

The Potential of Shore Power to Mitigate Air Pollution in Seaports: A Case Study of the Port of Bremerhaven Based on Vessel OPS Capability

Flóra Zsuzsanna Gulyás

gulyas@isl.org

Institut für Seeverkehrswirtschaft und Logistik

Aseem Kinra

Heriot-Watt University

Case Report

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Abstract

Introduction: Growing maritime traffic places increasing pressure on ports to reconcile climate mitigation objectives with the local health impacts of air pollution from ships at berth. Onshore power supply (OPS) can substantially reduce emissions by replacing auxiliary engine operation with electricity from the shore. However, its effectiveness and economic feasibility depend on vessel compatibility, infrastructure availability, electricity prices, and the wider energy system.

Case description: This study evaluates the environmental and economic impacts of OPS deployment at the Port of Bremerhaven for container, cruise, and car carrier vessels. The analysis is based on vessel-specific operational data from 3,369 port calls in 2024, covering 445 container vessels, 12 cruise vessels, and 296 car carriers. Three deployment scenarios are assessed, ranging from continued conventional fuel use to partial and full OPS adoption. The analysis considers changes in CO₂, CH₄, NO_x, SO_x, and PM_{2.5} emissions, operational costs, and monetised external costs.

Discussion and Evaluation: Annual OPS electricity demand could reach up to 533 GWh. Partial OPS deployment reduces operational costs by 23.2% (EUR 16.5 million) and total external costs by 23.4% (EUR 22.6 million) compared with the baseline. Under full OPS adoption, operational and external costs decrease by 80.0% and 97.4%, respectively. Container vessels provide the largest overall reduction potential due to their high number of port calls. Despite these benefits, OPS feasibility is highly sensitive to electricity pricing, vessel compatibility, infrastructure requirements, and the carbon intensity of electricity generation.

Conclusions: OPS can substantially reduce the environmental, societal, and operational impacts of ship hoteling, but its successful deployment requires coordinated infrastructure investment, competitive electricity pricing, and ship-side retrofiting. Future research should compare OPS with alternative berthing emission-reduction measures and apply the framework to ports outside the EU, where different regulatory, pricing, and energy-system conditions may lead to different implementation outcomes.

1. Introduction

Seaports function as key connection points between sea and land transportation for both passengers and cargo. Maritime transport covers extensive international routes, whereas land-based transport is concentrated within the port's immediate region and local surroundings (Rodrigue and Notteboom 2024). With continued growth in container throughput (Fig. 1a) and a steady recovery in passenger numbers following the sharp decline in 2020 (Fig. 1b), seaports are experiencing increased traffic not only at sea and within terminals but also in surrounding hinterland zones, partly driven by the clustering of industrial activity near ports.

Figure 1: Growth in container throughput (TEU) at the world's top 100 seaports (left) and cruise passenger numbers at the world's leading cruise ports (right). Sources: Institute for Shipping Economics and Logistics (2024) & Cruise Lines International Association (2025).

This results in elevated air pollution concentrations and associated health and environmental issues, which vary depending on geographic location and the population density of areas surrounding the port (Ducruet et al. 2024). A recent analysis by the EEA (Pozzoli et al. 2024) of air quality across 23 European ports revealed that, depending on local weather and geographic conditions, shipping contributes to varying but consistently significant levels of air pollution in port cities, with annual mean NO₂ and PM₁₀ concentrations in port areas often exceeding those in

surrounding regions. In several cases—such as in Antwerp, Marseille, and Naples—NO₂ levels already surpass the revised EU limit value of 20 µg/m³ set for 2030, while PM₁₀ concentrations above this threshold were observed in nine ports, including Barcelona, Gdańsk, and Piraeus.

Since the early 2010s, climate change, energy efficiency, and air pollution have become core environmental priorities for seaports (ESPO 2024). GHGs, though invisible, contribute to global climate change, whereas air pollutants are typically visible and lead to increased local pollution levels, contributing to issues like acid rain and respiratory health problems (Malm 1999). While efforts to cut climate-related emissions often also reduce air pollutants, this is not always the case, and the extent of the reduction can vary. To lower GHG emissions while preserving good air quality, the energy powering the electrical grid must shift toward renewable or emission-free sources (Commane and Schiferl 2022).

At the global level, the IMO provides the overarching framework for reducing GHG emissions from international shipping. Its revised 2023 GHG Strategy (IMO 2023) commits to net-zero GHG emissions by or around 2050, with indicative reduction checkpoints of at least 20% (striving for 30%) by 2030 and 70% (striving for 80%) by 2040 compared to 2008 levels. The strategy also calls for the uptake of zero- or near-zero-emission fuels. In addition, binding technical and operational measures under MARPOL Annex VI – including the Energy Efficiency Design Index (EEDI), the Energy Efficiency Existing Ship Index (EEXI), and the Carbon Intensity Indicator (CII) – require continuous improvements in ship efficiency (IMO 2021).

Building on this global framework, the EU has adopted a set of regional measures under the European Green Deal, targeting climate neutrality by 2050 and a 55% emissions reduction by 2030 (EC 2019). The Fit for 55 package (EC 2021) introduces binding instruments such as the FuelEU Maritime Regulation (European Parliament and Council of the European Union 2023), which limits the GHG intensity of marine fuels from 2025, and the extension of the EU Emissions Trading System (European Parliament and Council of the European Union 2023b) to maritime transport from 2024. In parallel, the Alternative Fuels Infrastructure Regulation (AFIR) mandates OPS in major EU ports by 2030 for container and passenger ships (European Parliament and Council of the European Union 2023c). Where shore power is available and mandatory but not used, a penalty of approximately EUR 1.50 per kWh will be applied to all energy consumed by a vessel during its port stay (DNV 2026).

Despite these initiatives, fossil fuel use has remained stable, as reflected in bunker fuel sales in Singapore, at the world's largest bunkering port, reaching over 54 million tonnes in 2024 (Singapore MPA 2024). The sales data shows continued demand for fossil fuels such as marine fuel oil (MFO), low-sulphur fuel oil (LSFO), and low-sulphur marine gas oil (LSMGO). In 2024, Singapore recorded bunker sales exceeding 54.9 million metric tonnes. In contrast, alternative fuels remain marginal: bio-blended fuels and methanol together accounted for just 1.6% of total sales, while no ammonia sales were recorded. Cleaner fuels still account for only a small share of maritime energy use (dos Santos et al. 2022), largely because the world's electricity generation capacity falls far short of what's needed to support large-scale production of green fuels for maritime use (Emblemsvåg 2025; Uzun et al. 2024).

