Poison in the water: **The call to ban scrubber discharge**

The health and environmental costs industry wants us to ignore

PACIFIC
ENVIRONMENT

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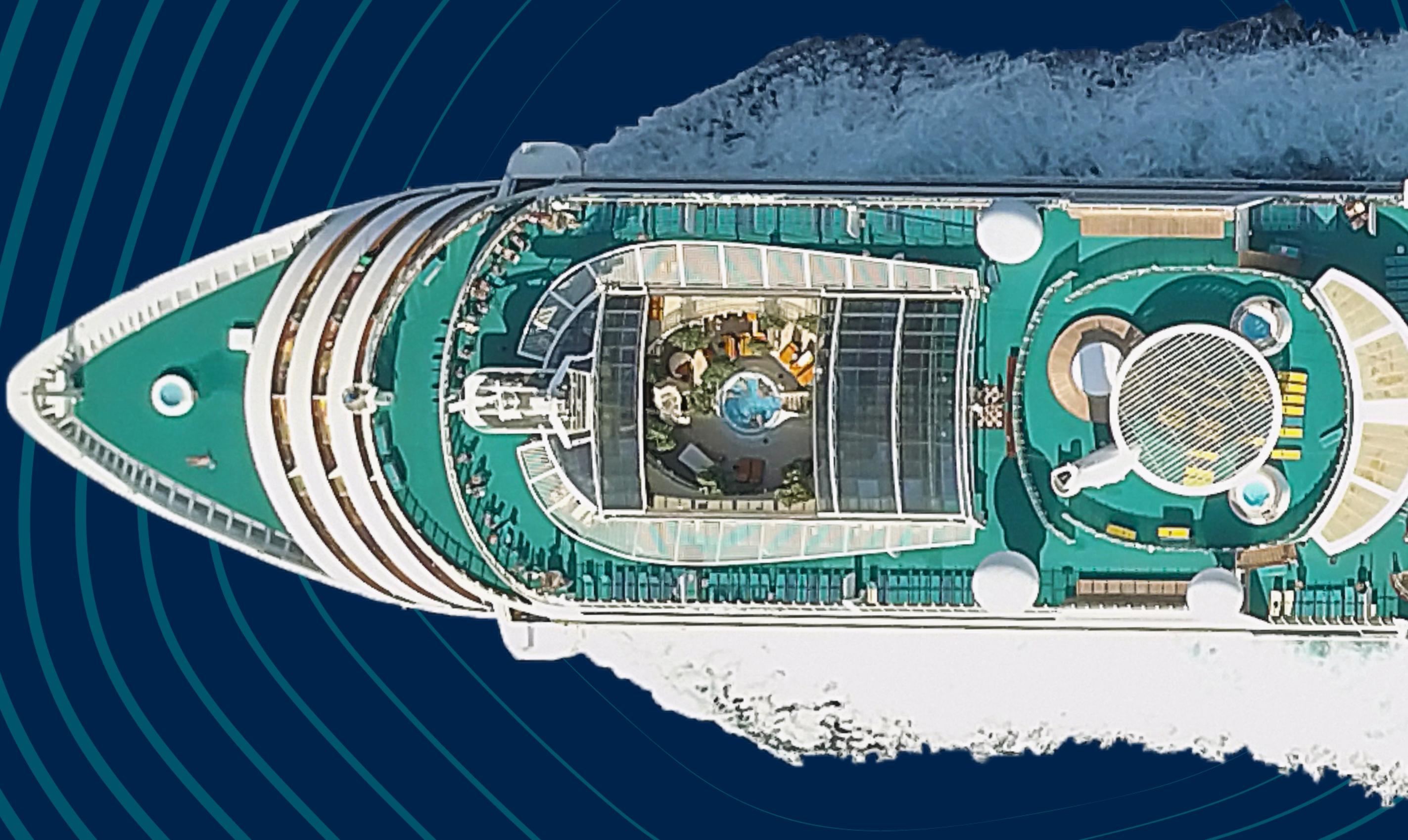

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Edward Carr and Samantha McCabe contributed to several sections of this report including technical modeling of scrubber economics and research on the status of scrubbers in the fleet, fuel prices and waste reception capacity.

