6	11	24	18	25,797
	Liquefied Gas Tanker	0	0	0	0	0	0	0
	Other Tanker	142	4	4	6	19	10	15,803
	Miscellaneous (C3)	217	3	3	8	20	7	10,624
	Offshore Support/Drillship	171	3	2	7	16	6	8,333
	Ferry/Roll-On/ Passenger (C3)	1	0	0	0	0	0	44
	Cruise	0	0	0	0	0	0	0
	RORO	25	0	0	1	3	1	1,634
	Reefer	0	0	0	0	0	0	0
	Yacht (C2/C3)	0	0	0	0	0	0	0
	Subtotal	4,162	74	68	185	421	178	252,767
Non-PHA	Bulk Carrier	339	6	5	14	34	14	19,891
	Vehicle Carrier	18	0	0	1	2	1	982
	General Cargo	531	9	8	21	50	20	28,872
	Container Ship	12	0	0	1	1	0	566
	Chemical Tanker	2,534	44	40	102	246	101	148,692
	Oil Tanker	1,466	41	37	62	141	105	155,049
	Liquefied Gas Tanker	2	0	0	0	0	0	387
	Other Tanker	862	22	20	40	93	56	82,649
	Miscellaneous (C3)	296	4	4	11	27	9	13,273
	Offshore Support/Drillship	196	3	3	8	19	7	9,904
	Ferry/Roll-On/ Passenger (C3)	20	0	0	1	2	1	831
	Cruise	0	0	0	0	0	0	0
	RORO	0	0	0	0	0	0	7
	Reefer	3	0	0	0	0	0	152
	Yacht (C2/C3)	0	0	0	0	0	0	0
	Subtotal	6,279	129	119	262	615	315	461,255
Total		10,441	204	187	447	1,035	493	714,022
Percent PHA		40%	37%	36%	41%	41%	36%	35%

Table 14 summarizes emissions from commercial HBC. Tugboats and towboats are the primary contributors to emissions in both PHA and non-PHA zones due to their higher engine power, more frequent operations, and larger population. These vessel types are typically engaged in intensive maneuvering and assistive tasks, which result in elevated emission levels.

PHA-related HBC emissions account for approximately 33–35% of the total HBC emissions. This percentage is slightly lower than that observed for OGVs, likely because many HBC operate primarily outside of PHA terminals or do not remain within the port for extended periods.

Table 14. 2019 PHA and Non-PHA HBC Emissions by Ship Type

Entity	Ship Type	NOx Tons	PM10 Tons	PM2.5 Tons	HC Tons	CO Tons	SO2 Tons	CO2 Tonnes
PHA	Tugboat	803	20	20	24	148	1	62,983
	Towboat/Pushboat	1,222	28	27	32	205	1	74,408
	Crew and Supply	0	0	0	0	0	0	14
	Work Boat	1	0	0	0	0	0	34
	Pilot	0	0	0	0	0	0	0
	Fishing (C1/C2)	0	0	0	0	0	0	0
	Misc. (C1/C2)	0	0	0	0	0	0	9
	Subtotal	2,026	48	47	56	353	1	137,448
Non-PHA	Tugboat	1,261	32	31	37	208	1	77,993
	Towboat/Pushboat	2,753	64	62	81	448	2	170,979
	Crew and Supply	5	0	0	0	1	0	380
	Work Boat	0	0	0	0	0	0	30
	Pilot	3	0	0	0	1	0	711
	Fishing (C1/C2)	16	1	1	1	3	0	1,042
	Misc. (C1/C2)	3	0	0	0	0	0	157
	Subtotal	4,041	97	94	119	661	3	251,292
Total		6,067	145	141	175	1,014	4	388,740
Percent PHA		33%	33%	33%	32%	35%	35%	35%

To further assess the validity of the emission estimation method, the study compared its results with those reported in the GMEI for 2019, as shown in Table 15. Key findings revealed the following:

1. OGV: The overall emissions from OGVs are broadly consistent between the two sources, including both PHA and non-PHA domains.

2. HBC: While non-PHA emissions from HBC align with the GMEI, this study reported significantly higher PHA emissions. This discrepancy may be a result of differences in vessel identification, operational assumptions, or improved matching in the AIS dataset used.

Table 15. Emission Inventory Comparison with the GMEI

Projects	Entity		NOx Tons	PM10 Tons	PM2.5 Tons	HC Tons	CO Tons	SO2 Tons	CO2 Tonnes
TTI	OGV	PHA	4,162	74	68	185	421	178	252,767
		Non-PHA	6,279	129	119	262	615	315	461,255
		Total	10,441	204	187	447	1,035	493	714,022
		Percent PHA	42%	40%	40%	43%	42%	40%	39%
	HBC	PHA	2,026	48	47	56	353	1	137,448
		Non-PHA	4,041	97	94	119	661	3	251,292
		Total	6,067	145	141	175	1,014	4	388,740
		Percent PHA	33%	33%	33%	32%	35%	35%	35%
GMEI	OGV	PHA	4,120	69	63	132	348	171	259,134
		Non-PHA	7,939	172	159	247	716	448	678,387
		Total	12,059	241	222	379	1,064	619	937,521
		Percent PHA	34%	29%	29%	35%	33%	28%	28%
	HBC	PHA	496	12	12	12	113	0.4	39,805
		Non-PHA	3,816	88	85	93	847	3	302,443
		Total	4,312	100	97	105	960	3	342,249
		Percent PHA	12%	12%	12%	11%	12%	12%	12%

Figure 13 displays the NOx emission distribution by vessel type for both PHA and non-PHA regions, comparing the current study and GMEI estimates. The OGV emission patterns align closely across both datasets. However, the current study reported higher emissions from towboats than tugboats, contrasting with the GMEI, where tugboats were more prominent. Again, this discrepancy may be a result of differences in vessel identification and database sources.

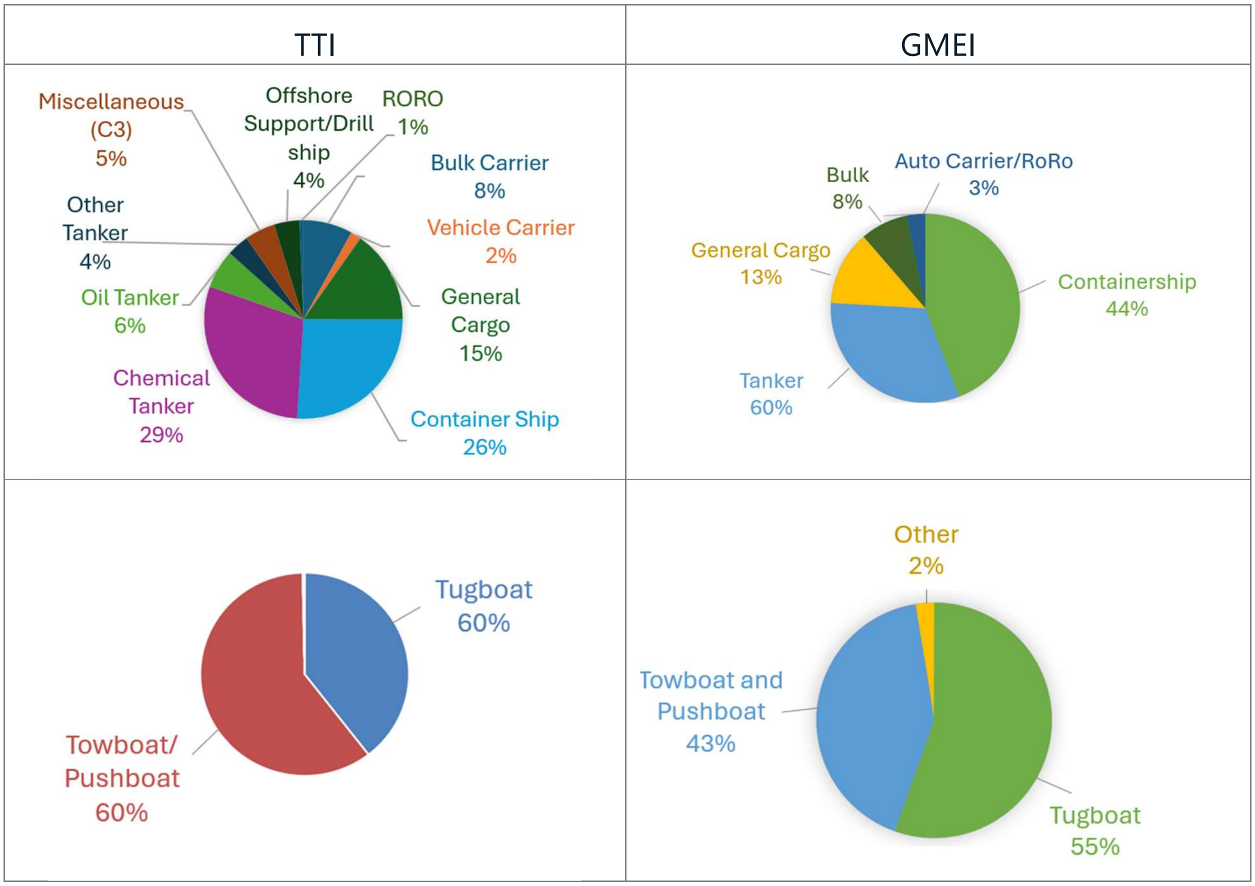


Figure 13. Comparison of PHA NOx Emissions with the GMEI by Ship Type

4.3 Comparison of Emission Inventory by Terminal

To better understand spatial emission patterns, the research team compared estimated emissions across different PHA terminals by vessel type.

Table 16 presents the total OGV emissions occurring within the PHA area, categorized by terminal. Among the terminals, Bayport Terminal is the largest contributor, responsible for more than twice the NOx emissions of Barbours Cut, the second highest. Turning Basin ranks third. Terminals with more frequent and higher-power vessel traffic, such as container ships and tankers, generate significantly more emissions.

Table 17 focuses specifically on OGV emissions in hotelling mode. The pattern remains similar, with Bayport Terminal again having the highest emissions, followed by Barbours Cut and Turning Basin. The relative contribution of at-berth emissions is substantial, which is driven by prolonged auxiliary engine use during cargo handling operations.

Table 16. 2019 PHA Total OGV Emissions by Terminal

Terminal	NOx Tons	PM10 Tons	PM2.5 Tons	HC Tons	CO Tons	SOx Tons	CO2 Tonnes
Bayport Terminal	1,538	28	25	70	154	67	93,398
Barbours Cut Terminal	744	14	12	37	84	33	45,994
Turning Basin	682	12	11	29	66	27	39,355
CARE Terminal	239	5	5	10	22	12	17,542
Jacintoport Terminal	168	3	2	7	16	6	8,780
Southside Wharves	241	4	4	10	24	10	15,147
Manchester Wharves	154	3	3	6	15	6	9,394
Woodhouse	191	3	3	8	19	8	11,163
Bulk Materials Handling	62	1	1	3	6	2	3,200
Sims Bayou	82	2	1	4	8	4	5,372
Industrial Park East	61	1	1	3	6	2	3,423

Table 17. 2019 PHA At-Berth OGV Emissions by Terminal

Terminal	NOx Tons	PM10 Tons	PM2.5 Tons	HC Tons	CO Tons	SOx Tons	CO2 Tonnes
Bayport Terminal	610	14	12	22	56	34	49,988
Barbours Cut Terminal	288	7	6	11	29	17	25,648
Turning Basin	407	8	7	15	38	18	26,589
CARE Terminal	115	3	3	4	11	8	11,327
Jacintoport Terminal	80	1	1	3	7	4	5,255
Southside Wharves	115	2	2	4	11	6	8,767
Manchester Wharves	61	1	1	2	6	3	4,438
Woodhouse	107	2	2	4	10	5	7,587
Bulk Materials Handling	23	0	0	1	2	1	1,577
Sims Bayou	29	1	1	1	3	2	2,987
Industrial Park East	33	1	1	1	3	1	2,169

Table 18 focuses on HBC emissions by terminal. Bayport again ranks highest, followed by Barbours Cut, largely due to higher levels of tugboat and towboat activity supporting vessel maneuvering and berthing. CARE Terminal has a higher proportion of HBC emissions than OGV emissions, probably due to its role in supporting barge and smaller vessel operations, which rely more heavily on tugboats and towboats for frequent maneuvering, shifting, and short-haul movements within the port.

Table 18. 2019 PHA Total HBC Emissions by Terminal

Terminal	NOx Tons	PM10 Tons	PM2.5 Tons	HC Tons	CO Tons	SOx Tons	CO2 Tonnes
Bayport Terminal	683	16	16	20	115	0	44,766
Barbours Cut Terminal	240	6	6	7	41	0	16,755
Turning Basin	199	5	5	5	35	0	12,696
CARE Terminal	238	5	5	5	52	0	21,385
Jacintoport Terminal	115	3	3	3	20	0	7,661
Southside Wharves	159	4	4	5	26	0	9,879
Manchester Wharves	102	2	2	3	17	0	6,320
Woodhouse	55	1	1	2	9	0	3,402
Bulk Materials Handling	108	2	2	3	18	0	6,805
Sims Bayou	124	3	3	4	20	0	7,614
Industrial Park East	7	0	0	0	1	0	507

Figure 14 compares the estimated terminal-level NOx emissions from this study with those reported in the 2019 GMEI. The overall trend in emissions distribution across terminals is similar between the two sources, supporting the reliability of the methodology. However, there is a slight difference in terminal-specific emissions, possibly due to variations in vessel classification, terminal boundary definitions, and the port-call algorithms used to assign emissions to terminals.

Together, the tables in this section highlight the importance of terminal-level differentiation in emissions management, with Bayport Terminal emerging as a critical target for mitigation strategies across both OGV and HBC operations.

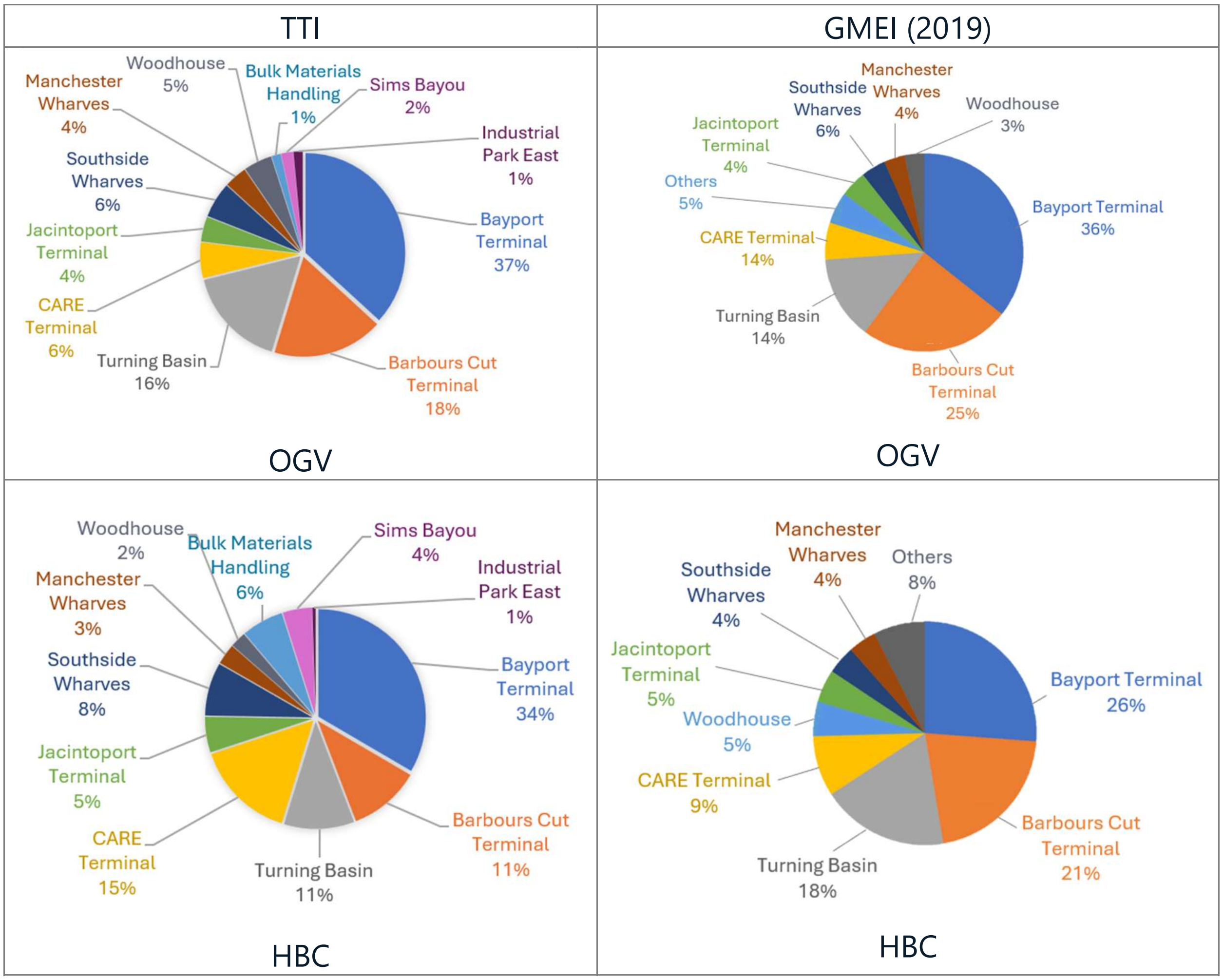


Figure 14. Comparison of PHA NOx Emissions with the GMEI by Terminal

4.4 Sensitivity Analysis

AIS data provide periodic updates on vessel locations and speeds, and these discrete signals are processed to define voyages. When a time gap occurs between two signals, indicating the vessel may have shut off its engine, the current voyage is considered to have ended, and a new voyage begins. A 30-minute time gap is used as the default to distinguish between activities.

As shown in Figure 15, longer time gaps tend to result in slightly higher emissions because the extended gap is still counted as part of the voyage. However, the overall impact of the time gap on emissions is minimal. The ratio of PHA emissions increases with longer time gaps. This occurs because vessel segments that previously left or visited a public terminal can merge with other segments, making the entire voyage

PHA-related under longer gap scenarios. Overall, the time gap to define a voyage is not significant.

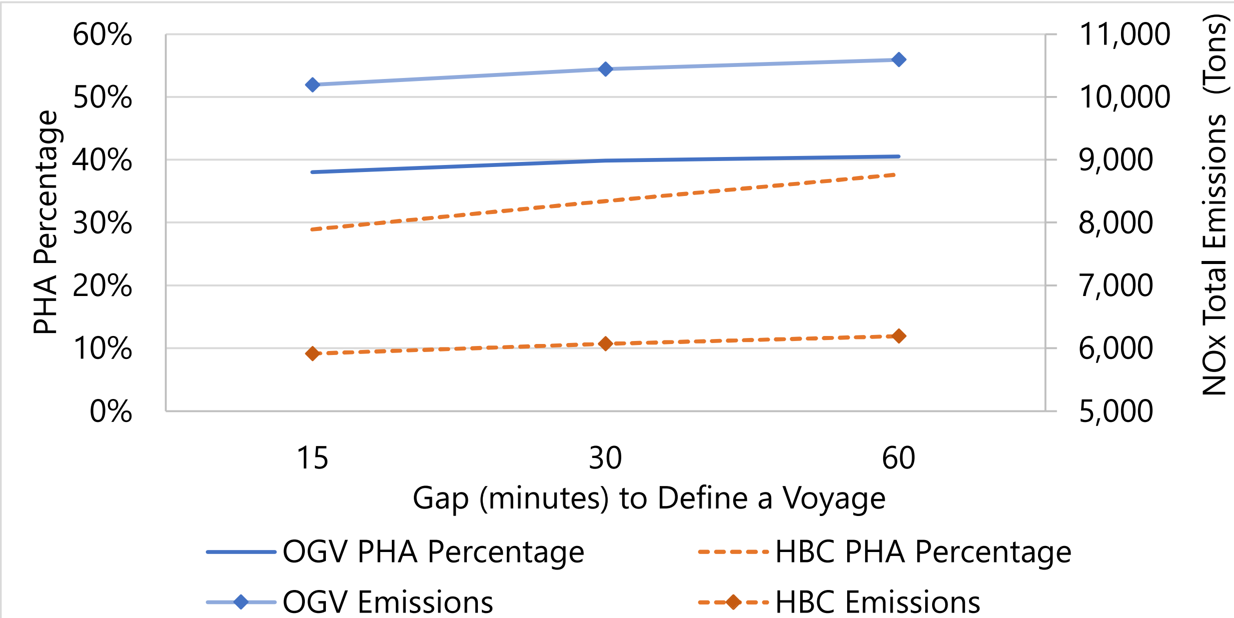


Figure 15. Sensitivity Analysis of Time Gap in Voyage Definition

In this study, a 40-minute threshold was used to define the minimum stay required to classify a vessel as having visited a public terminal. If a vessel remained at a public terminal for more than this threshold, the voyage was considered PHA-related. Figure 16 illustrates the ratio of PHA emissions under different scenarios, showing that the in-port time threshold is not particularly sensitive from 15 minutes to 120 minutes.

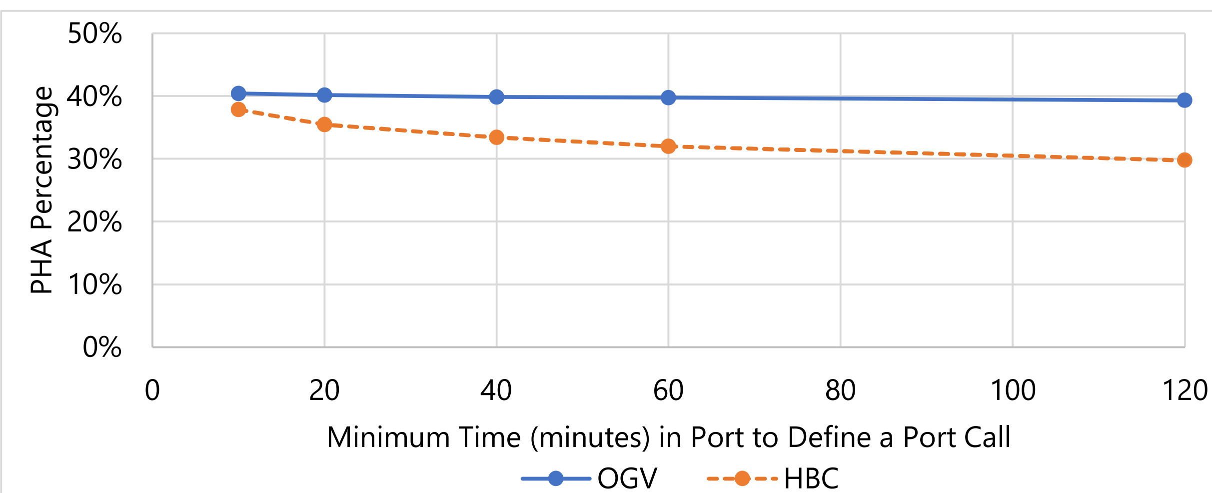


Figure 16. Sensitivity Analysis of the In-Port Time Threshold Used to Define Port Calls

4.5 Summary

The emission inventory results provide valuable insights into the contributions of different vessel types and terminals to overall emissions. OGVs, particularly tankers and container ships, are the dominant sources of both PHA and non-PHA emissions. HBC, especially tugboats and towboats, also play a significant role in emissions. Bayport Terminal has the highest emissions for both OGVs and HBC.

Comparison with the GMEI report indicates that the overall distribution of emissions by terminal follows a similar trend. However, there are notable discrepancies, particularly in the HBC non-PHA emissions, which may be a result of differences in ship classification, engine parameters, and port-call algorithms.

Table 19 details the comparison of PHA vessel counts between the GMEI and TTI data. A PHA vessel count refers to ships that visited a public terminal at least once during the year, while total unique ships include all vessels, even those that never visited public terminals. Although both sources agree that tugboats and towboats are the majority vessels, the GMEI reports more tugboats, while the TTI data show more towboats. The total ship count differences may also account for discrepancies in HBC emission calculations. Notably, a previous report (Environmental Defense Fund, 2014) identified 872 unique towboats/pushboats, 27 tugboats, and 61 ocean-going tugs in the Houston area, further supporting a higher composition of towboats.

Table 19. Comparison of the HBC Number in the POH

Ship Type	PHA Vessel Count (GMEI)	PHA Vessel Count (TTI)	Total Unique Ship (TTI)
Tugboat	669	179	327
Towboat/Pushboat	149	498	882
Crew and Supply	68	5	25
Work Boat	4	3	4
Pilot	5	0	2
Fishing (C1/C2)	0	0	45
Misc. (C1/C2)	123	1	3
Barge	0	2	3
Harbor Ferry	15	0	0
Government	7	0	0

5. EMISSION BENCHMARK (2022)

This project analyzed the 2022 emission inventory, establishing a baseline for future emission strategy analysis.

5.1 Vessel Composition

Figure 17 displays the vessel-matching results for the 2022 AIS data. Most OGVs were successfully matched using the Sea-Web database, while tugboats and towboats required supplemental matching with the TTI and U.S. Army Corps databases. In total, 4,479 commercial vessels were included in the emissions inventory, as summarized in Table 20. The table includes a detailed breakdown by U.S. EPA ship categories and subtypes.

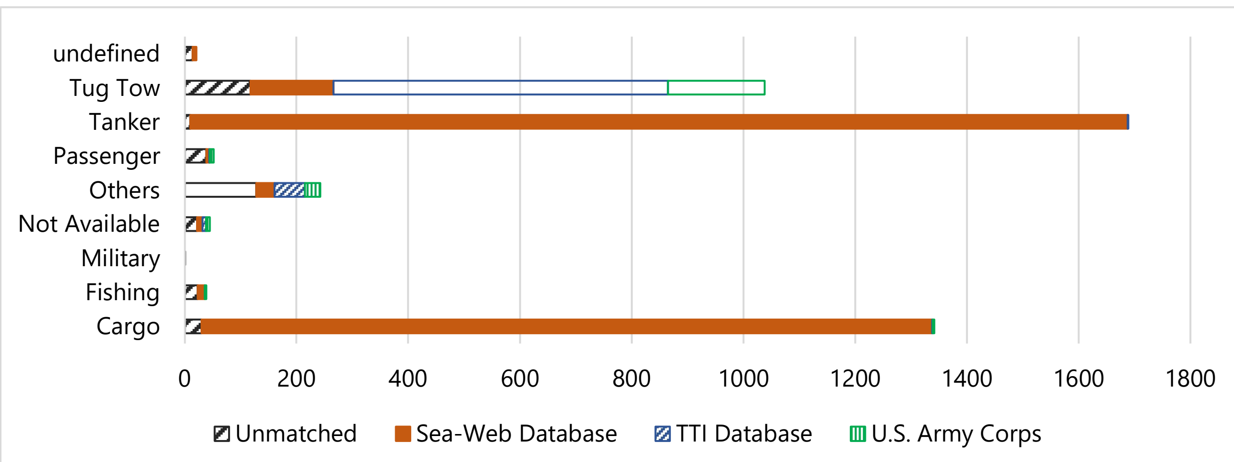


Figure 17. Matching Conditions of the 2022 AIS Data

Table 20. Number of Unique Vessels Matched to the U.S. EPA Ship Types

Category	Ship Type	Ship Subtype	Count
OGV	Bulk Carrier	Handysize	93
		Handymax	243
		Panamax	271
		Capesize	3
	Chemical Tanker	Smallest	2
		Small	11
		Handysize	125
		Handymax	757
	Container Ship	1,000 TEU	2
		2,000 TEU	13
		3,000 TEU	25
		5,000 TEU	82
		8,000 TEU	122
		12,000 TEU	60
	Ferry/Roll-On/Passenger (C3)	2,000 Ton	2
	General Cargo	5,000 DWT	6
		10,000 DWT	59
		Largest	321
	Miscellaneous (C3)	All C3 Misc.	53
	Offshore Support/Drillship	All Offshore Support/ Drillship	49
	Oil Tanker	Handymax	54
		Panamax	78
		Aframax	205
		Suezmax	112
		VLCC	2
	Other Tanker	All Other Tanker	470
	Reefer	All Reefer	1
	RORO	Largest	6
	Vehicle Carrier	4,000 Vehicles	2
		Largest	18
	Sum	-	3,247
HBC	Barge	–	1
	Crew and Supply	–	7
	Excursion	–	39
	Fishing (C1/C2)	–	38
	Misc. (C1/C2)	–	2
	Pilot	–	2
	Towboat/Pushboat	–	786
	Tugboat	–	353
	Work Boat	–	4
	Sum	-	1,232

Note: TEU = twenty-foot equivalent units; DWT = deadweight tons; VLCC = very large crude carrier.

Table 21 and Table 22 illustrate the distribution of propulsion engine tiers for OGVs and HBC in 2022. Compared to 2019 (Table 10 and Table 11), a modest improvement occurred in overall fleet compliance with higher emission standards. For OGVs, the proportion of Tier 3 engines increased from 1% in 2019 to 7% in 2022, indicating a gradual adoption of newer, cleaner engine technologies. For HBC, the share of Tier 1 engines grew significantly, from 4% to 12%. These trends indicate incremental progress in upgrading marine vessel engines, particularly among OGVs, though further effort may be required to accelerate compliance among HBC.

Table 21. 2022 OGV Propulsion Engine Tier by Vessel Type, %

Ship Type	T0	T1	T2	T3
Bulk Carrier	1%	38%	59%	2%
Chemical Tanker	4%	41%	43%	12%
Container Ship	4%	83%	13%	0%
Ferry/Roll-On/Passenger (C3)	100%	0%	0%	0%
General Cargo	4%	75%	20%	0%
Miscellaneous (C3)	0%	100%	0%	0%
Offshore Support/Drillship	22%	47%	18%	12%
Oil Tanker	1%	59%	30%	9%
Other Tanker	2%	44%	40%	13%
Reefer	100%	0%	0%	0%
RORO	0%	0%	100%	0%
Vehicle Carrier	10%	60%	30%	0%
Total	3%	53%	37%	7%

Table 22. 2022 HBC Propulsion Engine Tier by Vessel Type, %

Ship Type	T0	T1	T2	T3	T4
Crew and Supply	57%	0%	14%	29%	0%
Excursion	0%	100%	0%	0%	0%
Fishing (C1/C2)	73%	27%	0%	0%	0%
Misc. (C1/C2)	100%	0%	0%	0%	0%
Pilot	0%	0%	0%	50%	50%
Towboat/Pushboat	87%	8%	4%	0%	1%
Tugboat	71%	12%	7%	3%	6%
Work Boat	75%	0%	0%	25%	0%
Total	80%	12%	5%	1%	2%

5.2 Operation Summary

The operating patterns of OGVs and HBC within the POH are summarized in Figure 18 and Figure 19. For OGVs, hotelling is the predominant mode of operation across all ship types, accounting for over 80% of total operating time. Among vessel types, tankers exhibit the longest operating times, reflecting extended durations spent at berth for loading and unloading. For HBC, tugboats and towboats demonstrate the highest cumulative operating times. Similar to OGVs, hotelling represents the major share of HBC's operational mode since these vessels often remain in service areas or idle while awaiting assignments.

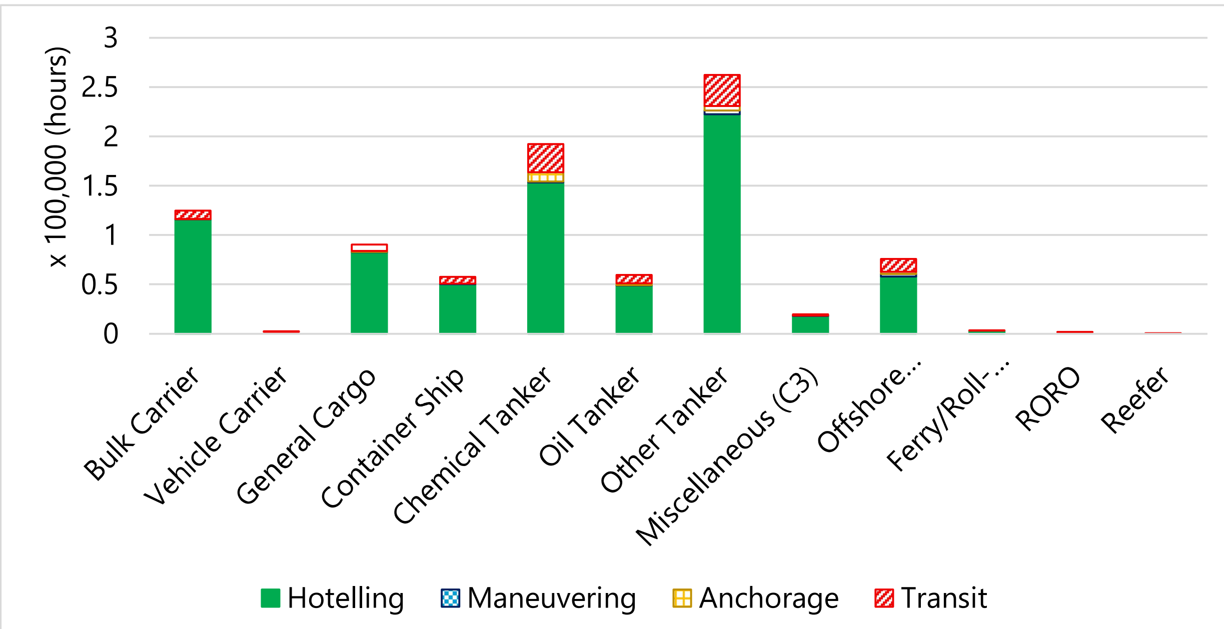


Figure 18. Operating Time of OGVs in 2022

Figure 19. Operating Time of HBC in 2022

5.3 Emission Inventory by Ship Types

This section provides a detailed breakdown of emissions from OGVs and HBC, respectively, with emissions separated into PHA and non-PHA sources.

5.3.1 OGV Emissions

Table 23 shows that bulk carriers, general cargo ships, container ships, and various types of tankers are the largest contributors to emissions within the PHA domain. Specifically:

- Container ships and other tankers are the top emitters across different pollutants. Container ships are responsible for 1,247 tons of NOx and 73,232 tonnes of CO2, while other tankers emit 924 tons of NOx and a notably higher 104,097 tonnes of CO2. Other tankers have a higher proportion of Tier 2 engines, with smaller NOx emission factors, causing less NOx amounts than container ships. However, CO2 emissions are primarily linked to fuel consumption and operating hours and are not directly affected by engine tier level. Other tankers operate for longer durations, leading to their elevated CO2 emissions despite lower NOx per unit activity.
- Container ships and other tankers are followed by bulk carriers, general cargo ships, and chemical tankers, each emitting over 600 tons of NOx and more than 38,000 tonnes of CO2 in the PHA region. Together, these five ship types represent the majority of PHA emissions from OGVs, underscoring their operational significance and environmental footprint at the port.

- Tankers also dominate the non-PHA category. In particular, other tankers emit 2,894 tons of NOx and 261,223 tonnes of CO_2, while chemical tankers contribute 2,380 tons of NOx and 149,153 tonnes of CO_2—both figures exceeding the emissions of any single vessel type in the PHA category. This finding suggests that private terminals have higher traffic, particularly for chemical and crude product handling, which tends to require extended berthing or loading/unloading times, contributing to elevated emissions.

The percentage of PHA emissions across pollutants for OGVs ranges from 37% to 39%. This is a significant portion, suggesting that targeted mitigation within PHA could lead to meaningful reductions in overall emissions, especially for local air quality.

5.3.2 HBC Emissions

Table 24 shows emissions from HBC, where towboats/pushboats and tugboats are the primary contributors in both PHA and non-PHA categories.

- Towboats/pushboats are the single largest source of HBC emissions, accounting for 1,100 tons of NOx and 68,568 tonnes of CO_2 in PHA areas, as well as 2,500 tons of NOx and 156,909 tonnes of CO_2 in non-PHA areas. Combined, they emit over 3,600 tons of NOx and 225,000 tonnes of CO_2, more than 50% of total HBC emissions, underscoring their intensive usage and operational hours in the region.
- Tugboats follow in second place, emitting over 2,000 tons of NOx and 140,000 tonnes of CO_2 combined (PHA and non-PHA), reinforcing their major role in maneuvering large vessels.

The percentage of HBC emissions within PHA areas ranges from 31% to 33%, slightly lower than the percentage for OGVs. This finding reflects the fact that a greater portion of HBC operations is not associated with PHA terminals.

5.3.3 Emission Sources

The emission source composition for 2022, shown in Figure 20, reveals that OGV emissions are dominated by auxiliary engines, while HBC emissions stem primarily from propulsion engines. Although both vessel categories spend substantial time in hotelling mode, HBC typically operate with smaller auxiliary engines, resulting in a lower share of emissions from that source.

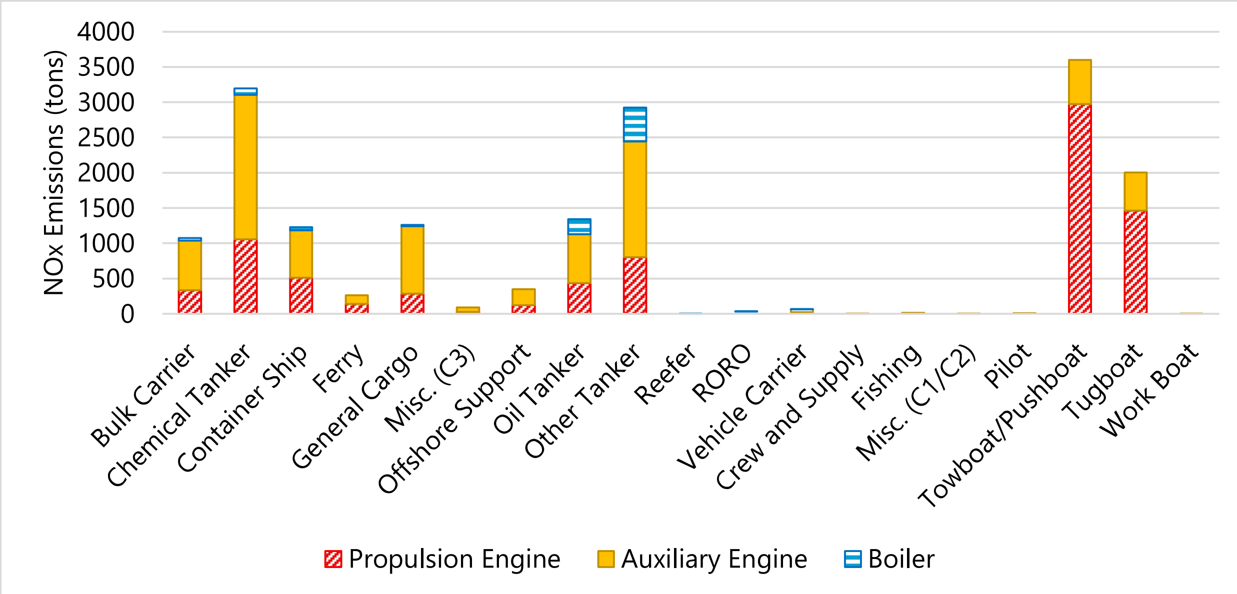


Figure 20. Emission Sources of OGVs and HBC in 2022

Table 23. PHA and Non-PHA OGV Emissions by Ship Type

Entity	Ship Type	NOx Tons	PM10 Tons	PM2.5 Tons	HC Tons	CO Tons	SO2 Tons	CO2 Tonnes
PHA	Bulk Carrier	696	13	12	29	70	31	45,778
	Vehicle Carrier	47	1	1	2	5	2	2,397
	General Cargo	699	12	11	28	66	27	38,859
	Container Ship	1,247	22	20	66	138	56	73,232
	Chemical Tanker	815	15	14	34	82	35	51,017
	Oil Tanker	243	7	7	11	25	19	27,838
	Other Tanker	924	27	25	49	112	71	104,097
	Miscellaneous (C3)	35	1	0	1	3	1	1,665
	Offshore Support/Drillship	156	4	4	11	25	10	13,394
	Ferry/Roll-On/ Passenger (C3)	0	0	0	0	0	0	0
	RORO	30	1	1	1	3	1	2,034
	Reefer	1	0	0	0	0	0	66
	Subtotal	4,893	102	94	233	530	252	360,376
Non-PHA	Bulk Carrier	379	7	6	16	38	15	22,562
	Vehicle Carrier	16	0	0	1	2	1	922
	General Cargo	559	9	8	22	53	21	30,845
	Container Ship	135	2	2	8	15	6	7,060
	Chemical Tanker	2,380	44	40	103	249	101	149,153
	Oil Tanker	1,101	32	29	48	114	82	121,596
	Other Tanker	2,894	71	66	157	333	183	261,223
	Miscellaneous (C3)	38	1	0	2	4	1	1,698
	Offshore Support/Drillship	193	3	3	9	21	8	10,889
	Ferry/Roll-On/ Passenger (C3)	9	0	0	0	1	0	377
	RORO	0	0	0	0	0	0	11
	Reefer	0	0	0	0	0	0	0
	Subtotal	7,706	170	156	367	829	418	606,337
Total		12,599	272	250	599	1,359	670	966,712
Percent PHA		39%	38%	38%	39%	39%	38%	37%

Table 24. PHA and Non-PHA HBC Emissions by Ship Type

Entity	Ship Type	NOx Tons	PM10 Tons	PM2.5 Tons	HC Tons	CO Tons	SO2 Tons	CO2 Tonnes
PHA	Tugboat	677	17	16	20	127	1	54,253
	Towboat/Pushboat	1,100	25	24	30	185	1	68,568
	Crew and Supply	0	0	0	0	0	0	10
	Work Boat	1	0	0	0	0	0	51
	Pilot	0	0	0	0	0	0	3
	Fishing (C1/C2)	0	0	0	0	0	0	16
	Misc. (C1/C2)	0	0	0	0	0	0	0
	Excursion	4	0	0	0	1	0	249
	Subtotal	1,782	41	40	50	312	1	123,150
Non-PHA	Tugboat	1,325	33	32	38	227	1	85,902
	Towboat/Pushboat	2,500	57	55	73	409	2	156,909
	Crew and Supply	1	0	0	0	0	0	65
	Work Boat	0	0	0	0	0	0	12
	Pilot	2	0	0	0	0	0	292
	Fishing (C1/C2)	11	0	0	0	2	0	686
	Misc. (C1/C2)	1	0	0	0	0	0	53
	Excursion	23	1	0	1	4	0	1,589
	Subtotal	3,863	91	88	112	643	2	245,508
Total		5,645	133	128	162	955	4	368,658
Percent PHA		32%	31%	31%	31%	33%	33%	33%

5.4 Emission Inventory by Terminals

This section presents the distribution of total and at-berth emissions by PHA terminal for OGVs. The data underscore the variation in emissions across terminals due to differences in vessel activity, terminal functions, and berthing durations.

5.4.1 Total Emissions (OGV)

Table 25 presents the OGV emissions by terminals. Bayport Terminal is the leading contributor to total OGV emissions, emitting over 1,538 tons of NOx and 112,865 tonnes of CO2 in 2022. This terminal alone accounts for more than 30% of the total NOx emissions reported among all PHA terminals, which reflects its high traffic volume, particularly from container ships and tankers that frequently call at Bayport.

Barbours Cut Terminal and Turning Basin Terminal also exhibit substantial emissions, with 1,049 tons and 913 tons of NOx, respectively. These terminals handle a broad mix of cargo types and vessel classes, contributing to their significant emission profiles.