Given the limited availability and uptake of alternative fuels, OPS¹ presents a more immediately scalable solution for reducing emissions at berth (Daniel et al. 2022; ESPO 2024). OPS allows vessels to connect to the electrical grid, replacing the need for onboard auxiliary engines that typically burn fossil fuels, such as marine diesel or heavy fuel oil, for power generation. While docked, ships typically rely on their onboard auxiliary engines to meet power demands—particularly high in the case of container and cruise ships (Rogosic et al. 2025). To eliminate the

environmental impacts of burning fossil fuels at berth, such as air pollution and noise, vessels can instead connect to an OPS (Glavinović et al. 2023). OPS relies on both adequate port infrastructure and ship-side compatibility. Although the technology is mature (DNV 2025), its uptake has progressed slowly. Despite early installations – including one of the first shore power systems in 1980 at the Port of Stockholm (EC 2023) – full-scale deployment remains challenging. As long as not all vessels are OPS-capable, a hybrid approach is necessary to accommodate both OPS-capable (retrofitted) and non-retrofitted ships (X. He et al. 2025).

1.1. Monetised Environmental and Economic Impacts of OPS

Monetising the environmental and health impacts has become standard in European research. Key references include the CE Delft Environmental Prices Handbook (2024), which provides updated EU27 marginal damage costs for pollutants, and the European Environment Agency's assessments of industrial and transport-related air pollution costs (2024).

Studies specifically addressing in-port (hoteling) emissions have quantified these external costs by vessel type and port. Innes and Monios (2018) estimated that OPS implementation at the Port of Aberdeen could avoid 4.8 t of CO₂, 108 t of NO_x, and 2.7 t of particulate matter emissions, corresponding to environmental benefits of approximately 57,000 GBP, GBP 1.1 million, and GBP 124,000, respectively. Gutierrez-Romero et al. (2019) found that OPS could reduce CO₂ emissions by around 10,000 t at the Port of Cartagena. Zis (2019) estimated avoidance costs of USD 10–30 per tonne of CO₂ and USD 540–1,600 per tonne of NO_x for Ro-Ro, cruise, and ultra-large container vessels. Stolz et al. (2021) assessed the large-scale deployment of OPS across 714 ports in Europe and the United Kingdom, estimating annual emission reductions of 3–5 million t CO₂, 86,431 t NO_x, and 4,130 t SO_x, among other pollutants. Similarly, Nguyen et al. (2021) reported reductions of 11.05% in NO_x emissions and 15.06% in SO_x emissions for container, bulk cargo, and cruise vessels at the Port of Kaohsiung. More recently, Uzun et al. (2024) estimated a reduction of 83.6% in total CO₂ emissions for Ro-Pax, tanker, bulk carrier, and general cargo vessels at Plymouth. Santosa et al. (2025) reported a reduction of 5,842 t CO₂ (61.4%) at Tanjung Emas, while Shi et al. (2026) found that OPS could reduce CO₂ emissions by 39% and air pollutant emissions by 60% at Yantian Port.

Other studies examine the operational economics of OPS, highlighting the potential cost savings and financial feasibility of shore power adoption. Lathwal et al. (2021) estimated annual savings of approximately 3,700 USD per large cargo vessel in Indian ports. Amaral et al. (2023) evaluated the economic implications of OPS implementation for cruise and cargo vessels in the Port of Lisbon under different operational scenarios.

Some studies combined environmental and economic considerations. Kim (2022) analysed both the economic and environmental benefits of OPS for container ships of different sizes at the Port of Busan, showing that the magnitude of benefits varies considerably with vessel size. Merkel et al. (2023) estimated environmental benefits of EUR 1.5–2.3 billion alongside energy cost savings of approximately EUR 709 million for Swedish ports. Similarly, Albo-López et al. (2024) found emission reductions of up to 87.1%, while operational costs ranged from a 29% increase to an 82% decrease depending on electricity price assumptions.

1.2. Research objective, research question, and the structure of the paper

Despite a growing body of research on OPS, significant gaps remain. While OPS is widely recognised as an effective measure for reducing emissions from ships during hotelling, comprehensive assessments that

systematically integrate environmental benefits, external costs, and the economic implications of inaction are still limited (Kizielewicz 2024). Existing studies typically demonstrate substantial emission reductions and potential cost savings; however, they are often confined to specific vessel types, single-country contexts, or stylised assumptions. Consequently, they rarely combine detailed port-level emission inventories with realistic operational cost structures across multiple vessel segments and under varying OPS uptake scenarios.

To address these shortcomings, this paper provides a comprehensive assessment of OPS implementation at the Port of Bremerhaven in 2024, focusing on container, cruise, and Ro-Ro vessels. The analysis integrates high-resolution hotelling emission estimates, the monetisation of external costs, and a detailed comparison of operational costs between onboard fuel consumption and shore-supplied electricity. It further evaluates three distinct adoption scenarios—baseline (no OPS), partial uptake, and full adoption—capturing the transition from current practices to full electrification of berth operations. This integrated framework offers a more nuanced and realistic evaluation of both the environmental externalities and economic implications of OPS than previously available in the literature.

Accordingly, the research is guided by the following questions:

1. What is the potential for emission and cost reductions associated with onshore power supply (OPS) during the hotelling of container, cruise, and car carrier vessels at the Port of Bremerhaven under different OPS adoption scenarios?
2. What policy implications can be derived for prioritising OPS investments?

The remainder of the paper is organised as follows. Sect. 1 *Introduction* has introduced the study background, reviews relevant OPS literature, examines factors influencing OPS effectiveness, identifies the research gap, and presents the study objectives and research questions. Sect. 2 *Methodology* explains the methodology and scenario framework. Sect. 3 *Baseline Analysis: current fleet, energy demand, and emissions* presents the baseline analysis, including fleet characteristics, shore power demand, fuel consumption and emissions in the Port of Bremerhaven. Sect. 4 *Results of the Scenario Analysis & Discussion* compares the OPS adoption scenarios, evaluates their economic implications, and derives policy recommendations. Finally, Sect. 5 *Conclusion, Limitations and Outlook* summarises the main findings, discusses limitations, and outlines avenues for future research.

2. Methodology

This study was conducted based on port call data of the Port of Bremerhaven to analyse exhaust gas emissions generated by container, cruise and car carrier vessels during hotelling (while berthed), as the Port of Bremerhaven is preparing to install OPS facilities for these three ship types (DNV 2024), however, implementation has been postponed from 2025 to 2026. The primary objective of this research is to estimate the potential emission reductions and associated external cost savings achievable through OPS compared to the current situation, in which shore power is not yet available. The study period spanned the entire year, from January 1st to December 31st, 2024.

To evaluate the emission reduction potential of OPS, three scenarios are considered:

- Scenario 1 (Baseline): 0% OPS adoption, representing the current situation with no shore power available; all vessels use onboard auxiliary engines during hotelling.