Executive **summary**

Extremely toxic discharge into our oceans from Exhaust Gas Cleaning Systems (EGCS, or scrubbers) continues to increase globally, threatening human health and the marine environment even in very low concentrations.

Scrubbers on ships remove toxic pollutants from the exhaust gasses produced by combustion engines burning heavy fuel oil (HFO). Scrubbers take these harmful pollutants *out of the air* and dump them *into the water.*

This paper examines arguments and issues impeding adoption of scrubber bans and makes the case for banning scrubbers.

Key takeaways

Scrubber economics

- While scrubbers may remain more cost-effective than using distillate fuels, the discharge of scrubber waste causes significant harm to marine ecosystems, which shifts the economic burden to other stakeholders, with damages quantified in the millions.

- The short payback period indicates that the return on scrubber investment is quickly realized, and most operators have already recouped their initial costs. Ninety-five percent of ships recovered the initial capital cost within five years, possibly even as quickly as one year.

- Findings align with other studies, showing that the majority of ships equipped with scrubbers have recovered their initial capital costs, or would do so during a phase-out period, making scrubber removal financially viable for most operators.

Environmental degradation

- Scrubber wastewater is highly toxic, significantly hotter and up to 100,000 times more acidic than the surrounding waters. It contains various pollutants, including heavy metals, polycyclic aromatic hydrocarbons (PAHs), nitrates and nitrites, sulfates and particulate matter. The presence of heavy metals and PAHs is especially concerning given their ability to persist in marine environments and accumulate within marine species. Even at extremely low concentrations — just 0.001% — scrubber pollutants can harm marine life and disrupt biological processes.

- Ships using HFO with scrubbers emit 70% more particulate matter, up to 4.5 times more black carbon and considerably more PAHs into the atmosphere compared to ships running on marine gas oil (MGO). This black carbon pollution is accelerating the Arctic meltdown and global warming.
- Scrubbers incentivize the continued use of HFO in Sulfur Emission Control Areas (SECAs), exacerbating air quality concerns in areas designated to be safeguarded from such impacts.
- Scrubber discharge is contaminated with heavy metals such as vanadium, nickel, zinc, copper, chromium, arsenic, cadmium, iron, lead, mercury, selenium and thallium. Ships with scrubber systems introduce an increased metal load to the environment compared to ships without scrubbers.
- Metal-PAH mixtures from scrubbers can result in "more-than-additive" co-toxicity, wherein the combined toxicity of the mixture exceeds the toxic effects of metals or PAHs on their own.

Human health risks

- Humans are exposed to toxic scrubber discharge via ingestion of contaminated seafood and drinking water, dermal contact and inhalation during recreational ocean activities and inhalation of air pollutants.
- PAH exposure has been linked to DNA damage, endocrine disruption, developmental abnormalities, lung deficiencies such as asthma, and disrupted cognitive development. Compared to other PAH sources, marine transport emissions — including scrubber-related pollution — contribute to significantly higher carcinogenic risk.

Food security, community impacts

Marine ecosystem disruption from scrubber use on maritime vessels raises significant health and environmental concerns for Indigenous and subsistence fishing communities. Toxic algal blooms linked to nutrient overload from scrubber-related nitrate and nitrite releases can devastate marine populations, threatening the resilience of communities that rely on seafood. Elevated PAHs and heavy metal loads in marine organisms also put seafood-dependent communities at higher risk of health complications.