5.4.2 At-Berth Emissions (OGV)

Table 26 details emissions associated with the hotelling mode at berth. Again, Bayport Terminal records the highest emissions, with 664 tons of NOx and 63,289 tonnes of CO2, indicating a higher activity level related to this facility. Notably, Turning Basin Terminal surpasses Barbours Cut in at-berth emissions, despite Barbours Cut having higher total emissions. This result may indicate that while Barbours Cut handles more active vessel movements, the total berthing time at Turning Basin is longer.

In summary, emissions are highly concentrated at a few terminals: Bayport, Barbours Cut, and Turning Basin account for the vast majority of both total and at-berth emissions within the PHA network. At-berth emissions contribute a substantial share of total emissions, highlighting the importance of shore power and other idle reduction strategies at key terminals.

Table 25. 2022 PHA Total OGV Emissions by Terminal

Terminal	NOx Tons	PM10 Tons	PM2.5 Tons	HC Tons	CO Tons	SOx Tons	CO2 Tonnes
Bayport Terminal	1,538	33	30	79	170	81	112,865
Barbours Cut Terminal	1,049	23	21	56	131	57	81,393
Turning Basin	913	18	16	38	90	43	61,895
CARE Terminal	307	7	7	13	31	18	26,494
Jacintoport Terminal	163	3	3	7	16	7	10,583
Southside Wharves	327	7	6	14	33	17	23,994
Manchester Wharves	146	3	3	6	14	7	9,992
Woodhouse	215	4	4	9	21	10	14,604
Bulk Materials Handling	73	1	1	3	7	3	4,720
Sims Bayou	74	2	2	4	8	6	8,326
Industrial Park East	89	2	1	4	9	4	5,509

Table 26. 2022 PHA At-Berth OGV Emissions by Terminal

Terminal	NOx Tons	PM10 Tons	PM2.5 Tons	HC Tons	CO Tons	SOx Tons	CO2 Tonnes
Bayport Terminal	664	17	16	26	66	42	63,289
Barbours Cut Terminal	459	12	11	17	50	31	48,869
Turning Basin	675	14	13	25	64	34	50,738
CARE Terminal	142	4	3	6	14	9	13,958
Jacintoport Terminal	67	1	1	2	6	3	5,092
Southside Wharves	150	3	3	6	15	8	11,542
Manchester Wharves	60	1	1	2	6	3	5,001
Woodhouse	148	3	3	6	14	7	11,083
Bulk Materials Handling	25	1	1	1	2	1	2,004
Sims Bayou	29	1	1	1	3	3	4,095
Industrial Park East	67	1	1	2	6	3	4,588

5.4.3 Total Emissions (HBC)

For HBC, Bayport Terminal is the dominant source, with 538 tons of NOx and 35,889 tonnes of CO2—primarily due to the high level of tugboat and towboat activity supporting frequent OGV movements. Notably, CARE Terminal also stands out, contributing 337 tons of NOx and 25,156 tonnes of CO2, largely from towboat operations. While Barbours Cut and Turning Basin also show substantial emissions, their totals remain lower than Bayport and CARE.

Table 27. 2022 PHA Total HBC Emissions by Terminal

Terminal	NOx Tons	PM10 Tons	PM2.5 Tons	HC Tons	CO Tons	SOx Tons	CO2 Tonnes
Bayport Terminal	538	13	12	16	91	0	35,889
Barbours Cut Terminal	198	5	5	6	34	0	13,719
Turning Basin	136	3	3	3	25	0	9,300
CARE Terminal	337	8	7	9	62	0	25,156
Jacintoport Terminal	169	4	4	4	33	0	13,513
Southside Wharves	108	3	2	3	18	0	6,790
Manchester Wharves	65	1	1	2	11	0	4,091
Woodhouse	29	1	1	1	5	0	1,850
Bulk Materials Handling	63	1	1	2	11	0	4,113
Sims Bayou	137	3	3	4	23	0	8,627
Industrial Park East	2	0	0	0	0	0	99

5.5 Emission Heatmaps

Figure 21 and Figure 22 depict the heatmaps of NOx emissions for OGVs and HBC in 2022, with each pixel representing a 100 × 100 m area. These visualizations provide a detailed spatial understanding of emission intensity across the POH.

OGV emissions are broadly distributed along the HSC and extend up to 9 nautical miles from the Bolivar anchorage area. In contrast, HBC emissions do not extend into the offshore region. Instead, they are concentrated near terminal areas, where intensive towboat and tugboat operations occur near berthing sites.

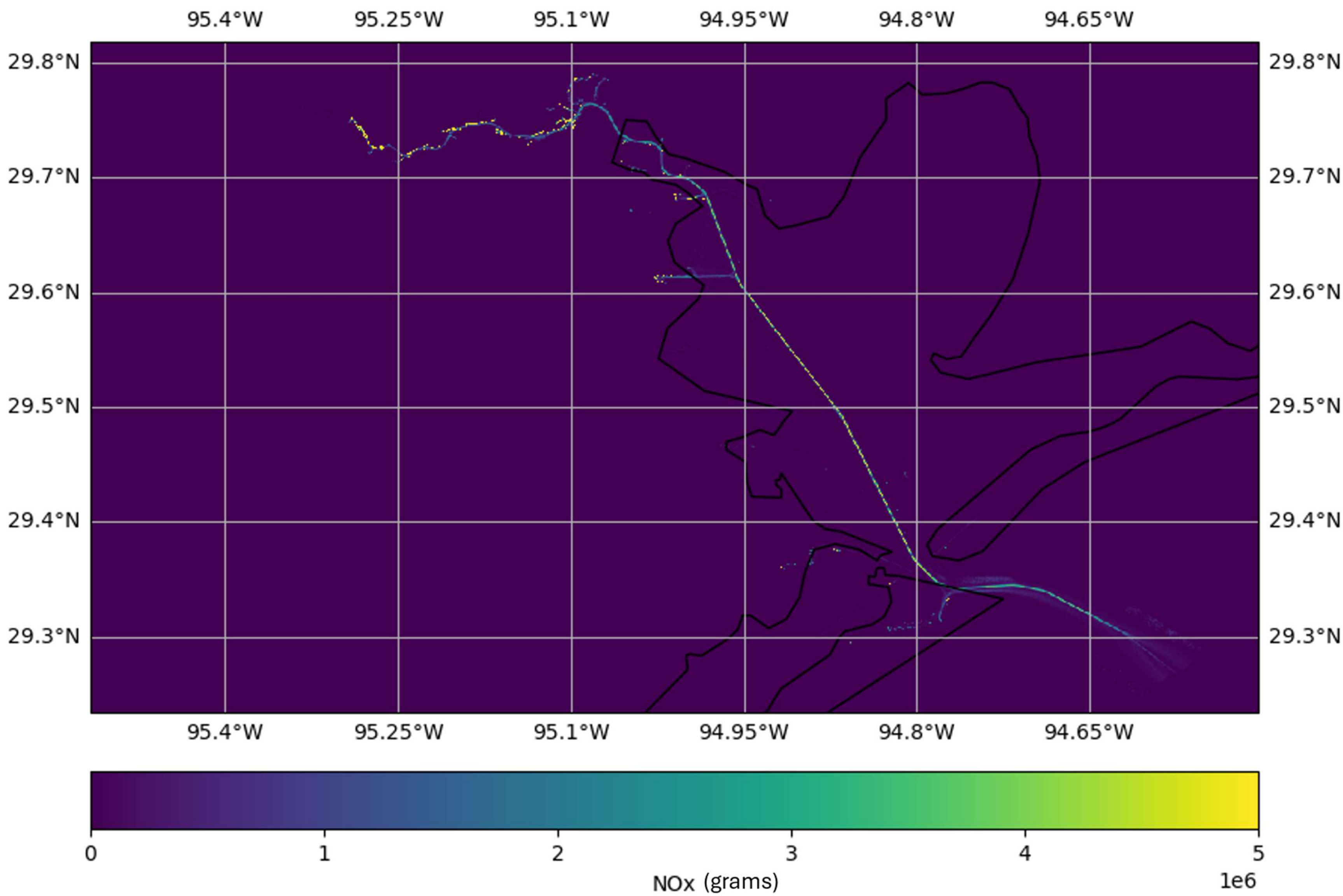


Figure 21. Heatmap of NOx from OGVs in 2022

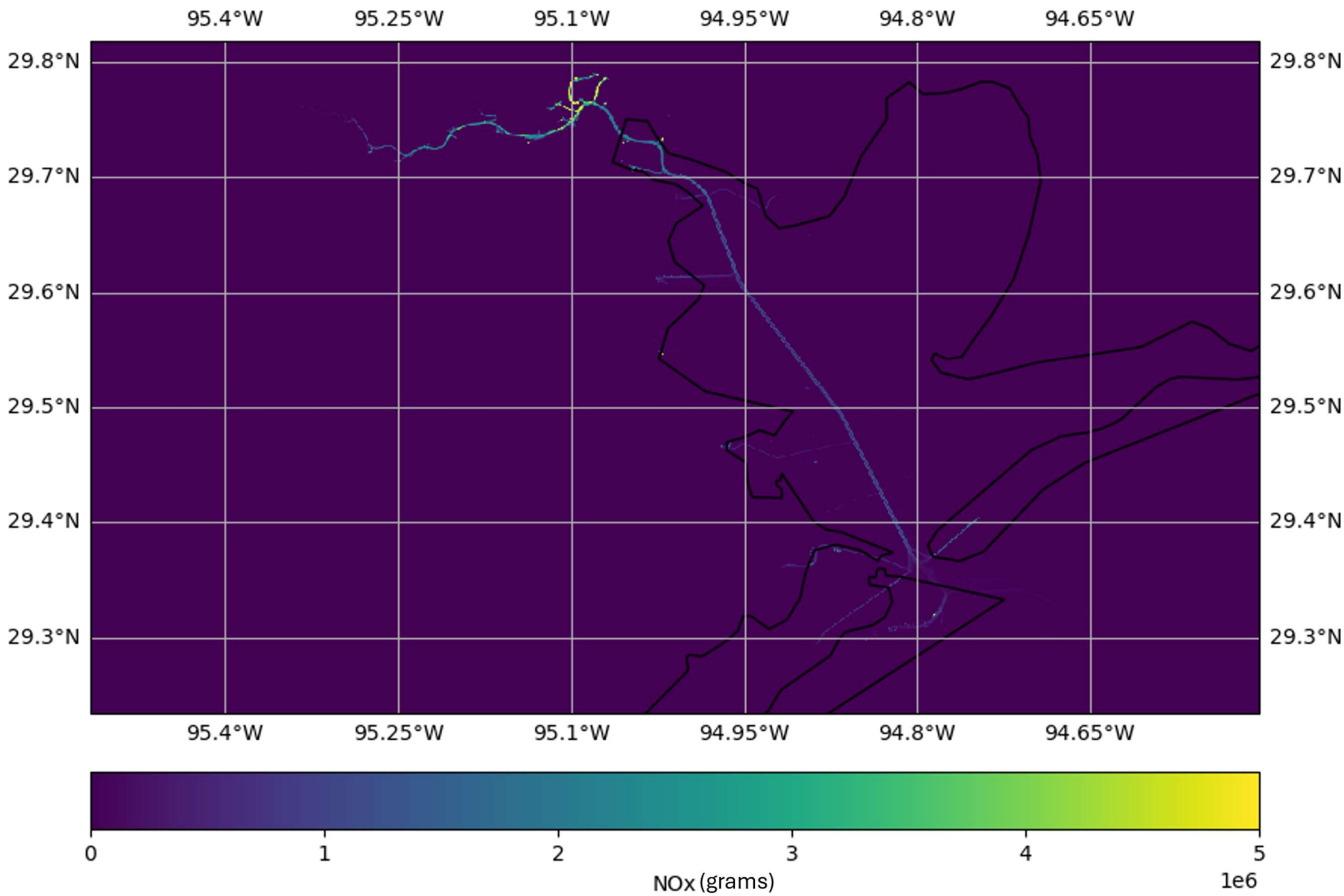


Figure 22. Heatmap of NOx from HBC in 2022

6. EMISSION REDUCTION STRATEGIES: LITERATURE REVIEW

The maritime sector is a vital component of international trade but also a significant source of air pollution. To mitigate its environmental impact, regulatory efforts such as the designation of ECAs by IMO have sought to limit emissions of NOx, SOx, and PM2.5.

Building on this regulatory context, the TTI research team conducted a focused review of emission reduction strategies applicable to port and vessel operations. The strategies evaluated include:

- Shore power (cold ironing).
- Engine tier regulation.
- Alternative fuels (e.g., biodiesel, LNG, hydrogen).
- Vessel electrification.
- Operational improvements.

6.1 Shore Power

Shore power, also known as shoreside power or cold ironing, has been adopted to reduce emissions from a vessel's auxiliary engines when it is at berth by connecting the vessel to an onshore electrical power source, thereby reducing auxiliary engine usage. Shore power entails three basic components: a shoreside electrical system and infrastructure, a cable management system, and a shipside electrical system (Kohli, 2009). The first large-scale shore power berth was introduced in 2004 in the Port of Los Angeles, which also introduced the world's first shore-power-compatible container ship (Safety4Sea, 2019). It is expected that over the coming years, several major ports will develop shore power infrastructure (International Renewable Energy Agency, 2021).

Shore power offers numerous environmental benefits. Studies indicate that it can lead to significant reductions in vessel emissions, including CO_2, SO_2, NO_x, and PM. Zis et al. (2014) analyzed the fuel consumption function of containerships while docked, estimating that if all containerships utilized shore power instead of onboard engines, port emissions could be reduced by approximately 48–70% for CO_2, 3–60% for SO_2, and 40–60% for NO_x. It is crucial to recognize that the overall reduction of emissions by shore power depends on how the electricity is generated. If shore power is generated entirely from clean energy sources, emissions can be significantly decreased.

Despite the promising environmental benefits offered by shore power, its implementation faces several challenges. Drawing from the findings of Tseng and Pilcher (2015) and Yin et al. (2020), the barriers to widespread adoption can be broadly categorized into three primary areas:

1. Geostrategic Challenges: Limited local grid capacity and a lack of regional or international coordination hinder widespread adoption of shore power infrastructure.
2. Technical Challenges: Variations in voltage standards, plug types, and system reliability reduce interoperability between vessels and terminals. Additionally, the low rate of ship retrofitting makes shore power economically unappealing, reinforcing a cycle of underutilization.
3. Financial Challenges: Shore power adoption is constrained by poorly targeted government subsidies and limited cost advantages compared to conventional onboard power generation.

In European ports, despite the installation of shore power infrastructure, its use is limited to certain types of container and passenger ships. As a result, CO_2 reductions are estimated to be no higher than 24% (Osipova & Carraro, 2023). Similarly, within the POH area, only the Port of Galveston currently offers shore power, which limits the overall potential of this technology (Ramboll US Consulting Corporation, 2022). These limited impacts are largely due to technical challenges. In Europe, incompatible voltage standards and plug types as well as the lack of onboard equipment collectively restrict the number of vessels able to connect to shore power. At Galveston, the limited shore power facilities combined with the low number of vessels equipped with compatible onboard systems means that actual emission reductions are expected to be minimal.

Given these challenges, it is essential for authorities to first invest in expanding shore power facilities and standardize charging systems to attract a greater number of vessel operators. However, to justify such investments and ensure efficient allocation of resources, a thorough benefit-cost analysis is crucial. Evaluating both the environmental benefits and economic costs helps policymakers and stakeholders make informed decisions that balance investment with potential returns. For example:

- Kaohsiung Harbor in Taiwan: Tseng and Pilcher (2015) analyzed the case of Kaohsiung Harbor in Taiwan, assuming 100 containerships docking at a terminal with an average berthing time of 16 hours each. Their study found that using shore power could reduce annual emissions of NOx and CO2, generating substantial monetary benefits based on health and environmental damage costs reported in a European study—the HEATCO project (Lee et al., 2010; Odgaard et al., 2005). The total extra annual investment and operating cost for implementing shore power under this scenario is about $960,000, which is significantly lower than the combined annual environmental benefit of $2.8 million. Therefore, the analysis demonstrates that adopting shore power at Kaohsiung is worthwhile since the environmental benefits clearly outweigh the investment costs.
- Port of Shenzhen, China: An International Council on Clean Transportation report (Wang et al., 2015) shows that at the Port of Shenzhen, adopting shore power for 80% of container ships could reduce NOx emissions by 94%, or about 3,196 tonnes annually. The average investment and operational expenses of reducing NOx through shore power are approximately $56,000 per ton.

In summary, while shore power presents a promising solution to reduce vessel emissions at berth, overcoming technical and infrastructure challenges is critical to unlocking its full potential. Strategic investments guided by comprehensive benefit-cost analyses will be key to accelerating adoption and maximizing environmental benefits. Continued collaboration among ports, vessel operators, and policymakers is essential to achieve widespread implementation and meaningful emission reductions (Kim, 2022; Yin et al., 2022).

6.2 Engine Tier Regulation

NOx emissions from engines are hazardous, causing respiratory illnesses in humans and environmental issues like acid rain and algal blooms. To address these impacts, both

IMO and U.S. EPA have developed regulatory frameworks targeting NOx emissions from ships.

- IMO Regulations: IMO regulates emissions under MARPOL Annex VI, an international treaty addressing air pollution from ships. This framework applies to marine diesel engines with a power output above 130 kW and includes a tiered system of NOx limits based on the construction date of the vessel (Marine Urea, 2012).

  The tier system comprises three standards, as classified below. Tier III engines have significantly lower NOx emission factors compared with Tiers I and II (Ni et al., 2020).

  - Tier I: Applies to engines on ships constructed on or after January 1, 2000.
  - Tier II: Applies to engines on ships constructed on or after January 1, 2011, requiring a 20% reduction in NOx emissions compared to Tier I.
  - Tier III: Applies to engines on ships constructed on or after January 1, 2016, but only when operating in designated ECAs, requiring up to an 80% reduction compared to Tier I.

- U.S. EPA Regulations: U.S. EPA regulates marine engine emissions in the United States through a separate tier system, with standards codified in 40 CFR Part 1042(Federal Register, 2020). The tier system is associated with the engine category, power range, and application.

  The engine category includes three sizes:

  - Category 1: <7 liters/cylinder (smallest, e.g., HBC).
  - Category 2: 7–30 liters/cylinder (medium, e.g., ferries, tugs).
  - Category 3: ≥30 liters/cylinder (large OGVs).

  Based on engine category, U.S. EPA standards span from Tier 1 to Tier 4:

  - Tier 1–3: Applied to all categories, with increasing stringency.
  - Tier 4: Applies only to new C1 and C2 engines ≥600 kW, requiring advanced aftertreatment (e.g., selective catalytic reactor [SCR], particulate filters). Tier 4 does not apply to C3 engines (U.S. EPA, 2020).

In summary, OGVs with C3 engines are regulated for NOx emissions under a three-tier system (Tier 1 to Tier 3) by both IMO and U.S. EPA. In contrast, HBC are subject to U.S.

EPA Tier 1 through Tier 4 standards, with Tier 4 applying to new, high-powered engines and being the strictest standard.

6.2.1 Technologies to Meet IMO Tier III Standards

To meet the IMO Tier III NOx emission standards, various technologies can be employed (Wik & Niemi, 2016). The selection often depends on a life-cycle cost evaluation, factoring in both investment and operating costs over the equipment's lifetime. Below is a summary of the candidate methods discussed:

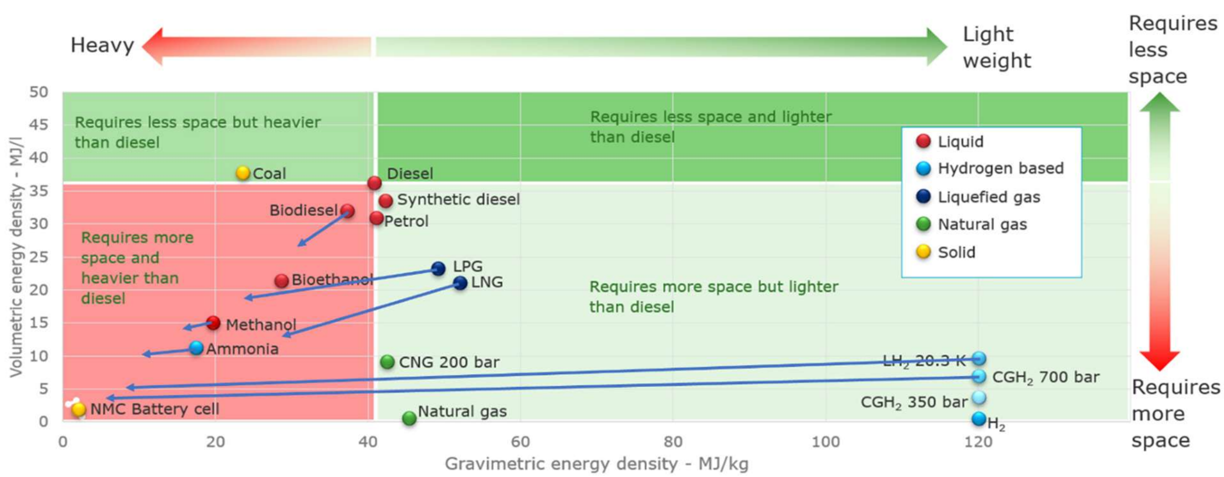
- Internal Engine Technologies:
    - High-Pressure Turbocharging: Implementing a two-stage turbocharging system with an extreme Miller cycle can reduce NOx emissions by 40–50% and improve fuel efficiency by 4–8% across the engine's operating range.
    - Exhaust Gas Recirculation: This technique reduces NOx emissions by about 60% by recirculating cooled exhaust gases into the combustion chamber, thus lowering cycle temperatures. However, it increases fuel consumption by 8% and can lead to significantly low-load smoke emissions.
- Water Injection Technologies:
    - Water Injection: Water directly injected into the combustion chamber acts as a temperature damper, reducing NOx by 25–50% with a slight increase in fuel consumption (0.5–2%). Methods include inlet air humidification, water/fuel emulsions, and direct water injection.
- Aftertreatment Solutions:
    - Selective Catalytic Reduction: This approach is highly effective, reducing NOx emissions by up to 95% (typically 80–85%) by injecting urea into the exhaust, which decomposes into ammonia and reacts with NOx on a catalytic substrate. Challenges include maintaining exhaust temperatures and managing potential clogging or blue haze formation.
    - Scrubbers: For SOx removal, both dry and wet methods are used, with wet scrubbers being more feasible. These systems can operate in a closed loop with zero discharge in enclosed areas but may increase back pressure and fuel consumption.
- Dual-Fuel Engines: These engines can run on both natural gas and HFO. In natural gas mode, they reduce NOx emissions by 85%, virtually eliminate SOx emissions, and lower CO2 emissions by 30%.

While no single technology may suffice to meet IMO Tier III standards on its own, a combination of methods (like SCR, dual-fuel engines, and optimized turbocharging) holds the most promise. For a four-stroke medium-speed engine over a 25-year operation period, with assumed fuel prices and operating profiles, the most promising solutions include (a) dual-fuel engines (running on natural gas in emission control areas), and (b) combinations of two-stage turbocharging and SCR (Wik, 2010).

6.3 Alternative Fuel Overview

Alternative fuels offer a viable option for reducing total emissions. Figure 23 (Anders, 2019) illustrates a comparative view of alternative fuels based on volumetric and gravimetric energy density, two critical properties that affect ship design and fuel storage infrastructure. The arrows in the figure illustrate how energy density is affected when accounting for real-world storage systems. Fuels requiring specialized storage—such as pressurization or cryogenic containment—experience significant reductions in effective gravimetric energy density, with liquid hydrogen (LH2) being particularly impacted.

The ideal marine fuel would be both lightweight and space efficient, occupying the top right quadrant of the graph. However, most low-carbon fuels entail trade-offs, particularly regarding storage volume and retrofitting complexity.



Source: Anders (2019)

Figure 23. Energy Densities for Different Energy Carriers

Common alternative fuels include:

- Biofuel: Biofuel is a general term that encompasses a wide variety of liquids and gases derived from biomass or bio-waste. This includes fatty acid methyl ester (FAME) biodiesel, hydrotreated renewable diesel, Fischer-Tropsch diesel, dimethyl ether, and bio-methanol (Alfa Laval, 2021). FAME, commonly known as biodiesel, is derived exclusively from lipids such as vegetable oils (e.g., palm oil, soybean oil, and rapeseed oil), animal fats (e.g., tallow oil), and used cooking oil. With an energy density similar to traditional marine diesel, biodiesel is compatible with existing engines and requires minimal modifications. Hence, among various biofuels, this study focused on biodiesel to evaluate its potential as an alternative fuel.
- LNG: Primarily composed of CH4, LNG is a cleaner fuel that produces fewer CO2 emissions and significantly reduces SOx and NOx. However, it requires cryogenic storage and specialized tanks, making retrofitting challenging. LNG is more energy dense than hydrogen, but less than marine diesel.
- Methanol (CH3OH): A liquid at ambient temperatures, methanol is easier to store than LNG and emits less CO2, SOx, and NOx. It can be produced from renewable sources, but its lower energy density requires more storage capacity on ships.
- Ammonia (NH3): Ammonia is a zero-carbon fuel during combustion, releasing only nitrogen and water vapor. However, it is toxic, challenging to handle, and requires substantial storage volume due to low energy density. Ammonia production is energy intensive and typically fossil fuel based, but green ammonia (produced with renewable energy) is being developed.
- Hydrogen (H2): Hydrogen is a zero-emission fuel when produced from renewable sources. Nonetheless, it has low energy density, requires high-pressure or cryogenic storage, and has limited existing infrastructure for hydrogen bunkering. Hydrogen is suitable for fuel cells but challenging for long voyages due to storage constraints.

6.3.1 Energy Density Summary

Table 28 (Blue Sky Maritime Coalition, 2022) summarizes the volumetric energy densities of common alternative fuels, expressed as a percentage relative to marine diesel. These metrics are critical when evaluating the feasibility of each fuel for maritime applications, especially for long-haul shipping, where onboard storage capacity is a major constraint. This project focused on analyzing the potential of biodiesel, LNG, and hydrogen to reduce emissions. Biodiesel, with 95% of diesel's energy density, is nearly drop-in ready and compatible with existing engines; LNG has a competitive fuel price with diesel and offers substantial NOx and SOx reductions despite a lower energy density (54%); and hydrogen, though presenting the lowest energy density (23%), stands out as a long-term zero-emission fuel when sourced renewably. These three fuels capture the trade-offs between immediate implementation and long-term sustainability.

Table 28. Volumetric Energy Density of Various Alternative Fuels

Fuel	Energy Density as a Percentage of Marine Fuel
Marine Diesel	100%
Biodiesel	95%
LNG	54%
Methanol	39%
Ammonia	39%
Hydrogen	23%

6.4 Alternative Fuels—Biodiesel

6.4.1 Advantages

Among various alternative fuels, biodiesel offers one of the most seamless transitions from traditional maritime fuel due to its high energy content and practical use in current systems. Biodiesel can be produced from various sources. Common crop-based sources include soy, rapeseed, and palm oil (Zhang et al., 2022). Algae-derived biodiesel is attracting more attention due to its high fuel yield per acre and its ability to grow on non-arable land (Khan et al., 2012). The advantages of biodiesel include:

- High Energy Content: Biodiesel retains approximately 95% of the energy density of traditional diesel, making it one of the most compatible alternatives in terms of fuel efficiency.
- Renewability: Biodiesel is derived from renewable sources, such as plants, waste oils, and algae, which can be replenished in a few years.
- Compatibility: Certain biodiesels, such as hydrotreated vegetable oil, are chemically similar to conventional diesel and can be used in existing diesel engines without modifications, unlike alternative fuels like hydrogen or ammonia (Lapuerta et al., 2011; No, 2014; Szeto & Leung, 2022; Zeman et al., 2019).

Biodiesel from waste oils and specific crops can reduce emissions compared to petroleum-based diesel due to differences in the chemical composition and combustion characteristics of biodiesel. The following list describes the reduction that can be achieved by biodiesel.

- SOx: Biodiesel typically has much lower sulfur content than petroleum-based diesel. This results in reduced SOx emissions when burned, contributing to cleaner air and fewer acid-rain-forming compounds.
- PM: Biodiesel generally produces fewer particulate emissions compared to traditional diesel because biodiesel contains fewer aromatic hydrocarbons and a higher oxygen content, which leads to more complete combustion (Agarwal et al., 2015).
- CO: The combustion of biodiesel tends to produce less carbon monoxide compared to fossil diesel, contributing to better air quality. This is due to biodiesel's higher oxygen content, which promotes more complete combustion, thereby contributing to improved air quality. However, the extent of the reduction can vary depending on the engine type, operating conditions, and biodiesel blend ratio.
- CO2: Biodiesel, especially from waste oils and certain crops, offers significant reductions in CO2 because the plants used to produce the feedstock (such as soy, rapeseed, or algae) absorb CO2 during their growth phase. Such life-cycle carbon emissions help offset the CO2 emissions produced when biodiesel is combusted in engines. This results in a net reduction of CO2 emissions.
- NOx: NOx emissions from FAME biodiesel combustion vary, sometimes resulting in higher NOx emissions depending on the engine and the biodiesel blend (Zhou et al., 2020).

6.4.2 Challenges

Despite its advantages, the use of biodiesel may raise concerns over feedstock sustainability and land use. Biofuel production requires significant resources such as land, water, and fertilizers. Large-scale biofuel production also competes with agriculture for arable land, potentially reducing land available for food production.

Biodiesel provides a renewable and lower-emission alternative to traditional marine fuels. There are two common types of biodiesel blends: B20 and B100, where B20 contains 20% and B100 contains 100% biodiesel. Compared with B100, B20 offers several advantages:

- It is more economically feasible since it contains only 20% biodiesel.

- It is compatible with most modern engines, requiring minimal modifications.
- It retains 99% of the energy density of traditional fuel, compared to 90−95% for B100 (American Bureau of Shipping, 2021).

To evaluate the emission reductions achieved by biodiesel, this project estimated the emission reductions for B20, as shown in Table 29. It is worth noting that these changes represent averaged values because factors such as engine type, engine load, combustion characteristics, and presence of emission control technologies (e.g., filters) can significantly influence the percentage changes in emissions.

Table 29. Emission Reduction Achieved by Biodiesel (B20)

Pollutant	Change (%)	Reference
PM2.5, PM10	16% ↓	Agarwal et al. (2015); Jayaram et al. (2011); Morris & Jia (2003)
SOx	90% ↓ * 20% = 18% ↓	Zhou et al. (2020); U.S. Department of Energy (2025a)
VOC	20% ↓	Antares Group Inc. (2004)
NOx, CO	No statistically significant change	Jayaram et al. (2011)
CO2	15% ↓	U.S. Department of Energy (2011)

6.5 Alternative Fuels—LNG

6.5.1 Advantages

LNG has gained more attention due to its ability to meet regulated emission limits. Notably, IMO set a sulfur content limit of 0.5% by weight for fuels used by OGVs starting in 2020 (Energy Information Administration, 2020). Additionally, within MARPOL sulfur ECAs, OGVs must use fuels with a sulfur content of less than 0.1%. LNG meets these standards with its favorable low sulfur content (0.004%) (Carr et al., 2023). Compared with diesel fuel, LNG can reduce the following pollutants (Ahmadi Ghadikolaei et al., 2016):

- CO2 can be reduced by 20% due to lower carbon content (Papadimitriou et al., 2015).
- NOx can be reduced by 50–80%, depending on the engine technology and with the use of exhaust gas recirculation or SCR systems (Papadimitriou et al., 2015).
- PM can be reduced by about 75–95% compared to HFO (Papadimitriou et al., 2015).
- SOx can be reduced by 90–100% (Papadimitriou et al., 2015).

The pollutant reduction is associated with engine types (Balcombe et al., 2021). Despite concerns regarding the potential increase of methane from LNG, the overall GHG emissions can be reduced by up to 20−27% for two-stroke slow-speed engines and 12−21% for four-stroke medium-speed engines compared with the use of HFO (Sphera GmbH, 2020).

6.5.2 Challenges

Nevertheless, there has been considerable debate about the well-to-wake total emissions of LNG. Although LNG shows reductions in CO2, NOx, SOx, and PM during ship operation, known as tank-to-wake emissions, its well-to-wake emissions, which consider the entire life cycle, may not be favorable. This concern is raised due to the potential methane slip (Kuittinen et al., 2023). Methane can escape into the atmosphere during the production, transportation, and combustion of LNG (Jensen et al., 2021; Schuller et al., 2019).

The application of LNG faces challenges from the perspective of engine, tank, and system costs, as well as a lack of LNG bunkering infrastructure (IMO, 2016). LNG cannot be directly used in diesel fuel tanks because it requires pressurization, necessitating additional costs to retrofit the vessel and fuel system. Considering the vessel's lifespan, replacing old ships is unlikely to be economically feasible. Moreover, LNG has a lower energy density compared to fossil fuel, meaning the vessel must carry a substantially higher fuel volume, along with new tanks, fuel systems, and safety equipment. Overall, vessel categories with greater flexibility regarding weight, space (above or below deck), and balance constraints are more likely candidates for retrofitting to accommodate alternative fuels (Blue Sky Maritime Coalition, 2022).

6.6 Alternative Fuels—Hydrogen

6.6.1 Advantages

Hydrogen has the potential to enable the transition from fossil fuels to carbon-free energy sources (Chen & Lam, 2022). When used in fuel cells, hydrogen produces no SOx, NOx, or PM. Additionally, hydrogen can be generated from a variety of renewable sources, such as water electrolysis powered by wind, ocean currents, and solar power. Such production from renewable sources is often regarded as "green hydrogen" (Acar & Dincer, 2022).

For ship refueling, wind power has been the focus of the research community for hydrogen production (Ortiz-Imedio et al., 2021; Pérez-Vigueras et al., 2023). Depending on water depth, bottom-fixed wind platforms are used in areas below 200 m, while floating platforms are deployed for depths exceeding this threshold. Typically, an offshore plant for producing liquid hydrogen includes a wind power plant to generate renewable electricity, a water treatment unit for demineralizing water, an electrolyzer to produce hydrogen, and a hydrogen liquefaction plant for storing and distributing hydrogen to ships. The size of wind farms is scaled to meet the hydrogen demand of ships (Bonacina et al., 2022; Wang & Pan, 2022).

6.6.2 Challenges

Despite its advantages, hydrogen presents several challenges as a marine fuel:

- Due to its low energy density, it requires costly high-pressure or cryogenic storage systems that demand more space and increase costs.
- Green hydrogen is still too costly to produce at a large scale.
- Hydrogen is also highly flammable and prone to leaks, requiring strict safety measures that increase complexity and expenses.

Given the current infrastructure constraints and limited storage capacity on ships, hydrogen is best suited for short-sea shipping or as part of a hybrid system with traditional fuels. This study aimed to explore its potential use in HBC and assess the resulting emission reductions.

6.6.3 Hydrogen Adoption Strategies

Given the current infrastructure constraints and limited storage capacity on ships, hydrogen is most suitable for short-sea shipping or as part of a hybrid system with traditional fuels. This project explored the application of hydrogen in HBC at the POH and evaluated emission reduction potential under two hydrogen adoption strategies:

- Full Hydrogen (Fuel-Cell Based): This strategy utilizes fuel cells powered exclusively by LH2. While offering zero-emission operation, it requires substantial onboard storage, extensive bunkering infrastructure, and significant capital investment.

  - HyZET tugboat: Lee (2023, 2024) analyzed the potential and cost of a hydrogen-powered tugboat (HyZET tugboat), estimating the hydrogen demand for a tugboat operating in the San Pedro Port Complex. The HyZET tugboat, with a capacity of 4,000 kg of hydrogen, can produce a maximum output of 5,100 KW, which is sufficient to replace some diesel-powered tugboats (Crowley, 2023).
- Hybrid Hydrogen (Dual-Fuel and Battery-Fuel-Cell Systems): To address the storage and range limitations of full hydrogen systems, hybrid hydrogen configurations have been developed. These systems combine hydrogen with either diesel engines or battery-electric powertrains, offering greater flexibility and reduced emissions.
  - Hydrotug 1 (CMB.TECH, 2024): This dual-fuel tugboat uses engines capable of co-combusting compressed hydrogen (CH2) and diesel. With an 85% hydrogen blend by mass, hydrogen accounts for over 94% of the vessel's total energy output due to its high energy density. Equipped with 415 kg of CH2, the tugboat can switch seamlessly to full diesel when hydrogen is unavailable, ensuring uninterrupted operations (Anglo Belgian Corporation, 2025).
  - ELEKTRA (EST-Floattech, 2021): This battery-electric pushboat supplemented with hydrogen fuel cells combines a 1,025 kW battery with a hydrogen fuel-cell system, delivering 1,325 kW of hybrid power. In battery-only mode, ELEKTRA can operate for 65 km over an 8-hour period, while hydrogen mode extends the range to over 100 km across a 16-hour day. This configuration enables zero-emission operation without relying on diesel, making it a clean and flexible option for inland and near-port applications.

By comparing these two strategies, this study evaluated the trade-offs between emissions impact, infrastructure readiness, and operational feasibility for hydrogen adoption in POH's HBC fleet.

6.7 Electrification

Electrification of maritime vessels offers a promising pathway to reduce emissions and improve operational efficiency. Electric propulsion systems, especially those with variable speed control, maintain efficiencies of up to 95% across a wide operating range. In contrast, internal combustion engines are much less efficient (typically up to 40%), with their best efficiency achieved only at higher loads and dropping sharply at lower loads, resulting in greater overall losses compared to electric systems. This makes electric propulsion a clear advantage for maritime applications (Hansen & Wendt, 2015).

6.7.1 Electrification Strategies

Electric propulsion systems for vessels can be categorized into full electric and hybrid electric configurations (Cherchi et al., 2021):

- Full Electric Systems: Full electric vessels are powered entirely by onboard batteries or energy storage systems. These vessels produce zero emissions during operation and are particularly suitable for short-distance harbor operations where frequent charging is feasible. Several full electric tugboats have already been introduced to the market:
    - eWolf (Crowley): This tugboat offers 4,200 kW of installed power and a 6,200 kWh battery capacity, with a charging time of 4.5 hours (Crowley, 2024a; Haun, 2024).
    - SAAM Volta and Chief Dan George (SAAM Towage): This vessel features 3,600 kWh batteries, with fast charging capabilities in 1–2 hours (Marine Log, 2024).
    - RSD-E Tug 2513 (Damen): This tugboat delivers 4,200 kW using a 2,800 kWh battery system, charging fully in just 2 hours (Damen, 2024).
- Hybrid Electric Systems: Hybrid electric vessels combine battery-electric propulsion with traditional engines (diesel or hydrogen) to extend range and ensure operational flexibility. These systems can operate on electricity during low-demand or idle periods and switch to combustion power for long-duration or high-energy missions:
    - Green Diamond (Kirby Inland Marine): This hybrid pushboat pairs a 1,243 kW battery system with a 1,600 hp (1,200 kW) diesel engine. It operates along the full 52-mile HSC and charges in approximately 6 hours (Ervin, 2023).
    - Hybrid eTug (Crowley): This hybrid tugboat combines a 4,520 kWh battery system with a diesel backup engine that can generate 2,260 kW (Crowley, 2024b).

While smaller vessels can rely on solar photovoltaic systems, larger vessels often require high-capacity batteries or hybrid configurations to meet performance demands (Koričan et al., 2023; Qazi et al., 2023).

6.7.2 Advantages and Challenges

Electrochemical batteries, particularly lithium-ion, are the most widely used energy storage systems in maritime electrification due to their maturity, cost-effectiveness, and favorable energy density. Lithium polymer batteries provide even higher energy density but come with trade-offs including higher costs, shorter life spans, and more complex disposal requirements (Chin et al., 2019).

While battery technology presents clear advantages, it also has environmental impacts and specific characteristics that need to be considered, such as energy density, number of battery cycles, cost, fast charging ability, and safety (Devarapali, 2024). Perčić et al. (2022) observed that electrifying a ship with a Li-ion battery can reduce CO2 emissions by 46% and NOx emissions by 98% compared to diesel power systems. However, there is an observed increase in SOx emissions of around 13%, primarily due to the manufacturing processes involved in battery production.

Despite these limitations, ongoing advancements in battery chemistry, system integration, and life-cycle recycling are helping to mitigate environmental trade-offs. As the technology matures and supporting infrastructure expands, battery-electric systems are becoming increasingly viable and sustainable solutions for decarbonizing short-sea and harbor vessel operations.

6.7.3 Operational Considerations

Despite these benefits, several practical constraints must be considered when adopting electric propulsion systems in tugboats and pushboats:

- Working Duration: Due to limited onboard battery capacity, full electric tugboats are more appropriate for operations with moderate energy requirements. Vessels with high duty cycles may require hybrid configurations or rapid charging solutions to avoid service interruptions.
- Hotelling Duration: Adequate idle time at berth is critical for recharging. Charging duration is influenced by both battery size and onshore charging infrastructure capabilities. Long hotelling periods can ensure full recharges and uninterrupted subsequent deployment (Hayton, 2023).

6.8 Vessel Speed Control

IMO designated ECAs in U.S. waters in 2010 to reduce marine emissions. While these regulations do not impose speed limits, higher speeds typically result in higher fuel costs, causing more emissions (Bialystocki & Konovessis, 2016). Therefore, speed reduction strategies have emerged as effective operational measures for emission mitigation.

6.8.1 Optimal Speed Management

Several studies researched the optimal speeds and routes within ECAs. For example:

- Fagerholt and Psaraftis (2015) analyzed the relation between optimal speeds and fuel costs for vessels using HFO outside an ECA and switching to low-sulfur fuel inside the ECA. The results showed that an increase in the price of HFO leads to a decrease in the optimal speed.
- Zhen et al. (2020) introduced a bi-objective mixed integer linear programming model, with a dual focus on optimizing navigation routes and speeds within and outside ECAs, seeking to minimize the cost of fuel while mitigating SO_2 emissions.
- Similarly, Ma et al. (2020) proposed an optimization model for vessel speed schemes inside and outside ECAs, seeking to optimize ship routes and speeds to minimize total navigation costs. The channel was separated into several segments to consider the influence of local winds and waves. The authors further suggested a multi-objective model to achieve a trade-off between a ship's total costs and total emissions of CO_2 and SO_x (Ma et al., 2021).
- Yang et al. (2020) considered the weather forecast, including wind and irregular waves, for an upcoming voyage. Two main functions were included for optimization: (a) fuel consumption function: the relationship between fuel consumption rate and sailing speed; and (b) sailing time function: the relationship between sailing time and sailing speed.

6.8.2 Advantages of Speed Reductions

Normally, vessel speeds are limited to below 12 knots because this measure can reduce emissions more effectively. Chang and Wang (2012) analyzed the relationship between vessel speed, travel time, and fuel consumption, concluding that the optimal speed for emission reductions lies between 11 and 12 knots. Their results showed that lowering vessel speed could cut CO_2 emissions by about 68.5%, while PM and NO_x were each reduced by roughly 68.3%, and SO_2 decreased by 55.4%. These findings highlight that speed reduction is one of the most direct and practical operational strategies available to shipping companies for lowering both fuel costs and environmental impacts. In addition, lowering vessel speed can reduce engine wear by lowering mechanical stress, potentially extending engine service life.