- Scenario 2 (Partial adoption): assuming that the vessels currently OPS-capable are using OPS during hotelling while the not-OPS-capable vessels are still using onboard auxiliary engines during hotelling.
- Scenario 3 (Full adoption): Assumes 100% OPS uptake for all eligible vessels during hotelling, with onboard fuel use largely replaced by shore-supplied electricity. Residual fuel consumption is limited to short connection and disconnection periods and to vessels with very short berthing times where OPS use is not feasible.

2.1. Input data characteristics

Our study utilises port call data from Lloyd’s List Intelligence Seasearcher (2026) for the entire year 2024. The primary dataset includes vessel identifiers (IMO numbers), berth information, arrival and departure times. This data was enriched with several external sources. Ship characteristics – including vessel type, year of construction, auxiliary engine data (MkW, RPM, SFOC) and environmental data regarding OPS capability – were obtained from Clarkson’s World Fleet Data (2025). The IMO Fourth GHG Study (IMO 2020) provided the emission factors of common maritime fuels (Table 1). As the Clarkson Database has some gaps in data, the ESI dataset offered some additional information on OPS availability (ESI 2025).

Table 1
Emission factors of common maritime fuels in kg
pollutant/tonne fuel (IMO 2020).

Fuel type	CO ₂	SO _x	NO _x	PM _{2.5}	CH ₄
MDO / MGO	3,206	1,37	56,71	0,90	0,05
HFO	3,114	50,83	75,90	7,55	0,05
LNG	2,750	0,03	13,44	0,11	8,27

2.2. Data preprocessing

To ensure the quality and consistency of the analysis, a multi-step data preprocessing procedure was implemented prior to modelling. This process included data cleaning, integration, enrichment, and the completion of missing values to ensure that variables required for emission calculations were complete. Subsequently, imputation techniques were used to address any remaining missing values. These included design parameters such as deadweight tonnage (DWT), auxiliary engine power, and revolutions per minute (RPM). If RPM data were unavailable, missing values were imputed based on averages from vessels within the same build year group and IMO size category for the relevant ship type.

The dataset was further enriched with each vessel’s keel-laying date, sourced from publicly available web data. This date is critical for determining the vessel’s applicable IMO NO_x Tier classification. In cases where the keel-laying date was unavailable, it was approximated as one year prior to the vessel’s recorded build year.

Based on the arrival and departure information, the time spent berthing has been calculated. During berthing, a total of one hour (30 minutes at the start and 30 minutes at the end) is deducted, as this represents the average time required to connect and disconnect the vessel to the OPS. Therefore, only berthing periods of two hours or longer are considered sufficient for OPS connection. Vessels berthed at the shipyard were excluded, as these ships were presumably undergoing extended maintenance and were therefore not connected to OPS.

Following these preprocessing steps, the final dataset comprises 443 container vessels, 12 cruise ships, and 297 car carrier vessels that berthed in Bremerhaven at least once during 2024. This dataset forms the analytical foundation for the subsequent shore power demand and emission modelling.

2.3. Calculation method: Shore power demand and fuel consumption

The shore power electricity demand was determined individually for each vessel. For every vessel i , the energy consumption while at berth was calculated as the product of its electrical power demand during hotelling (P_i , in MW) and its effective berthing duration (t_i , in hours):

$$E_i \text{ (MWh)} = P_i \text{ (MW)} \times T_i \text{ (h)}$$

The resulting energy demand per vessel was then aggregated across all three vessel types within each scenario, based on the respective OPS adoption rates (0% in Scenario 1, partial in Scenario 2, and 100% in Scenario 3).

2.4. Calculation method: Emission modelling

This study estimates exhaust gas emissions generated by container, cruise, and car carrier vessels during hoteling (at-berth) operations using an activity-based bottom-up modelling approach. The analysis covers air pollutants—including SO_x , NO_x , and $\text{PM}_{2.5}$ —as well as GHGs, including CO_2 and CH_4 . By combining vessel-specific operational data with fuel- and technology-dependent emission factors, realistic at-berth emissions are calculated. These serve as the basis for assessing the emission reduction potential of OPS. Although emissions are modelled at the level of individual vessel calls, the results are subsequently aggregated by vessel types. The resulting emissions were then aggregated across all three vessel types within each scenario.

Following a similar approach to Herrero et al. (2022), “inaction” emissions are calculated using vessel-specific activity data, including auxiliary engine power demand at berth, effective berthing time, and fuel consumption rates. For each vessel i and pollutant p , the emissions during berthing are given by:

$$E_{p,i} = P_{\text{aux},i} \times T_{\text{eff},i} \times LF_{\text{aux},i} \times EF_p \times N$$

where:

$E_{p,i}$ = emission of pollutant p (CO_2 , SO_x , NO_x , PM) from vessel i during hoteling (t),

$P_{\text{aux},i}$ = auxiliary engine power at berth (kW), specific to vessel type and size capacity,

$T_{\text{eff},i}$ = effective berthing time (hours), calculated as total berthing duration minus any non-operational periods (e.g., connection/disconnection time),

$LF_{\text{aux},i}$ = average auxiliary engine load factor (–), derived from vessel type and size,

EF_p = emission factor for pollutant p (CO_2 , SO_x , NO_x , PM), dependent on the fuel type used in the auxiliary engines,

N = number of calls in 2024.

The vessels in our analysis operate on HFO, MDO, MGO, or LNG in their auxiliary engines. Where specific auxiliary fuel data were unavailable, MDO was assumed as the default. The emission factors applied for each fuel type are provided in Table 1.

Table 1: Emission factors of common maritime fuels in kg pollutant/tonne fuel (IMO 2020).

For SO_x, emission factors were adjusted according to the maximum allowed sulphur content of the fuel. NO_x emissions were estimated considering the IMO NO_x Tier limits, inferred from the vessel’s keel-laying date. PM_{2.5} and CO₂ emissions were calculated proportionally to auxiliary fuel consumption. CH₄ was derived using fuel-specific factors and global warming potentials where applicable.

Total hotel emissions for each vessel type were first computed across all 2024 port calls. The potential emission reductions achievable through OPS according to the three scenarios were then quantified.

2.5. Calculation method: Operational costs and external damages

Operational costs in the three scenarios comprise fuel consumption and associated bunker fuel prices as well as electricity consumption and its corresponding prices.

Bunker fuel prices correspond to the 2024 average prices recorded in Rotterdam, calculated from 24 observations (two per month) across the three relevant fuel types used in the auxiliary engines (Table 2). Electricity prices for 2024 were calculated using the official average for non-household customers published by the German Federal Statistical Office (2026). This price, which includes all taxes, fees, levies, and charges, amounted to 0.17 EUR/kWh.