Scrubber use **on the rise**

Background and current landscape

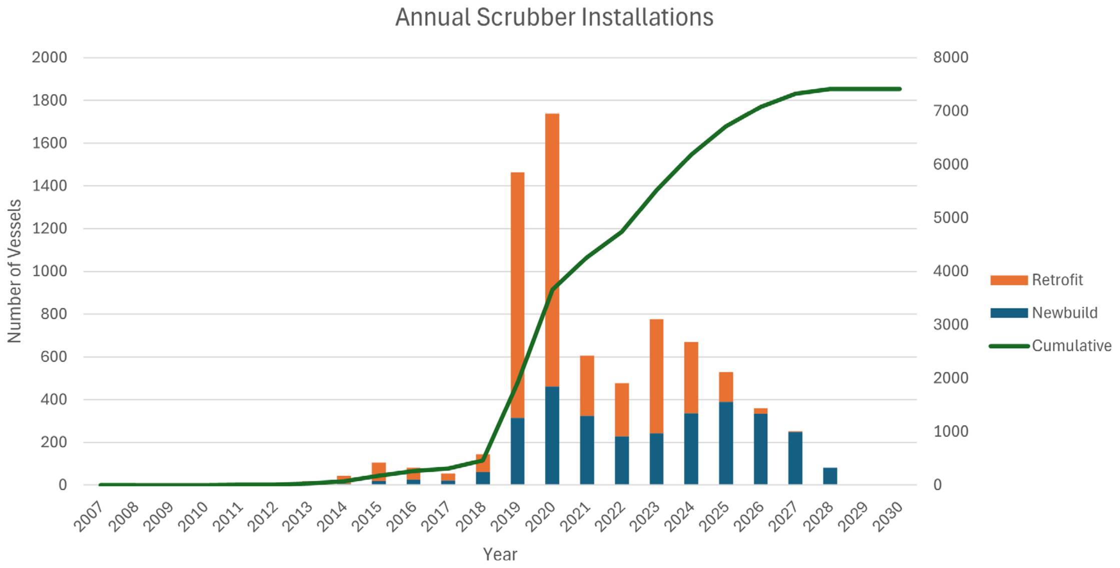
The development of exhaust gas cleaning systems (EGCS), also known as scrubbers, came about when regulations on the maximum sulfur content of marine fuels were adopted. These regulations aimed to reduce sulfur oxide (SO_x) pollution — linked to health issues including heart and lung diseases — from ship exhaust. Regulations such as those associated with the North American Emission Control Area mandated the use of low (1% or less) sulfur fuels, but also allowed fuels with a higher concentration to be used in concert with an EGCS as an alternative compliance mechanism.

This resulted in limited use of EGCS. Subsequent implementation of the International Maritime Organization (IMO) regulation on the maximum sulfur content of marine heavy fuel oil (HFO) globally, which went into effect Jan. 1, 2020 and reduced the maximum amount of sulfur allowed in HFO from 3.5% to 0.5%, resulted in more widespread adoption of scrubber systems. Even so, it was thought that EGCS systems would be used by a relatively small number of vessels, and that they would rapidly be phased out as enough compliant fuels became available. However, as the shipping industry discovered that the cost of installing an EGCS system could be recovered relatively rapidly (within a few years) by continuing to use less expensive high sulfur fuel, they not only remained in use, but began to proliferate throughout the industry.

Scrubber uptake by the global fleet

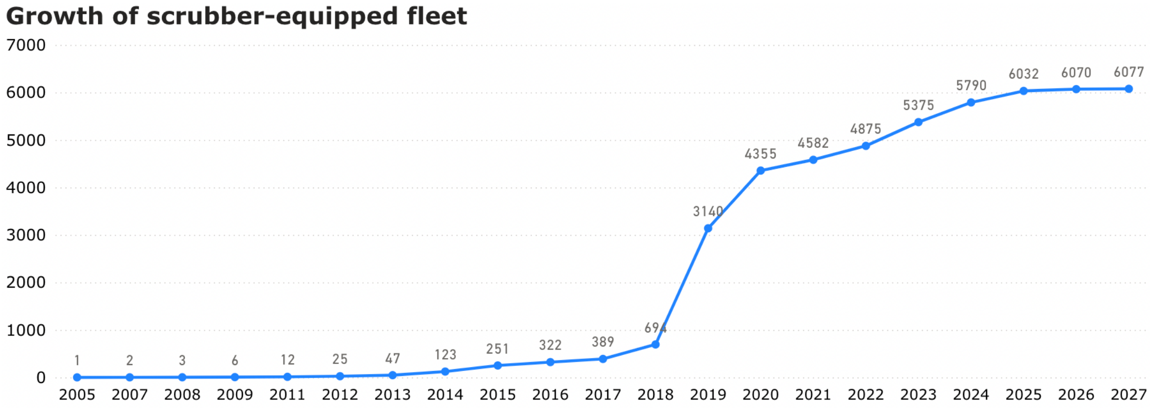
Use of scrubbers has skyrocketed in the last 20 years, resulting in billions of tons of toxic discharges into our oceans.

The number of scrubber-equipped ships in the global fleet increased from 243 in 2020 to more than 7,400 at the start of 2025 as shown in the graph below (Clarksons Research, 2025; Osipova et al., 2021).