6.8.3 Policy-Based Speed Control Strategies

Aside from ECAs, relevant policies to limit vessel speeds or facilitate smooth vessel navigation are proposed, including:

- Vessel Speed Reduction Program (VSRP) or Vessel Speed Reduction Incentive Program (VSRIP): The objective of a VSRP is to mitigate diesel PM and NOx emissions from OGVs by implementing speed reductions as they near or depart the port, typically within a range of 20 to 40 nautical miles (nm). Some ports will provide incentives, such as discounts on dockage fees, to encourage speed reduction, known as a VSRIP.
- Virtual Arrival (VA): The VA approach is used in maritime operations to improve efficiency in shipping, thereby reducing unnecessary emissions. VA allows vessels to adjust their speed during voyages to meet the required time of arrival at their destination, considering known delays at the port. For instance, if berth congestion is expected, VA can advise the vessel to slow down during transit, thereby reducing fuel consumption and emissions without affecting the actual docking schedule (Shao et al., 2024). One study observed that adopting the VA strategy along with implementing a carbon tax, VSRIP, and ECA policies can significantly reduce emissions (Han et al., 2023).
- Carbon Tax Policy: The carbon tax policy is not directly related to speed control, but the produced carbon tax can pose incentives to vessel operators to reduce their operational speeds.

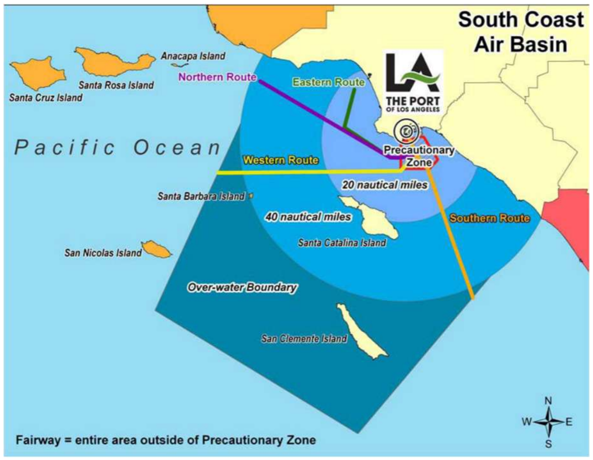
6.8.4 Port Case Studies and Incentive Programs

Several ports have adopted a VSRP to reduce emissions, as shown in Table 30 and Figure 24. Although navigating at the speed of 12 knots can reduce emissions the most, considering travel time lost, storage cost, or other costs, it may not be financially viable for each vessel. To encourage VSRP adoption and decrease vessel speeds, these ports offer incentives to vessel operators, such as discounts on dockage fees. These incentive schemes reportedly result in compliance rates exceeding 90% (U.S. EPA, 2021).

Table 30. Speed Limit, Zone Size, and Incentive of Vessel Speed Reduction Programs for Different Ports

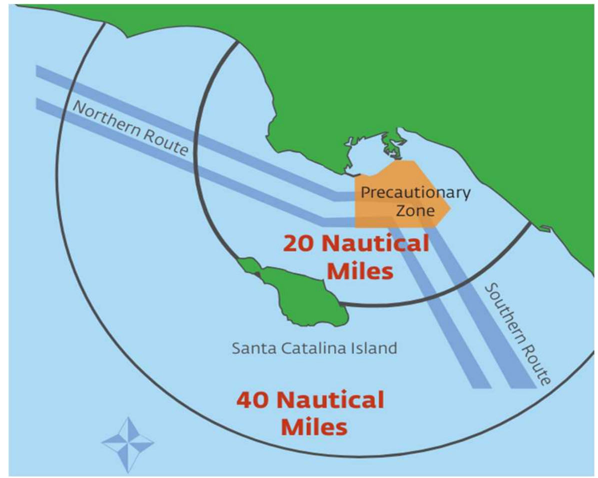
Port	Speed Limit	Zone Size	Incentive
Los Angeles	12 knots	20 nm or 40 nm from Point Fermin	Based on actual compliance performance, vessel operators will qualify for either the Tier 1 (20 nm) or Tier 2 (40 nm) incentive (Port of Los Angeles, 2008)
Long Beach	12 knots	20 nm or 40 nm from the Port of Long Beach (Green Flag Program)	Operators with 90%+ compliance within 20 nm over a year get a 15% dockage discount the next year; within 40 nm, they get a 25% discount (Port of Long Beach, 2019, 2022)
San Diego	12 knots (15 knots for cruise)	Starts at 40 nm from Point Loma to the port	This is a voluntary speed reduction program (U.S. EPA, 2021)
New York & New Jersey	10 knots	Starts at 20 nm outside the Territorial Sea Line to the port	Operators get financial rewards based on the Environmental Ship Index (Port of New York & New Jersey, 2013)

Los Angeles



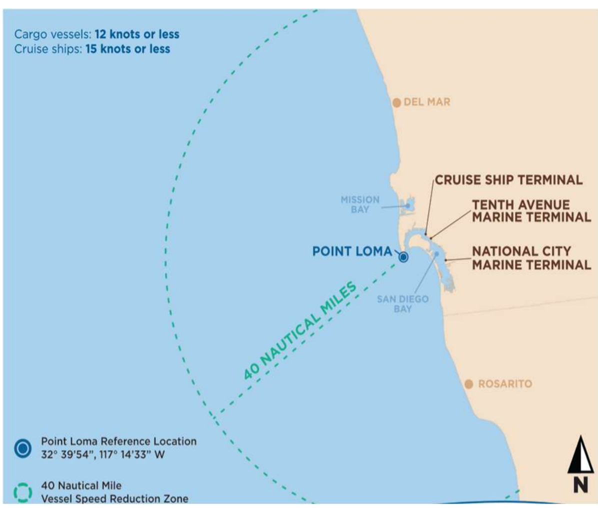
Source: Port of Los Angeles (2008)

Long Beach



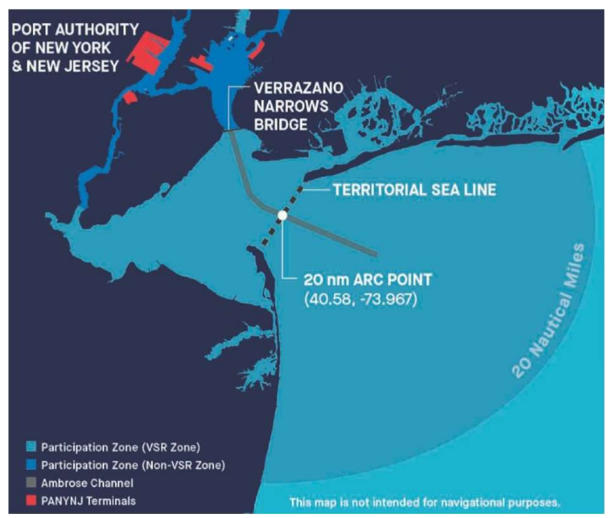
Source: Port of Long Beach (2019)

San Diego



Source: U.S. EPA (2021)

New York & New Jersey



Source: Port of New York & New Jersey (2013)

Figure 24. Vessel Speed Reduction Zones for Different Ports

6.9 Summary

To effectively reduce emissions, different ship types require tailored strategies based on their specific functions and operational patterns, as summarized in Table 31 (Blue Sky Maritime Coalition, 2022). Generally, HBC are more suitable for electrification, while OGVs benefit more from hybrid engines or retrofits for alternative fuels such as LNG, hydrogen, or ammonia. Most importantly, the successful implementation of these measures necessitates collaboration among port authorities, improvements in electricity infrastructure, and incentives for ship owners.

Effective emission reduction in maritime operations requires tailored strategies that reflect the functional characteristics and operating patterns of each ship type. As summarized in Table 31 (Blue Sky Maritime Coalition, 2022), HBC are generally more suitable for full electrification due to their shorter operating ranges and frequent port visits. In contrast, OGVs often benefit more from retrofitting to use alternative fuels such as LNG.

The implementation of these strategies requires collaboration among stakeholders and incentive programs that encourage shipowners to invest in cleaner technologies.

Table 31. Potential Emission Reduction Strategies by Ship Type

Ship Type	Function	Potential Strategy
Bulkers, containers, tankers, and ROROs	Transport heavy cargo over long, ocean-going voyages	• Electric Shore Power: Use shore power while docked to reduce emissions • LNG: Lower emissions and cost-effective for long-duration ocean voyages • Biofuels: Renewable energy source to reduce carbon footprint
Cruise vessels	Provide long-duration transportation for passengers and vehicles	• Electric Shore Power: Use shore power while docked to reduce emissions • LNG: Lower emissions for long voyages • Biofuels: Renewable energy source to reduce carbon footprint
Offshore supply vessels	Transport crew, equipment, and drilling supplies to offshore energy sites with long operation times	• LNG: Lower emissions and cost-effective for long operations • Hybrid Diesel Electric Engines: Efficient for dynamic positioning, reducing fuel consumption and emissions during active positioning tasks
Coastal and harbor tugs	Push or pull cargo in coastal areas, which are typically active for short durations	• Electrification: Electric propulsion systems reduce emissions and are suitable for short, high-power operations
Harbor ferries	Provide short-duration transportation for passengers and vehicles	• Battery Exchange or Recharge: Quick and efficient for short routes, reducing emissions significantly

7. EMISSION REDUCTION STRATEGIES: EVALUATION

7.1 Shore Power/Cold Ironing

Shore power, also known as cold ironing, presents a viable strategy for reducing emissions from OGVs or HBC while berthed. During docking, vessels typically run auxiliary engines to supply power for onboard systems. Shore power enables vessels to shut down these engines and instead draw electricity from the local grid, thereby reducing emissions of key pollutants such as NOx, SO2, PM2.5, and CO2.

7.1.1 Hotelling Time Analysis

Shore power can only be applied when vessels are in a hotelling state and are docked at terminals equipped with the necessary electrical infrastructure. To account for connection time and setup, a minimum hotelling threshold of 30 minutes is assumed for shore power to be viable. After this initial connection period, auxiliary engines are assumed to be shut down, enabling direct emission reductions.

Figure 25 presents the aggregate eligible hotelling durations for both OGVs and HBC at various terminals in the POH, highlighting Bayport, Barbours Cut, and Turning Basin Terminals as having the highest potential for shore power adoption. These terminals have extended vessel stays and higher volumes of traffic. Bayport and Barbours Cut are major container terminals, while Turning Basin is equipped with multipurpose facilities to provide steadfast cargo handling opportunities (Port Houston, 2020).

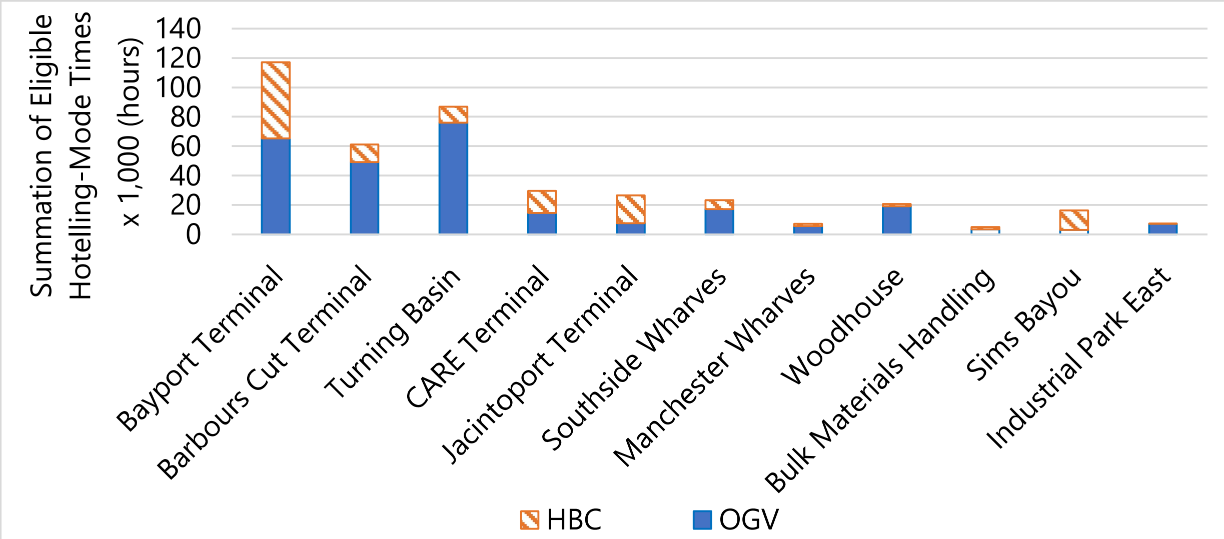


Figure 25. Eligible Hotelling Mode Time at Terminals

Figure 26 illustrates the average eligible hotelling time as a proportion of total annual operating time per vessel type. While OGVs spend less total time at the POH than HBC due to their long-haul operational nature, they typically exhibit longer individual port stays, making them more suitable candidates for shore power. Bulk carriers, general cargo ships, and container ships show the highest proportions of eligible hotelling time due to time-intensive loading and unloading processes. In contrast, tankers, which use pipelines for rapid liquid transfer, tend to have shorter port stays and often operate at non-PHA terminals, which limits their shore power applicability.

Although HBC spend more time at the POH annually, their operations are characterized by intermittent port visits and short layovers. Consequently, the share of eligible hotelling time for shore power use is relatively low for this group.

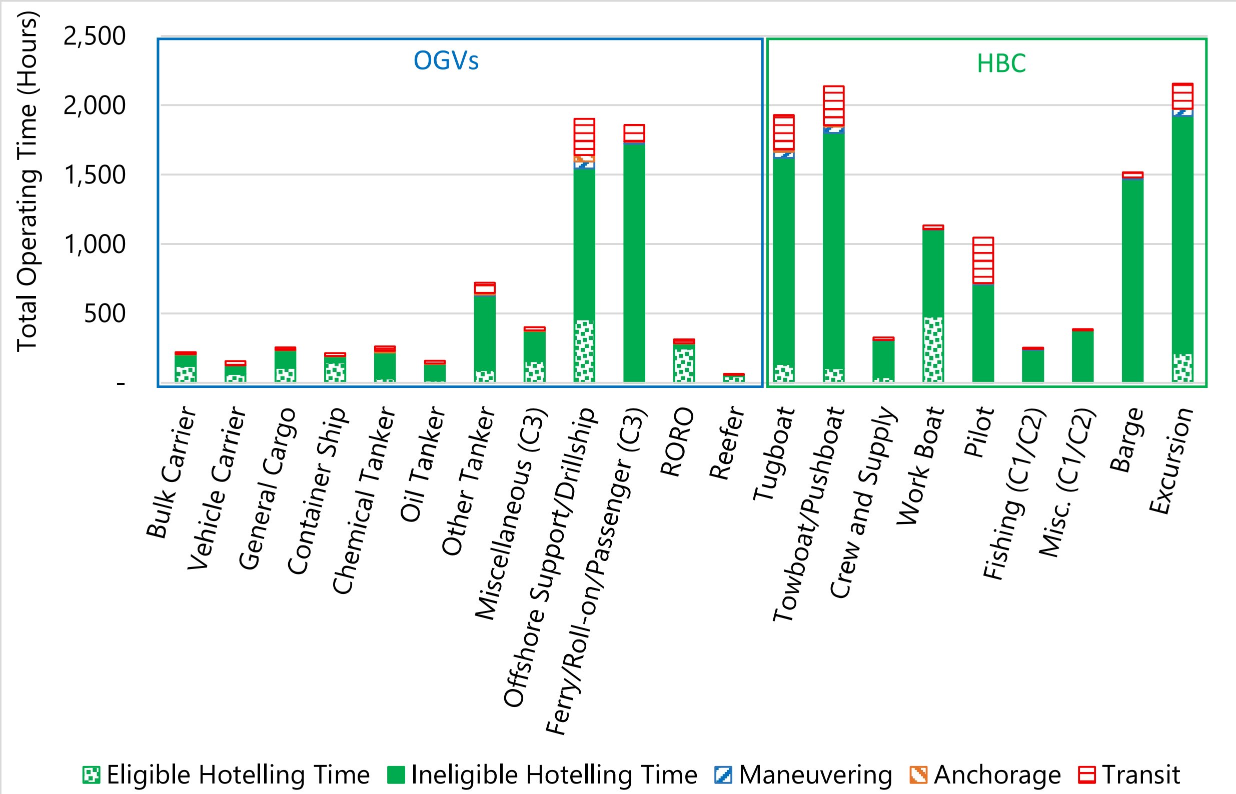


Figure 26. Eligible Hotelling Time for Shore Power per Vessel

7.1.2 Emission Reduction Analysis

This section presents the research team's evaluation of the emission reduction potential of converting eligible hotelling durations into avoided auxiliary engine emissions. The analysis assumed the following:

- Infrastructure Availability: All terminals at the POH are assumed to be fully equipped with shore power infrastructure without capacity limits.
- Electricity Source: Shore power is supplied through the existing Texas electricity grid without transmission losses. The current grid mix consists of approximately 49.3% natural gas, 22.7% wind, and 12.7% coal (U.S. EPA, 2023).
- Connection Threshold: Vessels are assumed to initiate shore power usage only after the first 30 minutes of hotelling time, accounting for crew setup and system connection procedures.

lTable 32 summarizes the emission factors from Texas power plants (U.S. EPA, 2023). These emissions are considerably lower than those from marine auxiliary engines. For example, NOx emission factors for MGO-fueled engines range from 13.2 g/kWh (Tier 0) to 2.6 g/kWh (Tier 3)—significantly higher than the 0.2 g/kWh from grid electricity. Likewise, grid-based CO2 emissions (335 g/kWh) are roughly half those of marine diesel (657 g/kWh).

Table 32. Emission Factors from Texas Power Plants

Pollutant	lb/MWh	g/kWh
PM2.5, PM10	0.048	0.0218
SO2	0.321	0.1458
VOC	0.0134	0.0061
NOx	0.446	0.2025
CO2	738.038	334.7933
CO	–	0

Note: PM10 is assumed to have the same reduction rate as PM2.5; CO data are typically not reported, so CO is assumed to be 0.

7.1.3 Emission Reduction Outcome

A detailed breakdown of emission reductions by pollutant and vessel type is provided in Appendix B.

Figure 27 shows the OGV emission reduction potential for NOx, PM2.5, CO2, and SO2, highlighting the variation in emission reduction potential across different vessel types. Bulk carriers, general cargo ships, and container ships show the most significant reductions, achieving approximately 30–40% NOx reductions. This high reduction potential stems from their extended port stays since these vessels often handle diverse cargo that requires detailed coordination and longer processing times.

In contrast, tankers show a lower emission reduction potential—around 5–10%—because their port operations are generally more efficient and faster due to direct liquid transfer through pipelines. These shorter port stays limit the eligible hotelling time for shore power use. Moreover, the majority of their activities are associated with non-PHA terminals, which are not eligible for shore power.

Among the pollutants, NOx exhibits the most pronounced reduction because ships produce a significant amount of it, and power plants can remove NOx more easily using existing technology. In comparison, reductions in CO2 emissions are more modest since electricity from the power grid is still largely generated using fossil fuels, particularly natural gas, meaning CO2 emissions are displaced rather than eliminated.

However, the emission reductions for HBC are minimal, as shown in Figure 28. This is mainly because HBC have shorter eligible shore power time and use smaller auxiliary engines. Most HBC engines are rated below 300 kW, while some OGVs use engines over 1,000 kW. As a result, shore power has less impact on reducing emissions for HBC. In addition, HBC have a lower sulfur EF for SO2 than do power plants, meaning that switching to shore power could actually increase SO2 emissions for these vessels.

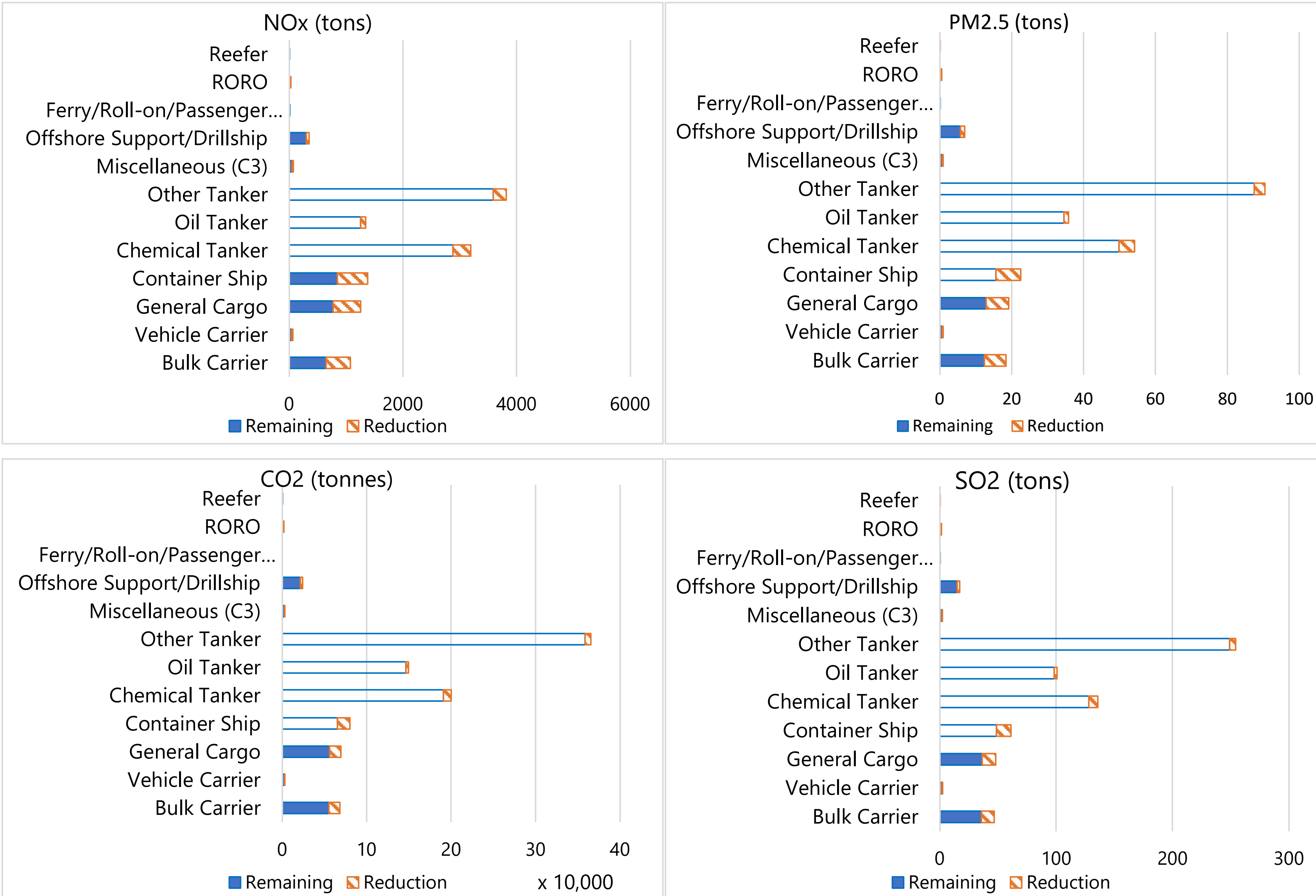


Figure 27. OGV Emission Composition with Shore Power: Potential Reductions versus Remaining Emissions

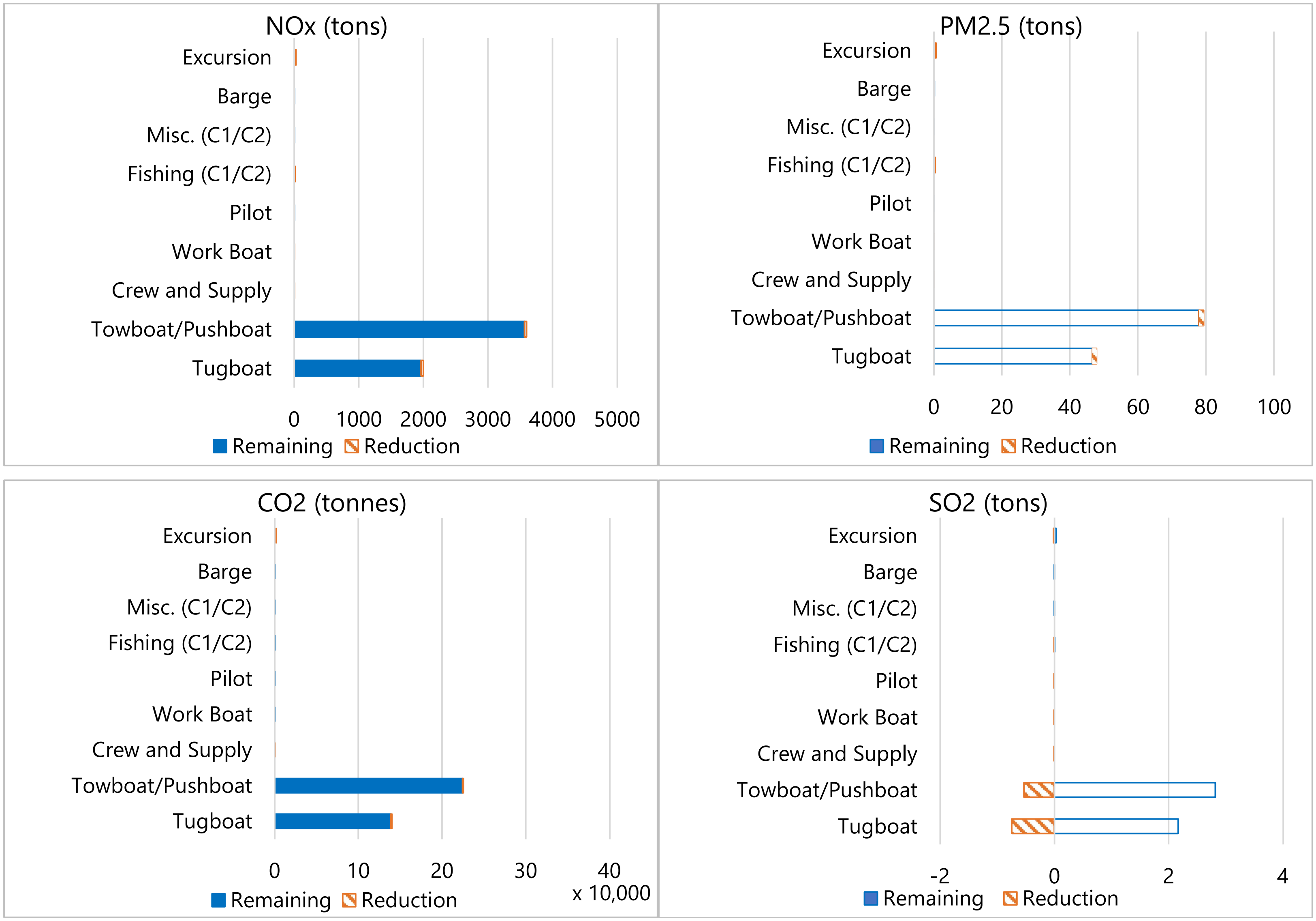


Figure 28. HBC Emission Composition with Shore Power: Potential Reductions versus Remaining Emissions

7.2 Engine Tier Regulation

7.2.1 Vessel Tier Data Description and Tier Upgrade Scenarios

U.S. EPA defines a series of engine tiers (Tier 0 to Tier 4) that regulate emission limits for marine engines, with higher tiers representing more stringent environmental standards. Figure 29 presents the engine tier distribution of vessels operating at the POH in 2022. The data indicate that most HBC are equipped with Tier 0 engines, while OGVs are primarily split between Tier 0 and Tier 1 engines.

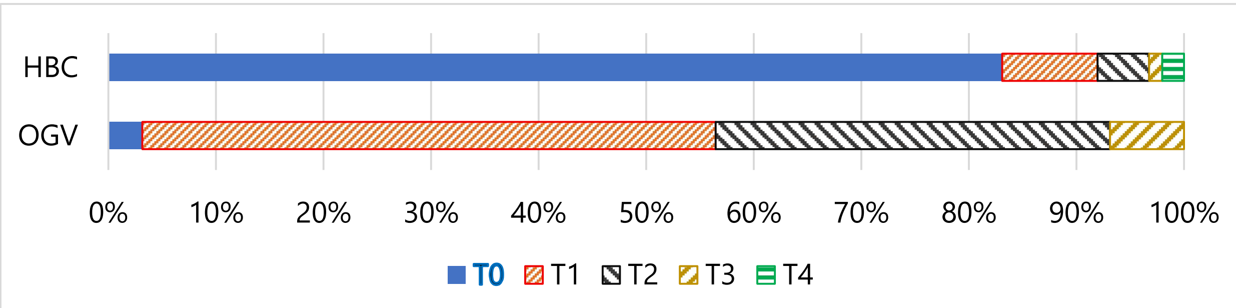


Figure 29. Tier Distribution of OGVs and HBC in 2022

The following upgrade scenarios were developed to estimate potential emission reductions:

- Strategy T1: Upgrade Tier 0 engines to Tier 1 for both OGVs and HBC.
- Strategy T2: Upgrade Tier 0 and Tier 1 engines to Tier 2 for both OGVs and HBC.
- Strategy T3: Upgrade Tier 0, Tier 1, and Tier 2 engines to Tier 3 for both OGVs and HBC.
- Strategy T3/T4: Upgrade Tier 0, Tier 1, Tier 2, and Tier 3 engines to Tier 4 for HBC, with OGVs remaining at Tier 3 (since Tier 3 is the optimal level for OGVs).

7.2.2 Emission Reduction Outcome

The emissions estimation under tier upgrade scenarios provides insights into the potential improvements in air quality. The following list provides an overview of emission reductions, and a more detailed breakdown of emission reductions by pollutant and vessel type is provided in Appendix B. Figure 30 illustrates the estimated emissions of NOx, PM2.5, CO2, and SO2, respectively, across the four scenarios.

- NOx Emissions: Tier upgrades show increasing reductions in NOx emissions across all scenarios, with T3 and T3/T4 scenarios delivering the most substantial reductions, particularly for OGVs.
- PM2.5 Emissions: Tier upgrades notably reduce PM2.5 emissions for HBC, especially in the T3 and T3/T4 scenarios. OGVs, however, see minimal improvement in PM2.5 emissions from tier upgrades alone because fuel types and engine types are more influential in their PM2.5 emissions.
- CO2 and SO2 Emissions: Since CO2 and SO2 emissions are not significantly affected by tier upgrades, they remain largely unchanged across all scenarios, suggesting that CO2 and SO2 reductions require alternative strategies beyond tier-based engine upgrades.

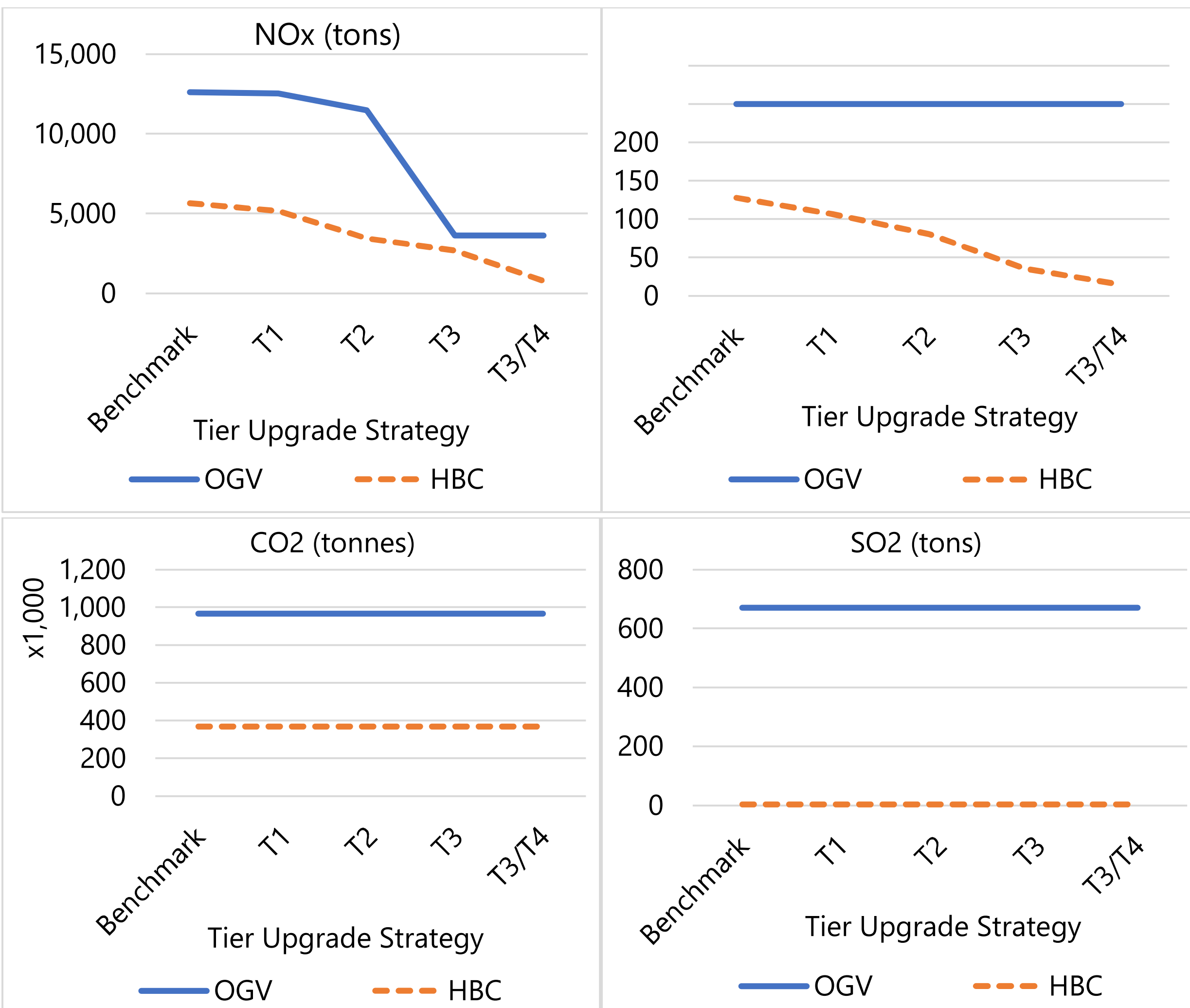
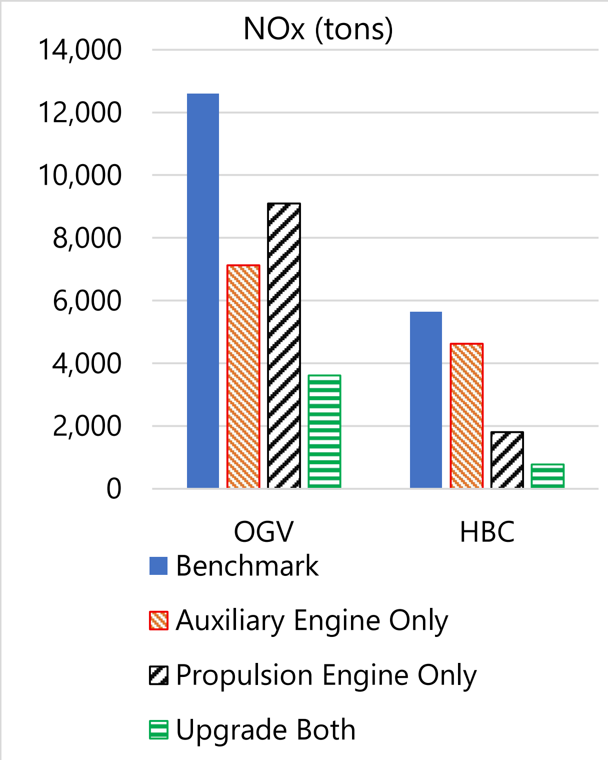


Figure 30. Emissions under Various Tier Upgrade Strategies

7.2.3 Emission Reduction Outcome by Engine Type

The research team evaluated the impact of the T3/T4 upgrade strategy, testing its effectiveness when applied to auxiliary engines only, propulsion engines only, and both, as displayed in Figure 31. Findings included the following:

- NOx Emissions: Upgrading auxiliary engines for OGVs yields greater benefits than upgrading propulsion engines. Because OGVs spend more time berthing in terminals than operating in open water channels in port areas, their auxiliary engines have longer work time, leading to greater NOx reductions while upgrading these engines. In contrast, HBC have more significant reductions when upgrading propulsion engines because the power of propulsion engines is much higher than auxiliary engines, leading to more evident improvement in propulsion engines.
- PM2.5 Emissions: OGVs do not benefit from tier upgrades in terms of PM2.5 reduction. However, for HBC, PM2.5 reductions are pronounced, especially for propulsion.
- CO2 and SO2 Emissions: CO2 and SO2 cannot be improved by upgrading tiers.



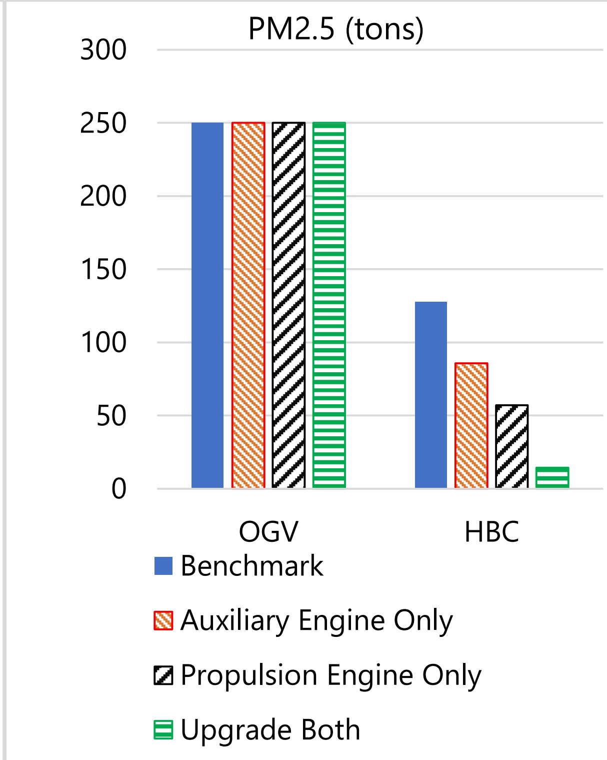


Figure 31. Emissions by Engine Type under T3/T4 Upgrade Scenario

7.3 Alternative Fuels—Biodiesel

7.3.1 Fuel Usage in 2022

Biodiesel has emerged as a promising alternative to traditional marine fuels, offering the potential for substantial emission reductions when used as a replacement for both MGO and RM/HFO (Foretich et al., 2021). To evaluate biodiesel adoption, it is essential to consider the current fuel types utilized by vessels operating within the POH domain.

Figure 32 shows that diesel is the predominant fuel used by both OGVs and HBC based on the fleet composition. Notably, HBC relies entirely on diesel, while among OGVs, the "other tanker" category shows the most significant number of LNG vessels, accounting for approximately 10%.

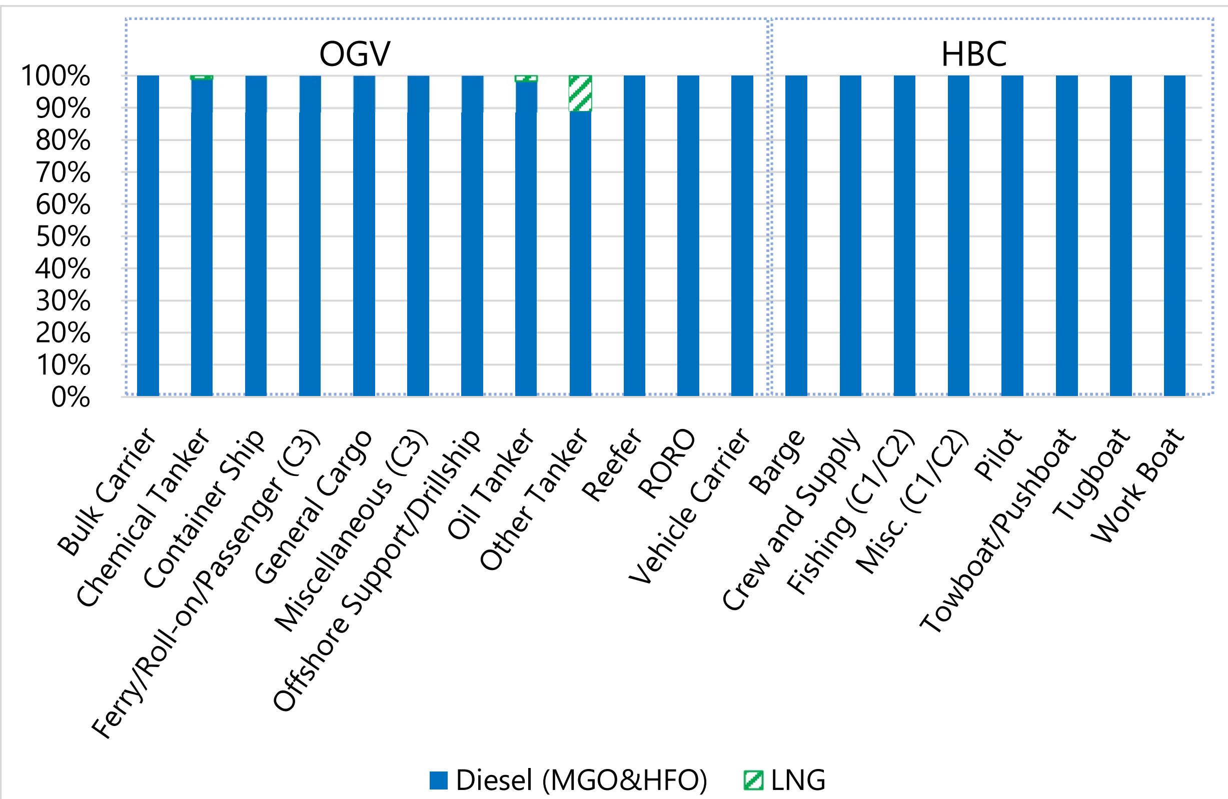


Figure 32. Fuel Usage by Ship Types

7.3.2 Emission Reduction Analysis

Biodiesel can be integrated into marine fuel systems with minimal engine modification. As noted in the literature review, biodiesel blends provide substantial reductions in several pollutants. For this analysis, B20—a blend of 20% biodiesel and 80% petroleum diesel—was selected since it is widely compatible with current marine engines and infrastructure.

Table 33 summarizes the expected reductions in emissions with the use of B20. The reductions in PM, SO2, VOC, and CO2 are particularly noteworthy, while NOx and CO emissions remain largely unchanged due to the nature of combustion in current diesel engines.

In this analysis, vessels currently using traditional diesel were identified, and the B20 emission reduction rates were applied to their baseline emissions.

Table 33. Emission Reduction by Biodiesel

Pollutant	Change (%)
PM2.5, PM10	16% ↓
SO2	18% ↓
VOC	20% ↓
NOx, CO	No change
CO2	15% ↓

7.3.3 Emission Reduction Outcome

A detailed breakdown of emission reductions by pollutant and vessel type is provided in Appendix B. Figure 33 and Figure 34 compare the NOx, PM2.5, CO2, and SO2 for both OGVs and HBC. The results align with the values presented in Table 33 since the majority of vessels use traditional diesels. SO2, PM, NOx, and CO see a notable decrease of approximately 15–20%. NOx and CO emissions, however, show no change when switching to biodiesel.

Given the widespread reliance on diesel across OGVs and HBC, the application of biodiesel offers a meaningful pathway toward lowering maritime emissions—especially in the short term—without the need for extensive retrofitting or operational changes.