Table 2
Average fuel prices based on the Port of Rotterdam in 2024.

Fuel type	Average prices in EUR/ t
MDO / MGO	724,4
HFO	472,7
LNG	697,0

The tax relief granted for shore-side electricity supply in Germany amounts to EUR 20 per MWh (EUR 0.02 per kWh), as set by the German Federal Ministry of Finance. According to an expert from bremenports GmbH, current internal assessments are based on subsidised electricity prices, and the same value is therefore applied in this study. This price is substantially lower than both the average European shore power price of approximately EUR 0.24 per kWh (Sustainable Ships 2026) and the OPS electricity price of EUR 0.316 per kWh used by Bestebreutje et al. (2026) for Bremerhaven. This discrepancy highlights the significant role of public support measures in promoting OPS adoption in German seaports.

Table 2: Average fuel prices based on the Port of Rotterdam in 2024.

External costs include air pollution health damages and climate damages. Merkel et al.(2023) used emission factors from van Essen et al. (2019), which are now outdated and lack geographic specificity. This analysis

instead employs the more recent Germany-specific unit damage values published by Eser et al. (2025). The air pollutants, expressed in EUR per tonne of pollutant, account for emission release height. For ship emissions (chimney height > 20 m), the “city” damage values were applied using the average of the categories “Combustion processes in industry” and “Small-scale combustion facilities”, adjusted to Bremerhaven’s population size. Climate damages were valued at 345 EUR per tonne of CO₂-equivalent and 5,800 EUR per tonne of CH₄, following the central scenario in Eser et al. (2025) (Table 3).

Table 3
Air pollutant health and climate damage value factors from Eser et al. (2025).

Air pollutant	Value factors in EUR/t emission	Climate gases	Value factors in EUR/t emission
PM _{2.5}	135,15	CO ₂	345
NO _x	38,75	CH ₄	5800
SO ₂	35,75		

Table 3: Air pollutant health and climate damage value factors from Eser et al. (2025).

Figure 2 presents the methodological process of this study:

Figure 2: Schematic representation of the research methodology.

3. Baseline Analysis: current fleet, energy demand, and emissions

3.1. Fleet composition and berthing activity in the Port of Bremerhaven

The Port of Bremerhaven is one of Germany’s major seaports and a key logistics hub in Northern Europe. In 2024, the port handled 4,441 million TEU in container throughput, 1,252,758 automobiles, and 291,594 cruise passengers (in- and outbound). These figures reflect a positive performance and an increasing trend, particularly in container volume, which continued into 2025 (bremenports GmbH & Co. KG 2026).

In 2024, the Port of Bremerhaven recorded over 8,000 port calls. Of these, 3,377 calls were made by the three vessel types analysed in this study: container ships, cruise vessels, and car carriers. These vessels accounted for a total berthing time of 113,650 hours. As shown in Table 4 (adapted from Bullock et al., 2023), container ships represented the largest share with 75,841 hours (67%), followed by car carriers with 31,635 hours (28%) and cruise vessels with 6,175 hours (5%). Of the total berthing time, 21,511 hours were generated by OPS-capable vessels.

Table 4
Berth time characteristics and shore power demand by vessel type (key values highlighted in grey).

Ship type	Hours at berth/year	Share of total berthing time	Hours at berth/year of OPS-capable vessels	Total vessel calls	OPS-capable vessel calls	Unique vessels	Hours/year per vessel	MWh/year per vessel
Container	75,841	67%	16,366	2,565	524	443	30	165
Cruise	6,175	5%	2,045	99	60	12	62	457
Car carrier	31,635	28%	3,100	713	47	297	44	155
Total	113,650	100%	21,511	3,377	631			

Table 4: Berth time characteristics and shore power demand by vessel type (key values highlighted in grey).

Container ships dominated berthing activity, representing 67% of the total berthing time for the three vessel types. Car carriers contributed 28%, while cruise vessels accounted for only 5%. Vessels equipped with OPS capability accumulated 21,511 hours, corresponding to approximately 19% of the total berthing time, indicating that *roughly one fifth of the total berthing time was technically eligible for shore power*. As shown in Fig. 3, of the 3,377 port calls by container ships, cruise vessels, and car carriers, 631 (19%) were OPS-capable, with container ships contributing 524 (20.4%) OPS calls, cruise vessels 60 (60.6%), and car carriers 47 (6.6%).

Figure 3: Number and proportion of port calls by ship type, distinguishing vessels with and without OPS capability (OPS yes / OPS no).

The distribution of auxiliary engine fuels varies across different vessel types. While container and cruise ships are predominantly powered by MDO/MGO (84% and 83%, respectively), car carriers use MDO/MGO (46%) and HFO (45%) in nearly equal shares (Table 5).

Table 5
Number of unique vessels by ship type and auxiliary fuel type.

Ship type / Fuel type	HFO	LNG	MDO
Container	67	6	370
Cruise	1	1	10
Car carrier	134	28	135

Table 5: Number of unique vessels by ship type and auxiliary fuel type.

3.2. Shore power demand and fuel consumption

The total annual shore power demand in the Port of Bremerhaven in 2024 amounts to 533 GWh, generated over 113,650 hours at berth across 3,377 vessel calls by container ships, cruise vessels, and car carriers. As shown in Table 6, this demand is unevenly distributed among the three vessel types. Container ships account for the largest share, with 436 GWh (82% of total demand), driven by their high number of calls (2,565) and substantial aggregate berthing time (75,841 hours). Cruise vessels, despite fewer calls (99 calls from only 12 unique ships), show the

highest energy intensity per vessel, averaging 457 MWh per vessel. Car carriers contribute 84 GWh, representing 16% of the total demand.

Table 6

Estimated shore power demand and fuel consumption by vessel type (container, cruise, and car carrier) with or without OPS-capability.

Ship type	Shore power demand of all vessels [GWh]	Shore power demand of OPS-capable vessels [GWh]	% of total shore power demand	Fuel consumption of all vessels [t]	Fuel consumption of OPS <i>not</i> -capable vessels [t]
Container	436	142	32%	75,841	58,502
Cruise	13	5	37%	6,175	1,652
Car carrier	84	9	11%	31,635	14,844
Total	533	155	29%	113,650	74,998

Of the total technical shore power demand, only 155 GWh (29%) is attributable to vessels currently equipped with OPS. This breaks down as follows: container ships represent the largest absolute OPS-capable demand, while cruise vessels show the highest share of OPS-capable demand relative to their total (37%). Car carriers have the lowest OPS-capable proportion (11%). These figures reflect the current technical eligibility for shore power connection based on the existing fleet.