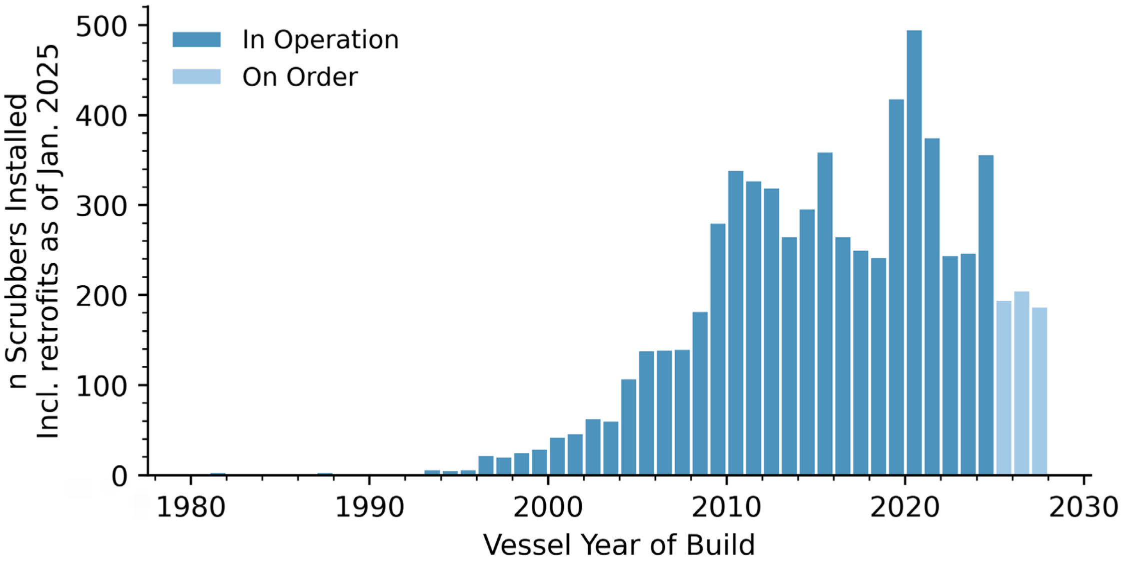
SOURCE: **Clarksons Research, 2025.**

This graph shows a count of scrubbers installed by year from IMO data. Note that estimates of total installs differ due to different data sources.



SOURCE: **IMO, 2025a.**

It appears scrubber use will continue to grow, with 592 more scrubbers under construction or on order as shown in the graph below.



Number of scrubbers installed by vessel year of build. SOURCE: S&P Global, 2025.