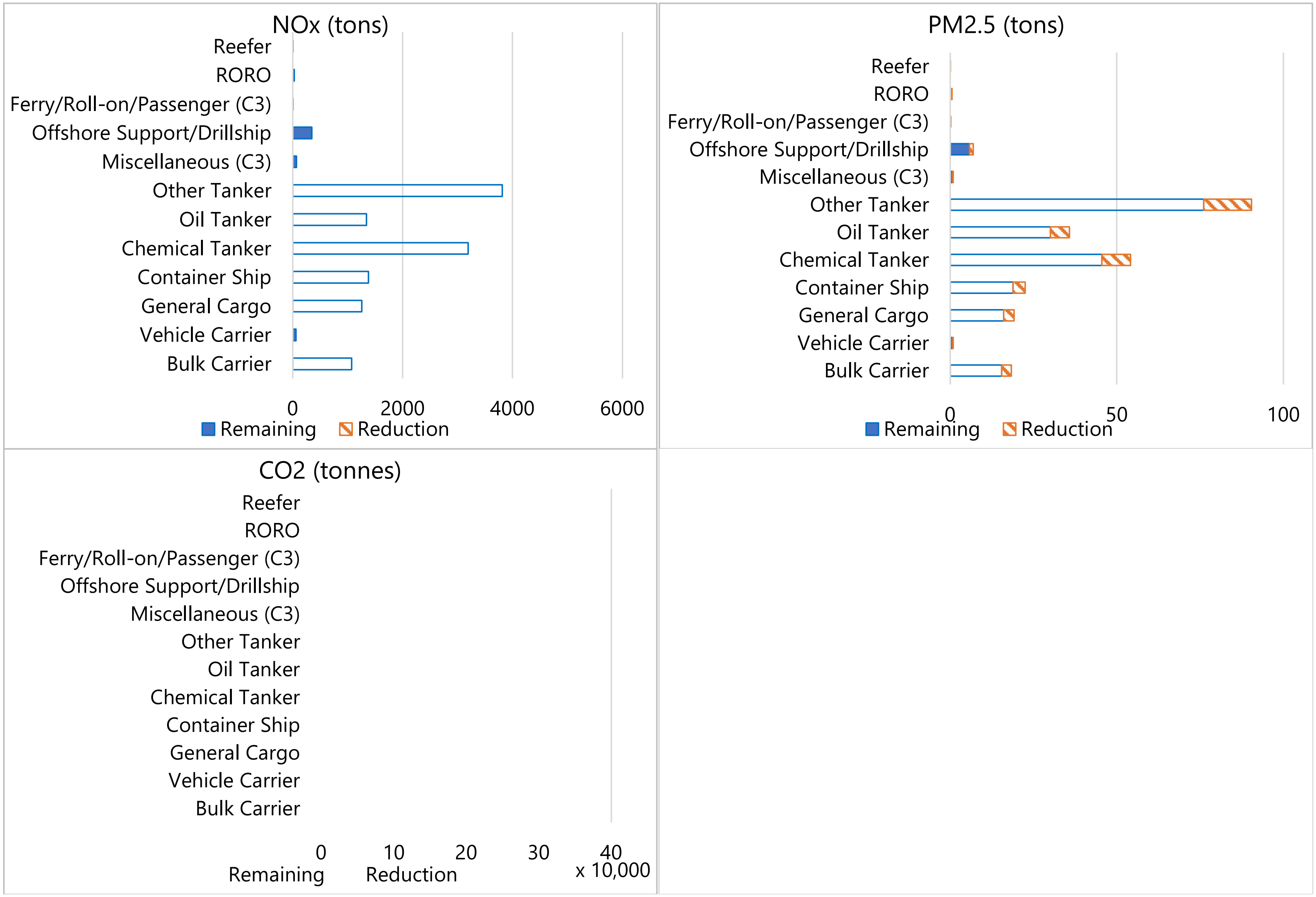


Figure 33. OGV Emission Composition with Biodiesel: Potential Reductions versus Remaining Emissions

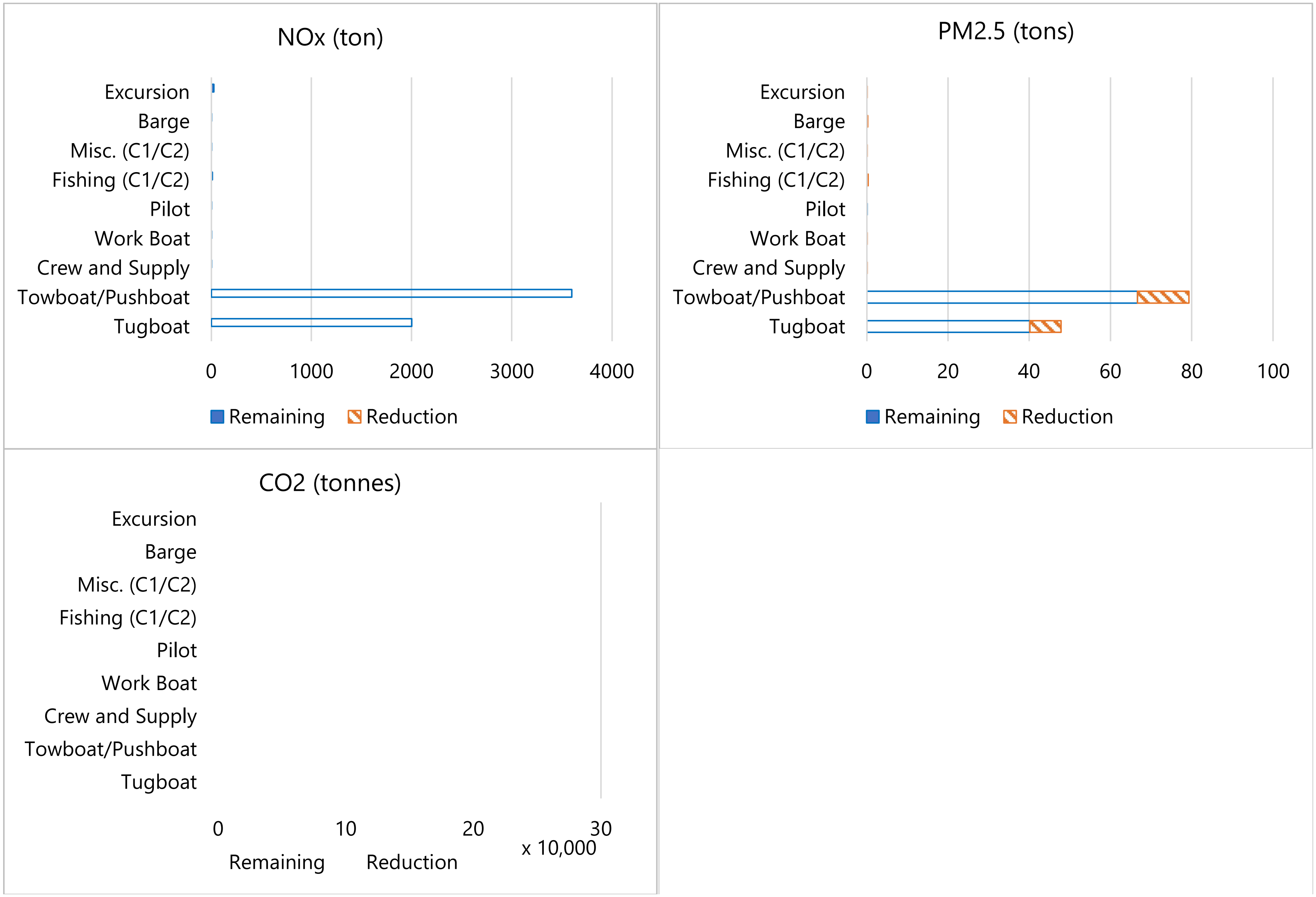


Figure 34. HBC Emission Composition with Biodiesel: Potential Reductions versus Remaining Emissions

7.4 Alternative Fuels—LNG

In the POH domain, only a limited number of vessels utilize LNG as a primary fuel. The adoption of LNG faces several practical and economic challenges, including the high capital cost of retrofitting or designing LNG-compatible engines, limited availability of LNG bunkering infrastructure, and concerns about methane slip during combustion. Despite these barriers, LNG is increasingly being considered a viable alternative fuel due to its potential to significantly reduce emissions and comply with stricter environmental regulations in ECAs.

7.4.1 Emission Reduction Analysis

To assess the emission reduction potential of LNG, this analysis assumed a complete transition of OGVs currently using conventional diesel fuels to LNG. Emission factors were reassigned based on guidance from U.S. EPA, and total vessel emissions were recalculated to estimate the net reductions.

7.4.2 Emission Reduction Outcome

A summary of emission reductions is provided below. A detailed breakdown of emission reductions by pollutant and vessel type is provided in Appendix B. Figure 35 illustrates the emission composition of OGVs for NOx, PM2.5, CO2, and SO2.

- NOx—reduced by 84%. LNG combustion occurs at lower temperatures than traditional marine fuels, which minimizes the formation of NOx, a byproduct of high-temperature combustion processes.
- PM2.5—reduced by 84%. LNG combustion produces negligible PM because it burns cleaner than heavier fuels such as MGO or HFO, which contain impurities that contribute to PM emissions.
- CO2—reduced by 40%. LNG has a higher hydrogen-to-carbon ratio than diesel fuels, resulting in more efficient energy release and lower CO2 emissions per unit of energy produced.
- SO2—reduced by 97%. LNG contains virtually no sulfur, unlike traditional marine fuels, making it highly effective in reducing SO2 emissions and ensuring compliance with global sulfur cap regulations.

These reductions underscore the environmental benefits of LNG as an alternative fuel for OGVs, particularly in terms of meeting stringent emissions standards. Despite its potential, LNG adoption must address the challenges of infrastructure development, cost, and methane emissions to become a fully sustainable solution for maritime transportation.

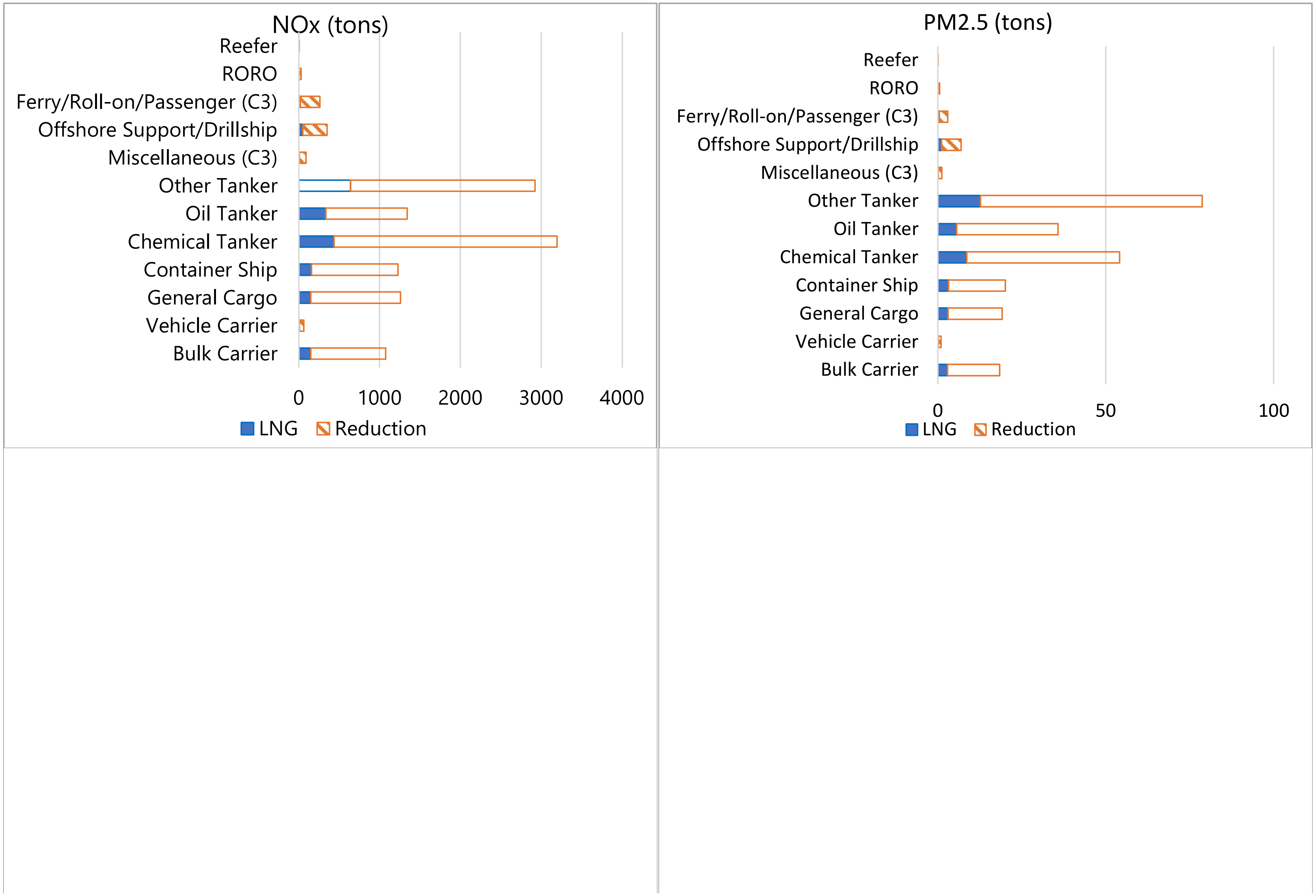


Figure 35. OGV Emission Composition with LNG: Potential Reductions versus Remaining Emissions

7.5 Alternative Fuels—Hydrogen

7.5.1 Examination of Full Hydrogen (Hydrogen Cell)

7.5.1.1 Assumptions

To assess the feasibility of hydrogen adoption for HBC, it was essential to evaluate whether the hydrogen storage capacity on these vessels can support the operational demands currently fulfilled by traditional fuels. The HyZET tugboat, designed by Crowley and shown in Figure 36 (Crowley, 2023), was used as a baseline for this assessment. The boat features a LH2 storage capacity of 4,000 kg and a refilling rate of 4,000 kg/hour (Lee, 2024).

Source: Crowley (2023)

Figure 36. HyZET Tugboat

The analysis was based on the following assumptions:

- Immediate Refueling: HBC berthing at terminals with hydrogen bunkering systems can refill their tanks immediately upon docking.
- Refueling in Voyage Gap: While berthing at hydrogen-enabled terminals, HBC are assumed to refill continuously during gaps between voyages.
- Unlimited Hydrogen Supply: The availability of hydrogen is assumed to be infinite, eliminating concerns about supply shortages.

- HyZET-Based Vessel Specification Assumption: All HBC are modeled using the specifications of the HyZET tugboat, which features a 4,000 kg LH2 storage capacity and a refueling time of 1 hour.

As the boat uses fuel cells to convert hydrogen energy and end up as liquid, the high heating value of hydrogen is 39.4 kWh/kg (Harrison et al., 2010). Assuming a fuel-cell efficiency of 60% (Bloomenergy, 2024), the effective usable energy rate is 23.64 kWh/kg. In other words, each kWh of usable energy requires approximately 0.0423 kg of hydrogen.

7.5.1.2 Emission Reduction Analysis

The algorithm used to examine the full hydrogen eligibility was as follows:

- In non-hotelling mode, the ship consumes energy relying on the LH2 demand.
- In hotelling mode, the ship can refill LH2 if the ship berths at hydrogen-enabled terminals. If the ship is not in such terminals, energy continues to be consumed at the hotelling rate.
- The ship stops refilling when it reaches the maximum of the hydrogen tank.
- If the ship used up all its liquid hydrogen, it is regarded as ineligible to adopt full hydrogen strategy.

As illustrated in Figure 37, the boat consumes hydrogen during the non-hotelling and hotelling mode. However, when the boat berths at a hydrogen-enabled terminal, it begins to refill its hydrogen tanks without consuming LH2, as shown in Figure 37(a). In contrast, Figure 37(b) depicts an ineligible vessel scenario, where the inability to refuel during Voyage 2 results in complete depletion of onboard hydrogen.

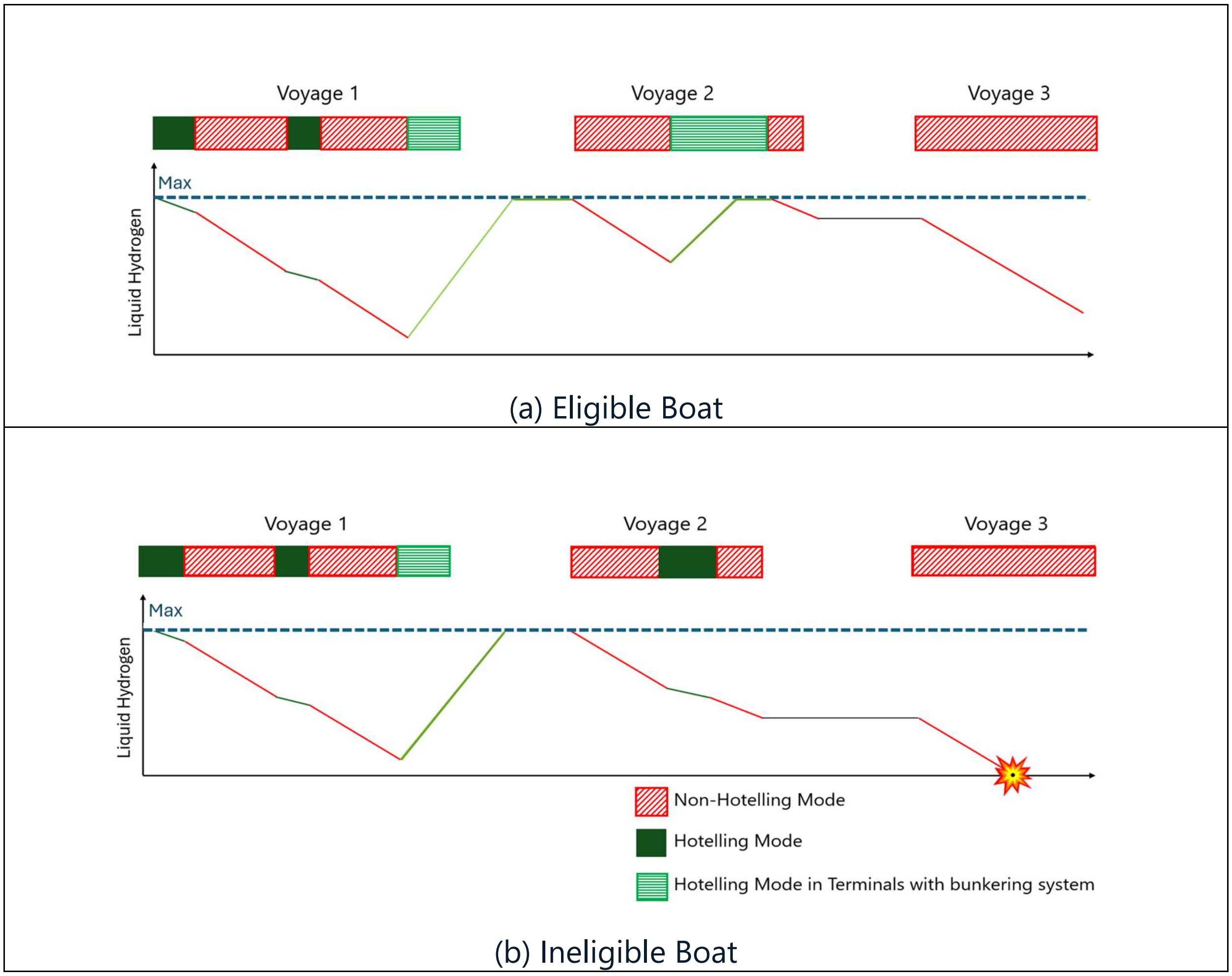


Figure 37. Hydrogen Amount Profile of Eligible and Ineligible Boats

7.5.1.3 Emission Reduction Outcome

Emission reduction potential was estimated under four deployment scenarios for hydrogen bunkering infrastructure:

- Scenario 1: All terminals are equipped with hydrogen bunkering systems.
- Scenario 2: Bayport, CARE, and Barbours Cut Terminals are equipped with hydrogen bunkering systems.
- Scenario 3: Bayport and CARE Terminals are equipped with hydrogen bunkering systems.
- Scenario 4: Only Bayport Terminal is equipped with a hydrogen bunkering system.

Figure 38 illustrates the NOx cumulative curve of LH2 storage capacity and emissions from eligible boats, given different hydrogen bunkering system deployments. The red vertical line indicates the available LH2 capacity; emissions to the left of this line represent the portion that can be covered by the current hydrogen supply, while emissions to the right remain uncovered due to insufficient onboard LH2 storage.

If LH2 comes from clean energy, such as wind farms, these covered emissions can be eliminated. The emission reduction of annual NOx from HBC is 23%, 14%, 12%, and 4%, respectively, highlighting the importance of infrastructure coverage. A detailed breakdown of emission reductions by Scenario 1 is provided in Appendix B.

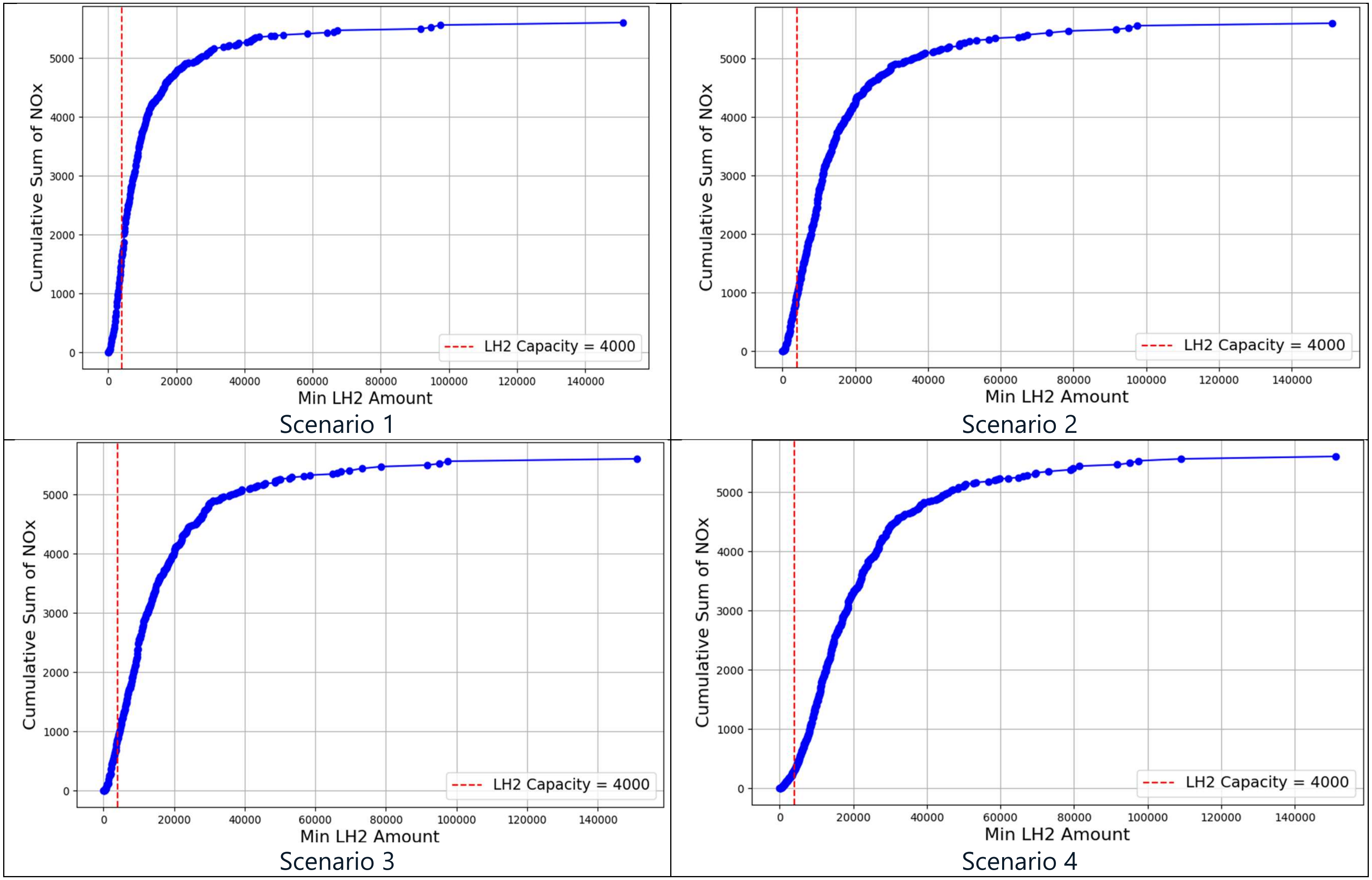


Figure 38. Cumulative Curve of HBC NOx Emissions versus Minimum LH2 Storage Capacity

7.5.2 Examination of Hybrid Hydrogen (Combustion with Hydrogen and Diesels)

7.5.2.1 Assumptions

Following the assessment of full hydrogen fuel-cell vessels, the research team evaluated the feasibility and emissions reduction potential of hybrid hydrogen systems for HBC. The analysis was based on the Hydrotug 1, a commercially available dual-fuel vessel developed by CMB.TECH (2024), as shown in Figure 39.

Source: CMB.TECH (2024)

Figure 39. Hydrotug 1

The Hydrotug 1 is powered by two BeHydro V12 dual-fuel medium-speed engines capable of co-combusting up to 85% hydrogen with 15% diesel by mass. Its onboard storage includes 415 kg of CH2 (Anglo Belgian Corporation, 2025). Key assumptions for the analysis included the following:

- Immediate Refueling: HBC berthing at hydrogen-enabled terminals can refill tanks immediately upon docking.
- Refueling in Voyage Gap: While berthing at hydrogen-enabled terminals, HBC are assumed to refill continuously during gaps between voyages, and all terminals are assumed to be equipped with hydrogen facilities.

- Unlimited Hydrogen Supply: Hydrogen is assumed to be infinitely available, removing supply constraints.
- Seamless Switching: Engines can operate entirely on diesel when hydrogen is unavailable, ensuring uninterrupted operation.
- Refueling Time: A full refuel requires 30 minutes.
- Hydrogen Energy Share: During operation, the fuel mixture consists of 85% hydrogen and 15% diesel by mass. Once the onboard LH2 is fully depleted, the vessel transitions to operating entirely on diesel fuel.

Hydrogen's lower heating value is 33.6 kWh/kg (Harrison et al., 2010), while diesel's is 11.8 kWh/kg. For a 1 kg dual-fuel mixture (0.85 kg hydrogen + 0.15 kg diesel), the resulting energy output is:

- Hydrogen: 0.85 kg × 33.6 kWh/kg = 28.56 kWh.
- Diesel: 0.15 kg × 11.8 kWh/kg = 1.77 kWh.
- Total: 30.33 kWh → Hydrogen energy share = 28.56 / 30.33 = 94.1%.

Assuming a combustion efficiency of 40% (Harrison et al., 2010), the usable energy from a 1 kg of fuel (0.85 kg of hydrogen) mixture will be 30.33 kWh * 0.4 = 12.13 kWh. Thus, consuming 1 kg of hydrogen can generate 14.27 kWh, and approximately 0.07 kg of hydrogen is required to produce 1 usable kWh of energy.

7.5.2.2 Emission Reduction Analysis

The algorithm to estimate emission reduction was as follows:

- In non-hotelling mode, the ship consumes energy relying on the mixture of CH2 and diesel. For each kWh of energy demand, 0.07 kg of hydrogen is consumed, representing 94.1% of the energy supply. This hydrogen usage is converted into corresponding emission reductions and recorded.
- In hotelling mode, the ship can refill CH2 if the ship berths in hydrogen-enabled terminals. During this time, energy demand is met, and 94.1% of it is attributed to hydrogen, resulting in corresponding emission reductions without drawing down the CH2 storage. If the ship is not in such terminals, CH2 is consumed at the hotelling rate, and corresponding emission reductions are recorded.
- The ship stops refueling when it reaches the maximum of the hydrogen tank.
- If the ship uses up all CH2, the vessel operates 100% on diesel, and no emission reduction is recorded.

In Figure 40, the upper curve represents CH2 storage levels, while the lower curve shows cumulative emission reductions. The vessel consumes hydrogen during both non-hotelling and hotelling modes. However, when berthed at a hydrogen-enabled terminal, it refuels its CH2 tanks without drawing down existing CH2 reserves. As long as CH2 remains available, 94.1% of the vessel's energy demand is met with hydrogen, and the corresponding emission reductions are calculated and recorded.

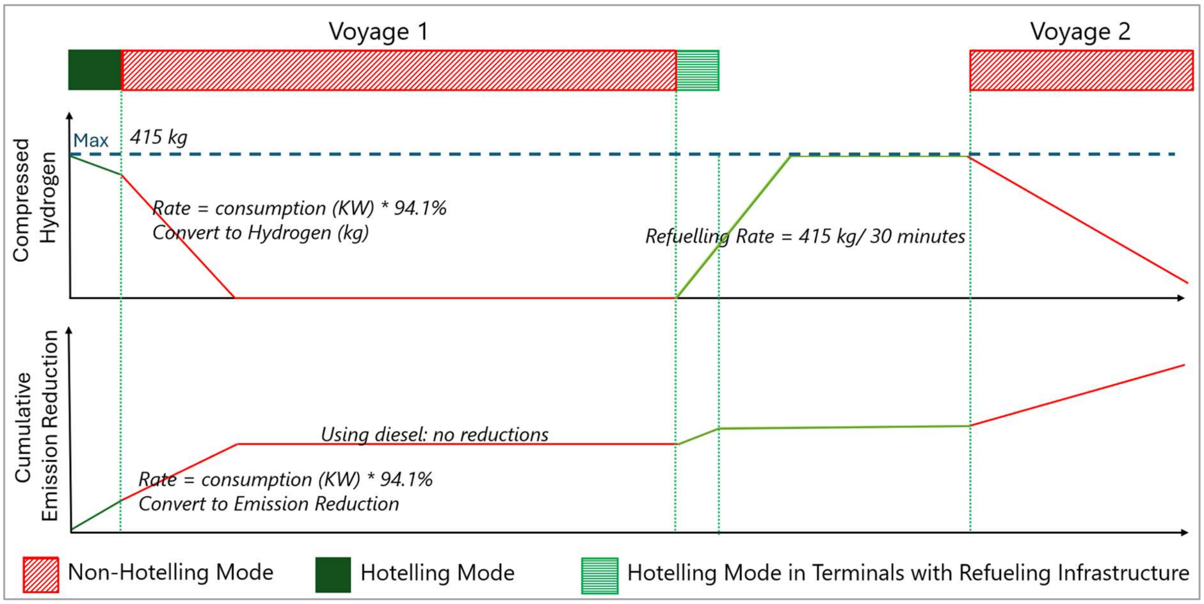


Figure 40. Cumulative Emission Reductions by Hybrid Hydrogen

7.5.2.3 Emission Reduction Outcome

A detailed breakdown of emission reductions achieved through hybrid hydrogen strategy is provided in Appendix B. Figure 41 presents the emission reduction potential for NOx, PM2.5, CO2, and SO2 among HBC. The results indicate an approximately 16% reduction for towboats and 14% for tugboats across these pollutants. These modest reductions underscore the limitations of hybrid systems in fully displacing diesel operations, particularly given that most HBC operate for extended durations and still require substantial diesel fuel support to meet their energy demands.

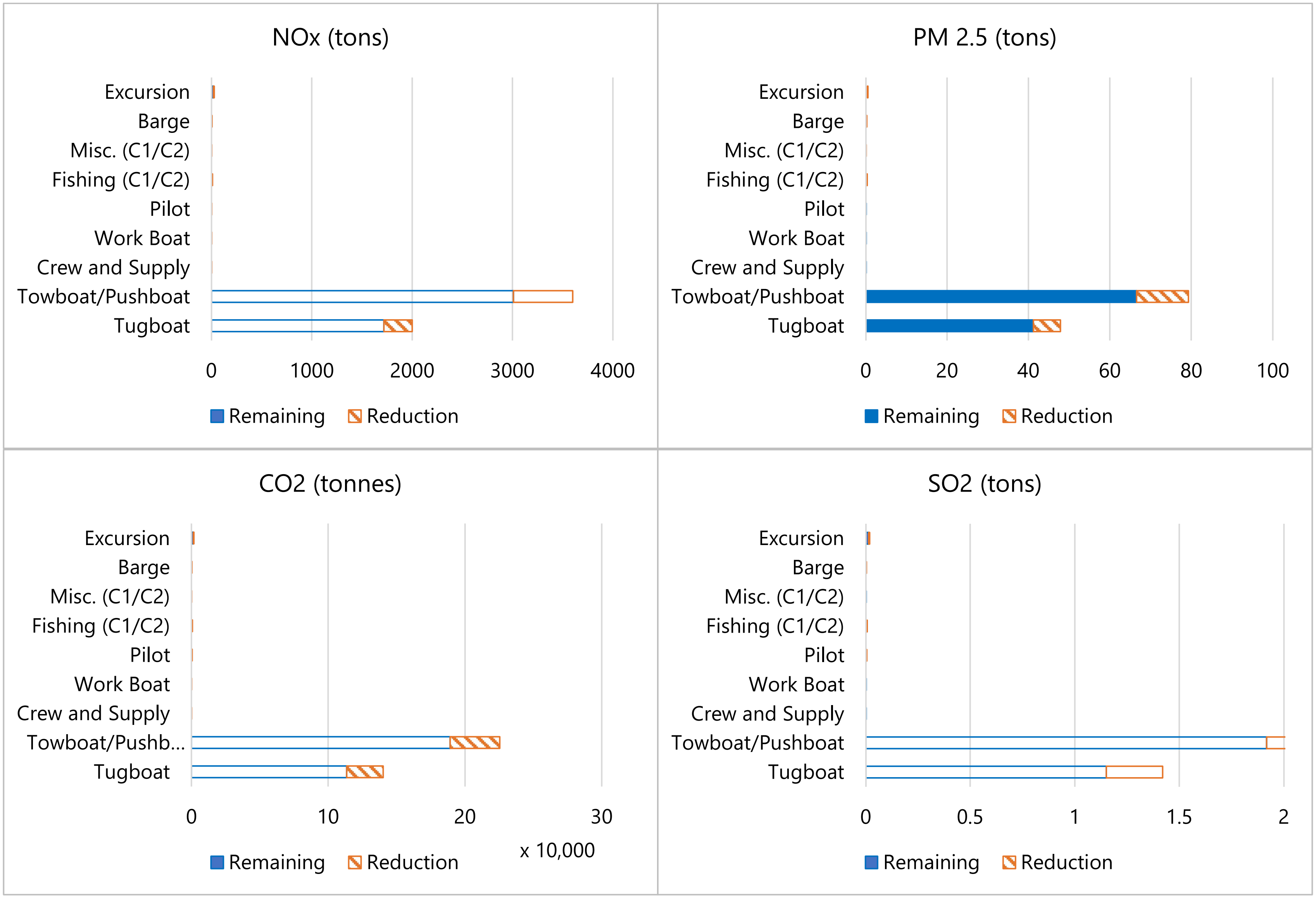


Figure 41. HBC Emission Composition with Hybrid Hydrogen: Potential Reductions versus Remaining Emissions

7.5.3 Summary

The evaluation of both full and hybrid hydrogen adoption for HBC at the POH offers important insights into the related technical feasibility and emissions reduction potential.

Full hydrogen strategy is promising when hydrogen is produced from renewable energy sources. Under a scenario where all terminals are equipped with hydrogen bunkering systems, eligible vessels could achieve a 23% reduction in annual NOx emissions from HBC. However, the approach requires each vessel to store up to 4,000 kg of LH2 and relies heavily on terminal access and operational compatibility. Vessel ineligibility arises when voyage lengths outstrip refueling opportunities, which is a common challenge in the POH's large geographic domain. Additionally, infrastructure costs for equipping all terminals and remodeling ships are expected to be high.

Hybrid hydrogen systems, which co-combust CH2 and diesel using dual-fuel engines, offer a more flexible alternative. These systems allow for partial emission reductions even when full refueling is not feasible. Assuming all terminals are equipped with hydrogen bunkering systems, the Hydrotug 1 model achieves up to 14–16% NOx emission reduction. This hybrid strategy maintains operability over long distances while still achieving significant environmental benefits.

In conclusion, both hydrogen pathways—full and hybrid—offer measurable emission reductions when paired with widespread terminal infrastructure. However, their cost, eligibility limitations and infrastructure demands must be carefully weighed. As such, a detailed benefit-cost analysis for both full hydrogen and hybrid hydrogen solutions was performed and is presented in a later section to support strategic decision-making.

7.6 Electrification

7.6.1 Examination of Full Electrification

Full electrification of HBC presents an attractive pathway for zero-emission maritime operations when powered by clean energy. However, practical constraints such as limited battery capacity, long charging times, and extended operational demands pose significant challenges, especially in a large and geographically dispersed port like the POH.

7.6.1.1 Assumptions

For this analysis, the eWolf, developed by Crowley (2024a), was used as the baseline vessel (Figure 42). It features a battery capacity of 6,200 kWh and requires approximately 4.5 hours for a full charge.

Source: Crowley (2024a)

Figure 42. eWolf

The analysis was conducted under the following assumptions:

- Immediate Charging: HBC berthing at charging-enabled terminals can immediately begin recharging upon docking.
- Charging in Voyage Gap: While berthing at charging-enabled terminals, HBC are assumed to refill continuously during gaps between voyages, and all terminals are assumed to be equipped with charging facilities.
- Unlimited Charging Infrastructure: The availability of charging spots is assumed to be infinite. This assumption simplified the analysis by focusing solely on vessel voyage patterns and their electrification eligibility, without considering the specific number of charging stations.
- Versatile Capability: The eWolf is assumed to handle both tugboat and towboat operations.

7.6.1.2 Emission Reduction Analysis

The eligibility examination logic is presented below and followed a similar approach to the hydrogen eligibility analysis described in Section 7.5.1:

- During non-hotelling mode, the energy rate that electric ships consume is equivalent to that of diesel-engine ships.

- During hotelling mode, the ship charges if docked at a terminal with charging infrastructure. If not, energy continues to be consumed at the hotelling rate.
- The ship stops charging once its battery reaches maximum capacity.
- If the ship depletes its battery entirely, it is considered ineligible for full electrification.

7.6.1.3 Emission Reduction Analysis

Figure 43 presents the cumulative curve of NOx emissions versus minimum battery capacity for HBC. To ensure all HBC qualify for full electrification, a maximum battery capacity of 2,100,000 kWh would be required, which is unrealistic. Covering half of the HBC fleet still demands a minimum of 50,000 kWh battery capacity. Compared to the eWolf’s maximum battery capacity of 6,200 kWh, the curve shows that less than 5% of ships are qualified, indicating that the operational patterns in the POH domain are unsuitable for full electrification.

This ineligibility is primarily due to the expansive area of the POH domain. For instance, the distance from the anchorage area to Bayport Terminal—the nearest terminal—is approximately 50 km. A round trip requires 6 hours at an average speed of 9 knots, exceeding the eWolf's maximum operational time (Haun, 2024). As a result, full electric vessels cannot effectively support OGV assistance duties, especially for terminals located farther inland.

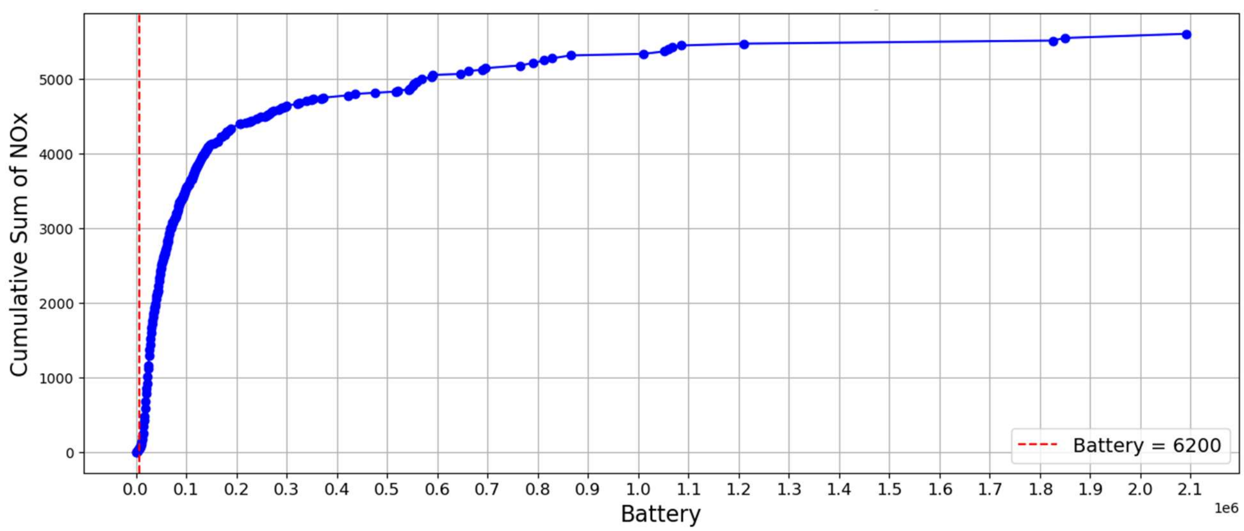


Figure 43. Cumulative Curve of HBC NOx Emissions (tons) versus Minimum Battery Capacity (kWh)

7.6.2 Examination of Hybrid Electrification

7.6.2.1 Assumptions

Given the limitations of full electrification, a hybrid model that combines battery storage with a diesel-engine backup was examined using the hybrid eTug (Figure 44). The vessel features a 4,520 kWh battery and operates on battery power until depletion (Crowley, 2024b), requiring 3 hours to fully recharge.

Source: Crowley (2024b)

Figure 44. Hybrid eTug

7.6.2.2 Emission Reduction Analysis

The assumptions for this strategy included the following:

- Immediate Charging: HBC berthing at charging-enabled terminals can immediately begin recharging upon docking.
- Charging in Voyage Gap: While berthing at charging-enabled terminals, HBC are assumed to refill continuously during gaps between voyages, and all terminals are assumed to be equipped with charging facilities.
- Unlimited Charging Infrastructure: The availability of charging spots is assumed to be infinite. This assumption simplified the analysis by focusing solely on vessel voyage patterns and their electrification eligibility, without considering the specific number of charging stations.
- Grid Electricity Supply: Similar to shore power, the electricity used to charge hybrid vessels is assumed to be supplied from the existing Texas grid without

transmission losses. Emission factors associated with this electricity are based on data from U.S. EPA (2023), as shown in Table 32 (Section 7.1).

- Versatile Capability: The hybrid eTug is assumed to perform both tugboat and towboat tasks.
- Battery-First Operation: The battery is used as the primary energy source until depleted.
- Diesel Backup: When the battery is exhausted, the diesel engine powers the vessel, resulting in no additional emission reductions.

Figure 45 illustrates the hybrid model's emission reduction mechanism. During Voyage 1, the vessel operates entirely on battery power until depletion, achieving emission reductions according to the energy consumed. Once the battery is depleted, the vessel switches to diesel, and no further reductions occur until recharging begins at a terminal. During hotelling at a charging-enabled terminal, the battery recharges, contributing to emission reductions in hotelling mode. The recharged battery further achieves emission reductions during non-hotelling operations in Voyage 2.