Table 6: Estimated shore power demand and fuel consumption by vessel type (container, cruise, and car carrier) with or without OPS-capability.

3.3. Air pollutants and climate gases

The auxiliary engine activity of container ships, cruise vessels, and car carriers during berthing in the Port of Bremerhaven generates considerable emissions of both air pollutants and GHGs. Table 7 presents the baseline emissions inventory for key air pollutants and climate gases (NO_x, SO_x, PM_{2.5}, CO₂, and CH₄) broken down by vessel type. Container ships are responsible for the largest share of emissions in most categories, particularly CO₂ (60% of total) and NO_x (67%), which aligns with their dominant position in berthing time (67%) and energy demand. Car carriers, despite lower overall activity, contribute disproportionately to methane (CH₄) emissions (76%). Cruise vessels show lower absolute emissions but remain relevant due to their high energy intensity per vessel. These figures reflect current real-world fuel consumption patterns at berth and serve as the reference point for subsequent scenario analysis.

Table 7
Baseline emissions at berth in 2024 by vessel type (tonnes).

Pollutant [t]	Container vessels	Cruise vessels	Car carriers	Total
SO _x	52	5	15	72
NO _x	1,237	207	388	1,833
PM _{2.5}	9	1	3	12
CO ₂	85,911	27,736	29,017	142,664
CH ₄	8	2	31	41

Table 7: Baseline emissions at berth in 2024 by vessel type (tonnes).

4. Results of Scenario Analysis & Discussion

Under Scenario 1 (baseline), just like how it works today, vessel operations during berthing remain fully dependent on conventional fuel use, resulting in high operational and external costs. The findings indicate substantial external impacts related to air pollution and climate damages, with total external costs exceeding operational costs for several vessel categories. This highlights the significant environmental and public health burden associated with continued reliance on fossil-fuel-based auxiliary engines at berth (Table 8).

Table 8
Scenario 1: No OPS use while hotelling (baseline)

Cost component	Container	Cruise	Car carrier	Total [million EUR /year]
<i>Operational costs</i>				
Fuel costs	59.5	1.9	9.6	71.0
Electricity costs	0.0	0.0	0.0	0.0
Total operational costs	59.5	1.9	9.6	71.0
<i>External costs</i>				
Air pollution health damages	51.0	8.3	15.9	75.3
Climate damages	12.7	4.1	4.4	21.2
Total external costs	63.7	12.4	20.4	96.5

Table 8: Scenario 1: No OPS use while hotelling (baseline)

Not surprisingly, even the partial use of OPS could lead to substantial reductions in both air pollutants and climate-relevant GHGs across all vessel types, although the magnitude of the effect varies considerably between ship types and pollutants (Fig. 4). Container vessels, which represent the largest share of OPS-equipped ships, therefore offer the greatest overall reduction potential across most emission categories. By connecting to OPS, these vessels could achieve an 18% reduction in CO₂ emissions, corresponding to almost 26,000 tonnes. The reduction potential for NO_x is also significant, amounting to 386 tonnes (– 21%). Cruise vessels show more

modest savings, with reductions of around 2–3% across different emission types, the highest absolute reduction being observed for CO₂ at 3,173 tonnes. Car carriers exhibit comparatively lower reduction potentials across most pollutants. The main exception is methane (CH₄), where they achieve the highest relative reduction potential, with 27 tonnes avoided, corresponding to a 66% reduction.

Figure 4: Baseline scenario vs. Scenario 2: total emissions and reduction potential of OPS-capable container, cruise and car-carrier vessels.

Accordingly, Scenario 2 demonstrates that the introduction of shore power and partial electrification can substantially reduce the environmental impacts associated with vessel berthing operations (Table 9). Compared with Scenario 1, significant reductions are achieved in both air pollution health damages and climate-related external costs, resulting in an overall decrease in total external costs of more than 23%, despite the introduction of EUR 3.1 million in electricity costs. These findings indicate that shore power can play an important role in supporting port decarbonisation and improving primarily health damages related to air pollution.

Table 9
Scenario 2: OPS-capable vessels using OPS while hotelling

Cost component	Container	Cruise	Car carrier	Total [million EUR /year]	Change vs. Scenario 1 [million EUR /year]	Change vs. Scenario 1 (%)
<i>Operational costs</i>						
Fuel costs	42.0	1.2	8.4	51.5	-19.6	-27.6%
Electricity costs	2.8	0.1	0.2	3.1	+ 3.1	N/A
Total operational costs	44.8	1.2	8.6	54.6	-16.5	-23.2%
<i>External costs</i>						
Air pollution health damages	35.1	6.5	15.8	57.5	-17.8	-23.7%
Climate damages	8.9	3.6	3.9	16.4	-4.8	-22.6%
Total external costs	44.0	10.2	19.7	73.8	-22.6	-23.4%

Table 9: Scenario 2: OPS-capable vessels using OPS while hotelling

In Scenario 3 (Full OPS adoption), the picture becomes even more pronounced. Operational costs drop dramatically by approximately 84% to EUR 11.1 million, as fuel costs are almost entirely replaced by electricity costs (EUR 10.7 million). External costs are expected to decline by over 97%, highlighting the very high environmental benefit of full OPS implementation. Under this scenario, fuel consumption at berth would be reduced to almost zero and largely replaced by electricity supplied from the shore. Limited fuel use would still occur during the approximately one-hour connection and disconnection procedures, as well as for vessels with planned berthing times of less than one hour, for which OPS connection may not be feasible.

Table 10: Scenario 3: All container, cruise and car carrier vessels using OPS while hotelling

Table 10
Scenario 3: All container, cruise and car carrier vessels using OPS while hotelling

Cost component	Container	Cruise	Car carrier	Total [million EUR /year]	Change vs. Scenario 1 [million EUR /year]	Change vs. Scenario 1 (%)
Operational costs						
Fuel costs	0.3	0.0	0.1	0.4	-70.6	-99.0%
Electricity costs	8.7	0.3	1.7	10.7	+ 10.7	N/A
Total operational costs	9.1	0.3	1.8	11.1	-59.9	-80.0%
External costs						
Air pollution health damages	1.6	0.1	0.3	2.0	-73.2	-97.3%
Climate damages	0.9	0.1	0.2	1.2	-48.2	N/A
Total external costs	2.5	0.2	0.5	3.3	-121.5	-97.4%

While a full OPS transition (Scenario 3) appears most favourable in terms of operational costs and direct emissions within the model framework, its real-world effectiveness depends on broader energy system conditions. When considering air pollution-related health impacts and climate damages, it should be noted that these impacts cannot be assumed to be entirely eliminated. Several recent insights highlight important limitations and challenges. First, findings reported by the Port of Rotterdam (2026) demonstrate that increasing electricity demand does not automatically translate into lower emissions when renewable generation is insufficient. In the Netherlands, higher electricity demand led to increased coal- and gas-fired power generation, resulting in a comparable rise in CO₂ emissions. Second, Yao et al. (2025) identified another overlooked aspect of electrification: charging infrastructure itself can become a source of particle emissions, as direct current fast-charging power cabinets were found to contribute to local air-quality impacts. This issue should not be neglected when evaluating the broader implementation of OPS systems. Finally, Ross et al. (2025) point to a design and operational mismatch in LNG-powered vessels. Although shore power reduces auxiliary engine use during berthing, LNG tanks continue to generate boil-off gas, while many ships still lack efficient systems to manage these emissions cleanly. Given that LNG has overwhelmingly dominated alternative fuel orders – accounting for 85% of such orders between January and April 2026 (Clarksons Research 2026) – this incompatibility between LNG propulsion and OPS deserves careful consideration.