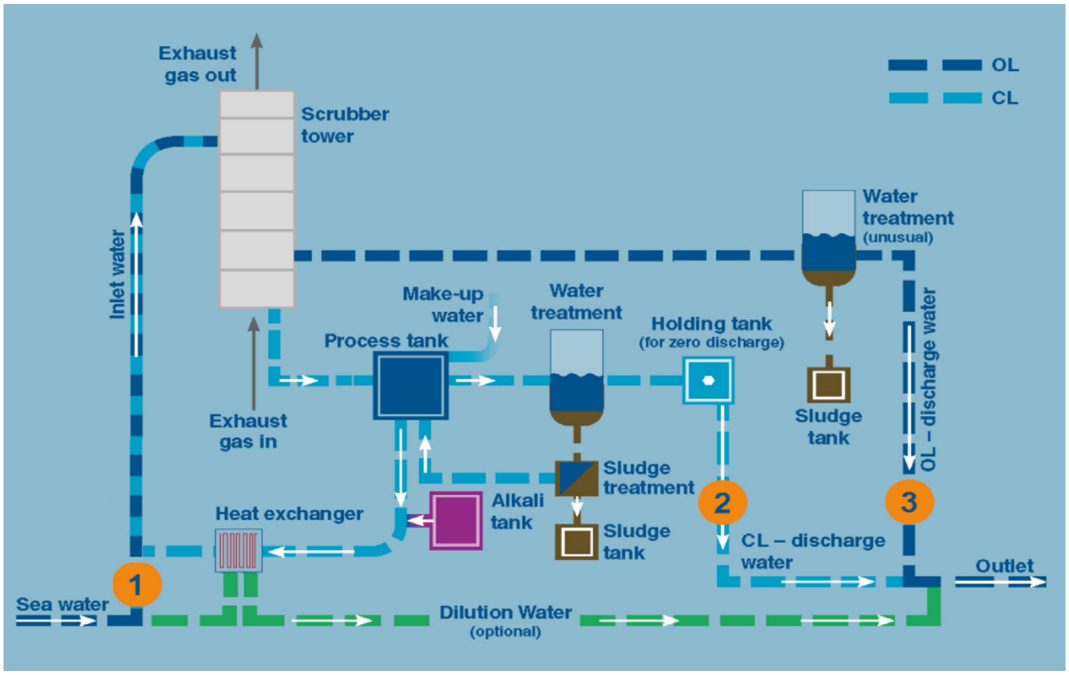
Investments in scrubbers began growing moderately from 2005 to 2018, coinciding with the introduction of emission control areas (ECAs) in North America and Europe, which imposed stricter sulfur regulations. In North America, the ECA came into effect on Aug. 1, 2012, initially limiting sulfur content in fuel to 1.0%, which was further reduced to 0.1% on Jan. 1, 2015. The European ECAs, which include the Baltic Sea ECA and the North Sea ECA, were established earlier and came into force in 2006 and 2007, respectively, with limits tightening further to 0.1% by Jan. 1, 2015. These ECAs primarily target sulfur emissions from ship exhausts (but also regulate nitrogen oxides and compliance can indirectly reduce particulate matter). They require either the use of low-sulfur fuels or the use of scrubbers to treat exhaust gases, enabling vessels to continue using high-sulfur fuels (i.e., Heavy Fuel Oil or HFO) while meeting the emission standards.

Although the IMO 2020 sulfur cap was adopted in 2016, it did not go into effect until 2020 (IMO, 2019). The most significant surge in scrubber installations occurred between 2018 and 2019, driven by the imminent compliance deadline. From 2018 to 2020, the total number of scrubbers installed increased by 6.3 times from 694 to 4,355. The data show that the majority (52%) of scrubbers are installed on vessels built after 2015, and nearly three-quarters (72.6%) of scrubbers on vessels in operation were installed on vessels built after 2010.

Types of scrubbers

Scrubber systems are categorized into three types: open-loop (OL), closed-loop (CL) and hybrid, which switch between OL and CL operation modes (Achten et al., 2024). In OL systems (81% of the scrubber fleet), SO_x molecules from exhaust gas react with a fine seawater mist to form sulfuric acid (DNV, 2024). Also captured from exhaust gas are other combustion (pyrogenic) and fuel-derived (petrogenic) compounds, including polycyclic aromatic hydrocarbons (PAHs), heavy metals such as vanadium and nickel, nitrates and nitrites (Achten et al., 2024; Lunde Hermansson, Hassellöv, et al., 2024). OL scrubber systems release this toxic discharge directly into the water at an estimated global total discharge volume of 10 billion cubic meters (m^3) per year, according to an International Council on Clean Transportation (ICCT) analysis (Osipova et al., 2021).