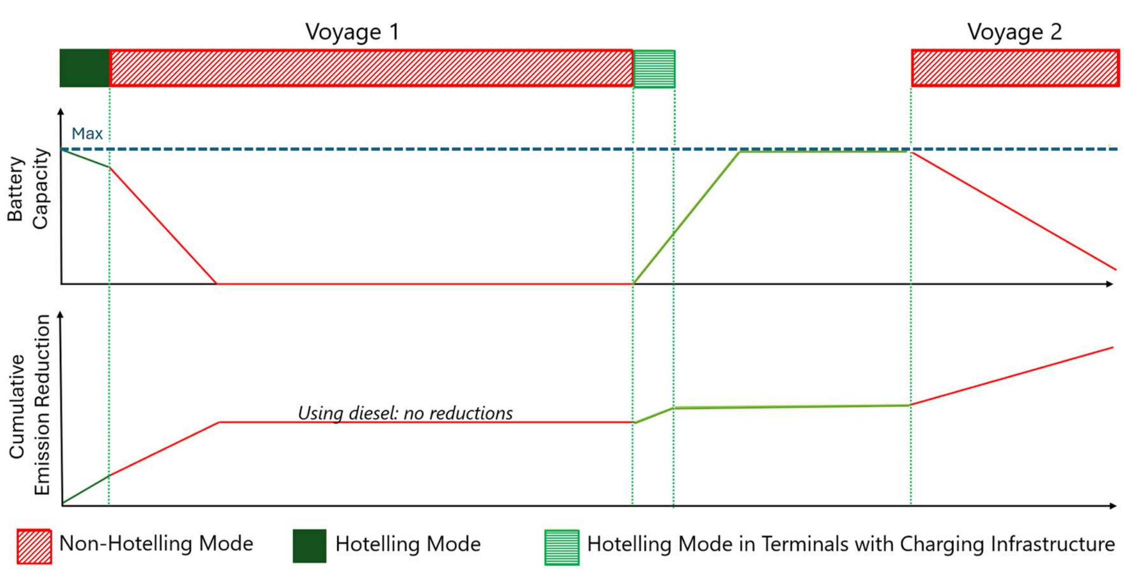


Figure 45. Cumulative Emission Reductions by Hybrid Electrification

7.6.2.3 Emission Reduction Outcome

A detailed breakdown of emission reductions achieved through hybrid electrification is provided in Appendix B. Figure 46 presents the emission reduction potential for NOx, PM2.5, CO2, and SO2 assuming full HBC adoption of hybrid eTugs. The results demonstrate that NOx emissions are reduced by 16% for towboats and 14% for tugboats, while PM2.5 falls by 12% and 14%, respectively. CO2 reductions are more modest, with 10% for towboats and 8% for tugboats, due to emissions from power plants heavily relying on natural gas.

Notably, SO2 emissions increase by 16–17% since Texas's electricity grid still includes coal-fired power plants, which emit more sulfur than the ultra-low-sulfur diesel used by vessels. This offset highlights that while hybrid systems reduce most pollutants, their full benefits depend on a cleaner energy grid.

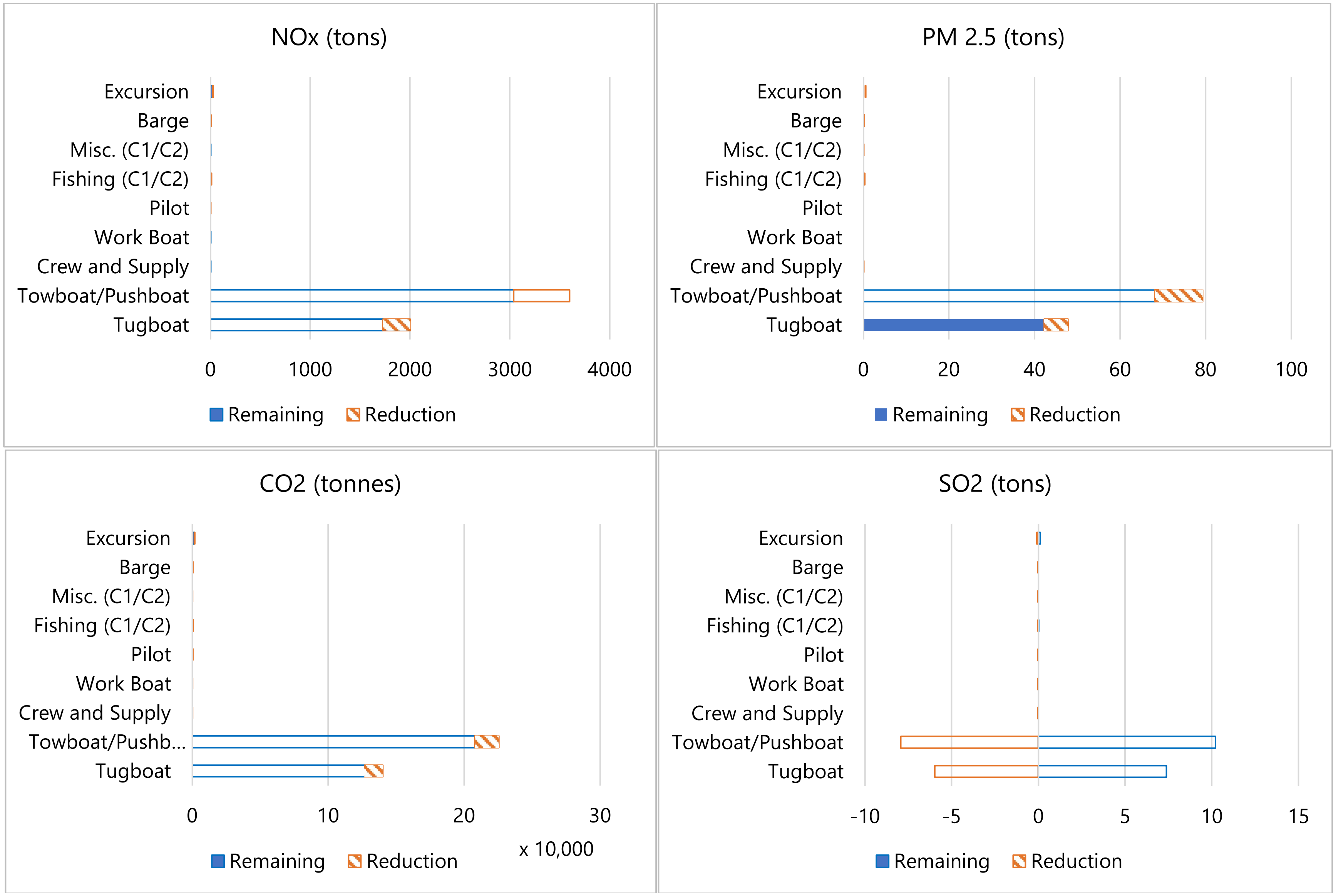


Figure 46. HBC Emission Composition with Hybrid Electrification: Potential Reductions versus Remaining Emissions

7.6.3 Summary

The analysis of both full and hybrid electrification in the POH reveals significant insights into the related feasibility and potential for emission reductions.

Full electrification, while promising in theory, faces substantial challenges in the POH due to the large operational area and long distances between terminals. The limited battery capacity of fully electrified vessels is insufficient to cover the extensive range and assist OGVs from anchorage areas to terminals. As a result, only a small fraction of vessels in the POH would be eligible for full electrification, leading to minimal emission reductions. The distance and operational patterns make full electrification impractical in the POH, resulting in limited environmental benefits.

Hybrid electrification, on the other hand, presents a more viable solution. By combining battery power with a diesel-engine backup, hybrid systems allow for reduced emissions when operating on battery power. Hybrid electrification is also more flexible to cover longer distances with the diesel engine. The hybrid eTug model, for instance, demonstrates a 16% reduction in emissions for towboats and a 14% reduction for tugboats.

In conclusion, hybrid electrification presents a promising pathway for reducing emissions in the POH, overcoming the limitations of full electrification while maintaining operational flexibility. However, achieving these reductions depends on the involvement of all terminals and HBC, which could be expensive. Therefore, it is essential to find a balance between reducing emissions, managing costs, and optimizing battery efficiency to ensure the approach remains sustainable and effective.

7.7 Vessel Speed Control

The emission speed control strategy focuses on the transit mode for OGVs. While vessels may travel at higher speeds to reduce travel time, doing so can lead to increased pollutant emissions and energy consumption. This section presents the research team’s examination of current speed patterns by ship type and recommendations on optimal speeds to minimize pollutant emissions and energy use.

7.7.1 Vessel Speed Patterns

Before analyzing optimal speeds for emission reduction, it is important to understand the current speed distribution by ship type in transit mode. Figure 47 and Figure 48 illustrate the speed distribution, with the y-axis representing the observed number of activity segments. Typically, a segment ranges from 1 to 5 minutes, depending on the message transmission frequency.

The speed distribution indicates that most OGVs travel below 20 knots, except for "other tankers." This category includes vessels that cannot be specifically classified as a particular type of tanker, resulting in a broader and more varied speed distribution.

Figure 49 presents the spatial distribution of all OGVs within the HSC. Each pixel (cell) represents an area of approximately 100 × 100 m. The average speed in each cell is calculated based on the total number of activity segments captured within the cell. The figure shows that the average speed along the channel is around 8–12 knots, with slightly higher speeds observed near the Galveston anchorage area.

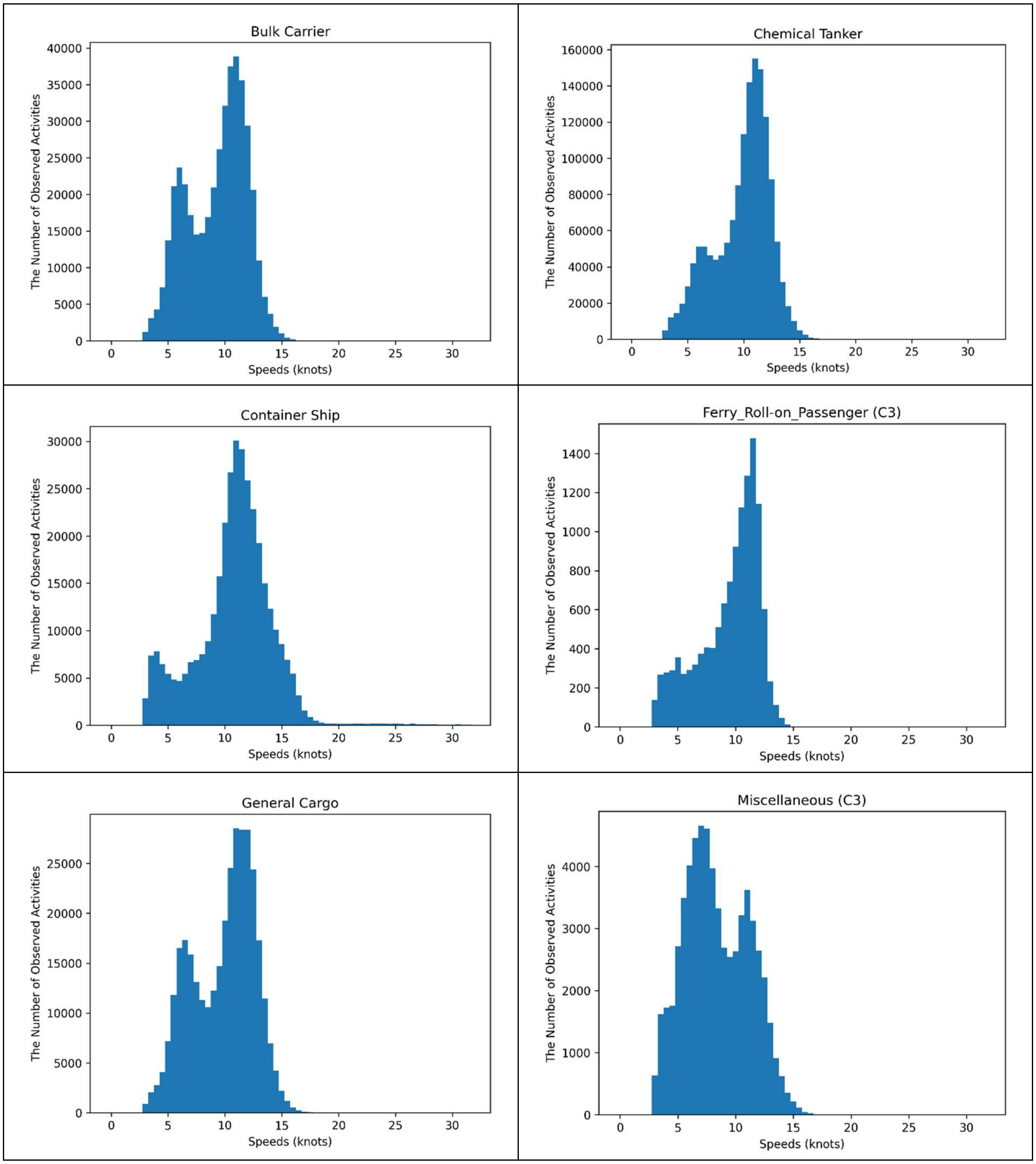


Figure 47. Transit Mode Speed Distribution by Ship Type (1/2)

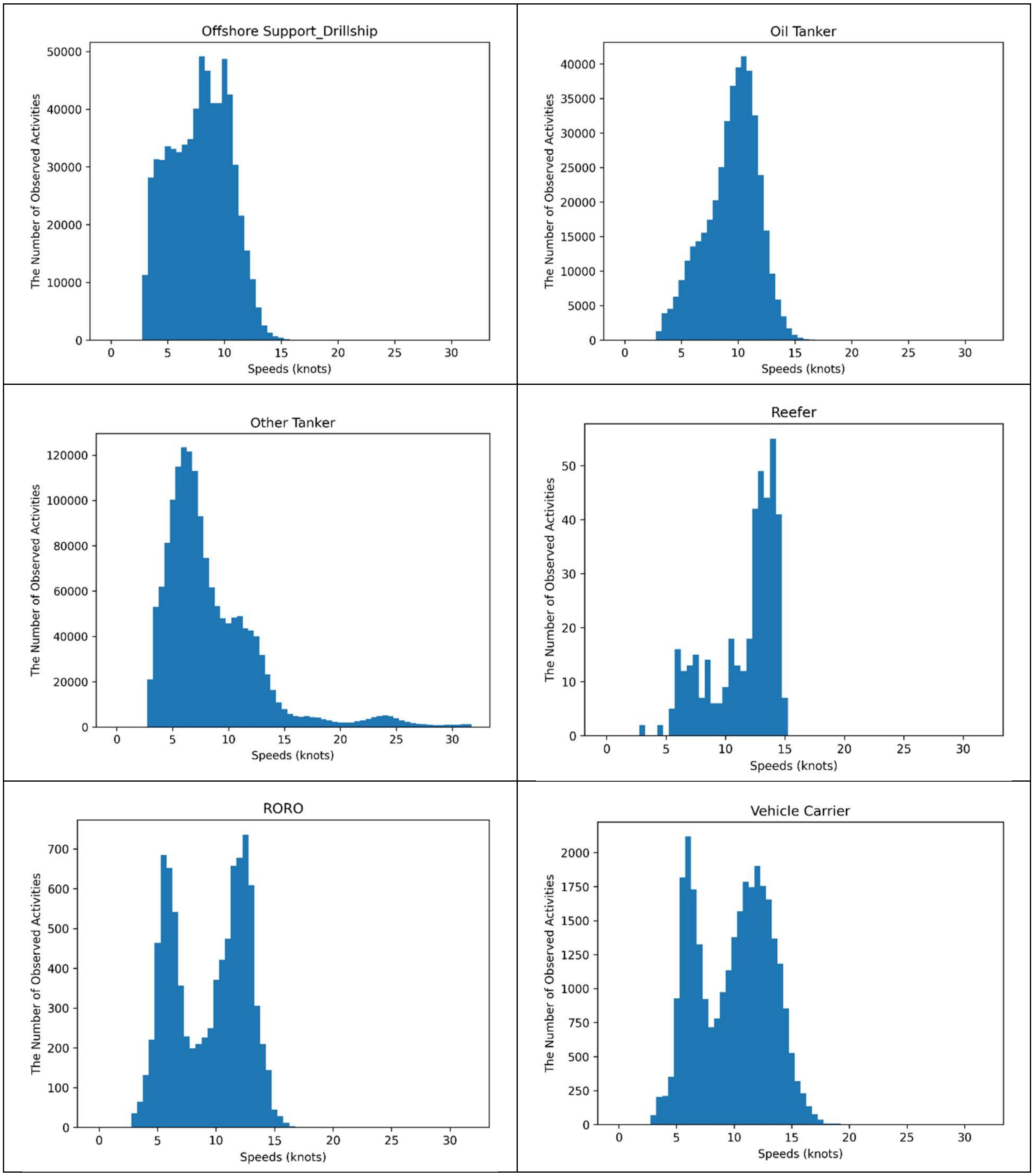


Figure 48. Transit Mode Speed Distribution by Ship Type (2/2)

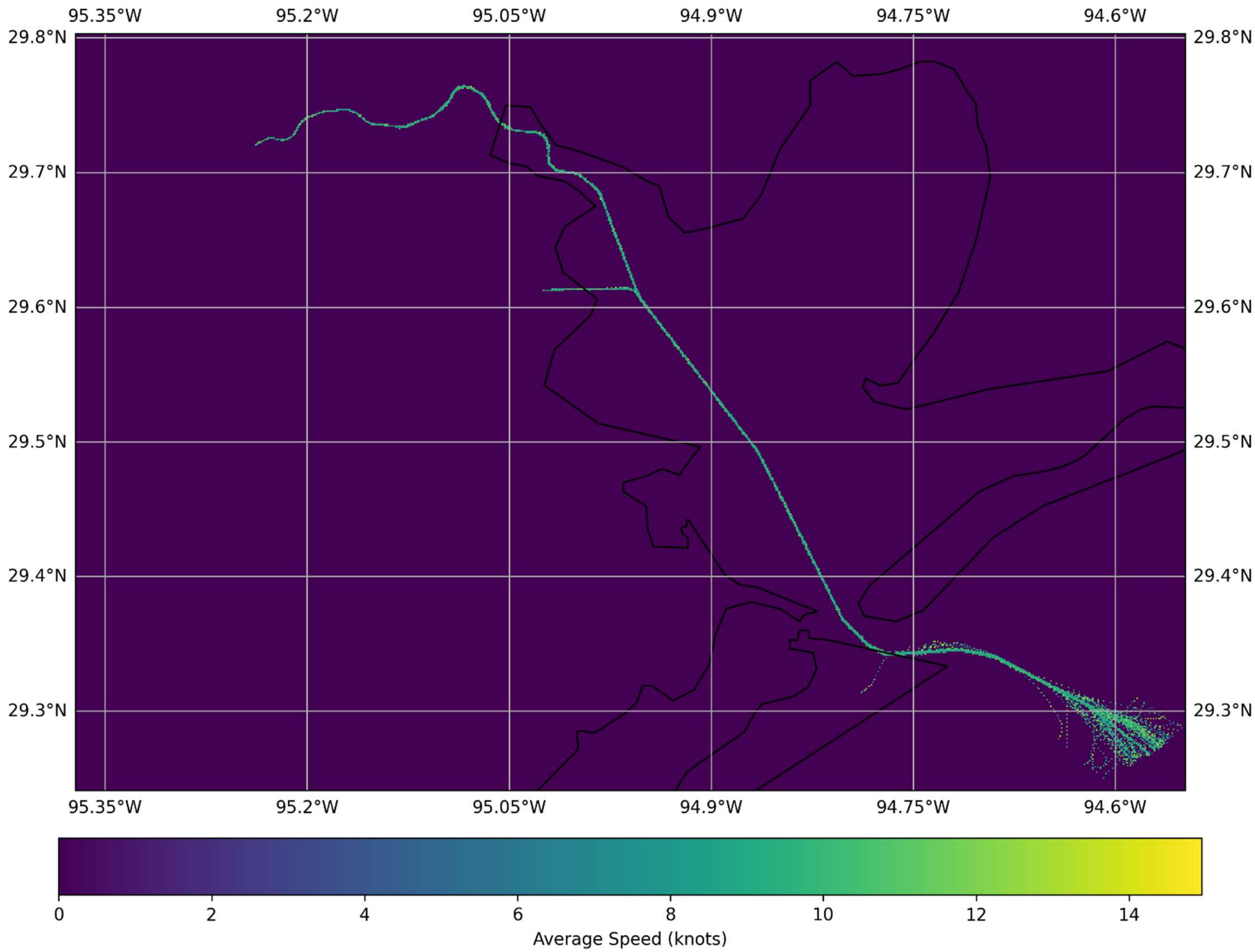


Figure 49. Average Speed on the HSC

7.7.2 Optimizing Speeds for Emission Reduction

The formulas to estimate emissions for propulsion, auxiliary engines, and boilers for OGVs are shown below:

$$E_p = P_p \times A \times EF_p \times LLAF \quad \textit{Equation 7.1}$$

$$E_a = P_a \times A \times EF_a \quad \textit{Equation 7.2}$$

$$E_b = P_b \times A \times EF_b \quad \textit{Equation 7.3}$$

where:
E_p, E_a, E_b: Emissions from propulsion, auxiliary engines, and boilers, respectively.
P_p, P_a, P_b: Engine power for propulsion, auxiliary engines, and boilers, respectively.
A: Activity duration.
EF_p, EF_a, EF_b: Emission factor for propulsion, auxiliary engines, and boilers, respectively.
$LLAF$: Low load adjustment factor.

Let $dist$ be the distance of an activity segment. The activity duration (A) can be presented by $dist/A$. The total emissions are then given by:

$$E_{total} = E_p + E_a + E_p$$

$$= P_{ref} \times (\frac{V}{V_{ref}})^3 \times \left(\frac{D}{D_{ref}}\right)^{\frac{2}{3}} \times A \times SM \times EF_p \times LLAF + P_a \times A \times EF_a + P_b \times A \times EF_b$$

$$= P_{ref} \times (\frac{V}{V_{ref}})^3 \times \left(\frac{D}{D_{ref}}\right)^{\frac{2}{3}} \times (\frac{dist}{V}) \times SM \times EF_p \times LLAF + P_a \times (\frac{dist}{V}) \times EF_a + P_b \times (\frac{dist}{V}) \times EF_b) \quad \textit{Equation 7.4}$$

The load adjustment factor is defined as:

$$LLAF = table\ value\left(\frac{P}{P_{ref}}\right) = table\ value\left((\frac{V}{V_{ref}})^3 \times \left(\frac{D}{D_{ref}}\right)^{\frac{2}{3}}\right) \quad \textit{Equation 7.5}$$

Equation 7.4 captures the key factors influencing total emissions over a given distance. For propulsion engines, power is proportional to speed raised to the power of three. After incorporating the activity duration term $(\frac{dist}{V})$, the dependency on speed reduces to the power of two. In contrast, emissions from auxiliary engines and boilers decrease with higher speeds since their power consumption is typically assumed to be constant in transit mode.

7.7.3 Emission Reduction Analysis—Individual Tailored Speed (Single Pollutant)

To determine the optimal speed that minimizes emissions, one could theoretically differentiate Equation 7.4 with respect to speed. However, since LLAF is derived from discrete table values based on engine load, it creates a non-continuous function that is not easily differentiable. Instead, a simulation-based approach is used to evaluate emissions across a range of speeds over a fixed distance. This method allows for visualization of the relationship between speed and total emissions and identification of the speed that yields the minimum emissions.

Figure 50 provides an example of an emission speed curve for NOx over a fixed distance, demonstrating that traveling at 8 knots emits the least NOx. The zigzag fluctuation in the curve results from the LLAF since this factor is derived from a table based on engine load. As speed increases, engine load may shift from one category to another (e.g., from 5% to 6% engine use), altering the LLAF value.

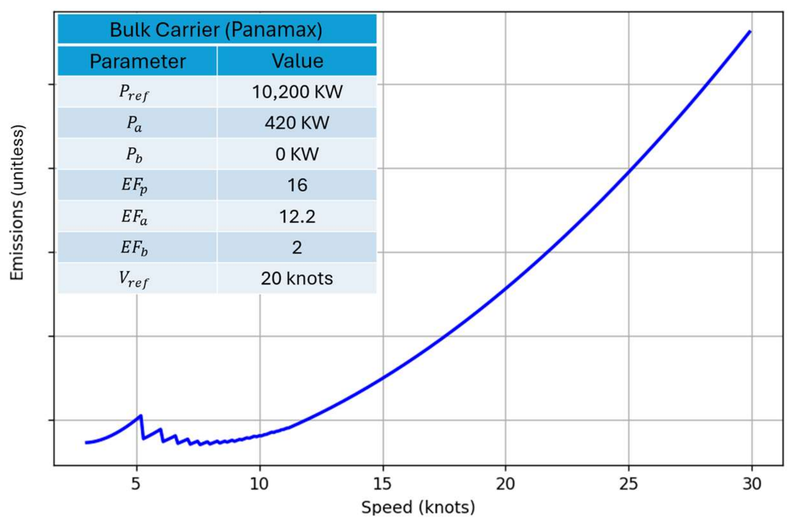


Figure 50. Example of NOx Emission and Speed Curve

To apply the optimized speed to vessels, the voyage data have to be revised. Given the suggested speed (V_{new}) to replace the original speed (V_{old}), the new activity duration (A_{new}) is calculated as $V_{old}A_{old}/V_{new}$. Figure 51 shows the pollutant reductions after applying tailored speeds to each vessel, where the speeds are computed using the NOx emission curve. The result demonstrates significant reductions in NOx emissions and moderate improvements in CO2. However, PM2.5 and SO2 show less improvement, with some vessels showing no improvement or even a slight increase. This outcome highlights that the optimal speed for reducing one pollutant may not be ideal for others.

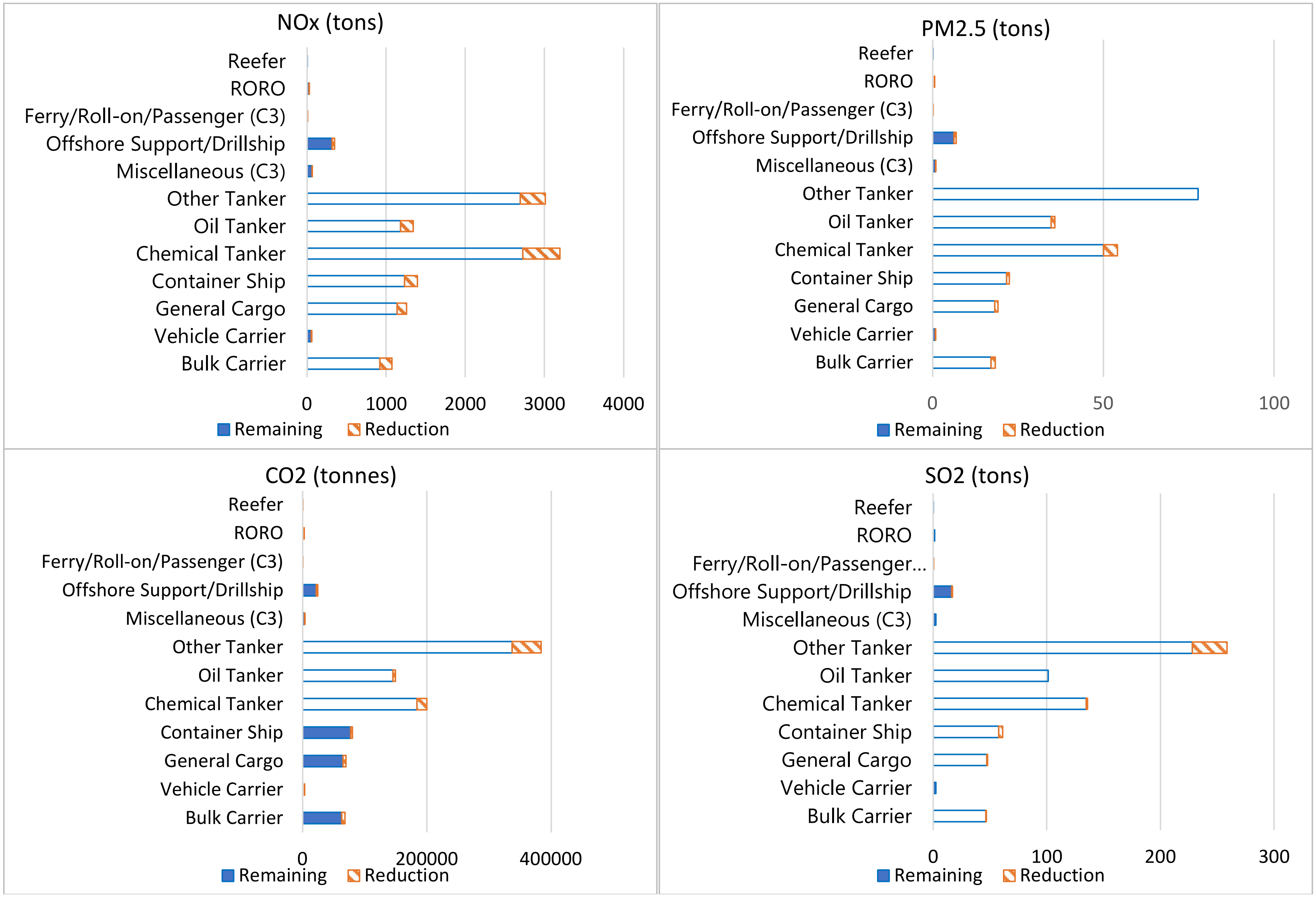


Figure 51. OGV Emission Composition with Tailored Speed Control: Potential Reductions versus Remaining Emissions

7.7.4 Emission Reduction Analysis—Ship-Type Tailored Speed (Multiple Pollutants)

Applying a unique speed limit for each vessel may not be realistic. This section focuses on the speed that achieves the minimum emissions across all ship types. Figure 52 demonstrates that different pollutants exhibit distinct emission patterns, using the "other tanker" category as an example.

Since emission scales vary widely among pollutants, Figure 53 normalizes the emissions between 3 and 15 knots using the following formula:

$$E' = \frac{E - E_{min}}{E_{max} - E_{min}} \qquad \textit{Equation 7.6}$$

where:
E_{max}, E_{min}: Maximum and minimum emissions within the speed range.
E, E': Original and normalized emission amounts.

After normalization, the emissions will scale between 0 and 1. The figure shows that targeting CO2 or NOx reductions often results in lower speeds, while CO or VOC reductions favor higher speeds. Therefore, speed determination depends on the pollutant reduction focus.

Based on the normalized curve of Figure 53, this project evaluated two scenarios for combining pollutant curves:

- Scenario 1: Equal Weighting. Since seven types of pollutants are targeted in emission reduction, each pollutant curve is assigned an equal weight of approximately 14.28%.
- Scenario 2: Impact-Based Weighting. This scenario considers the environmental and health impacts of each pollutant, assigning different weights as follows:
    - NOx—25%: Is a major contributor to smog and acid rain, with harmful effects on respiratory health.
    - PM10 (particulate matter < 10 μm)—20%: Is associated with severe respiratory and cardiovascular issues.
    - PM2.5 (fine particulate matter < 2.5 μm)—20%: Is more dangerous than PM10 due to its ability to penetrate deeper into the lungs.
    - VOC—10%: Acts as a precursor to ground-level ozone (smog).
    - CO—5%: Is toxic at high concentrations but has a relatively lower impact on long-term environmental damage.

- SO2—10%: Contributes to acid rain and respiratory diseases.
- CO2—10%: Is the common target for decarbonization.

Figure 54 presents the results for OGVs with higher emissions. The outcomes of the two weighting schemes are quite similar. The recommended speed range for general tankers is 8–10 knots. However, container ships and general cargo vessels show a different trend. These vessel types often feature higher power and maximum speed capacities, which shift the emissions curve to the right. As a result, speed control for container ships may increase to 12 knots to achieve the lowest weighted normalized emissions.

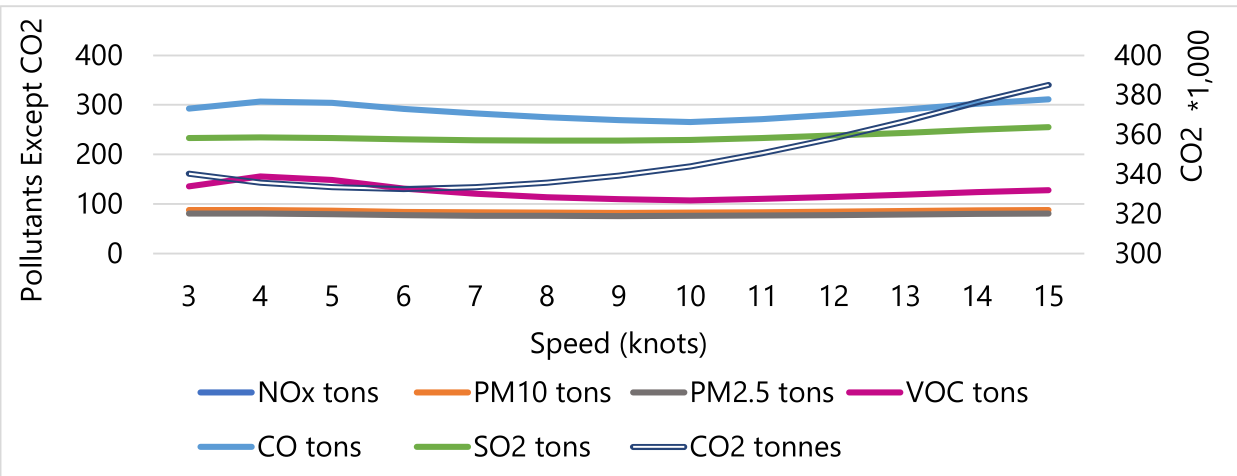


Figure 52. Pollutant Emissions at Varying Speeds for "Other Tanker" Vessels

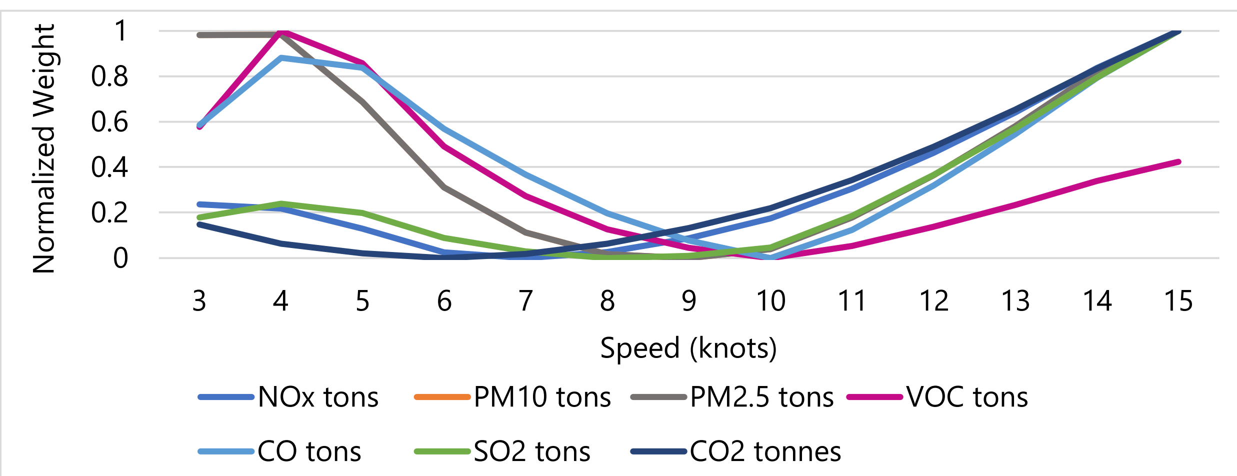


Figure 53. Normalized Pollutant Emissions across Speed Ranges for "Other Tanker" Vessels

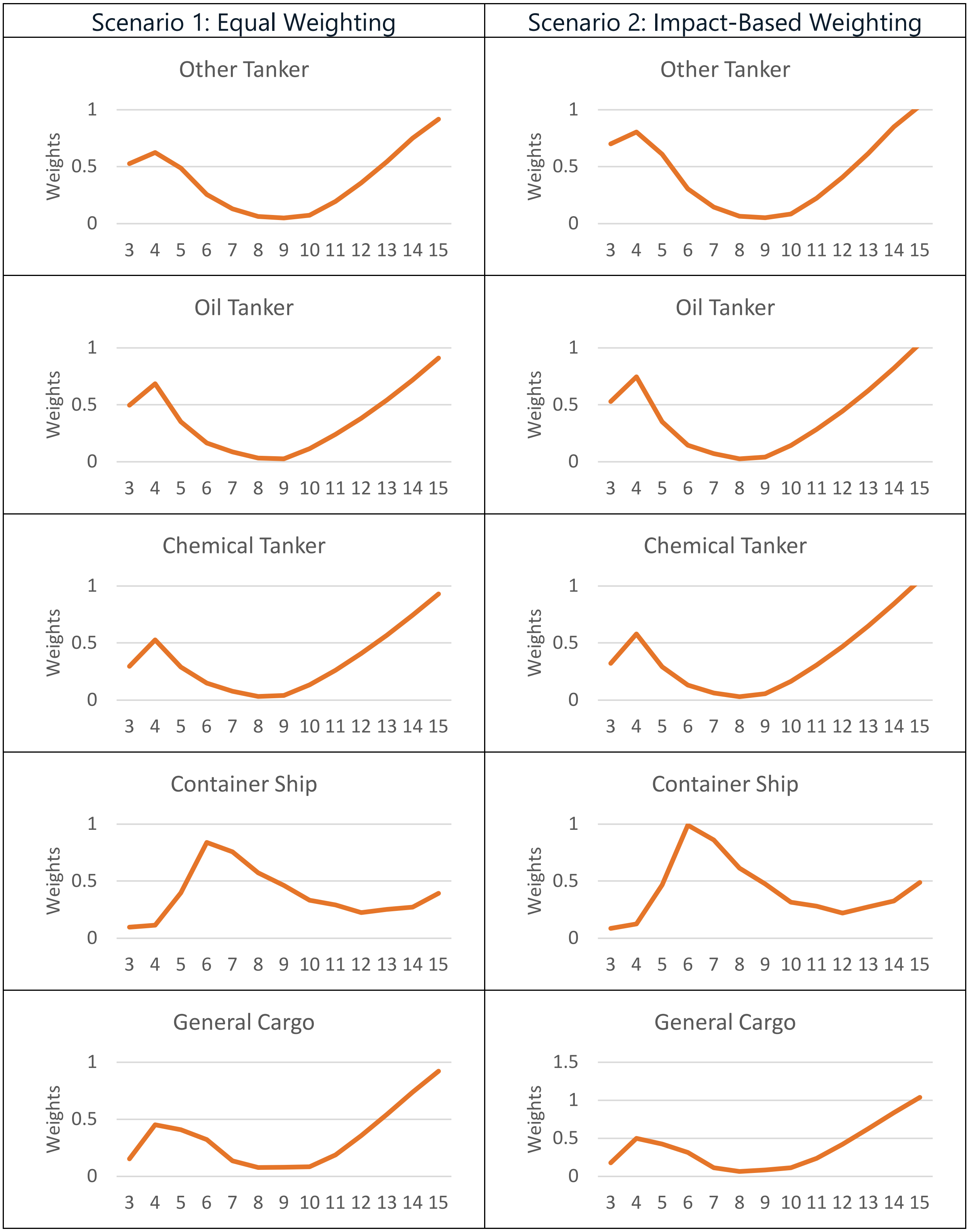


Figure 54. Curves of Speeds and Weighted Normalized Emissions by Ship Type

7.7.5 Emission Outcome

Based on the observations from Figure 54 (some minor ship types are not listed in the figure), the recommended speeds for the two weighting strategies are shown in Table 34. Both strategies suggest similar speeds for most ship types, generally ranging from 8 to 12 knots.

Figure 55 compares NOx emissions under four strategies: general speed control for all OGVs, two weighting strategies with ship-type-specific speeds, and individual customized speed control. The general speed control achieves the lowest NOx emissions at 7 knots, resulting in 10,507 tons of NOx. The individual customized speed control further reduces emissions to 10,378 tons. The two weighting strategies produce emissions of 10,658 and 10,617 tons, respectively, showing similar performance to both the general and individual customized approaches. Overall, all strategies demonstrate significant NOx reductions compared to the benchmark of 11,801 tons.

Table 34. Suggested Speed (Knots) by Different Weighting Strategies

OGV Ship Type	Equal Weight	Impact Based Weighting
Bulk Carrier	8	8
Vehicle Carrier	12	11
General Cargo	8	8
Container Ship	12	12
Chemical Tanker	8	8
Oil Tanker	9	8
Other Tanker	9	9
Miscellaneous (C3)	7	7
Offshore Support/Drillship	8	8
Ferry/Roll-On/Passenger (C3)	8	8
RORO	12	10
Reefer	11	11

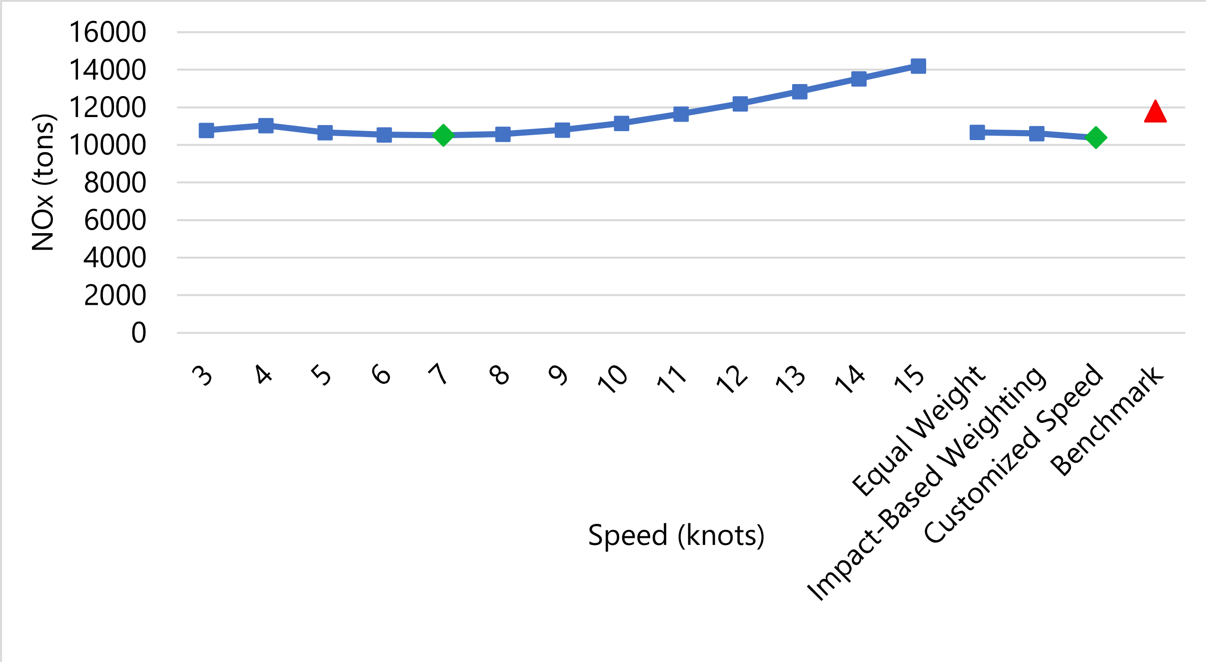


Figure 55. NOx Emissions under Unified, Ship-Type Tailored, and Individual Tailored Speed Control

7.7.6 Summary

The emission reduction analysis for vessel speed control demonstrated that tailored speed strategies could significantly reduce NOx emissions. The individual tailored speed control method achieved the greatest emission reduction, bringing NOx emissions down to 10,378 tons compared to the benchmark of 11,801 tons. The general speed control strategy, which applied a uniform speed of 7 knots for all OGVs, also performed well, resulting in 10,507 tons of NOx emissions.