Overall, the results of this study yield several important policy implications for the deployment of OPS in maritime transport and its role in decarbonisation strategies:

First, the **economic attractiveness of OPS is highly sensitive to electricity pricing policy**. Under the current preferential taxation according to the German Electricity Duty Act, partial OPS adoption (Scenario 2) already reduces total operational costs by 23.1% compared to the baseline, even after adding EUR 3.1 million in electricity costs. In the full adoption scenario, operational costs fall by 84%. These outcomes would be significantly less favourable – or even negative – if the reduced electricity tax rate were removed. If non-household market

electricity prices (approximately EUR 0.13–0.175 per kWh in 2024) were applied without the tax reduction, the additional electricity costs in Scenarios 2 and 3 would rise sharply, approaching or even exceeding fuel costs in the baseline. This underlines that OPS adoption is not only a technological or infrastructural challenge but is *strongly shaped by regulatory price settings*. Maintaining or further optimising such preferential taxation therefore represents a powerful and cost-effective policy lever for accelerating OPS uptake.

Second, **even partial OPS deployment generates substantial societal benefits**. Scenario 2 reduces external costs by 23.5% (EUR 22.7 million per year), particularly air pollution-related health damages. Full adoption (Scenario 3) could reduce external costs by more than 97%, demonstrating strong scalability of benefits.

Third, a **significant gap remains between private operational costs and societal external costs**. While shipping companies and ports primarily consider the EUR 71 million baseline fuel costs, society bears additional external costs of EUR 96.5 million. OPS helps close this gap by internalising part of these damages.

Fourth, **the effectiveness of OPS as a decarbonisation tool is closely linked to the wider energy system, ship fuel choices, and indirect impacts**. While full OPS adoption can drastically cut local vessel emissions, net climate and environmental benefits depend heavily on the carbon intensity of the electricity grid and careful management of infrastructure-related emissions. Emissions shifting from ships to power plants must be monitored and minimised through parallel renewable energy expansion and microgrid integration. The current incompatibility with dominant LNG fleets further underscores the need for holistic fuel and energy strategies.

Fifth, **policymakers and port authorities must proactively address external challenges and competitiveness risks**. High upfront costs and technical barriers – particularly for older vessels and grid-constrained locations – risk slowing adoption and creating uneven playing fields. Targeted subsidies, grants for retrofits (especially for smaller or older fleets), and public-private cost-sharing models are essential to mitigate negative impacts on competitiveness. Support for modular retrofit solutions can further reduce barriers for legacy vessels. Grid capacity assessments and coordinated network planning should precede large-scale OPS rollout to avoid bottlenecks and inefficient infrastructure spending.

Sixth, while port authorities bear primary responsibility for addressing external costs – particularly local air pollution and health impacts – **the effectiveness of OPS depends on coordinated action from both ports and shipping companies**. Installing OPS infrastructure alone is insufficient; ships must also be equipped (or retrofitted) to connect to and use shore power. Coordinated action across ports is essential to avoid fragmented development and inefficient competition. Harmonised technical standards, consistent pricing principles, and joint planning can prevent ports from under-investing or competing on electricity costs, thereby accelerating the overall transition. At present, however, such coordination remains limited. Ports with similar wholesale electricity prices can still face markedly different total OPS costs due to variations in national tariff structures, taxation regimes, grid fees, and local network constraints, creating unequal conditions for OPS deployment and operation (Bestebreurtje et al. 2026).

In conclusion, OPS proves to be a highly effective decarbonisation measure when supported by appropriate electricity taxation and infrastructure planning. Its benefits are conditional on supportive electricity pricing, a progressively cleaner electricity grid, ship-side retrofitting, and careful management of infrastructure-related emissions. As highlighted by Gulyás et al. (2025), the long-term planning and implementation of emissions reduction measures are essential for maximising environmental benefits and ensuring that decarbonisation efforts remain effective over time. Provided these dependencies are actively addressed - including mitigating

emissions shifts and the current incompatibility with LNG fleets - OPS has strong potential to become a genuinely transformative solution rather than merely a partial one.

The findings are relevant to multiple stakeholders and maritime decision areas (Buer et al. 2019): port authorities can use them to prioritise investments in high-impact vessel segments; policymakers can refine electricity pricing schemes and incentive mechanisms; shipping companies can better assess retrofitting and operational decisions; and energy providers can anticipate future demand for grid planning.

5. Conclusion, Limitations and Outlook

As long as alternative fuels are not yet available, delaying the implementation of OPS in seaports results in substantial emissions. Monetising these emissions reveals a major economic and social burden that could be avoided. In the case of the Port of Bremerhaven, the potential reduction in health-harming pollutants and GHGs is substantial: even partial electrification could reduce external costs by up to 23.4%, equivalent to approximately EUR 22.6 million. Thanks to Germany's subsidised electricity prices, shipping companies could benefit from substantially lower fuel costs while experiencing only a marginal increase in electricity expenses. Full electrification could nearly eliminate all emissions under specific conditions and reduce total operational costs by up to 80%. The approach described in this paper is transferable to other seaports, enabling them to assess step-by-step adoption scenarios.

As international and European regulations increasingly mandate the use of OPS, reliable access to electricity and competitive electricity pricing are becoming critical competitive factors for ports, terminal operators, and shipping companies alike. This study contributes to the ongoing debate by providing a detailed, scenario-based assessment of OPS deployment at the Port of Bremerhaven. Through the analysis of three realistic adoption pathways – Scenario 1 (baseline with 0% OPS), Scenario 2 (partial adoption of existing OPS-capable vessels), and Scenario 3 (full adoption) – the paper quantifies the environmental, economic, and external cost implications of shore power implementation.