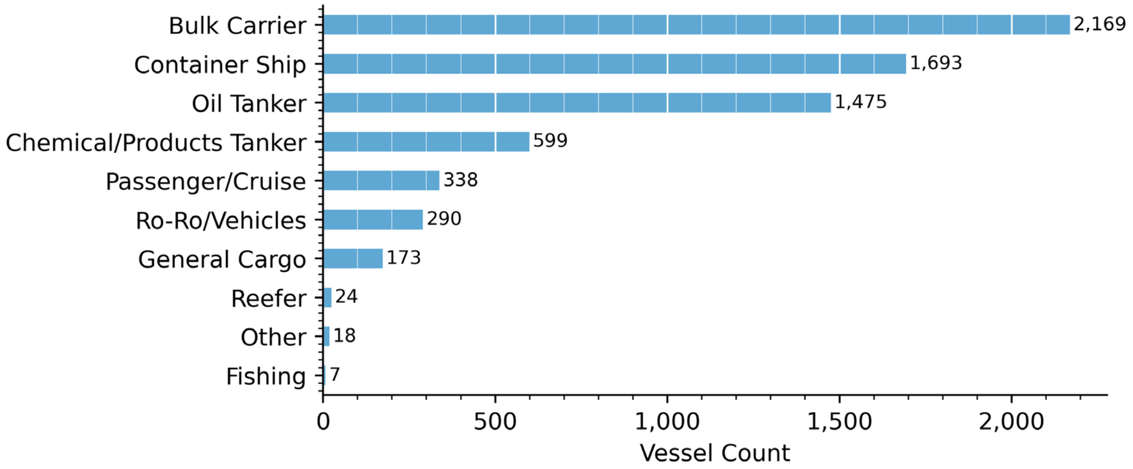
CL systems (1% of the scrubber fleet) function similarly, recirculating water plus a strong base additive (e.g., sodium hydroxide, or NaOH) to scavenge SO_x from exhaust gas (DNV, 2024; Lunde Hermansson, Hassellöv, et al., 2024). The resulting effluent is stored in a holding tank until port reception or open sea disposal is possible. Although released less frequently, the sludge produced by a CL system contains significantly higher pollutant concentrations than discharge from an OL system (Achten et al., 2024). OL scrubbers are the most common systems installed on ships because they are cheaper, dispose of their waste directly into the sea instead of at specified dumping sites and do not require chemical additives to boost alkalinity (Osipova et al., 2021).



Schematic representation of OL and CL scrubber systems. SOURCE: Achten et al., 2024.

Types of ships using scrubbers

Data from IHS Seaweb show 6,194 scrubbers installed and on operational vessels, with an additional 592 vessels under construction or noted in the orderbook (S&P Global, 2025). Bulk carriers lead the count of installs, with 2,169 scrubbers on record, followed by container ships (1,693) and oil tankers (1,475). Together these three vessel types account for over 85% of scrubbers installed.

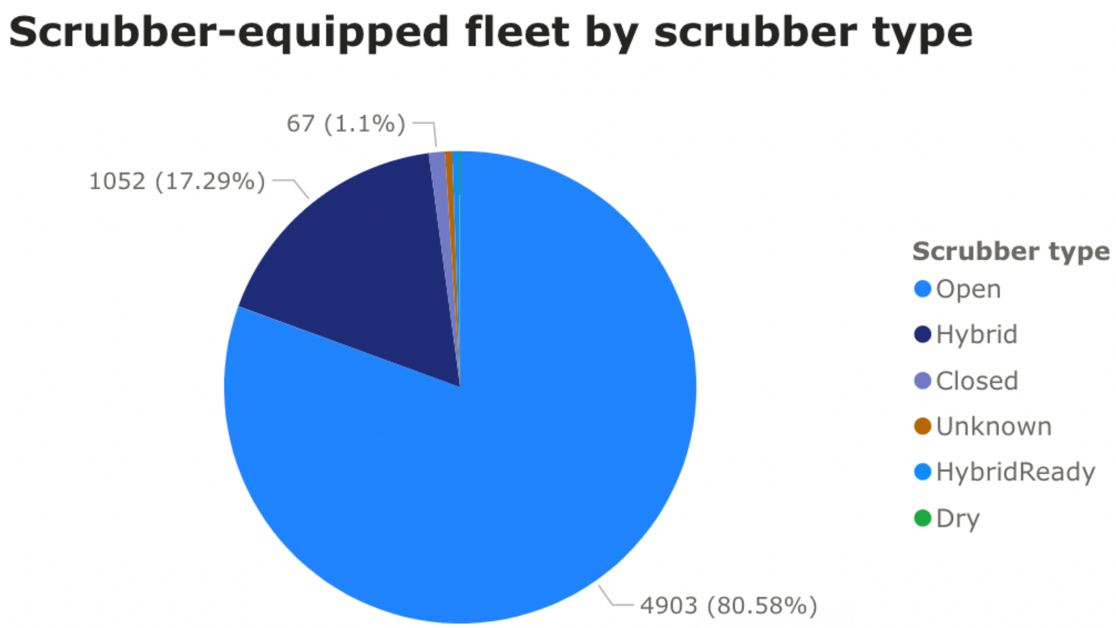


Number of scrubbers installed by vessel type. SOURCE: S&P Global, 2025.