The two weighting strategies—equal weighting and impact-based weighting—produced similar results, with emissions of 10,658 and 10,617 tons, respectively. These strategies suggested speeds between 8 and 12 knots for most ship types, offering a practical compromise between general and individualized approaches.

Overall, the findings highlight that while individualized speed control offers the most emission reductions, the weighting strategies present a viable and more easily implementable alternative, with performance close to the best possible outcome. Implementing these strategies could help achieve substantial NOx reductions and contribute to improved air quality and environmental sustainability at the POH.

7.8 Operational Inefficiencies and Emission Reduction Potential

Vessel operations are directly tied to fuel consumption and air pollutant emissions. While route optimization is effective in open waters, such flexibility is limited within the POH, where fixed navigation routes constrain vessel maneuverability. In this context, operational efficiency—particularly speed control and scheduling—becomes critical to reducing fuel use and emissions.

As highlighted in the preceding sections, vessel speed strongly affects emissions during transit. However, this section focuses on prolonged idle times—defined as speeds ≤ 1 knot—within the HSC, which signal scheduling inefficiencies. These idle periods often result from suboptimal coordination, causing delays, unnecessary energy use, and excess emissions.

7.8.1 Operational Inefficiency Analysis

To quantify, define the inefficient stay ratio as:

$$Inefficient\ Stay\ Ratio = \left(\frac{Time\ with\ Speed < 1\ knot\ outside\ the\ berths}{Total\ Time\ with\ Speed < 1\ knot\ in\ the\ POH, including\ HSC\ and\ berths}\right)$$

Figure 56 presents the inefficient stay ratios for OGVs and HBC. Among OGVs, "other tankers" exhibit the highest inefficient stay ratio, exceeding 10%, indicating a significant opportunity for operational improvement. Container ships, by contrast, have an average ratio of approximately 3%, while other types of OGVs maintain ratios below 2%. These findings suggest that tanker operations in particular may benefit from enhanced scheduling or process optimization.

For HBC, especially tugboats and towboats, inefficient stay ratios range between 2% and 4%. This finding is likely attributable to their operational role, which involves idling while waiting for and assisting OGVs in navigation and berthing procedures.

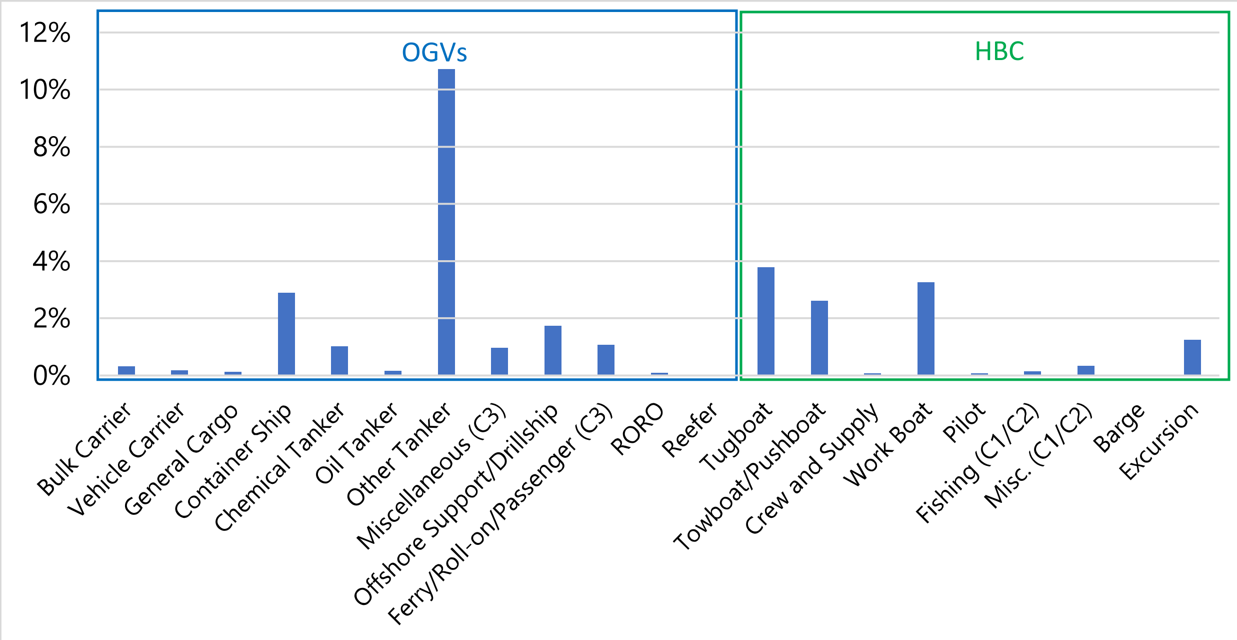


Figure 56. Inefficient Stay Ratio of OGVs and HBC

7.8.2 Emission Reduction Outcome

Figure 57 and Figure 58 illustrate the potential emission reductions for OGVs and HBC, respectively, in relation to the removal of inefficient stays within the HSC. As shown in Figure 56, only the "other tanker" category exhibits a notable inefficient stay ratio, with about 10% of its ≤1-knot activity occurring within the HSC. As a result, this vessel type demonstrates a meaningful potential for emission reductions through improved scheduling and operational efficiency. In contrast, other vessel types show minimal inefficient stays under similar conditions, leading to only limited opportunities for emission reductions.

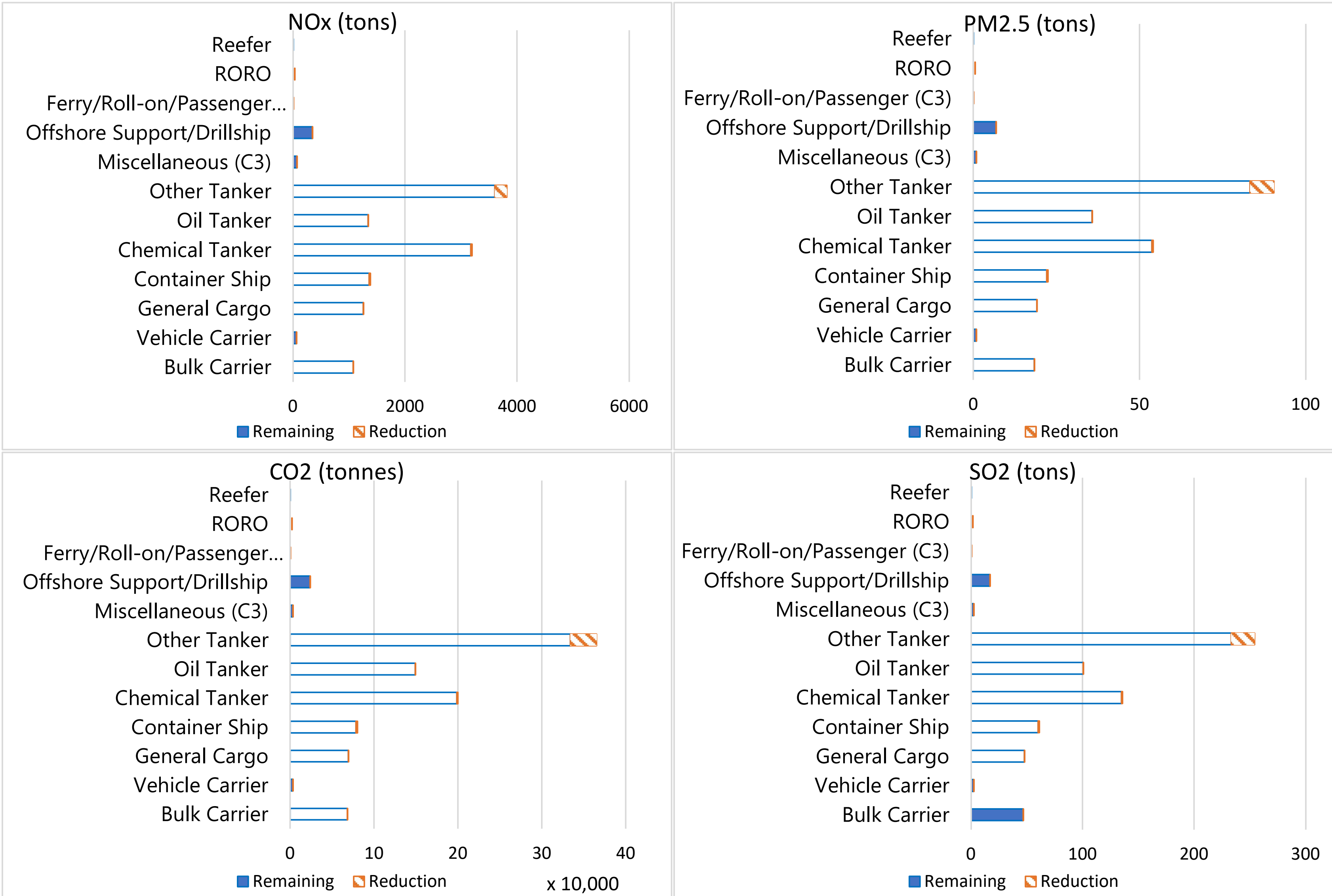


Figure 57. OGV Emissions with Operational Enhancement: Potential Reductions versus Remaining Emissions

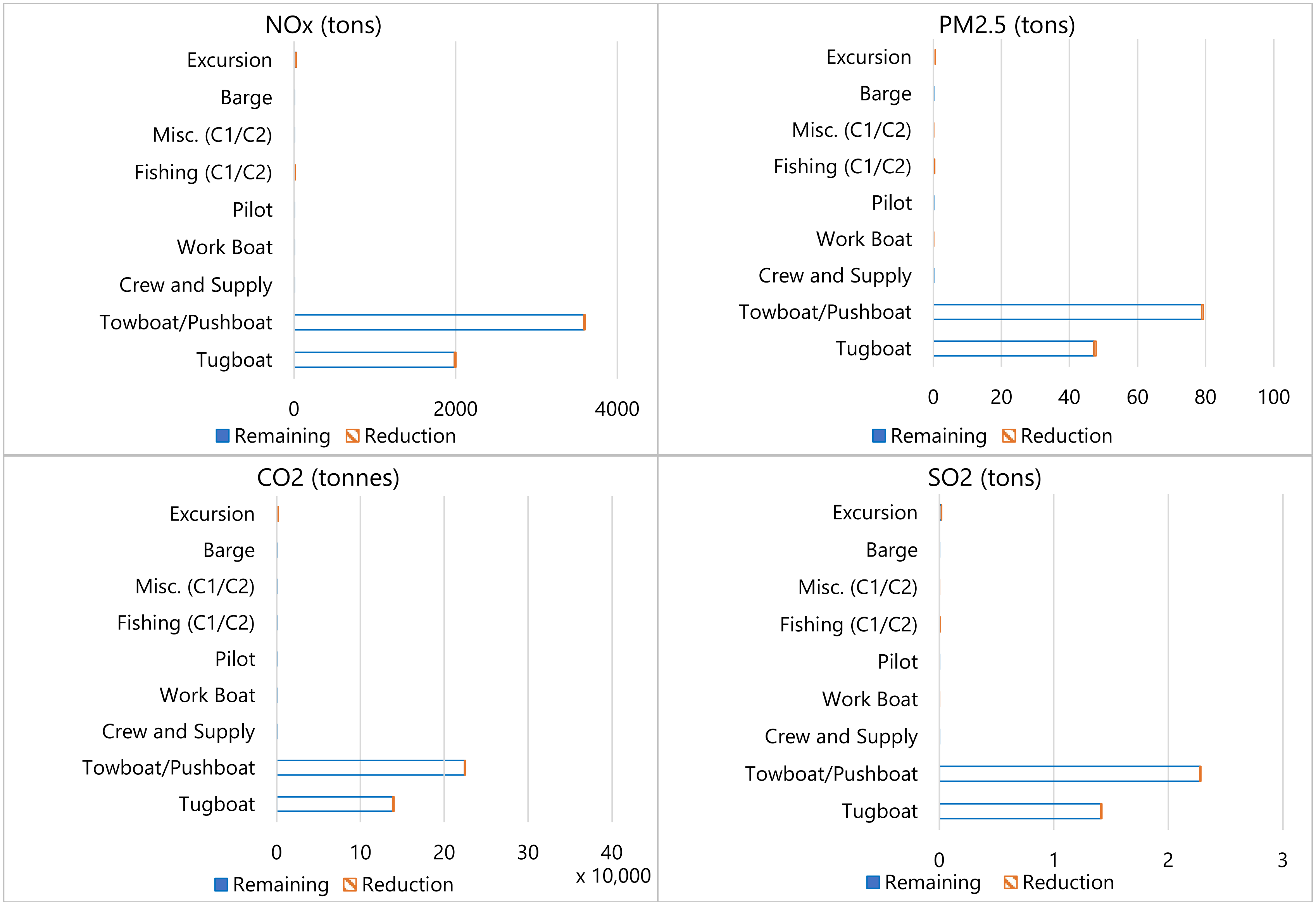


Figure 58. HBC Emissions with Operational Enhancement: Potential Reductions versus Remaining Emissions

Further spatial analysis, presented in Figure 59 and Figure 60, identifies specific zones within the HSC where inefficient stays frequently occur. Each pixel in the figures represents an area of approximately 100 m × 100 m. Notable hotspots include Bolivar Roads to Redfish, Bayport Ship Channel to Barbours Cut, and downstream of Barbours Cut Terminal. These locations may experience higher levels of vessel congestion, coordination delays, or inefficient berth assignment, contributing to prolonged idle times.

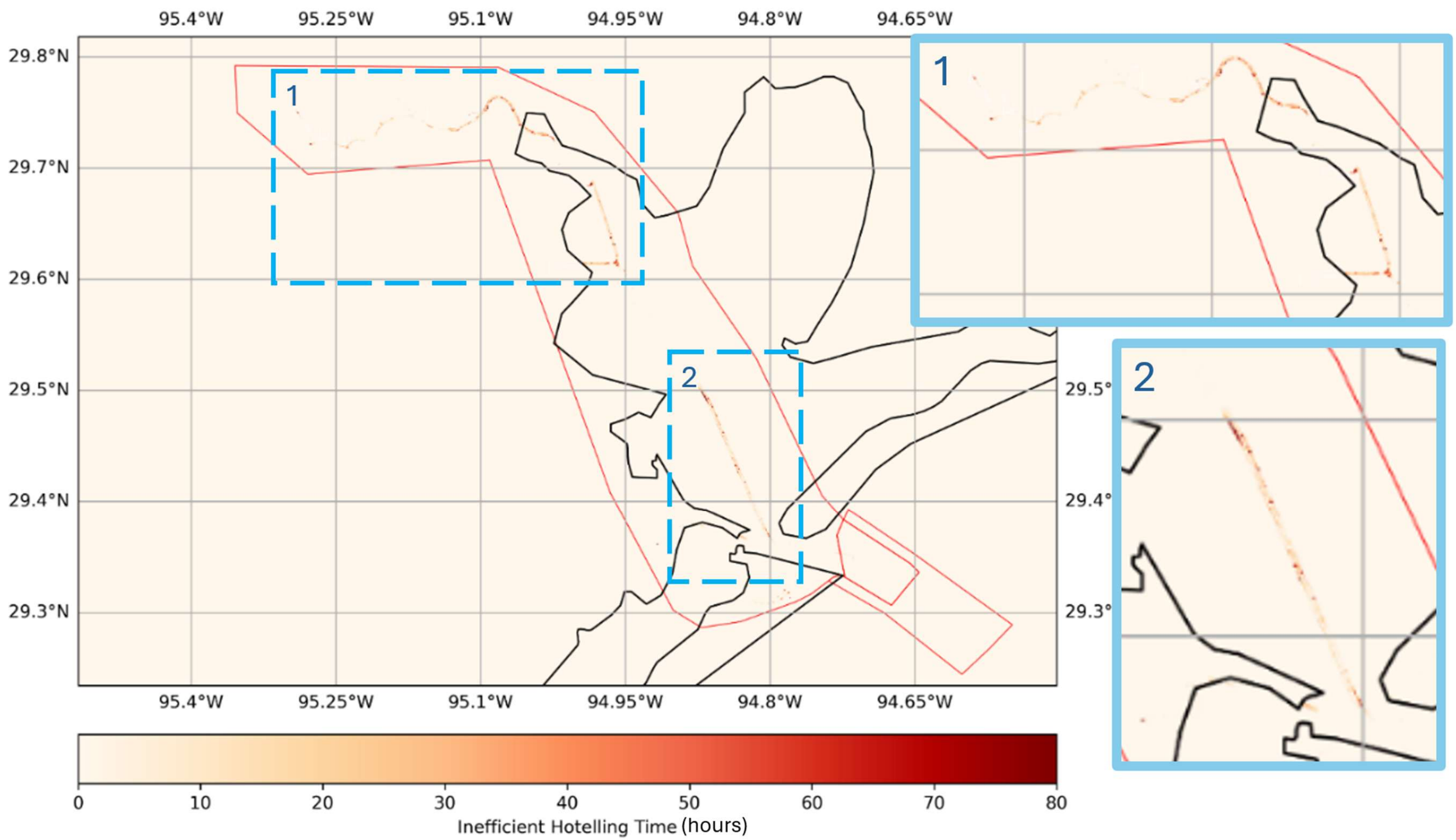


Figure 59. Spatial Distribution of Inefficient Stays of OGVs

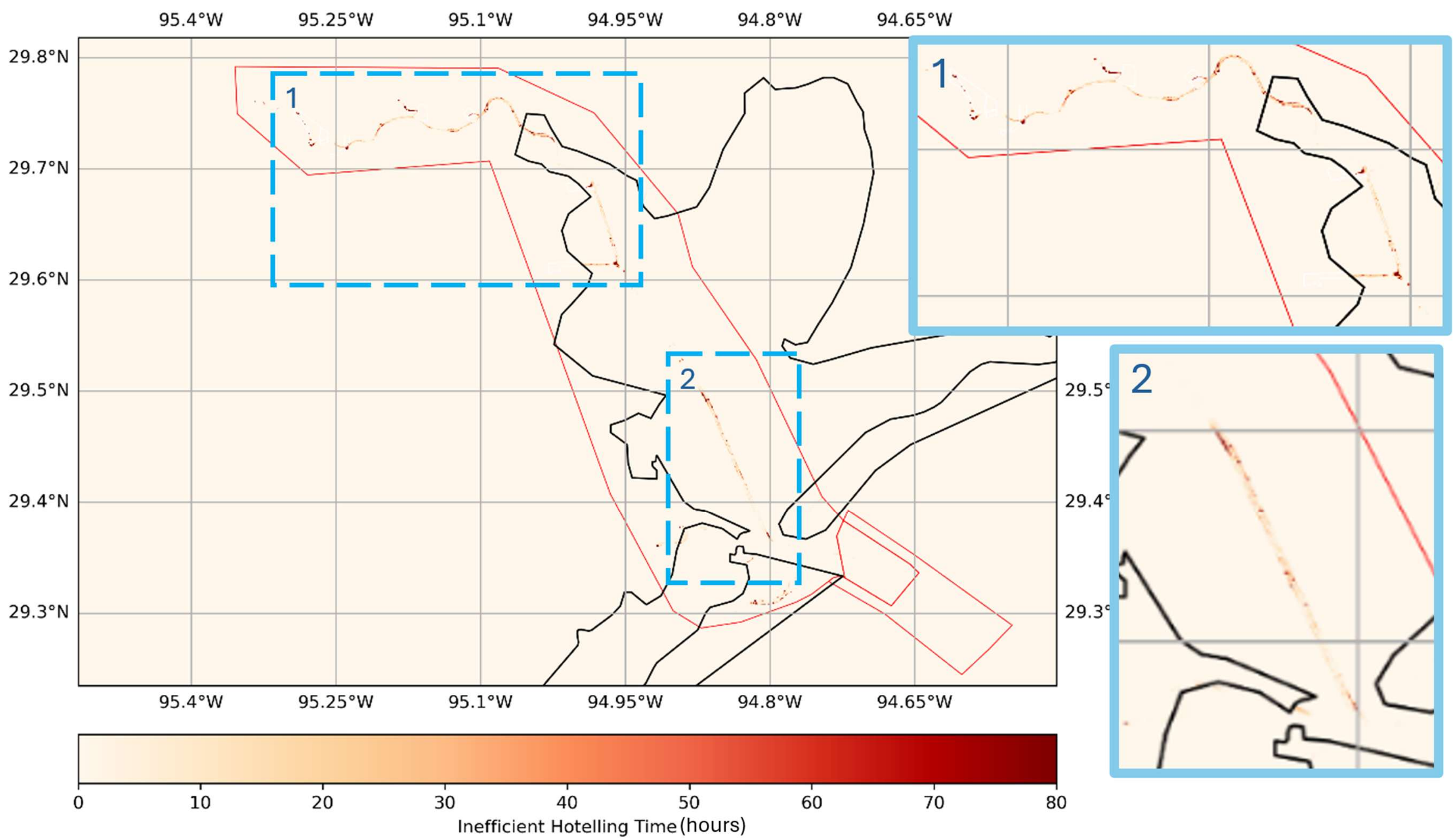


Figure 60. Spatial Distribution of Inefficient Stays of HBC

8. BENEFIT-COST ANALYSIS

8.1 Cost Estimation

To evaluate the suitability of various emission reduction strategies, it is essential to understand their associated costs. The TTI research team conducted a comprehensive review of relevant literature and cost sources to estimate the expenses related to infrastructure development, vessel retrofitting or procurement, and operational costs. These estimates are summarized in Table 35.

The cost categories included:

- Facility Costs: Infrastructure required at terminals or ports (e.g., charging stations, LNG terminals, hydrogen fueling systems).
- Vessel Retrofit or Purchase Costs: Expenses related to retrofitting existing vessels or acquiring new ones configured for low-emission operation.
- Operational Costs: Fuel or energy expenses, converted to a $/kWh basis for comparison, incorporating both fuel energy density and engine efficiency.

Table 35. Cost Estimation to Implement Relevant Strategies

Strategy	Facility Cost	Vessel Retrofit/Purchase Cost	Operational Cost*	Source(s)
Shore Power/Cold Ironing	$30 million per terminal	$500,000/vessel	$0.036/kWh	Eastern Research Group (2017); U.S. EIA (2025)
Engine Tier Regulation	Not applicable	$0.05~$10 million	Not applicable	ENVIRON International Corporation (2004)
Alternative Fuels—Biodiesel (B20)	Minimal infrastructure changes	Minimal retrofit costs (assume $0.1 million)	$3.53/gallon → $0.211/kWh	U.S. Department of Energy (2025b)
Alternative Fuels—LNG	$50 million per terminal	$20 million	$810/mt → $0.135/kWh	Business Plan (2025); ShipUniverse (2024); Titan (2025)
Alternative Fuels—Hydrogen	$41 million (LH2)	$30 million (new one of full hydrogen) $35 million (new one of hybrid hydrogen)	$8/kg → $0.338/kWh (fuel cells) → $0.529/kWh (engine combustion)	Lee (2024); Stetson & Satyapal (2020); Hydrogen Central (2025); H2IQ (2024)
Hybrid Electrification	$72,000 per unit (assume 10 units/terminal)	$11 million (new one of hybrid)	$0.036/kWh	Dexter Marine Group (2022); Professional Mariner (2019); New West Technologies (2015)
Vessel Speed Control	Not applicable	Operational costs may increase or decrease	Not applicable	–
Benchmark—MGO Price	–	–	$800/mt → $0.149/kWh	Ship&Bunker(2025)

* All fuel prices were converted into energy-equivalent units based on fuel energy content and engine or battery efficiency.

- B20: 1 gal = 1.11 GGE, 1 GGE = 33.40 kWh, $3.53/gal → $0.095/kWh, @45% → $0.211/kWh
- LNG: 48.0 MJ/kg, 1 mt = 48,000 MJ = 13,333 kWh, $810/mt → $0.060/kWh, @45% → $0.135/kWh
- Hydrogen (Fuel Cell): 39.4 kWh/kg, $8/kg→ $0.203/kWh, @60% → $0.338/kWh
- Hydrogen (Engine): 33.6 kWh/kg, $8/kg→ $0.238/kWh, @45% → $0.529/kWh
- MGO: 42.7 MJ/kg, 1 mt = 42,700 MJ = 11,861 kWh, $800/mt → $0.067/kWh, @45% → $0.149/kWh

8.2 OGV Fuel Comparisons

This section presents the research team's evaluation of the biodiesel and LNG fuel strategies for OGVs, which involved comparing them against a benchmark scenario:

- Benchmark: OGVs continue operating with their existing diesel engines.
- Biodiesel Strategy: OGVs powered by diesel are converted to run on biodiesel.
- LNG Strategy: OGVs powered by diesel are converted to run on LNG.

These two strategies were selected because they are currently more feasible for implementation in OGVs. Biodiesel requires minimal modifications to existing ships and offers a higher energy density compared with other biofuels. LNG provides a moderate energy density at a relatively affordable cost. In contrast, hydrogen and electrification were not considered for OGVs in this study, as their energy storage capacity remains limited and they are not yet widely applied to OGVs.

8.2.1 Cost Specification

The energy consumption of vessels (in kilowatt-hours) was used to estimate fuel costs, with relevant parameters listed in Table 36. Notably, LNG has the lowest fuel cost, at $0.135/kWh, slightly cheaper than diesel ($0.149/kWh), while biodiesel is the most expensive, at $0.211/kWh. However, fuel price alone does not determine the most cost-effective strategy because retrofit and infrastructure costs vary significantly.

Biodiesel requires only modest upgrades, with a typical retrofit cost of $0.1 million per ship and no additional terminal infrastructure. Assuming a 30-year vessel lifespan and a 3% interest rate, the annualized ship retrofit cost is just $5,102 (California EPA, 2005).

In contrast, LNG adoption involves significantly higher upfront costs, including vessel retrofits and terminal infrastructure upgrades. As shown in Table 37, retrofit and crew training expenses vary by ship type. However, compared with traditional diesel, LNG offers operational savings due to its cleaner combustion: vessels avoid the need for scrubbers and are subject to lower emission-related fees. These benefits are reflected in annualized savings, offsetting some retrofit costs. Additionally, LNG infrastructure requires a $50 million investment per terminal, with an annualized cost of $2.5 million per terminal. These terminal costs are allocated to vessel types in proportion to their respective fuel consumption.

Table 36. Ship and Terminal Cost Assumptions for OGV Fuel Strategies

Strategy	Fuel Cost	Ship Retrofit Cost	Ship Lifespan	Terminal Cost	Terminal Lifespan	Interest	Annualized Ship Retrofit Cost	Annualized Terminal Cost
Diesel	$0.149/kWh	–	–	–	–	–	–	–
Biodiesel	$0.211/kWh	$0.1 M	30 years	–	–	3%	$5,102	–
LNG	$0.135/kWh	See Table 37	30 years	$50 M	30 years	3%	See Table 37	$2.6 M

Table 37. LNG Initial Retrofit and Crew Training Cost (Million $)

Cost Category	Bulk Carrier	Vehicle Carrier	General Cargo	Containe r Ship	Chemical Tanker	Oil Tanker	Other Tanker	Misc. (C3)	Offshore Support	Ferry	RORO	Reefer
Initial Retrofit & Crew Training	$23 M	$23 M	$30 M	$30 M	$26 M	$26 M	$26 M	$14 M	$14 M	$17 M	$14 M	$23 M
Annualized Maintenance Cost	–$0.38 M	–$0.38 M	–$0.5 M	–$0.5 M	–$0.43 M	–$0.43 M	–$0.43 M	–$0.23 M	–$0.23 M	–$0.28 M	–$0.23 M	–$0.38 M
Annualized Compliance Cost	–$0.31M	–$0.31 M	–$0.4 M	–$0.4 M	–$0.35 M	–$0.35 M	–$0.35 M	–$0.19 M	–$0.19 M	–$0.23 M	–$0.19 M	–$0.31 M
Overall Annualized Cost	$0.48 M	$0.48 M	$0.63 M	$0.63 M	$0.55 M	$0.55 M	$0.55 M	$0.29 M	$0.29 M	$0.36 M	$0.29 M	$0.48 M

To estimate the total cost for each ship type, retrofit costs were adjusted based on the proportion of time each vessel spent hotelling at the POH relative to other ports. This adjustment reflected the share of retrofit investment effectively utilized at the POH. It was assumed that all terminals are equipped with the appropriate fuel bunkering infrastructure, and terminal costs are allocated to each ship type in proportion to their fuel consumption.

Figure 61 shows the additional cost of the biodiesel strategy per vessel compared to the benchmark scenario. Due to higher biodiesel fuel prices, operating costs increase. The retrofit costs for biodiesel are minimal, and this strategy does not require additional terminal infrastructure investment. As a result, the total additional cost is primarily driven by fuel expenditures.

In contrast, the LNG strategy benefits from lower fuel prices, yielding fuel cost savings relative to the benchmark, as illustrated in Figure 62. However, LNG adoption entails substantial capital investment for both ship retrofitting and terminal upgrades. Compared to the cost of retrofitting vessels, the facility cost is relatively minor, meaning that the total additional cost is largely determined by the ship-related expenses.

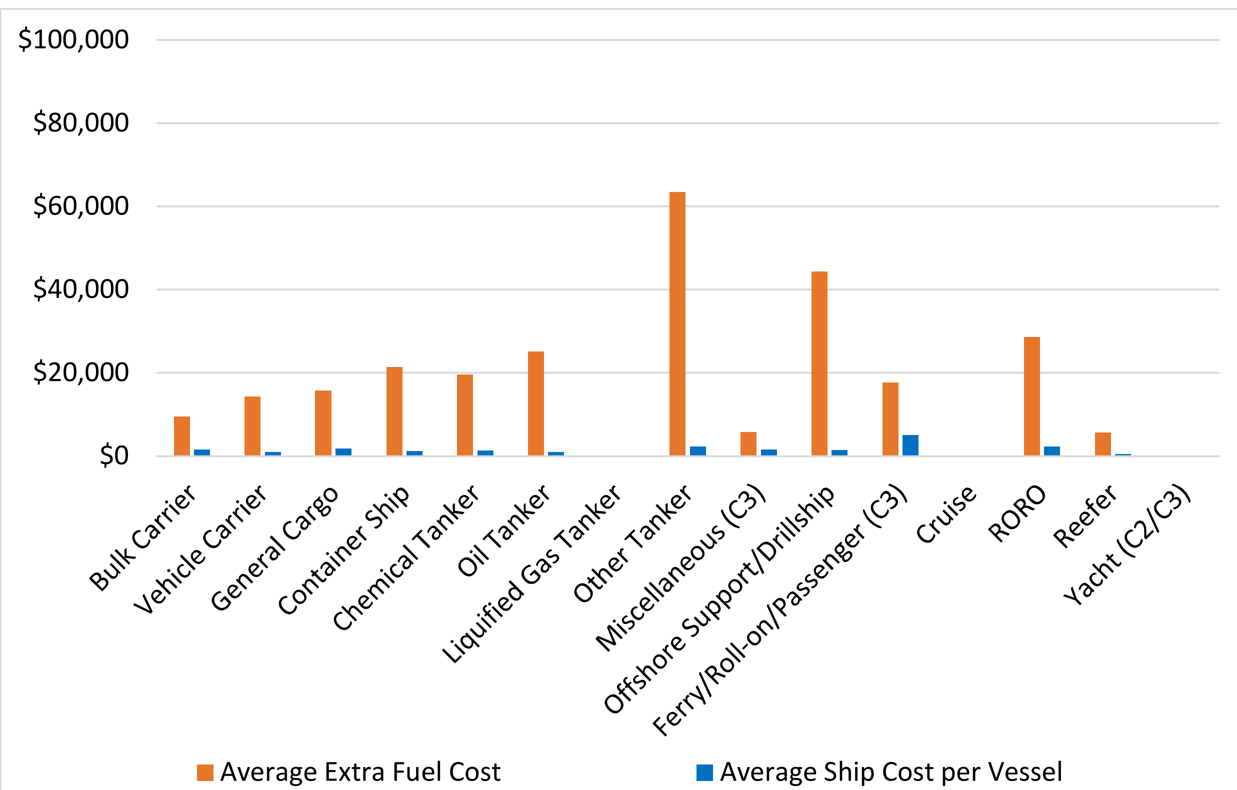


Figure 61. Additional Costs of Biodiesel Strategy per OGV Compared to Benchmark

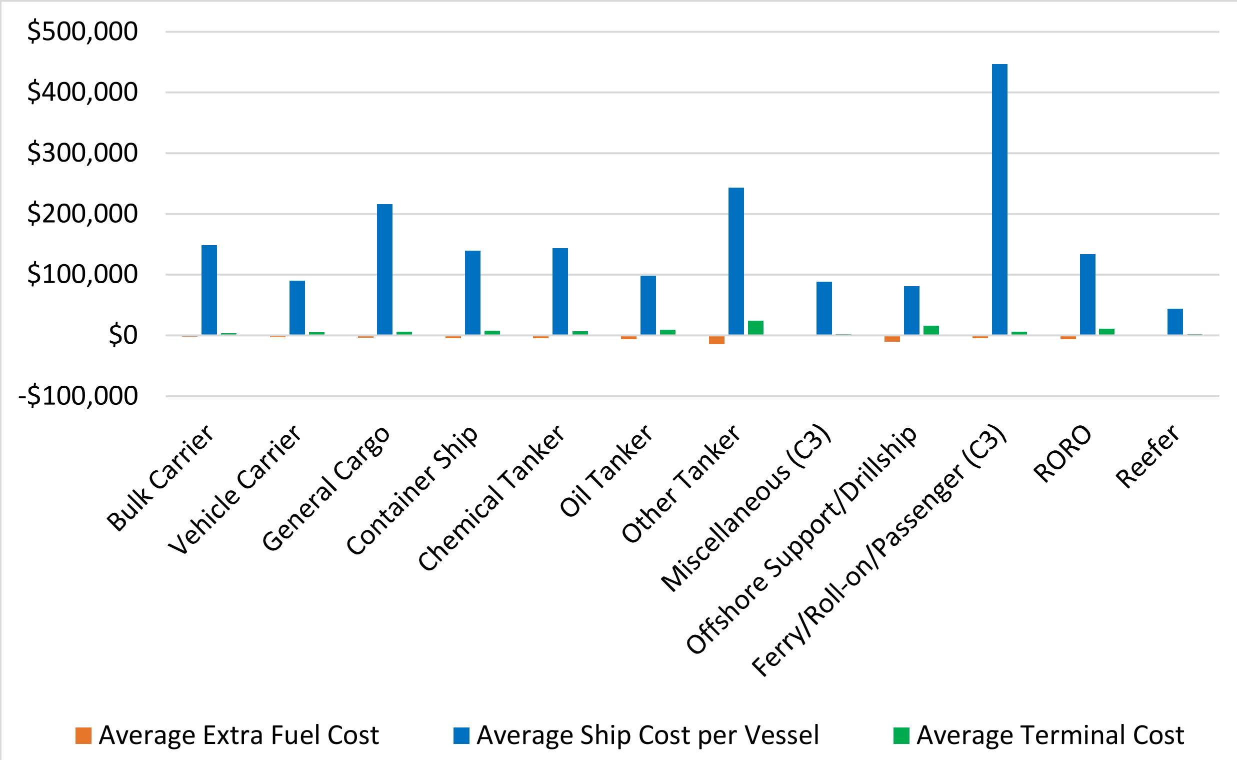


Figure 62. Additional Costs of LNG Strategy per OGV Compared to Benchmark

8.2.2 Cost-Effectiveness of Emission Reductions

The total emissions under both strategies are summarized below and shown in Figure 63:

- Biodiesel: Provides moderate reductions in PM2.5, CO2, and SO2 emissions but offers negligible benefits for NOx reduction.
- LNG: Achieves substantial reductions in NOx, PM2.5, CO2, and SO2 due to cleaner combustion characteristics.

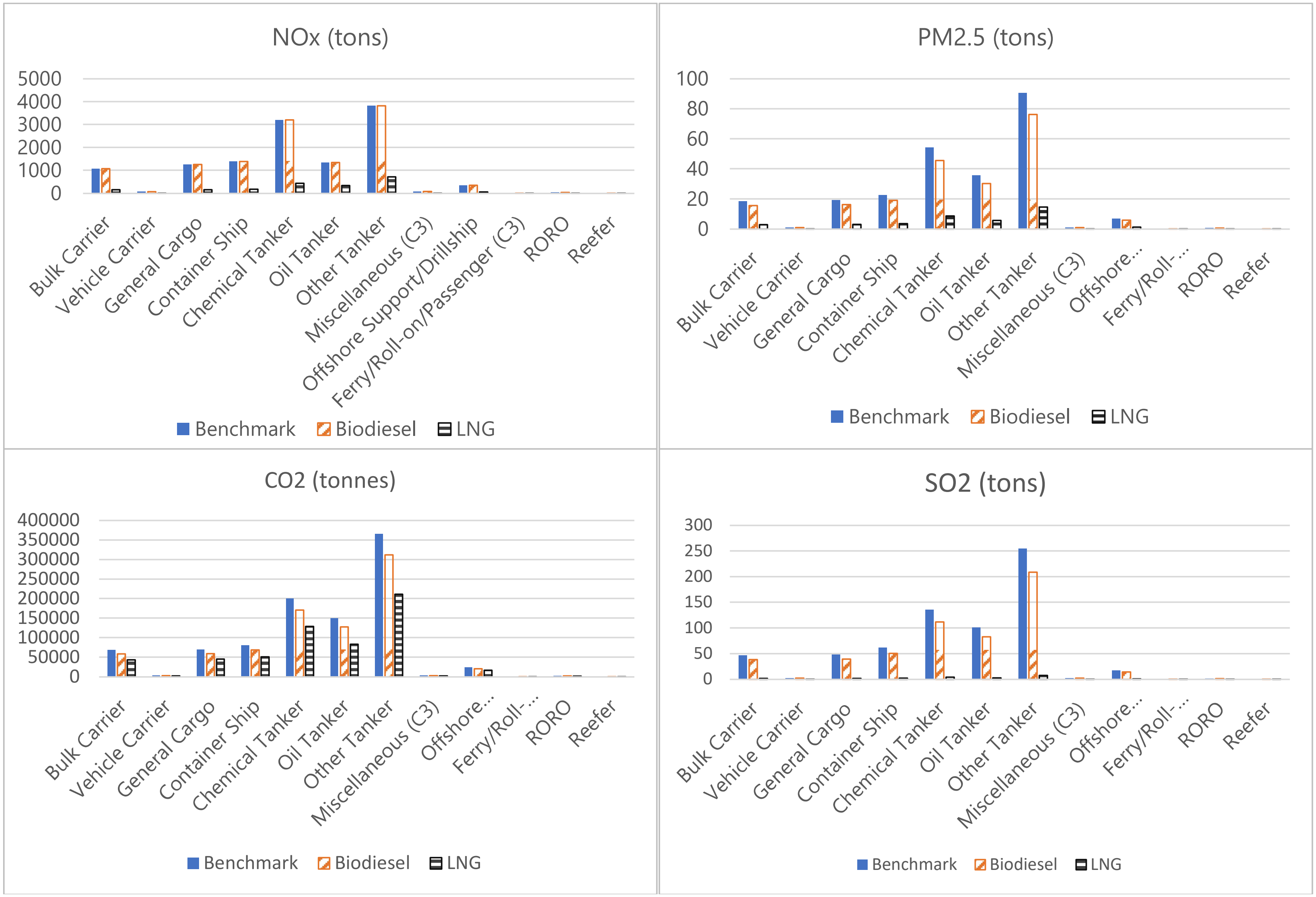


Figure 63. Total Emissions of Different Fuel Strategies

Table 38 presents the pollutant reductions per million dollars invested for the biodiesel strategy across various vessel types, offering insight into their cost-effectiveness in emission mitigation. The biodiesel strategy shows consistent reductions in PM2.5, CO2, and SO2 across all vessel categories, with PM2.5 reductions averaging around 0.4–0.5 tons per million dollars and CO2 reductions ranging from 1,246 to 1,939 tonnes, making it particularly effective in reducing carbon emissions. SO2 reductions are also moderate, typically between 1.1 and 1.7 tons per million. However, biodiesel provides no meaningful NOx reductions, limiting its environmental benefit.

By contrast, as indicated in Table 39, the LNG strategy delivers significant reductions in NOx emissions, with values as high as 70 tons per million dollars for offshore support vessels and above 10 tons for several cargo ship types. While LNG's impact on PM2.5, CO2, and SO2 is less pronounced than biodiesel, it still provides measurable benefits, especially for tankers and container ships. These results underscore LNG's advantage as a more comprehensive emissions reduction strategy, particularly for NOx, while biodiesel serves as a more targeted, cost-effective solution for CO2 and PM2.5 reduction with minimal infrastructure investment.

Table 38. Pollutant Reduction per Million Dollars (Biodiesel Strategy)

Pollutant Reduction	Bulk Carrier	Vehicle Carrier	General Cargo	Container Ship	Chemical Tanker	Oil Tanker	Other Tanker	Misc. (C3)	Offshore Support	Ferry	RORO	Reefer
NOx (tons/$M)	–	–	–	–	–	–	–	–	–	–	–	–
PM2.5 (tons/$M)	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.5	0.4	0.5	0.5
CO2 (tonnes/$M)	1,511	1,638	1,547	1,757	1,618	1,929	1,939	1,296	1,624	1,246	1,652	1,608
SO2 (tons/$M)	1.2	1.4	1.3	1.6	1.3	1.6	1.7	1.1	1.4	1.0	1.4	1.3

Table 39. Pollutant Reduction per Million Dollars (LNG)

Pollutant Reduction	Bulk Carrier	Vehicle Carrier	General Cargo	Container Ship	Chemical Tanker	Oil Tanker	Other Tanker	Misc. (C3)	Offshore Support	Ferry	RORO	Reefer
NOx (tons/$M)	10.1	30.1	13.2	27.9	21.2	22.3	29.3	13.9	70.0	9.6	31.2	26.0
PM2.5 (tons/$M)	0.2	0.4	0.2	0.4	0.4	0.7	0.7	0.2	1.4	0.1	0.6	0.3
CO2 (tonnes/$M)	274.3	626.1	290.3	677.4	548.1	1,466.5	1,454.6	226.5	1,874.4	128.4	919.5	532.6
SO2 (tons/$M)	0.5	1.3	0.6	1.4	1.0	2.2	2.3	0.5	3.9	0.3	1.7	1.0

8.3 HBC Fuel Comparisons

For HBC, the research team evaluated the cost-effectiveness of several alternative fuel technologies compared to the current diesel-based operations. Based on findings presented in Section 7.5, full electrification was excluded from this analysis due to limited battery capacity to support the majority of HBC operations.