The findings demonstrate that OPS offers substantial emission reduction potential and external cost savings, even under partial adoption. Moreover, the results highlight the decisive role of electricity pricing policy, particularly the preferential taxation under the German Electricity Duty Act, in determining the economic attractiveness of OPS. By linking technical potential, emission reductions, operational costs, and external benefits, this study offers actionable insights for designing effective policy frameworks that balance environmental ambitions with economic competitiveness in maritime transport.

Despite these contributions, several limitations should be acknowledged. The analysis relies on historical vessel data and assumptions regarding auxiliary engine fuel types and technical characteristics, as detailed vessel-specific information was not consistently available. The auxiliary engine parameters applied in this study are based on the IMO Fourth GHG Study (2020), which is scheduled to be updated in 2026. Revisions to these parameters may affect future estimates of emissions and associated costs. In addition, the analysis assumes full OPS utilisation, which may not always be the case due to operational delays or inefficiencies at the port. Thus, alternative data sources within transportation could be usefully explored in the future (Kinra et al. 2019). Finally, the economic assessment is subject to uncertainties associated with developments in global energy markets. Recent geopolitical tensions and disruptions in major energy-producing regions have contributed to increased volatility in fuel prices and fuel availability.

Future research should incorporate sensitivity analyses of fuel and electricity prices, updated IMO emission factors, and dynamic changes in fleet composition and grid carbon intensity. Applying the framework to ports outside the European Union could provide valuable insights into OPS under different regulatory, pricing, and environmental policy conditions. Further research should also compare OPS with alternative emission-reduction measures during berthing, such as battery systems, scrubbers, and other emerging technologies, considering their environmental, economic, and infrastructure requirements. Last but not least, the creation of a formalised decision-support system (Kinra et al. 2017) and tool (Bhardwaj and Kinra 2025) that can aid policymakers in their assessments and port decarbonisation pathways should be explored further.

List of abbreviations

- CH4 methane
- CO2 carb on dioxide
- EEA European Environment Agency
- EUR euro
- GBP pfund sterling
- GHG greenhouse gas
- GWh Gigawatt hour
- HFO heavy fuel oil
- IMO International Maritime Organisation
- LNG liquified natural gas
- MDO marine diesel oil
- MGO marine gas oil
- MWh megawatt hour
- N/A not applicable
- OPS on-shore power supply
- PM2.5 particles for an aerodynamic diameter of 2.5 µg/m³
- SOx sulphur oxides
- NOx nitrogen oxides
- TEU Twenty-Foot Equivalent Unit

Declarations

Author Contribution

All authors whose names appear on the submission made substantial contributions to the conception of the work, revised it critically for important intellectual content, approved the version to be published, and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Data Availability

All data supporting the findings of this study are available within the paper.

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Footnotes

1. As Kizielewicz et al. (2024) summarise, various terms are used interchangeably to describe OPS, including shore-to-ship power (SSP), cold ironing, shore-side electricity (SSE), high-voltage shore connection (HVSC), alternative maritime power (AMP), and cold ironing (CI). In this paper, the term 'OPS' is used to encompass all of these variations.

Figures

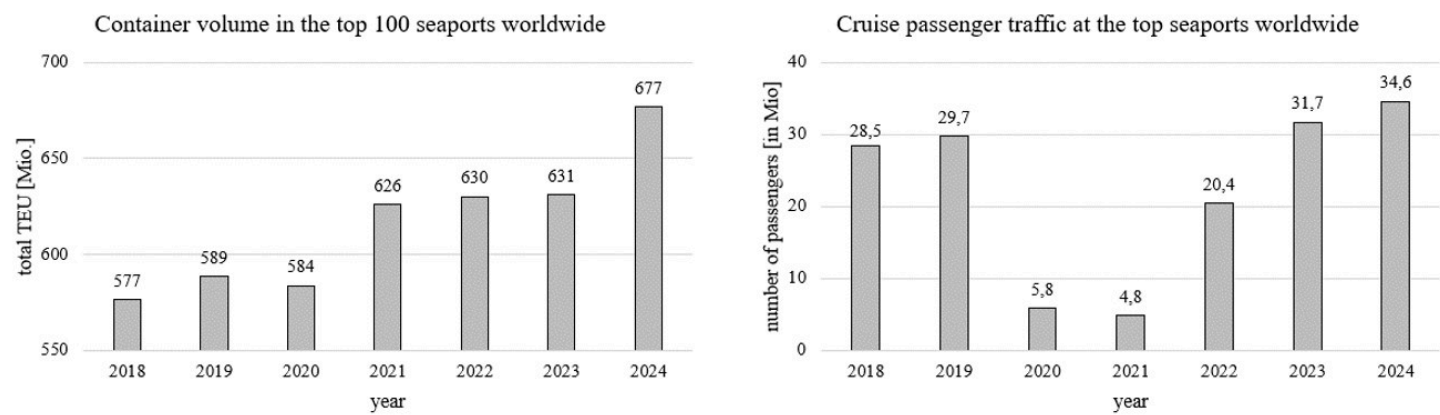


Figure 1

Growth in container throughput (TEU) at the world’s top 100 seaports (left) and cruise passenger numbers at the world’s leading cruise ports (right). Sources: Institute for Shipping Economics and Logistics (2024) & Cruise Lines International Association (2025).

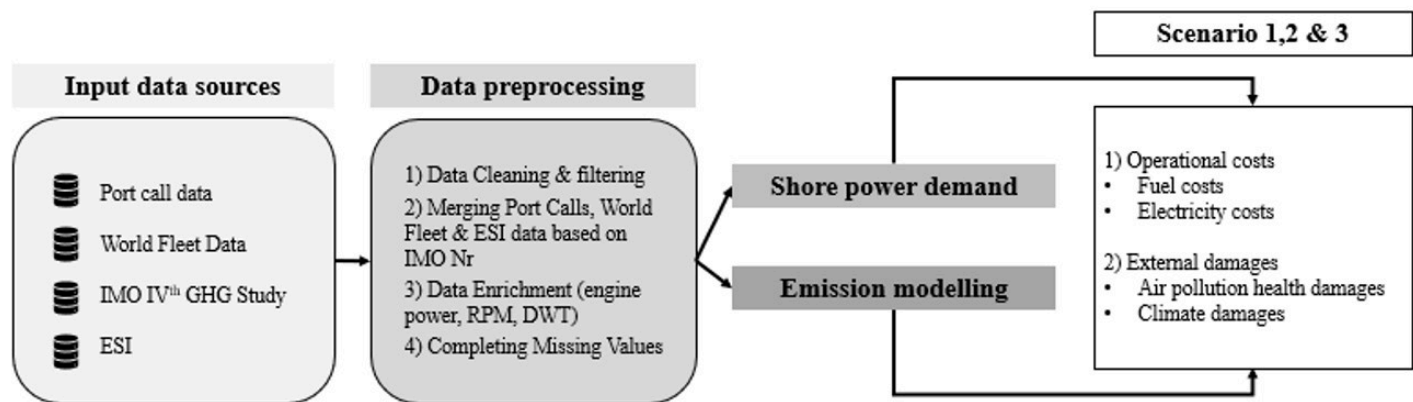


Figure 2

Schematic representation of the research methodology.