The ranking order of the top three vessel types varies depending on whether deadweight tonnage (DWT) or power in kilowatts (kW) is considered. DWT is a measurement used in the shipping industry to express how much weight a ship can safely carry. It includes the weight of cargo, fuel, fresh water, ballast water, provisions, passengers and crew. In the context of ships, kW refers to the power output of the engines or other machinery. Power ratings in kilowatts help indicate the propulsion or electrical generation capacity of a vessel.

Bulk carriers lead DWT, followed by oil tankers and container ships. In terms of installed engine power, however, container ships take the lead, followed by bulk carriers and oil tankers. Under the kW ranking, passenger vessels rise higher in the order. These variations reflect the operational priorities of each vessel type. Bulk carriers and oil tankers typically prioritize carrying capacity over speed, whereas container ships are optimized for speed and efficiency (Miller, 2021).

Det Norske Veritas (DNV) Alternative Fuels Insight data, provided through the International Maritime Organization's (IMO) Future Fuels portal, shows that over 80% of the scrubbers installed are open-loop (IMO, 2025a), which use the alkaline properties of seawater to moderate the flow of acidifying particles into the exhaust plume and pass those emissions to the wastewater effluent.



More than 80% of scrubbers are open loop, 17% are hybrid, and 1% are closed loop.
SOURCE: IMO, 2025a.

Health risks and impacts of scrubber discharge

Scrubber wastewater is **highly toxic, significantly hotter and up to 100,000 times more acidic than the surrounding waters.** It contains various **pollutants, including heavy metals, polycyclic aromatic hydrocarbons (PAHs), nitrates and nitrites, sulfates and particulate matter.**

The presence of heavy metals and PAHs is especially concerning given their ability to persist in marine environments and accumulate within marine species. **Even at extremely low concentrations — just 0.001% — scrubber pollutants can harm marine life and disrupt biological processes** (Magnusson & Granberg, 2022). While research directly linking human health outcomes to scrubber effluent is limited, general studies on the harmful effects of PAHs, heavy metals and other scrubber-related contaminants offer valuable insights. Drawing on findings from peer-reviewed risk assessments, toxicological analyses and scrubber-specific academic research, this report synthesizes current research to assess the potential consequence of increasing scrubber use.

The major chemical components of scrubber effluent — **PAHs, heavy metals, nitrites and nitrates** — have all been shown to **negatively impact human health.** The IMO has identified three primary situations in which humans might be exposed to these contaminants from EGCS discharge:

1. **Recreational activities in the sea,** including dermal exposure from swimming, inhalation of chemicals partitioning into the air from the seawater and accidental swallowing of seawater.

2. **Oral consumption of seafood** in which discharge pollutants have bioaccumulated.

3. Contact with drinking water from a source contaminated by scrubber discharge (e.g., desalinated seawater), including dermal exposure from showering, inhalation of volatilized chemicals during shower or ingestion of drinking water (IMO, 2022).

A fourth indirect source of exposure to toxic scrubber effluent — one not mentioned by the IMO — **is marine ecosystem disruption.** Nitrates and nitrites from the breakdown of nitrogen oxides (NO_x) in scrubber exhaust enter the water column via scrubber discharge and cause **eutrophication, i.e., nutrient enrichment** (Ytreberg et al., 2021). Rapid growth of algae and other aquatic plants as a result of this increased nutrient availability can deplete oxygen levels and cause **mass die-offs of marine species.** For communities that subsist on marine organisms, such disruptions to the marine ecosystem can have **devastating effects on food availability.**

Atmospheric emissions from the continued combustion of HFO with a scrubber system represent a fifth point of human exposure. **The IMO also fails to acknowledge air pollution as a risk of scrubber use, despite the evidence of increased particulate matter, black carbon and PAH emissions.**

Polycyclic aromatic hydrocarbons (PAHs)

PAHs are widespread environmental contaminants primarily formed during the incomplete combustion of organic materials such as fossil fuels and wood (Abdel-Shafy & Mansour, 2016). Industrial activities comprise the dominant sources of PAHs, although natural processes such as volcanic eruptions and wildfires can also contribute to their presence in the environment. PAHs, characterized by two or more benzene or cyclopentadiene rings, are persistent and capable of traveling long distances (Wang et al., 2023). **They enter marine ecosystems via oil spills, surface runoff, atmospheric deposition and wastewater discharge — particularly from scrubber systems.** Chemical analyses indicate that scrubber PAHs are of petrogenic origin — that is, from unburnt fuel due to incomplete combustion in the ship engine (Achten et al., 2024; Du et al., 2022).