The following fuel strategies were considered, assuming all terminals are equipped with the necessary infrastructure to support each option:

- Benchmark: HBC continue operating with their existing diesel engines.
- Biodiesel: HBC powered by diesel engines are converted to run on biodiesel.
- Hybrid Electric: All HBC are replaced with hybrid electric vessels based on the hybrid eTug design, equipped with a 4,520 kWh battery.
- Hybrid Hydrogen (Hybrid CH2): All HBC are replaced with hybrid hydrogen vessels modeled after the Hydrotug 1, featuring 415 kg of compressed hydrogen storage.
- Full Hydrogen (Full LH2): Only HBC eligible for full hydrogen conversion are retrofitted with fuel-cell systems using 4,000 kg of liquid hydrogen storage, modeled after the HyZET design; non-eligible vessels continue operating with their existing fuel type.

8.3.1 Cost Specification

Table 40 summarizes the key cost assumptions used to evaluate alternative fuel strategies for HBC, including both ship retrofit and terminal infrastructure investments. Each strategy is assessed based on fuel price per kilowatt-hour, upfront capital costs for vessel conversion, infrastructure requirements at terminals, and a 30-year asset lifespan with a 3% interest rate. While biodiesel and hybrid electric options involve relatively lower retrofit and infrastructure costs, hydrogen-based strategies require significant capital investments, particularly for terminal upgrades.

Table 40. Ship and Terminal Cost Assumptions for HBC Fuel Strategies

Strategy	Fuel Cost	Ship Retrofit Cost	Ship Lifespan	Terminal Cost	Terminal Lifespan	Interest	Annualized Ship Retrofit Cost	Annualized Terminal Cost
Benchmark	$0.149/kWh (Diesel)	–	–	–	–	–	–	–
Biodiesel	$0.211/kWh	$0.05 M	30 years	–	–	3%	$2,250	–
Hybrid Electric	$0.036/kWh	$11 M	30 years	$0.72 M	30 years	3%	$561,212	$36,734
Hybrid Hydrogen (Internal Combustion Engine)	$0.529/kWh	$35 M	30 years	$41 M	30 years	3%	$1,785,674	$2.0 M
Full Hydrogen (Fuel Cell)	$0.338/kWh	$30 M	30 years	$41 M	30 years	3%	$1,530,578	$2.0 M

To estimate the total cost of each strategy, the research team began by calculating the fuel expenses for each vessel based on its energy consumption (in kilowatt-hours), which was then multiplied by the corresponding unit fuel cost. The additional fuel cost was obtained by comparing this amount to the benchmark diesel scenario. Ship retrofit costs were adjusted based on the vessel's ratio of time spent hotelling at the POH relative to other ports. This adjustment reflects the portion of retrofit investment effectively utilized at the POH. Terminal infrastructure costs assume all terminals are equipped with the required fueling or charging facilities, and these costs are allocated proportionally to each ship type according to their respective fuel usage.

The annual additional expenses of each alternative fuel strategy, compared with the diesel baseline, are as follows:

- Biodiesel (Figure 64): This strategy results in a slight fuel cost increase due to the higher unit price of biodiesel, and it requires minimal retrofit investment, making it a low-barrier option in terms of upfront capital.
- Hybrid Electric (Figure 65): Hybrid electric benefits from lower fuel costs due to cheaper electricity and requires less investment than hydrogen in vessels and terminals, making it more cost-effective than hybrid hydrogen.
- Hybrid Hydrogen (Figure 66): Hybrid hydrogen incurs higher fuel expenses and substantial investments in both vessel retrofitting and terminal infrastructure, making it the most capital-intensive option. The retrofit costs are so significant that the associated terminal expenses become relatively negligible by comparison.
- Full Hydrogen (Figure 67): Full hydrogen is used only for eligible vessels to improve efficiency. While fuel costs remain high, overall retrofit expenses are lower than hybrid hydrogen since only part of the fleet is converted.

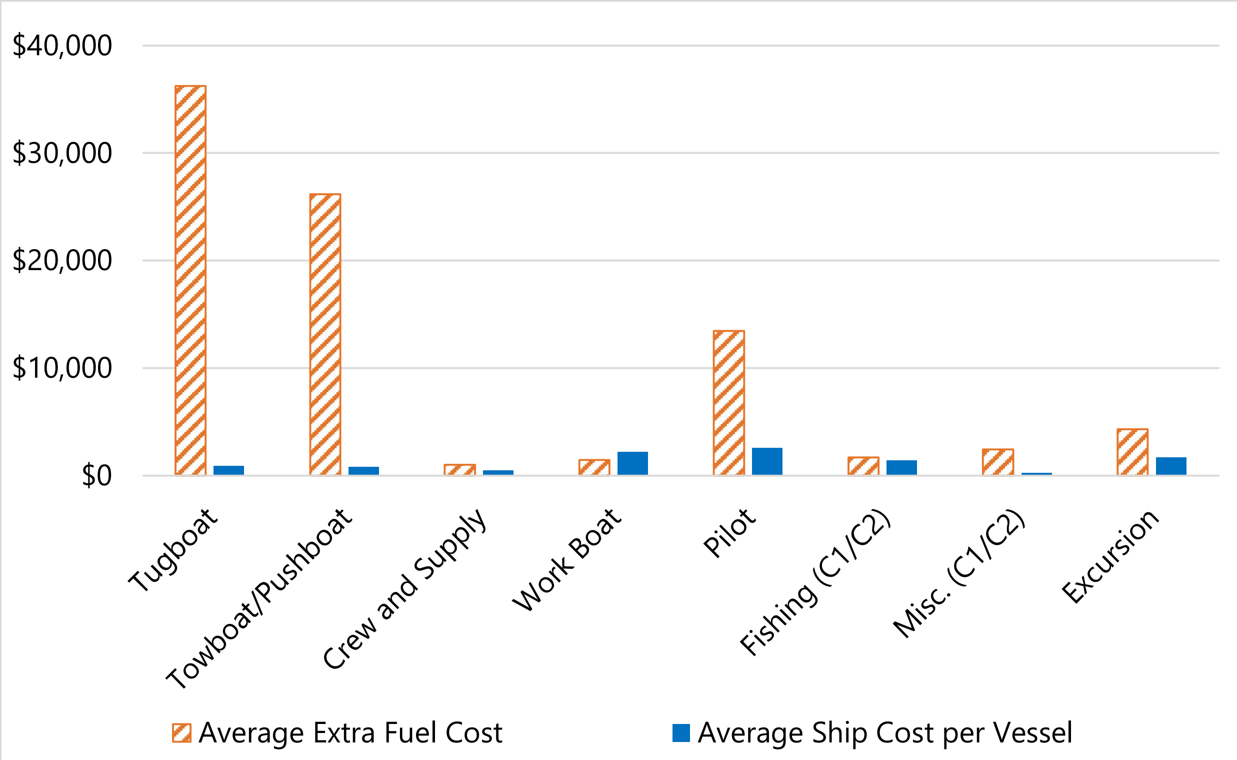


Figure 64. Additional Costs of Biodiesel Strategy per HBC Compared to Benchmark

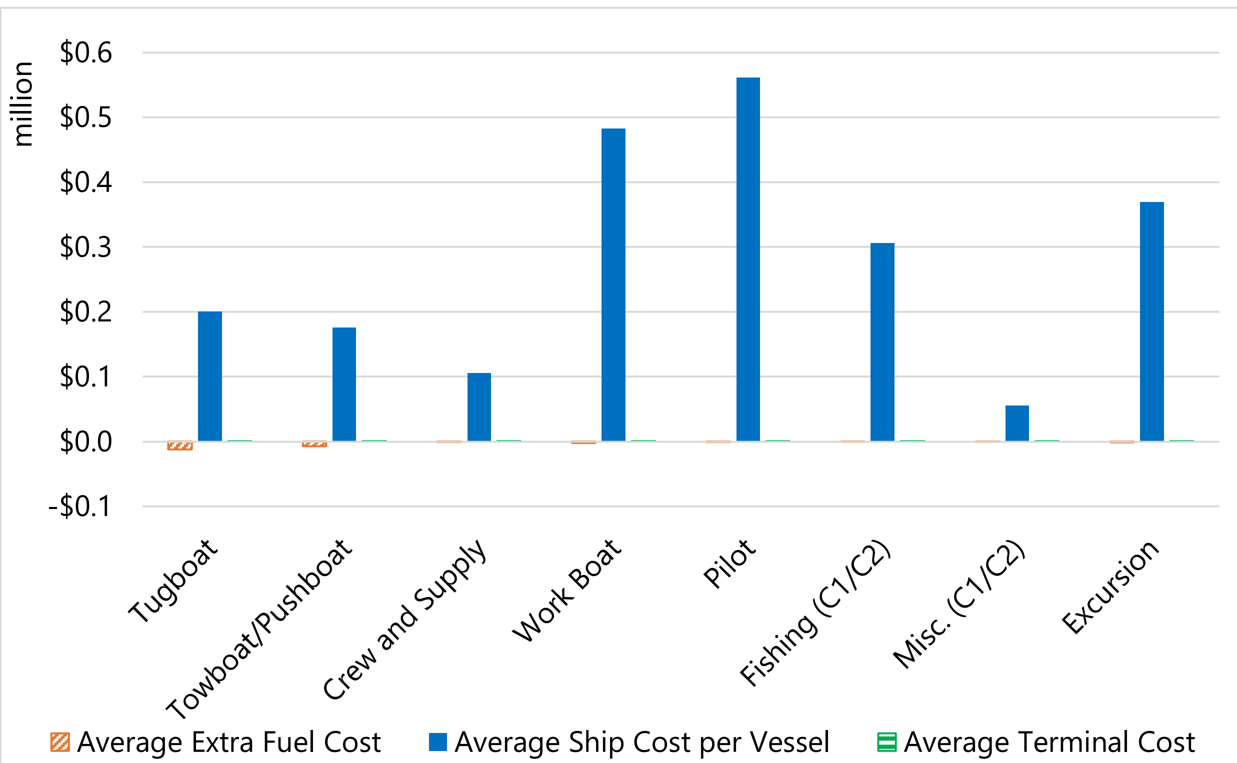


Figure 65. Additional Costs of Hybrid Electric Strategy Compared to Benchmark

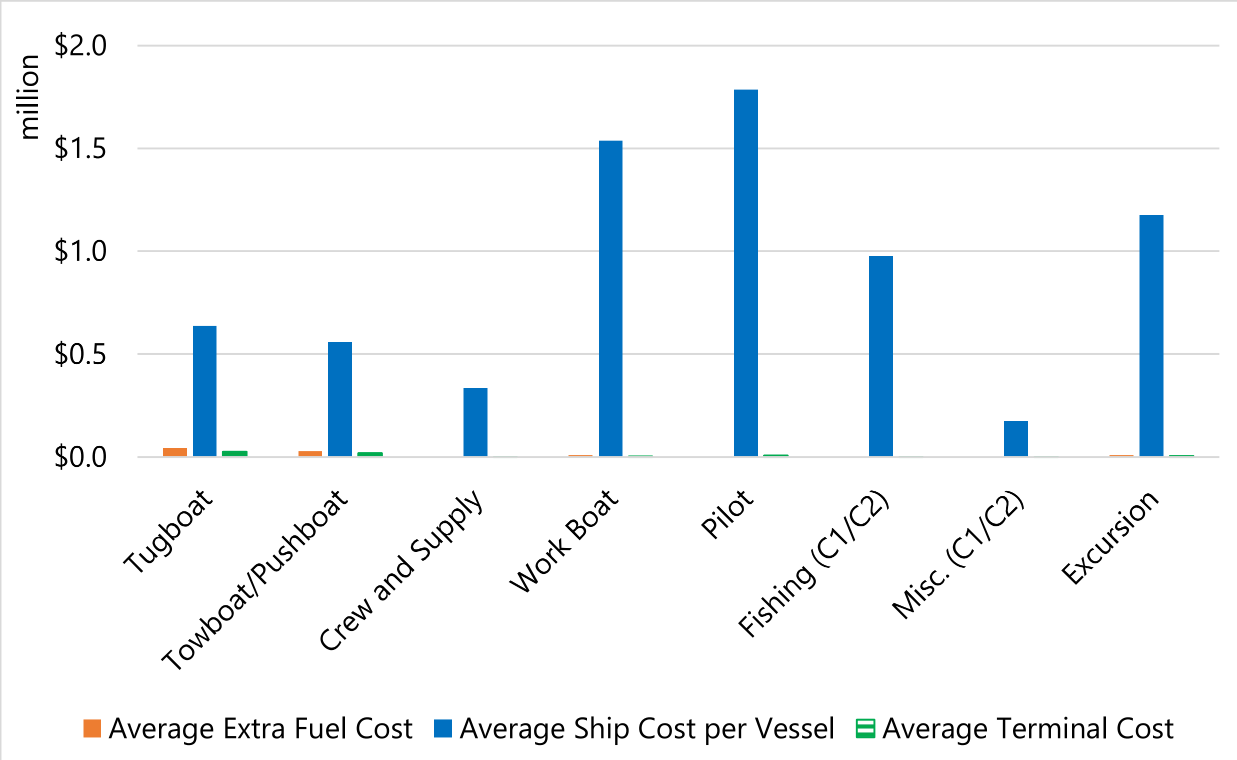


Figure 66. Additional Costs of Hybrid Hydrogen Strategy Compared to Benchmark

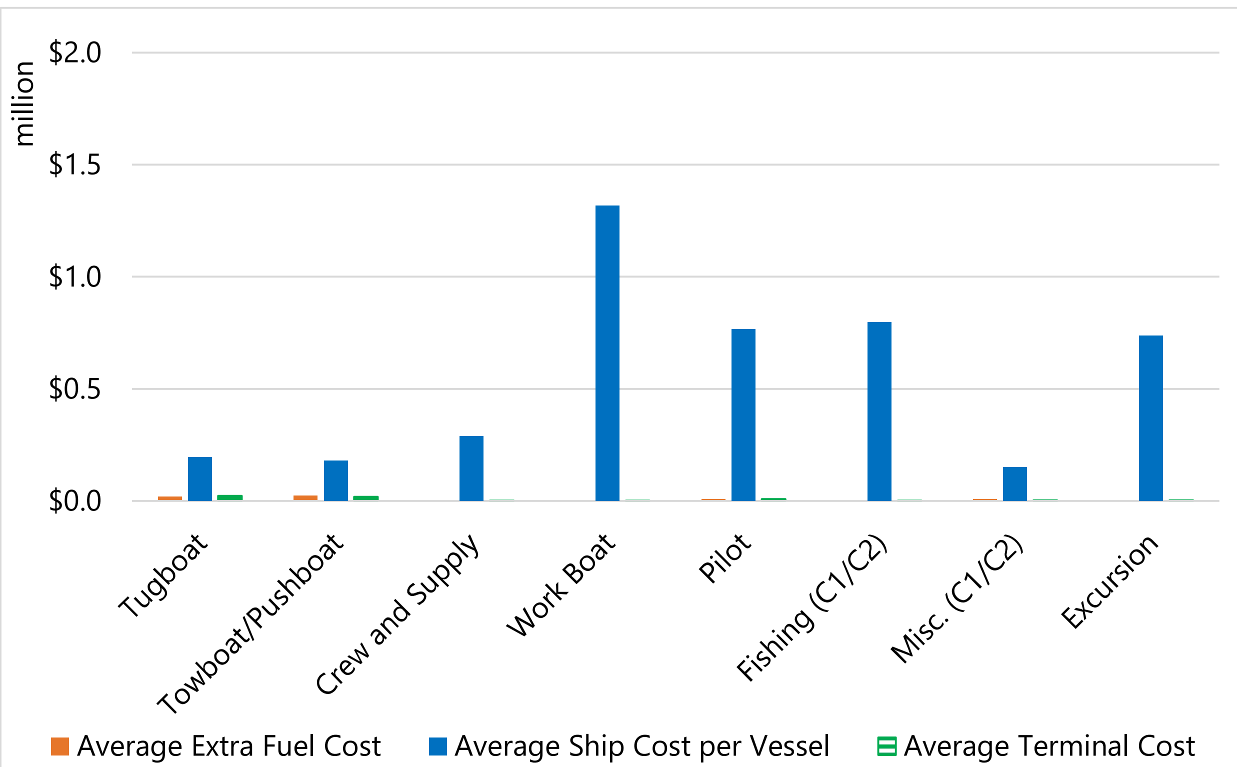


Figure 67. Additional Costs of Full Hydrogen Strategy Compared to Benchmark

8.3.2 Cost-Effectiveness of Emission Reductions

Figure 68 presents the estimated emission reductions under each strategy, as detailed below:

- Biodiesel provides limited NOx reductions but achieves moderate PM2.5 and CO2 reductions of approximately 15–16%. It is particularly effective in reducing SO2 emissions by around 90%.
- Hybrid electric leads to about a 14–16% reduction in NOx. However, since the electricity is sourced from local power plants, CO2 reductions are limited to around 10%, and SO2 emissions increase compared to the diesel benchmark.
- Hybrid hydrogen results in an 11–15% reduction of major pollutants because the effectiveness is constrained by the limited storage capacity of hydrogen and batteries.
- Full hydrogen achieves the highest emissions reduction, covering approximately 23% of total emissions by leveraging the greater hydrogen storage capacity available in eligible vessels.

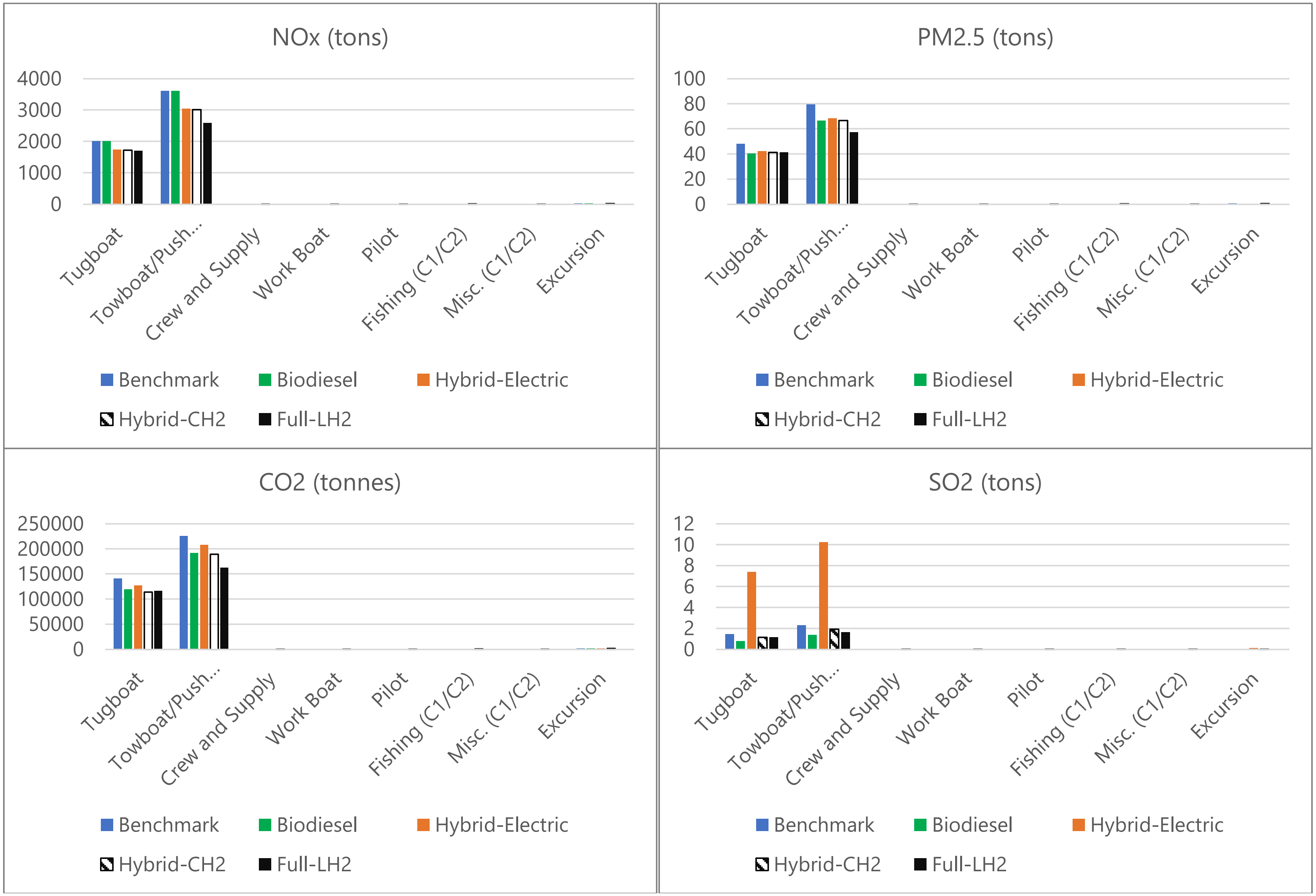


Figure 68. Emission Comparisons Given Different Fuel Strategies for HBC

Table 41, Table 42, Table 43, and Table 44 detail emission reductions per million dollars invested, accounting for fuel, retrofit, and terminal costs across multiple vessel categories. As shown in the tables:

- Biodiesel emerges as the most cost-effective option for achieving CO2 and PM2.5 reductions, particularly for tugboats and towboats. It delivers noticeable pollutant reductions while requiring minimal engine modifications and no additional terminal investment. However, biodiesel cannot reduce NOx effectively, making it less attractive for NOx reduction-focused goals.
- Hybrid electric achieves a better balance between cost and emissions benefit. Although its upfront retrofit and terminal costs are still significant, its reliance on cheaper electricity results in strong cost efficiency, especially for NOx reductions. The pollutant reduction per dollar is more favorable than hybrid hydrogen. However, the benefits in PM2.5 and CO2 reductions are moderate compared to biodiesel, and SO2 emissions may increase relative to the diesel baseline due to emissions from local electricity generation.
- Hybrid hydrogen shows limited emissions reduction per dollar. The high costs of both onboard hydrogen-compatible engines and terminal infrastructure reduce the overall cost-effectiveness. While reductions in NOx are achieved, especially for tugboats and towboats, the high cost per ton of pollutant reduced diminishes its value as a primary strategy.
- Full hydrogen offers high NOx and CO2 reductions per dollar by targeting only eligible vessels for fuel-cell retrofits, while allowing non-eligible ships to continue using diesel. This selective application improves the return on investment, making it more cost-effective than a fleet-wide hybrid hydrogen conversion. However, its benefit is limited by the smaller portion of the fleet that can adopt this technology and its continued high fuel cost.

Overall, while each strategy contributes to emission reduction, biodiesel provides the broadest return across vessel types for CO2 and PM2.5 reductions with low capital requirements. Hybrid electric stands out for NOx reduction under a moderate budget, and full hydrogen offers a targeted solution for deep decarbonization in specific vessel segments. Hybrid hydrogen, though technically viable, ranks lowest in cost-effectiveness due to its high infrastructure and fuel costs.

Table 41. Pollutant Reduction per Million Dollars (Biodiesel Strategy)

Pollutant	Tugboat	Towboat/ Pushboat	Crew and Supply	Work Boat	Pilot	Fishing (C1/C2)	Misc. (C1/C2)	Excursion
NOx (tons)	–	–	–	–	–	–	–	–
PM2.5 (tons)	0.584	0.599	0.525	0.392	0.115	0.457	0.971	0.388
CO2 (tonnes)	1,604	1,595	1,107	653	1,382	900	1,491	1,182
SO2 (tons)	0.050	0.043	0.021	0.034	0.017	0.012	0.018	0.072

Table 42. Pollutant Reduction per Million Dollars (Hybrid Electric Strategy)

Pollutant	Tugboat	Towboat/ Pushboat	Crew and Supply	Work Boat	Pilot	Fishing (C1/C2)	Misc. (C1/C2)	Excursion
NOx (tons)	4.079	4.251	0.574	0.514	0.045	0.127	1.078	0.388
PM2.5 (tons)	0.084	0.085	0.014	0.017	0.000	0.003	0.020	0.007
CO2 (tonnes)	201	134	21	17	4	4	27	14
SO2 (tons)	−0.090	−0.060	−0.010	−0.007	−0.002	−0.002	−0.012	−0.006

Table 43. Pollutant Reduction per Million Dollars (Hybrid Hydrogen Strategy)

Pollutant	Tugboat	Towboat/ Pushboat	Crew and Supply	Work Boat	Pilot	Fishing (C1/C2)	Misc. (C1/C2)	Excursion
NOx (tons)	1.138	1.246	0.211	0.155	0.018	0.047	0.364	0.125
PM2.5 (tons)	0.027	0.027	0.005	0.005	0.000	0.001	0.007	0.003
CO2 (tonnes)	106	76	15	10	3	3	18	8
SO2 (tons)	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000

Table 44. Pollutant Reduction per Million Dollars (Full Hydrogen Strategy)

Pollutant	Tugboat	Towboat/ Pushboat	Crew and Supply	Work Boat	Pilot	Fishing (C1/C2)	Misc. (C1/C2)	Excursion
NOx (tons)	3.526	5.829	0.548	0.192	0.066	0.160	2.838	0.330
PM2.5 (tons)	0.079	0.128	0.016	0.007	0.001	0.005	0.102	0.007
CO2 (tonnes)	291	362	37	12	31	10	166	22
SO2 (tons)	0.003	0.004	0.000	0.000	0.000	0.000	0.002	0.000

8.4 Shore Power

8.4.1 Cost Specification

This section presents the examination of the benefit-cost analysis for shore power for OGVs. Table 45 summarizes the cost assumptions for evaluating shore power feasibility, assuming OGV and HBC share the same ship retrofit cost. The analysis was based on a diesel fuel cost of $0.149/kWh and an electricity cost of $0.036/kWh, reflecting the economic advantage of using grid electricity over marine diesel during port stays. Retrofitting a vessel to accept shore power is estimated at $0.5 million per ship, with an expected service life of 30 years. Onshore infrastructure installation is projected to cost $30 million per terminal, with a 30-year lifespan (Clean & Prosperous Washington, 2022). Applying a 3% interest rate to annualize these capital expenditures results in an estimated annual retrofit cost of $25,510 per vessel.

Table 45. Ship and Terminal Cost Assumptions for Shore Power

Diesel Fuel Cost	Electricity Cost	Ship Retrofit Cost	Ship Lifespan	Terminal Cost	Terminal Lifespan	Interest	Annualized Ship Retrofit Cost	Annualized Terminal Cost
$0.149/kWh	$0.036/kWh	$0.5 M	30 years	$30 M	30 years	3%	$25,510	$1.5 M

In the benefit-cost analysis, ship retrofit costs were adjusted according to each vessel's proportion of time spent hotelling at the POH relative to other ports. This adjustment ensured that the investment in shore power retrofitting was accurately attributed to the portion of use specific to POH operations. Additionally, the analysis assumed that all terminals at the POH are fully equipped with shore power infrastructure. The total terminal cost was then distributed proportionally across different ship types based on their respective electricity consumption while docked.

8.4.2 Fuel Cost Savings and Implementation Costs

Figure 69 illustrates the fuel cost savings after using shore power. The fuel cost savings are achieved due to the lower price of electricity compared to marine diesel fuel. OGVs demonstrate significant fuel cost savings owing to their prolonged berthing periods. Among them, RORO, container ships, and tankers stand out since they often engage in time-intensive operations such as loading and unloading large quantities of cargo. In contrast, HBC exhibit minimal fuel cost savings. Their shorter and more intermittent berthing operations limit the use of shore power, reducing its potential benefits.

Figure 70 details the additional costs involved in implementing shore power, including vessel retrofitting and terminal infrastructure upgrades. Since OGVs benefit more from shore power due to their longer berthing times, they are assigned a larger share of terminal costs. When both terminal costs and fuel cost savings are considered, the fuel savings can offset the retrofit and terminal facility cost, leading to economic benefits. In contrast, HBC has a higher retrofit cost attribution but limited benefits from shore power, making the investment less cost-effective for this fleet.

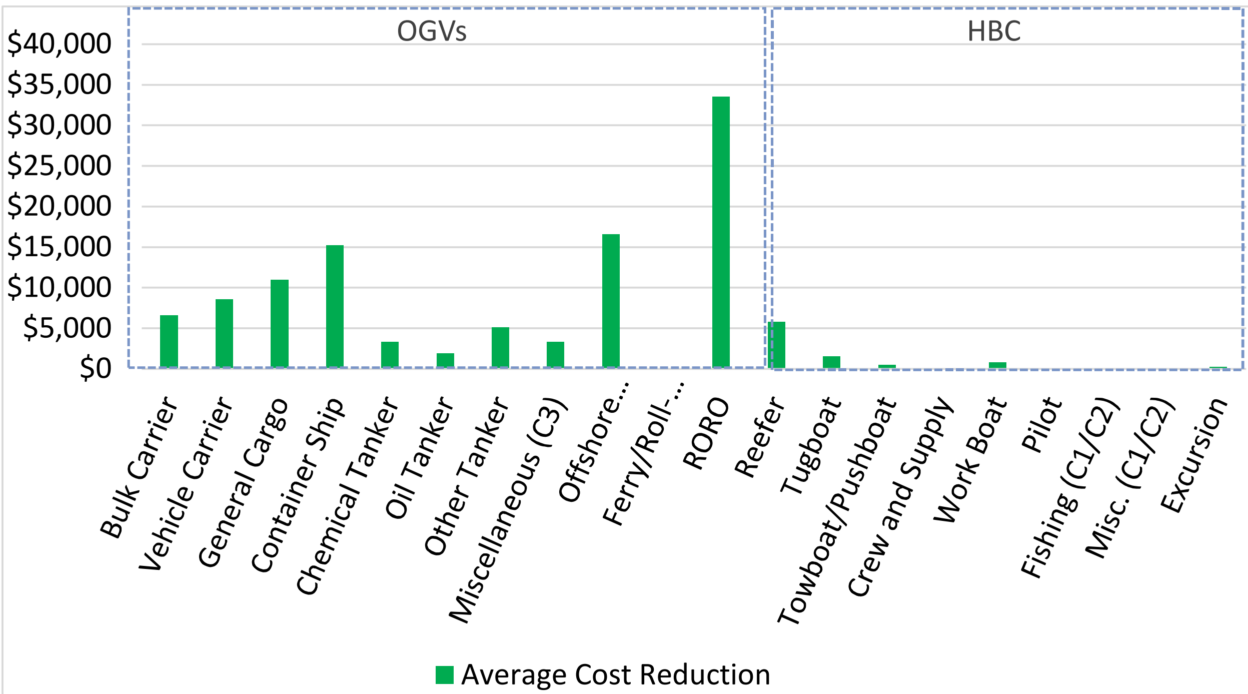


Figure 69. Fuel Cost Savings per Ship with Shore Power

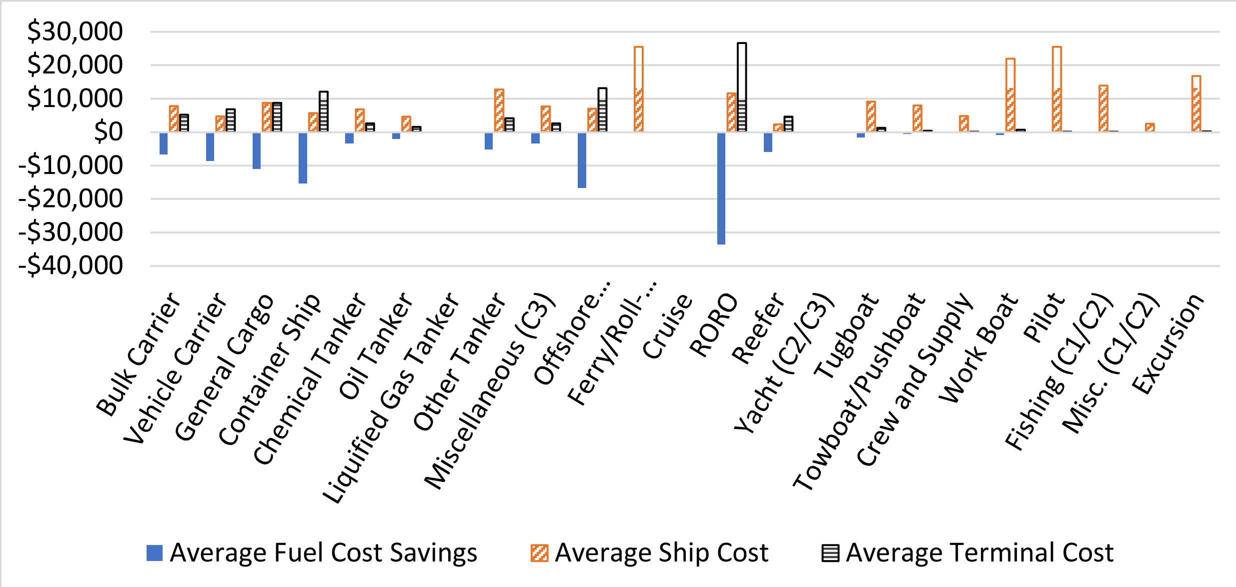


Figure 70. Costs of Adopting the Shore Power Strategy

8.4.3 Cost-Effectiveness of Emission Reductions

Table 46 and Table 47 summarize the emission reductions achieved per million dollars invested in shore power. The results indicate that shore power is more effective for OGVs in terms of pollutant reduction per dollar spent.

Among OGVs, container ships achieve over 699 tons of NOx and nearly 19,300 tonnes of CO2 reduction per million dollars invested. Other high-performing types include reefers and ROROs. Vehicle carriers, general cargo, and tankers also yield meaningful emission reductions, though to a lesser extent.

In contrast, the benefits for HBC are limited. Tugboats perform best among this group, reducing 11.6 tons of NOx and 539 tonnes of CO2 per million dollars invested. Other HBC types, such as towboats, crew vessels, and work boats, show much lower effectiveness. This ineffectiveness is largely due to the operational characteristics of HBC, including intermittent durations and lower auxiliary engine loads. Consequently, shore power investments for HBC result in lower emission reductions per dollar when compared to OGVs. Additionally, the emission factor of SO2 from HBC is lower than that of the regional power grid, which reduces the environmental benefits of this strategy for HBC.

8.4.4 Summary

In summary, shore power is more cost-effective for OGVs, particularly container ships, reefers, and RORO vessels. Prioritizing shore power implementation for vessels with high hotelling power demand and long berthing times can maximize environmental benefits and ensure a higher return on investment in emissions reduction.

Table 46. Pollutant Reduction per Million Dollars (OGV Shore Power Strategy)

Pollutant Reduction	Bulk Carrier	Vehicle Carrier	General Cargo	Container Ship	Chemical Tanker	Oil Tanker	Other Tanker	Misc. (C3)	Offshore Support	Ferry	RORO	Reefer
NOx (tons)	107.3	339.3	193.0	699.4	57.4	46.8	46.4	55.9	274.0	–	717.0	689.3
PM2.5 (tons)	1.51	4.23	2.50	8.94	0.79	0.67	0.60	0.71	6.77	–	10.57	7.69
CO2 (tonnes)	3,253	9,128	5,398	19,294	1,706	1,451	1,339	1,527	14,606	–	22,798	16,599
SO2 (tons)	2.77	7.77	4.59	16.42	1.44	1.23	1.06	1.30	12.43	–	19.40	14.13

Table 47. Pollutant Reduction per Million Dollars (HBC Shore Power Strategy)

Pollutant Reductions	Tugboat	Towboat/ Pushboat	Crew and Supply	Work Boat	Pilot	Fishing (C1/C2)	Misc. (C1/C2)	Excursion
NOx (tons)	11.6	5.7	2.0	3.7	0.0	0.0	–	1.3
PM2.5 (tons)	0.40	0.22	0.08	0.14	0.00	0.00	–	0.03
CO2 (tonnes)	539	193	63	117	0	0	–	45
SO2 (tons)	−0.24	−0.09	−0.03	−0.05	0.00	0.00	–	−0.02

8.5 Tier Upgrade

8.5.1 Cost Specification

Tier upgrades represent a retrofit strategy aimed at reducing emissions through technological improvements, such as engine upgrades and exhaust aftertreatment systems. Cost assumptions for retrofitting ships to comply with various tier standards are presented in Table 48, under the assumption that all ship types incur the same retrofit cost for each tier. Notably, only HBC are eligible for Tier 4 upgrades.

Retrofit costs increase substantially with higher tiers, with OGVs being significantly more expensive to upgrade than HBC. For example, Tier 3 retrofits for OGVs require a capital investment of $10 million per vessel, resulting in an annualized cost of approximately $837,666 over a 15-year lifespan. In contrast, HBC Tier 3 upgrades are considerably more modest, with an annualized cost of approximately $35,169. Tier 4 retrofits, applicable only to HBC, require a $500,000 investment per vessel, resulting in an annualized cost of $41,883. This cost disparity highlights the financial challenge of implementing high-tier retrofits for OGVs and suggests that widespread adoption would likely require substantial incentives or regulatory pressure.

Note that in previous sections, ship retrofits for alternative fuels (e.g., LNG) were modeled over a 30-year vessel lifespan under the assumption that such conversions occur early in a ship’s operating life, allowing the significant retrofit costs to be amortized. Additionally, new LHG engines typically have a longer service life than the modified old engines. In contrast, tier upgrades were limited to 10–15 years because components of modified old engines typically wear out sooner. Additionally, tier retrofits are more feasible for older vessels because they involve comparatively lower investment costs.

Table 48. Ship Retrofit Cost Assumptions for OGV and HBC Tier Upgrade

Tier Strategy	OGV Retrofit Cost	HBC Retrofit Cost	Retrofit Lifespan	Interest	OGV Annual Cost	HBC Annual Cost
T1	100,000	50,000	10 years	3%	$11,723	$5,862
T2	250,000	100,000	10 years	3%	$29,308	$11,723

T3	10,000,000	300,000	15 years	3%	$837,666	$35,169
T4	–	500,000	15 years	3%	–	$41,883

8.5.2 Cost-Effectiveness of Emission Reductions

Table 49 through Table 51 present the cost-effectiveness of NOx and PM2.5 reductions, measured in tons reduced per million dollars invested. Since tier upgrades primarily target NOx for OGVs, and both NOx and PM2.5 for HBC, other pollutants, such as SO2 and CO2, are not discussed here.

8.5.2.1 NOx

Table 49 shows that among OGVs, Tier 1 retrofits deliver the highest NOx reductions per dollar, particularly for offshore support vessels (410 tons) and chemical tankers (225 tons). Tier 2 achieves moderate reductions but is less cost-effective than Tier 1. While Tier 3 strategies incorporate more advanced technologies, they offer substantially lower NOx reduction efficiency (e.g., only 1.9 tons per million dollars for container ships), indicating diminishing returns at higher investment levels.

Table 50 indicates that for HBC vessels, Tier 2 generally provides the greatest NOx reductions per dollar across all vessel types, such as 582 tons for tugboats. Although Tier 4 offers lower overall reductions compared to Tier 2, it still outperforms Tier 3 for most vessel types, particularly towboats.

8.5.2.2 PM2.5

Table 51 displays the PM2.5 reduction performance for HBC. Tier 1 shows the highest cost-effectiveness for most vessel categories, especially tugboats (16.6 tons). PM2.5 reduction efficiency declines steadily with each higher tier. While Tier 4 provides some improvement over Tier 3), it remains less effective than Tier 1 and Tier 2 in most cases.

8.5.3 Summary

In summary, NOx reduction per million dollars invested is generally more efficient for HBC than OGVs due to lower overall retrofit costs for HBC vessels. Among OGV strategies, the cost-effectiveness of NOx reduction declines with higher tiers, indicating that Tier 1 is likely the most economical option. For HBC, Tier 2 offers the best benefit-cost performance for NOx reduction, while Tier 1 is most effective for PM2.5. Tier 4 remains a viable option since it achieves the greatest overall reductions in both NOx and PM2.5, despite its higher cost.

Table 49. NOx Pollutant Reduction (Tons) per Million Dollars (OGV Tier Upgrade Strategy)

Strategy	Bulk Carrier	Vehicle Carrier	General Cargo	Container Ship	Chemical Tanker	Oil Tanker	Other Tanker	Misc. (C3)	Offshore Support	Ferry	RORO	Reefer
T1	34	112	129	181	225	276	81	0	410	37	0	121
T2	23	80	47	91	83	74	117	20	220	33	0	104
T3	5.2	15.4	8.8	18.6	13.4	14.4	17.2	4.3	33.8	4.6	9.6	13.6

Table 50. NOx Pollutant Reduction (Tons) per Million Dollars (HBC Tier Upgrade Strategy)

Strategy	Tugboat	Towboat/ Pushboat	Crew and Supply	Work Boat	Pilot	Fishing (C1/C2)	Misc. (C1/C2)	Excursion
T1	297	258	13	6	0	7	90	0
T2	582	520	29	16	0	19	176	32
T3	251	225	13	7	0	9	78	15
T4	413	367	21	10	0	13	116	26

Table 51. PM2.5 Pollutant Reduction (Tons) per Million Dollars (HBC Tier Upgrade Strategy)

Strategy	Tugboat	Towboat/ Pushboat	Crew and Supply	Work Boat	Pilot	Fishing (C1/C2)	Misc. (C1/C2)	Excursion
T1	16.6	9.5	1.8	1.1	0	1.0	13.0	0
T2	13.6	10.8	1.2	0.6	0	0.6	6.3	0.5
T3	8.4	6.8	0.6	0.3	0	0.3	3.7	0.4
T4	10.2	8.3	0.7	0.4	0	0.4	4.4	0.5

8.6 Vessel Speed

Vessel speed significantly affects both engine efficiency and travel time. Along the HSC, vessel speeds are diverse because operators often adjust their speeds in response to factors such as congestion levels and navigational difficulty. For this analysis, the research team assumed that vessels are capable of adjusting their speed along the HSC and will fully adhere to the prescribed speed strategies.

The current diverse speed distribution in the HSC was treated as the benchmark scenario. This benchmark was used to evaluate the changes in fuel costs, travel time, and emissions under different speed strategies.

8.6.1 Fuel Cost and Travel Time Impacts

Figure 71 illustrates the change in fuel cost per ship under various speed strategies relative to the benchmark scenario. In general, slower speeds result in reduced energy consumption (measured in kilowatt-hour) over a given distance, leading to lower fuel costs. However, operating at lower engine loads can cause inefficiencies that result in increased pollutant emissions.

The results show that other tankers, offshore support vessels, and ferries are particularly sensitive to speed changes. While most vessel types realize fuel cost savings at reduced speeds, some vessels show little or no savings beyond a certain threshold (e.g., above 10 knots), and for others, savings persist even up to 12 knots.

Figure 72 presents the average change in travel time under different speed strategies. As expected, reduced speeds increase travel time. Again, other tankers, offshore support vessels, and ferries show the highest sensitivity. For most vessel types, negative travel time changes begin to appear after adopting the 8- to 10-knot strategies, suggesting that many vessels currently operate at speeds within this range.

The primary reason these three vessel types are more sensitive to speed strategies has to do with their high operational transit time. Although their total transit times are not the highest, they have higher average time per vessel. Consequently, they are more sensitive to changes in speed strategies.