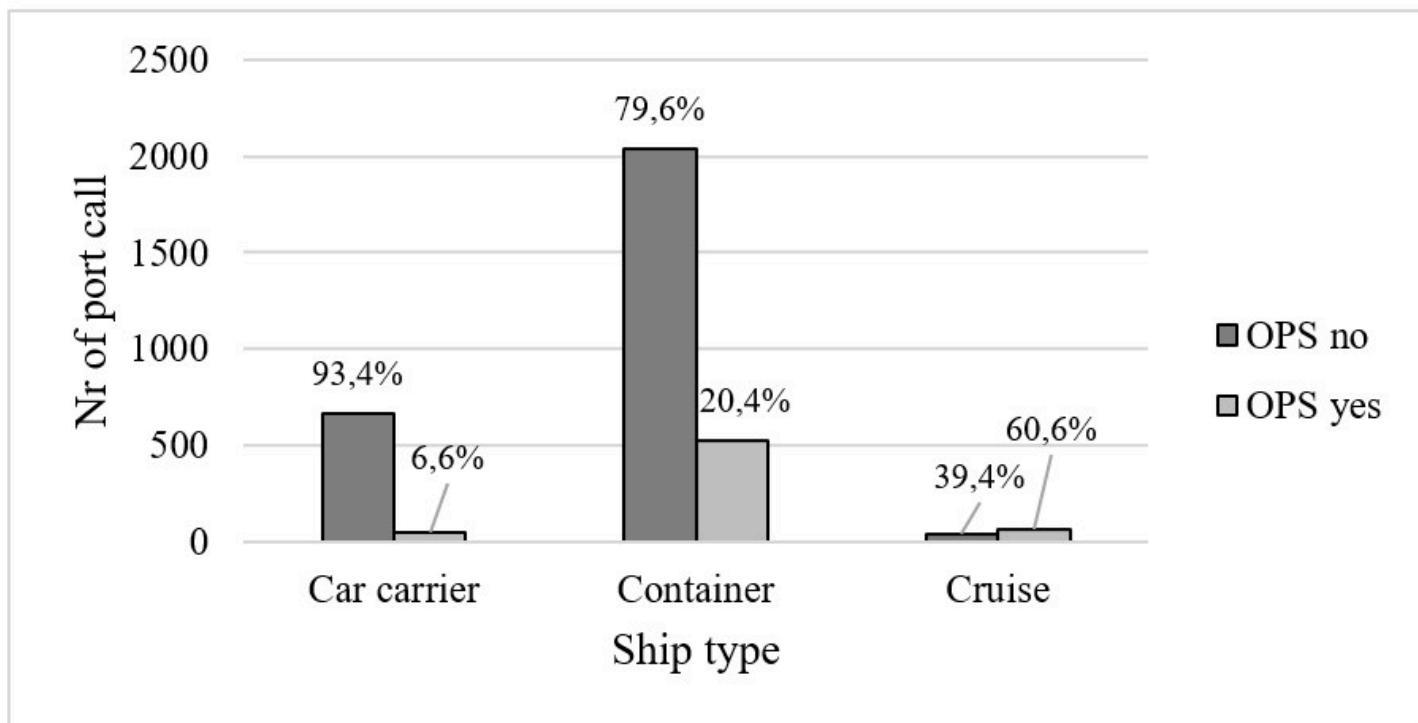


Figure 3

Number and proportion of port calls by ship type, distinguishing vessels with and without OPS capability (OPS yes / OPS no).

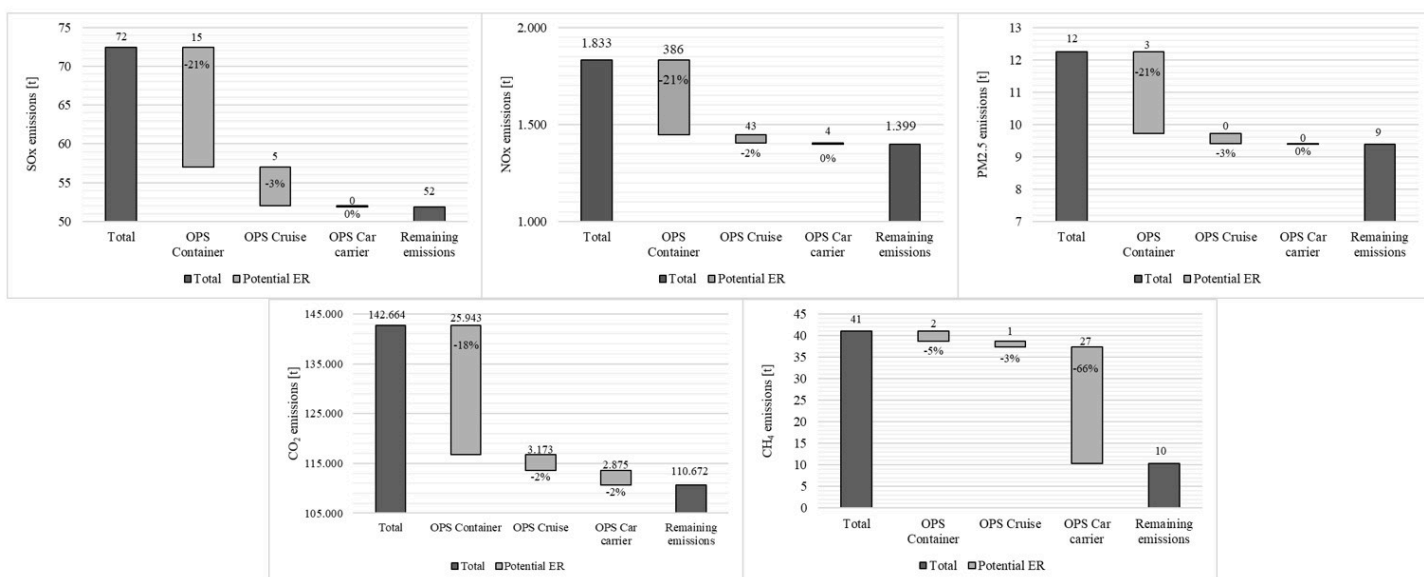


Figure 4

Baseline scenario vs. Scenario 2: total emissions and reduction potential of OPS-capable container, cruise and car-carrier vessels.