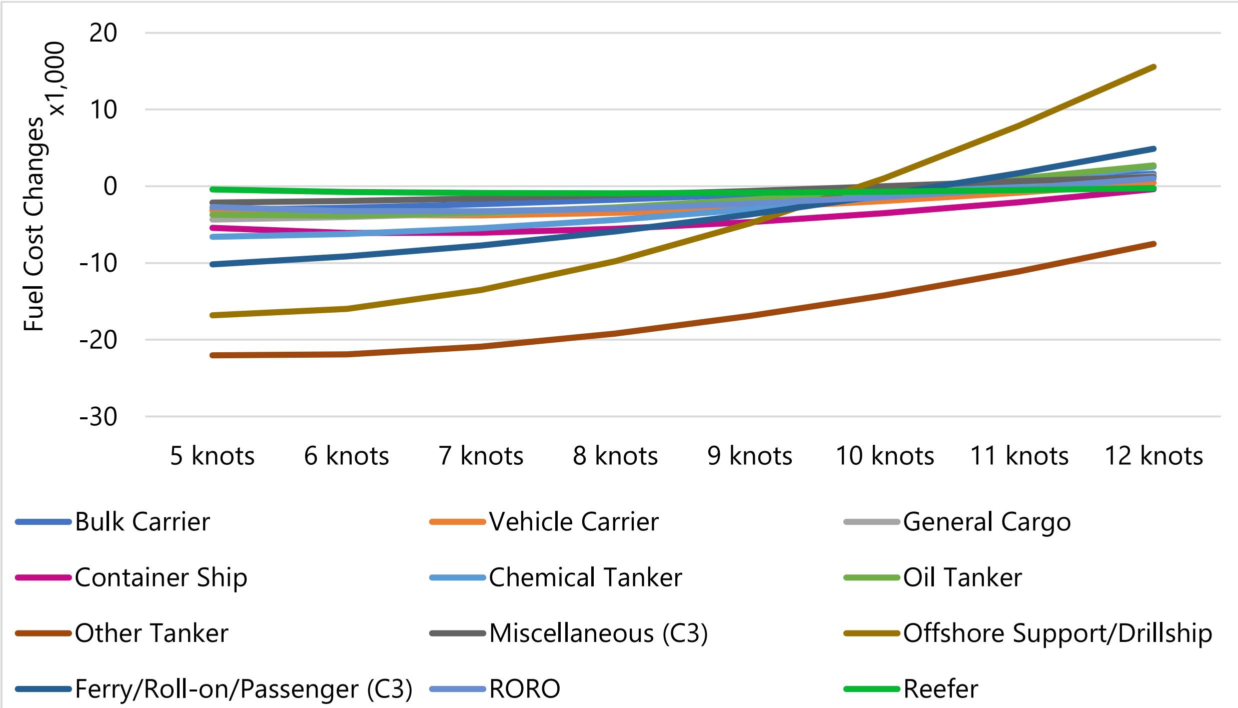


Figure 71. Average Fuel Cost Change under Different Speed Strategies

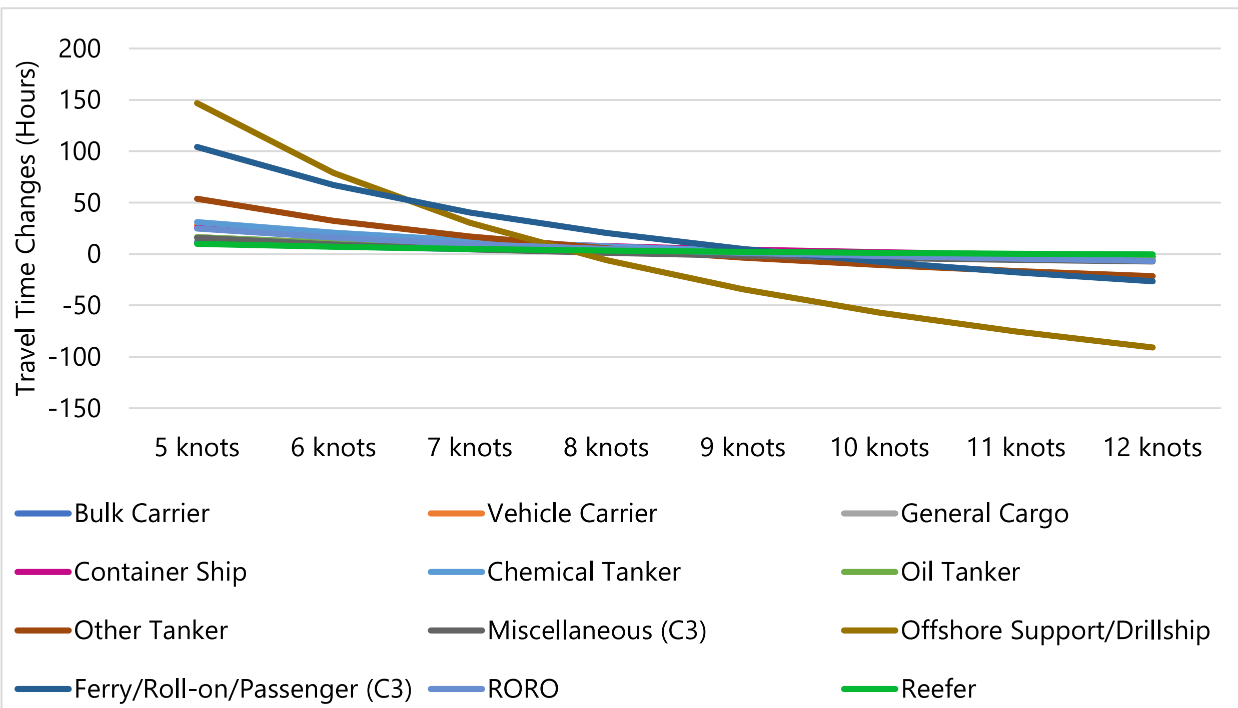


Figure 72. Average Travel Time Change under Different Speed Strategies

8.6.2 Delay Cost Specification

To evaluate the benefits of different vessel speed strategies, the research team considered both fuel costs and travel time costs. The following components were associated with the time value to convert time into monetary terms:

- Operational Cost (Martinez, 2022). A modern container ship valued at $200 million over a 20-year service life incurs a depreciation cost of about $1,142 per hour. When fixed operating expenses are included, the total hourly cost is estimated at $1,500 to $2,000, depending on vessel type.
- Port Demurrage Charges (Abraham, 2024).Most terminals offer 2–7 days of free container storage, after which demurrage charges apply. These fees, imposed by ports or shipping lines for exceeding the free time, typically range from $75 to $300 per container per day, depending on the port or carrier.
- Penalties for Delayed Container Returns (Rosa, 2022). Ocean carriers charge demurrage and detention fees when containers are not returned on time, with fees applied per container per day. The highest charges are seen at five major U.S. ports, led by the Port of New York at $3,182 per container.
- Opportunity Cost (Lost Earnings). Slower speeds extend voyage times and reduce earning potential. For vessels under time-charter contracts, this loss is measured by the time-charter equivalent, which typically ranges from $20,000 to $35,000 per day.

Table 52 presents the estimated hourly cost of travel delay by vessel type, which was used to monetize travel time impacts in the benefit-cost analysis. If the travel time change under a speed strategy was negative (i.e., faster travel), no additional cost was assumed. However, if the travel time increased, the additional cost was calculated and included in the benefit-cost analysis.

8.6.3 Cost-Effectiveness

Speed strategies can reduce emissions at no additional cost or increase emissions while incurring greater operational expenses. Table 53 summarizes the cost efficiency of various speed strategies, where each value falls into one of the following categories:

- Negative value without an asterisk (*). Indicates NOx reductions with net cost savings—the strategy is both environmentally and economically beneficial.
- Negative value with an asterisk. Indicates increased emissions and increased costs—the strategy is both environmentally and economically detrimental.

- Positive Value. Indicates NOx reductions achieved at a net cost—the strategy is environmentally beneficial but economically less favorable.

The favorable speed for each vessel type is the one that maximizes NOx reduction while avoiding or minimizing additional costs, represented by positive and negative values without an asterisk. For bulk carriers, general cargo ships, and tankers, the most cost-effective speeds are around 9–10 knots. By contrast, container ships and certain tankers perform better at 11–12 knots. This is because these vessel types tend to operate at larger scales and have higher installed engine speeds, meaning their engines are most efficient at slightly higher cruising speeds.

Table 52. Estimated Hourly Cost of Port Delay by OGV Vessel Type

Value of Delay	Bulk Carrier	Vehicle Carrier	General Cargo	Container Ship	Chemical Tanker	Oil Tanker	Other Tanker	Misc. (C3)	Offshore Support	Ferry	RORO	Reefer
$/hour	1,000	2,000	1,000	5,000	2,000	2,000	2,000	1,000	5,000	1,000	2,000	3,000

Table 53. NOx Pollutant Reduction (Tons) per Million Dollars (OGV Speed Strategy)

Strategy	Bulk Carrier	Vehicle Carrier	General Cargo	Container Ship	Chemical Tanker	Oil Tanker	Other Tanker	Misc. (C3)	Offshore Support	Ferry	RORO	Reefer
5 knots	24	−2*	17	2	8	8	23	9	1	9	−2*	−3*
6 knots	50	3	34	−2*	14	20	42	22	3	16	2	−0*
7 knots	106	8	81	−1*	24	36	107	53	7	27	7	4
8 knots	448	27	233	3	43	78	−137	−1,046	−80	53	31	9
9 knots	−211	111	−475	8	114	−21,842	−41	−126	−91	436	−2,038	16
10 knots	−184	−130	−131	39	−126	−160	−72	−768	17	−169	−142	30
11 knots	−79*	−214	214	−69	−47*	−92*	−51	−97*	−61*	−99*	−413	127
12 knots	−99*	157	−77*	−255	−95*	−105*	−69	−108*	−67*	−117*	27	−181

Note:

- − : NOx decreases and cost decreases.
- −* : NOx increases and cost increases.
- + : NOx decreases and cost increases.

8.6.4 Speed Deviation Analysis Using Confidence Intervals

To support strategy implementation, the research team assessed whether current vessel speeds along the HSC align with the recommended 7–10 knot range. This range was identified as optimal for achieving NOx reductions with either reasonable investment or even net savings for most vessel types.

The researchers divided the region into grid cells of approximately 100 × 100 m and extracted all observed vessel speeds within each cell. For each grid, the researchers calculated the confidence interval (CI) of the local vessel speed distribution to assess whether the operational behavior aligned with the desired range.

If the CI fully contained or overlapped the target range (7–10 knots), the researchers assigned a deviation of 0, indicating acceptable speed. If the CI was entirely outside the target range, the researchers computed the minimum distance between the CI and the target interval. For example:

- CI = [4, 6] ⇒ deviation = 1 (entirely too slow).
- CI = [4, 8] ⇒ deviation = 0 (overlaps the lower bound).
- CI = [12, 14] ⇒ deviation = 1 (entirely too fast).

Figure 73 illustrates the transit-mode deviation heatmap, where white regions indicate grids where vessel speeds are within the preferred range; blue regions show negative deviations (i.e., vessel speeds are too low); and red regions show positive deviations (i.e., vessel speeds are too high).

Overall, the HSC exhibits speeds within the preferred range, indicating efficient navigation through this main corridor. However, several upstream segments of the channel show negative deviations, likely due to narrower or curved pathways that restrict maneuverability and limit achievable speeds. Additional negative deviations are observed surrounding the terminals because vessels are slowing down to wait for docking clearance.

On the other hand, the Galveston Bay area shows more frequent positive deviations, where vessel speeds exceed the target range. This result may be attributed to vessels entering from the open ocean, where they often maintain higher speeds before decelerating to conform to the channel’s operating environment. The wider and deeper channel geometry in this region may also afford vessels greater flexibility to travel at will.

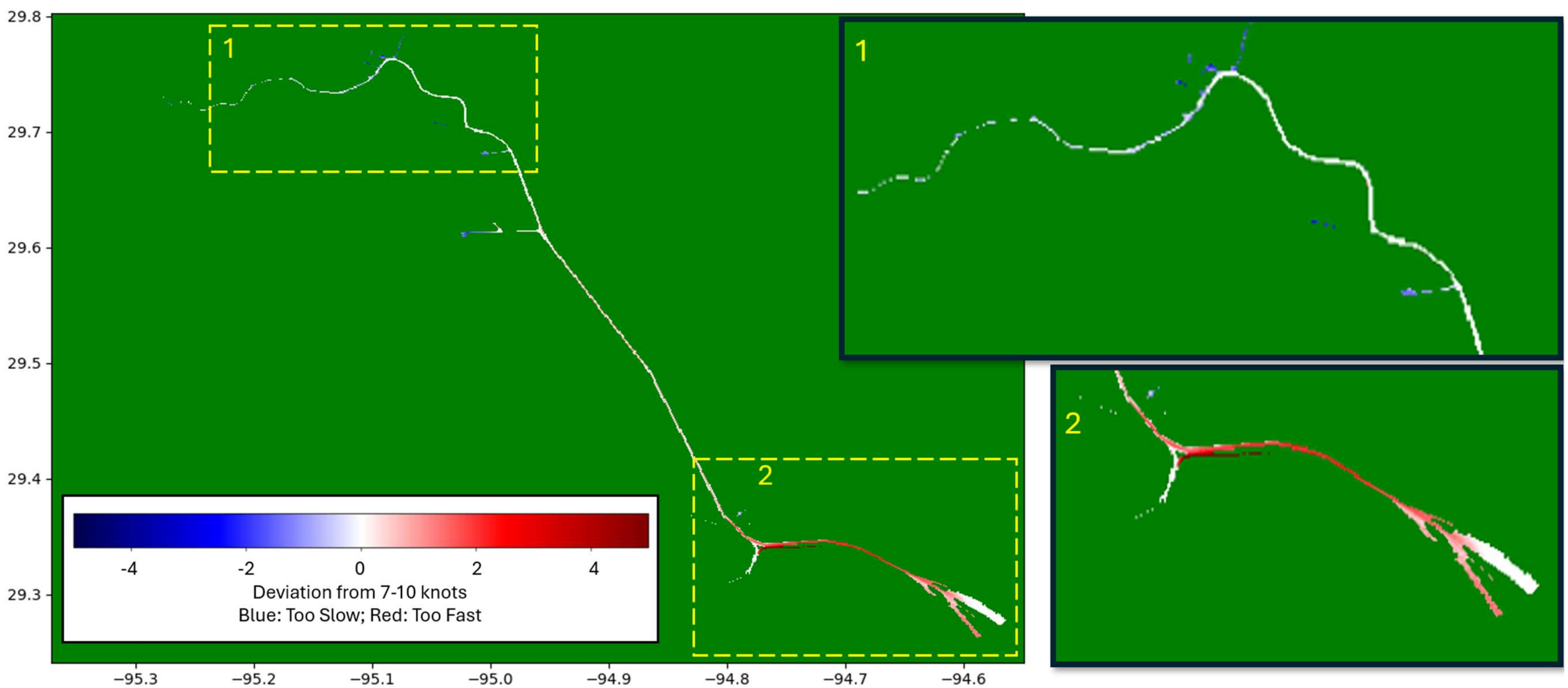


Figure 73. Speed Deviation Plotting versus Optimal Speeds

8.7 Operational Enhancement

Inefficient stays (defined as time spent at speeds ≤1 knot along the HSC) can lead to unnecessary fuel consumption, delays, and increased emissions. These inefficiencies often stem from inaccurate scheduling and poor communication between vessels and port operations. By reducing idle time through improved scheduling, traffic management, and vessel coordination, stakeholders can achieve (a) fuel cost savings, (b) delay cost savings, and (c) emission reductions.

To quantify these benefits, the research team evaluated total emission reductions and monetary savings for each vessel type, where the value of time is shown in Table 52 for OGVs and Table 54 for HBC.

8.7.1 OGVs

Table 55 summarizes total pollutant reductions and idle time cost savings for OGVs. Among vessel types, other tankers exhibit the highest total emission reductions and idle time value, with over 212.7 tons of NOx and $0.52 million in delay cost. Container ships and chemical tankers also yield significant emission reductions, highlighting the potential benefits of improving communication and coordination between vessels and terminals.

8.7.2 HBC

Table 56 summarizes pollutant reductions and cost savings from operational enhancements for HBC vessels. Towboats and tugboats show the greatest benefits, with up to 16.5 tons of NOx reduced and over $36,000 in savings. These gains reflect their high auxiliary power use during idle periods. Other HBC types show limited impact due to shorter idle times and lower engine loads. Overall, operational improvements for towboats and tugboats offer the most cost-effective emission reductions in this fleet.

Table 54. Estimated Hourly Cost of Port Delay by HBC Vessel Type

Value of Delay	Tugboat	Towboat/ Pushboat	Crew and Supply	Work Boat	Pilot	Fishing (C1/C2)	Misc. (C1/C2)	Excursion
$/hour	$1,500	$1,200	$1,000	$800	$2,000	$600	$500	$1,000

Table 55. OGV Pollutant Reduction and Dollar Savings (Operation Enhancement)

Category	Bulk Carrier	Vehicle Carrier	General Cargo	Container Ship	Chemical Tanker	Oil Tanker	Other Tanker	Misc. (C3)	Offshore Support	Ferry	RORO	Reefer
NOx (tons)	1.6	0.1	0.7	20.1	20.2	1.3	212.7	0.4	2.9	0.1	0.0	–
PM2.5 (tons)	0.0	0.0	0.0	0.4	0.4	0.0	7.2	0.0	0.1	0.0	0.0	–
CO2 (tonnes)	108.4	3.8	39.9	1,584.9	1,413.2	206.9	31,212.7	23.1	224.2	2.5	1.7	–
SO2 (tons)	0.1	0.0	0.0	1.1	0.9	0.1	21.0	0.0	0.2	0.0	0.0	–
Savings (thousands)	$377	$8	$108	$7,562	$3,406	$201	$52,997	$180	$5,084	$35	$3	–

Table 56. HBC Pollutant Reduction and Dollar Savings (Operation Enhancement)

Category	Tugboat	Towboat/ Pushboat	Crew and Supply	Work Boat	Pilot	Fishing (C1/C2)	Misc. (C1/C2)	Excursion
NOx (tons)	16.5	13.5	0.0	0.0	0.0	0.0	0.0	0.1
PM2.5 (tons)	0.6	0.5	0.0	0.0	0.0	0.0	0.0	0.0
CO2 (tonnes)	1,141.6	856.0	0.0	1.5	0.0	0.7	0.1	5.8
SO2 (tons)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Savings (thousands)	$26,593	$36,432	$1	$112	$1	$7	$1	$822

9. CONCLUSION AND RECOMMENDATIONS

This study provides a comprehensive assessment of current maritime emissions at the POH and evaluates the potential effectiveness of a range of control strategies.

Phase 1 of this study highlighted several important insights into vessel-related emissions at the POH. OGV operations are dominated by tankers, container ships, general cargo ships, and bulk carriers, while HBC activity is driven largely by tugboats and towboats. Terminals operated by the PHA were found to account for 30–40% of total emissions, with Bayport Terminal standing out as the single largest contributor. In terms of vessel type, container ships contribute most to PHA-related emissions, whereas tankers are the leading source at non-PHA facilities. For HBC, the prevalence of towboats and their extended operating hours make them the primary emission source. A comparison with the 2019 GMEI showed general consistency in OGV estimates but revealed notably higher HBC emissions at PHA terminals in this study, likely due to higher tugboat and towboat activity assumptions.

Building on the Phase 1 findings, Phase 2 focused on evaluating potential emission reduction strategies. This phase involved simulating the impacts of control measures and conducting a benefit–cost analysis to identify the most effective and feasible options. Findings from phase 2 include:

- **Alternative Fuels for OGVs**. Biodiesel is the most cost-effective near-term solution, as it requires minimal retrofitting and is compatible with most existing engines. However, its benefits for NOx reduction are limited, and its overall emission reductions (PM2.5, CO_2, SO_2) are less than those achieved with LNG. Over the longer term, LNG represents a more promising option due to its superior environmental performance and cost per unit of energy comparable to diesel. If the POH supports LNG adoption through retrofit incentives and convenient refueling infrastructure, broader deployment could deliver substantial environmental gains.
- **Alternative Fuels for HBC**. For HBC, biodiesel similarly offers the lowest-cost and most compatible option. Hydrogen adoption, by contrast, requires extensive retrofitting and higher fuel costs. Full hydrogen systems can achieve significant reductions but are only feasible for a limited subset of vessels. Hybrid electric systems provide a more practical pathway, offering flexibility and generally greater cost-effectiveness than hydrogen, though their reliance on grid electricity could increase SO_2 emissions depending on the regional energy mix.

- **Shore Power Implementation**. Shore power can reduce emissions for both OGVs and HBC, though its cost-effectiveness differs. For OGVs, which have substantial auxiliary demands, shore power displaces large amounts of onboard fuel use, yielding significant savings and reductions. For HBC, however, smaller auxiliary loads make shore power less impactful and less cost-effective.
- **Engine Tier Upgrades**. Upgrading to higher-tier engines has a notable effect on NOx reductions. While moving OGVs to Tier 3 and HBC to Tier 4 would maximize benefits, the associated costs are high. Given the current fleet composition, upgrading OGVs to Tier 1 and HBC to Tier 2 presents the most cost-effective balance between emissions reduction and investment.
- **Speed Optimization**. Vessel speed plays a critical role in emissions. Higher speeds increase power demand and emissions, while very low speeds reduce engine efficiency and can also elevate emissions. Model simulations suggest that maintaining speeds around 8–10 knots offers the best balance between minimizing NOx emissions and managing operational costs for most vessel types.
- **Operational Improvements**. Vessel movement analysis shows that unnecessary idling, often caused by scheduling and communication inefficiencies, contributes to avoidable emissions. For example, over 10% of the "other tanker" category's hotelling time involves idle activity within the channel. Improved coordination and scheduling can reduce idle time, cut fuel consumption, and lower emissions while streamlining port logistics.

Recommendations

Based on these findings, the research team recommends the following implementation strategies to reduce emissions from CMV activities at POH:

- **Fuel Transition Roadmap for OGVs and HBC.** Encourage near-term adoption of biodiesel through voluntary programs and pilot projects, while developing a medium-term strategy to expand LNG infrastructure and retrofit support. In the long term, monitor and evaluate the feasibility of emerging fuels such as methanol, ammonia, and green hydrogen for broader deployment.
- **Targeted Incentive and Grant Programs.** Establish cost-sharing or incentive programs to support Tier engine upgrades, prioritizing the highest-emitting vessels such as towboats and container ships. Explore external funding opportunities (e.g., EPA Diesel Emissions Reduction Act (DERA) grants, state clean air funds) to offset retrofit and upgrade costs.
- **Strategic Shore Power Deployment.** Focus initial shore power investments at PHA's Bayport and Barbours Cut Terminals, where container ships account for the largest share of emissions. Implement a phased approach that prioritizes OGVs first, then expands to other vessel categories as cost-effectiveness improves.

- **Operational Efficiency Initiatives.** Partner with the U.S. Coast Guard, pilots, and terminal operators to minimize unnecessary idling and hotelling. Improved vessel traffic management and scheduling systems can reduce idle time, lower emissions, and improve overall logistics efficiency across the Houston Ship Channel.
- **Voluntary Vessel Speed Reduction Program.** Implement incentive-based programs to encourage OGVs to maintain optimal speeds (8–10 knots). Consider linking participation to reduced port fees, environmental certification credits, or recognition programs similar to those at other major U.S. ports.
- **Integration into Regional Planning.** Incorporate study findings into PHA's sustainability strategies and regional air quality planning efforts. Align port initiatives with state and federal air quality goals to maximize benefits and ensure consistency with broader regulatory frameworks.

It is important to note, however, that the conclusions, results, and recommendations presented in this report are inherently dependent on the assumptions made regarding vessel operations, technology adoption, and cost estimates. These assumptions were developed using the research team's best professional judgment and publicly available data sources. As such, outcomes may differ under alternative assumptions, and future updates with more refined data will be essential to ensure the continued relevance and accuracy of the findings.

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APPENDIX A: SHIP DATA MATCHING PROCEDURE

This project used the Sea-Web database to determine the ship type in the AIS data in 2019 and 2022. The ship types in ShiptypeLevel4 were mainly used to classify the vessels in a general category. For OGVs, the information on DWT, gross tonnage, and TEUs was used to further determine the ship subtype in the U.S. EPA category, as shown in Table 57. For HBC, the maximum power was employed to distinguish tugboats and towboats, as presented in

Table 58.

The unmatched vessels were further matched using the TTI database and U.S. Army Corps of Engineers Digital Library, as shown in Table 59 and Table 60.

Table 57. Vessel Matching for OGVs Based on Sea-Web Data

Ship Types in ShiptypeLevel4	Further Identification		EPA Ship Type	EPA Ship Subtype
Bulk, Carrier	0 ≤ DWT ≤ 9,999		Bulk Carrier	Small
Bulk, Carrier	10,000 ≤ DWT ≤ 34,999		Bulk Carrier	Handysize
Bulk, Carrier	35,000 ≤ DWT ≤ 59,999		Bulk Carrier	Handymax
Bulk, Carrier	60,000 ≤ DWT ≤ 99,999		Bulk Carrier	Panamax
Bulk, Carrier	100,000 ≤ DWT ≤ 199,999		Bulk Carrier	Capesize
Bulk, Carrier	DWT ≥ 200,000		Bulk Carrier	Capesize Largest
Cruise	0 ≤ Gross Tonnage ≤ 1,999		Cruise	2,000 Ton
Cruise	2,000 ≤ Gross Tonnage ≤ 9,999		Cruise	10,000 Ton
Cruise	10,000 ≤ Gross Tonnage ≤ 59,999		Cruise	60,000 Ton
Cruise	60,000 ≤ Gross Tonnage ≤ 99,999		Cruise	100,000 Ton
Cruise	Gross Tonnage ≥ 100,000		Cruise	Largest
Tanker	Oil (ShiptypeLevel3)	0 ≤ DWT ≤ 59,999	Oil Tanker	Handymax
Tanker	Oil (ShiptypeLevel3)	6,0000 ≤ DWT ≤ 89,999	Oil Tanker	Panamax
Tanker	Oil (ShiptypeLevel3)	90,000 ≤ DWT ≤ 119,999	Oil Tanker	Aframax
Tanker	Oil (ShiptypeLevel3)	120,000 ≤ DWT ≤ 199,999	Oil Tanker	Suezmax
Tanker	Oil (ShiptypeLevel3)	DWT ≥ 200,000	Oil Tanker	VLCC
Tanker	Chemical (ShiptypeLevel3)	0 ≤ DWT ≤ 4,999	Chemical Tanker	Smallest
Tanker	Chemical (ShiptypeLevel3)	5,000 ≤ DWT ≤ 9,999	Chemical Tanker	Small
Tanker	Chemical (ShiptypeLevel3)	10,000 ≤ DWT ≤ 19,999	Chemical Tanker	Handysize
Tanker	Chemical (ShiptypeLevel3)	DWT ≥ 20,000	Chemical Tanker	Handymax
Tanker	Liquefied Gas (ShiptypeLevel3)	0 ≤ DWT ≤ 49,999	Liquefied Gas Tanker	50,000 DWT
Tanker	Liquefied Gas (ShiptypeLevel3)	50,000 ≤ DWT ≤ 99,999	Liquefied Gas Tanker	100,000 DWT
Tanker	Liquefied Gas (ShiptypeLevel3)	100,000 ≤ DWT ≤ 199,999	Liquefied Gas Tanker	200,000 DWT
Tanker	Liquefied Gas (ShiptypeLevel3)	DWT ≥ 200,000	Liquefied Gas Tanker	Largest
Tanker	Others		Other Tanker	All Other Tanker
Container Ship	0 ≤ TEU ≤ 999		Container Ship	1,000 TEU
Container Ship	1,000 ≤ TEU ≤ 1,999		Container Ship	2,000 TEU
Container Ship	2,000 ≤ TEU ≤ 2,999		Container Ship	3,000 TEU
Container Ship	3,000 ≤ TEU ≤ 4,999		Container Ship	5,000 TEU
Container Ship	5,000 ≤ TEU ≤ 7,999		Container Ship	8,000 TEU

Ship Types in ShiptypeLevel4	Further Identification	EPA Ship Type	EPA Ship Subtype
Container Ship	8,000 ≤ TEU ≤ 11,999	Container Ship	12,000 TEU
Container Ship	12,000 ≤ TEU ≤ 14,499	Container Ship	14,500 TEU
Container Ship	TEU ≥ 14,500	Container Ship	Largest
General Cargo	0 ≤ DWT ≤ 4,999	General Cargo	5,000 DWT
General Cargo	5,000 ≤ DWT ≤ 9,999	General Cargo	10,000 DWT
General Cargo	DWT ≥ 10,000	General Cargo	Largest
Refrigerated Cargo Ship	–	Reefer	All Reefer
Offshore Support Vessel	Displacement ≥ 5	Offshore Support/Drillship	All Offshore Support/ Drillship
Offshore Support Vessel	Displacement < 5	Crew and Supply (HBC)	–
Research Vessel	Displacement ≥ 5	Miscellaneous (C3)	All C3 Misc.
Research Vessel	Displacement < 5	Misc. (C1/C2) (HBC)	–
Passenger/RORO	Gross Tonnage <= 1,999	Ferry/Roll-On/Passenger (C3)	2,000 Ton
Passenger/RORO	Gross Tonnage >= 2,000	Ferry/Roll-On/Passenger (C3)	Largest
RORO Cargo	Gross Tonnage <= 4,999	RORO	5,000 Ton
RORO Cargo	Gross Tonnage >= 5,000	RORO	Largest
Vehicles Carrier	> 4,000 cars (ShiptypeGroup)	Vehicle Carrier	4,000 Vehicles
Vehicles Carrier	Others	Vehicle Carrier	Largest

Table 58. Vessel Matching for HBC Based on Sea-Web Data

Ship Types in ShiptypeLevel4	Further Identification	EPA Ship Type
Pusher Tug, Tug	MaxPower ≤ 3500 KW	Towboat/ Pushboat
Pusher Tug, Tug	3500 KW < MaxPower ≤ 5000 KW	Tugboat
Pusher Tug, Tug	MaxPower > 5000 KW	Offshore Support/Drillship (OGV)
Crew and Supply Crew Boat	–	Crew and Supply
Fishing	–	Fishing (C1/C2)
Buoy/Lighthouse Vessel Anchor Hoy	–	Misc. (C1/C2)
Pilot	–	Pilot
Pollution Control Vessel	–	Work Boat

Table 59. Vessel Matching Using the TTI Database of Houston, Freeport, and Corpus Christi

Ship Type	EPA
Towing—Inland	Towboat/Pushboat
Towing/Pushing, Inland Waterways	Towboat/Pushboat
Vessel—Towing (length of tow > 200 m or breadth > 25 m)—Inland	Towboat/Pushboat
Tug—Inland	Tugboat

Table 60. Vessel Matching Using U.S. Army Corps of Engineers Digital Library

VTCC	EPA
3A35	Towboat/Pushboat
3A36	Tugboat

APPENDIX B: EMISSION REDUCTIONS

This appendix details annual emission reductions in 2022 under different strategies.

- Shore power for OGVs and HBC: Table 61.
- Engine tier upgrade (Tiers 1–4) for OGVs and HBC: Table 62–Table 65.
- Biodiesel adoption for OGVs and HBC: Table 66.
- LNG conversion for OGVs: Table 67.
- Full hydrogen fuel cells for HBC: Table 68.
- Hybrid hydrogen for HBC: Table 69.
- Hybrid electrification for HBC: Table 70.

Table 61. Emission Reductions by Shore Power Strategies

Category	Ship Type	NOx Tons	PM10 Tons	PM2.5 Tons	HC Tons	CO Tons	SO2 Tons	CO2 Tonnes
OGVs	Bulk Carrier	424	7	6	16	43	11	12,852
	Vehicle Carrier	20	0	0	1	2	0	546
	General Cargo	484	8	6	17	45	12	13,541
	Container Ship	536	8	7	19	50	13	14,786
	Chemical Tanker	313	5	4	12	31	8	9,290
	Oil Tanker	88	2	1	3	9	2	2,729
	Other Tanker	228	4	3	8	24	5	6,573
	Miscellaneous (C3)	21	0	0	1	2	0	564
	Offshore Support/Drillship	49	1	1	3	9	2	2,595
	Ferry/Roll-On/ Passenger (C3)	0	0	0	0	0	0	0
	RORO	20	0	0	1	2	1	643
	Reefer	1	0	0	0	0	0	18
	Sum	2,183	36	30	81	217	54	64,137
HBC	Tugboat	36	1	1	1	7	−1	1,673
	Towboat/ Pushboat	35	1	1	1	6	−1	1,193
	Crew and Supply	0	0	0	0	0	0	2
	Work Boat	0	0	0	0	0	0	10
	Pilot	0	0	0	0	0	0	0
	Fishing (C1/C2)	0	0	0	0	0	0	0
	Misc. (C1/C2)	0	0	0	0	0	0	0
	Excursion	1	0	0	0	0	0	30
	Sum	73	3	3	3	14	−1	2,908

Table 62. Emission Reductions by Tier Upgrade (T1 Scenario)

Category	Ship Type	NOx Tons	PM10 Tons	PM2.5 Tons	HC Tons	CO Tons	SO2 Tons	CO2 Tonnes
OGVs	Bulk Carrier	1	0	0	0	0	0	0
	Vehicle Carrier	1	0	0	0	0	0	0
	General Cargo	10	0	0	0	0	0	0
	Container Ship	5	0	0	0	0	0	0
	Chemical Tanker	38	0	0	0	0	0	0
	Oil Tanker	3	0	0	0	0	0	0
	Other Tanker	4	0	0	0	0	0	0
	Miscellaneous (C3)	0	0	0	0	0	0	0
	Offshore Support/Drillship	12	0	0	0	0	0	0
	Ferry/Roll-On/ Passenger (C3)	1	0	0	0	0	0	0
	RORO	0	0	0	0	0	0	0
	Reefer	0	0	0	0	0	0	0
	Sum	74	0	0	0	0	0	0
HBC	Tugboat	173	10	10	2	9	0	0
	Towboat/ Pushboat	325	12	12	3	12	0	0
	Crew and Supply	0	0	0	0	0	0	0
	Work Boat	0	0	0	0	0	0	0
	Pilot	0	0	0	0	0	0	0
	Fishing (C1/C2)	1	0	0	0	0	0	0
	Misc. (C1/C2)	0	0	0	0	0	0	0
	Excursion	0	0	0	0	0	0	0
	Sum	500	23	22	6	21	0	0

Table 63. Emission Reductions by Tier Upgrade (T2 Scenario)

Category	Ship Type	NOx Tons	PM10 Tons	PM2.5 Tons	HC Tons	CO Tons	SO2 Tons	CO2 Tonnes
OGVs	Bulk Carrier	55	0	0	0	0	0	0
	Vehicle Carrier	7	0	0	0	0	0	0
	General Cargo	143	0	0	0	0	0	0
	Container Ship	154	0	0	0	0	0	0
	Chemical Tanker	277	0	0	0	0	0	0
	Oil Tanker	102	0	0	0	0	0	0
	Other Tanker	338	0	0	0	0	0	0
	Miscellaneous (C3)	9	0	0	0	0	0	0
	Offshore Support/Drillship	48	0	0	0	0	0	0
	Ferry/Roll-On/ Passenger (C3)	2	0	0	0	0	0	0
	RORO	0	0	0	0	0	0	0
	Reefer	0	0	0	0	0	0	0
	Sum	1,134	0	0	0	0	0	0
HBC	Tugboat	765	18	18	10	112	0	0
	Towboat/ Pushboat	1,423	31	30	22	197	0	0
	Crew and Supply	0	0	0	0	0	0	0
	Work Boat	0	0	0	0	0	0	0
	Pilot	0	0	0	0	0	0	0
	Fishing (C1/C2)	5	0	0	0	1	0	0
	Misc. (C1/C2)	0	0	0	0	0	0	0
	Excursion	10	0	0	0	2	0	0
	Sum	2,203	49	48	33	313	0	0

Table 64. Emission Reductions by Tier Upgrade (T3 Scenario)

Category	Ship Type	NOx Tons	PM10 Tons	PM2.5 Tons	HC Tons	CO Tons	SO2 Tons	CO2 Tonnes
OGVs	Bulk Carrier	796	0	0	0	0	0	0
	Vehicle Carrier	48	0	0	0	0	0	0
	General Cargo	971	0	0	0	0	0	0
	Container Ship	1,047	0	0	0	0	0	0
	Chemical Tanker	2,360	0	0	0	0	0	0
	Oil Tanker	862	0	0	0	0	0	0
	Other Tanker	2,563	0	0	0	0	0	0
	Miscellaneous (C3)	57	0	0	0	0	0	0
	Offshore Support/Drillship	246	0	0	0	0	0	0
	Ferry/Roll-On/ Passenger (C3)	8	0	0	0	0	0	0
	RORO	22	0	0	0	0	0	0
	Reefer	1	0	0	0	0	0	0
	Sum	8,981	0	0	0	0	0	0
HBC	Tugboat	1,038	34	35	34	130	0	0
	Towboat/ Pushboat	1,916	56	58	63	240	0	0
	Crew and Supply	1	0	0	0	0	0	0
	Work Boat	1	0	0	0	0	0	0
	Pilot	0	0	0	0	0	0	0
	Fishing (C1/C2)	6	0	0	0	1	0	0
	Misc. (C1/C2)	1	0	0	0	0	0	0
	Excursion	14	0	0	1	2	0	0
	Sum	2,975	90	93	98	373	0	0

Table 65. Emission Reductions by Tier Upgrade (T3/T4 Scenario)

Category	Ship Type	NOx Tons	PM10 Tons	PM2.5 Tons	HC Tons	CO Tons	SO2 Tons	CO2 Tonnes
OGVs	Bulk Carrier	796	0	0	0	0	0	0
	Vehicle Carrier	48	0	0	0	0	0	0
	General Cargo	971	0	0	0	0	0	0
	Container Ship	1,047	0	0	0	0	0	0
	Chemical Tanker	2,360	0	0	0	0	0	0
	Oil Tanker	862	0	0	0	0	0	0
	Other Tanker	2,563	0	0	0	0	0	0
	Miscellaneous (C3)	57	0	0	0	0	0	0
	Offshore Support/Drillship	246	0	0	0	0	0	0
	Ferry/Roll-On/ Passenger (C3)	8	0	0	0	0	0	0
	RORO	22	0	0	0	0	0	0
	Reefer	1	0	0	0	0	0	0
	Sum	8,981	0	0	0	0	0	0
HBC	Tugboat	1,707	43	42	49	130	0	0
	Towboat/ Pushboat	3,124	71	71	88	240	0	0
	Crew and Supply	1	0	0	0	0	0	0
	Work Boat	1	0	0	0	0	0	0
	Pilot	1	0	0	0	0	0	0
	Fishing (C1/C2)	10	0	0	0	1	0	0
	Misc. (C1/C2)	1	0	0	0	0	0	0
	Excursion	23	0	0	1	2	0	0
	Sum	4,868	115	114	138	373	0	0

Table 66. Emission Reductions by Biodiesel

Category	Ship Type	NOx Tons	PM10 Tons	PM2.5 Tons	HC Tons	CO Tons	SO2 Tons	CO2 Tonnes
OGVs	Bulk Carrier	0	3	3	9	0	8	10,251
	Vehicle Carrier	0	0	0	1	0	0	498
	General Cargo	0	3	3	10	0	9	10,455
	Container Ship	0	4	4	15	0	11	12,044
	Chemical Tanker	0	9	9	27	0	24	29,874
	Oil Tanker	0	6	6	12	0	18	22,260
	Other Tanker	0	16	14	41	0	46	53,371
	Miscellaneous (C3)	0	0	0	1	0	0	504
	Offshore Support/Drillship	0	1	1	4	0	3	3,642
	Ferry/Roll-On/ Passenger (C3)	0	0	0	0	0	0	57
	RORO	0	0	0	0	0	0	307
	Reefer	0	0	0	0	0	0	10
	Sum	0	43	40	120	0	121	143,263
HBC	Tugboat	0	8	8	12	0	0	21,023
	Towboat/ Pushboat	0	13	13	21	0	0	33,822
	Crew and Supply	0	0	0	0	0	0	11
	Work Boat	0	0	0	0	0	0	10
	Pilot	0	0	0	0	0	0	44
	Fishing (C1/C2)	0	0	0	0	0	0	105
	Misc. (C1/C2)	0	0	0	0	0	0	8
	Excursion	0	0	0	0	0	0	276
	Sum	0	21	21	32	0	1	55,299

Table 67. Emission Reductions by LNG

Category	Ship Type	NOx Tons	PM10 Tons	PM2.5 Tons	HC Tons	CO Tons	SO2 Tons	CO2 Tonnes
OGVs	Bulk Carrier	926	17	15	46	−30	45	25,041
	Vehicle Carrier	55	1	1	3	−1	2	1,148
	General Cargo	1,110	18	16	50	−26	47	24,468
	Container Ship	1,206	21	19	74	−34	59	29,303
	Chemical Tanker	2,759	49	46	137	−81	132	71,233
	Oil Tanker	1,006	33	30	59	−126	98	66,060
	Other Tanker	3,103	82	76	206	−278	247	153,972
	Miscellaneous (C3)	66	1	1	3	−1	2	1,070
	Offshore Support/Drillship	298	6	6	20	−8	17	7,988
	Ferry/Roll-On/ Passenger (C3)	9	0	0	0	0	0	115
	RORO	26	1	0	1	−1	1	758
	Reefer	1	0	0	0	0	0	24
	Sum	10,566	228	210	599	−587	651	381,179

Table 68. Estimated Emission Reductions for HBC Using Full Hydrogen Fuel Cells (Scenario 1: Assuming Hydrogen Bunkering Available at All Terminals)

Category	Ship Type	NOx Tons	PM10 Tons	PM2.5 Tons	HC Tons	CO Tons	SO2 Tons	CO2 Tonnes
HBC	Tugboat	296	7	7	8	58	0	24,375
	Towboat/ Pushboat	1,014	23	22	28	170	1	62,908
	Crew and Supply	1	0	0	0	0	0	76
	Work Boat	1	0	0	0	0	0	63
	Pilot	0	0	0	0	0	0	49
	Fishing (C1/C2)	5	0	0	0	1	0	307
	Misc. (C1/C2)	1	0	0	0	0	0	53
	Excursion	10	0	0	0	2	0	649
	Sum	1,327	30	29	36	231	1	88,482

Table 69. Estimated Emission Reductions for HBC Using Hybrid Hydrogen

Category	Ship Type	NOx Tons	PM10 Tons	PM2.5 Tons	HC Tons	CO Tons	SO2 Tons	CO2 Tonnes
HBC	Tugboat	284	7	7	8	58	0	26,514
	Towboat/ Pushboat	591	13	13	15	101	0	36,212
	Crew and Supply	1	0	0	0	0	0	36
	Work Boat	1	0	0	0	0	0	60
	Pilot	0	0	0	0	0	0	11
	Fishing (C1/C2)	2	0	0	0	0	0	109
	Misc. (C1/C2)	0	0	0	0	0	0	6
	Excursion	6	0	0	0	1	0	390
	Sum	284	7	7	8	58	0	26,510

Table 70. Estimated Emission Reductions for HBC Using Hybrid Electrification

Category	Ship Type	NOx Tons	PM10 Tons	PM2.5 Tons	HC Tons	CO Tons	SO2 Tons	CO2 Tonnes
HBC	Tugboat	271	6	6	8	57	−6	13,374
	Towboat/ Pushboat	563	12	11	14	98	−8	17,780
	Crew and Supply	0	0	0	0	0	0	16
	Work Boat	1	0	0	0	0	0	32
	Pilot	0	0	0	0	0	0	5
	Fishing (C1/C2)	1	0	0	0	0	0	48
	Misc. (C1/C2)	0	0	0	0	0	0	3
	Excursion	6	0	0	0	1	0	196
	Sum	271	6	6	8	57	−6	13,372