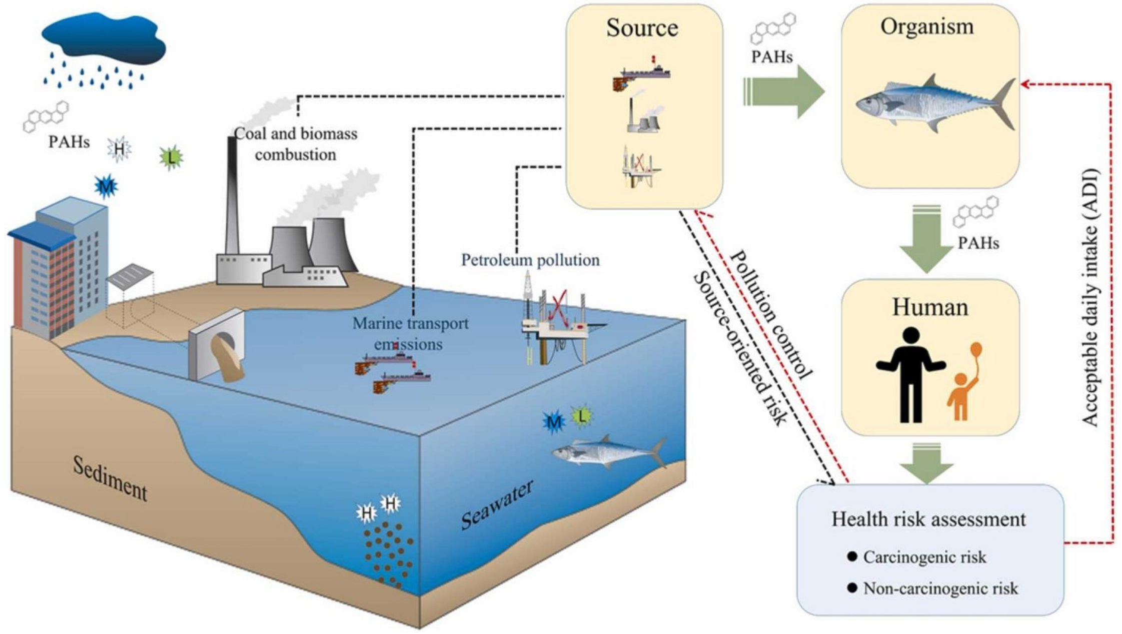
PAHs are hydrophobic compounds that readily accumulate in the fatty tissues of marine organisms, leading to their bioaccumulation in marine species (Abdel-Shafy & Mansour, 2016; Wang et al., 2023). Humans are exposed to PAHs from the ingestion of contaminated seafood. PAHs exposure has been linked to **DNA damage, endocrine disruption and developmental abnormalities.** Exposure in children has been associated with **asthma and disrupted cognitive development,** while adults may exhibit **decreased pulmonary function and lung deficiencies** (Ephraim-Emmanuel et al., 2023).

Different PAH compounds, based on their specific chemical structures, distribute and accumulate in different tissue types. How toxic a compound is depends on the target tissue's ability to metabolize it (Gauthier et al., 2014). High molecular-weight compounds (HMW PAHs) like benzo[a]pyrene exhibit greater toxicity than low molecular-weight PAHs (LMW PAHs) such as phenanthrene (Achten et al., 2024). Alkylated PAHs, particularly those with three to five rings, are even more toxic than their non-alkylated counterparts and contribute to the toxicity of oil pollution in aquatic ecosystems (Du et al., 2022; García-Gómez et al., 2023). While over 200 PAHs have been identified in the environment, many of which are carcinogenic, mutagenic or teratogenic, the U.S. Environmental Protection Agency (EPA) has classified only 16 non-alkylated PAHs as priority pollutants for regulation (Wang et al., 2023).

Several studies have tested PAH concentrations from scrubber effluent. In the most recent peer-reviewed analysis, Achten et al. (2024) assessed the concentrations, distribution and potential ecotoxicity of 71 PAHs, including the 16 EPA-listed compounds and their alkylated species. Water samples from hybrid ship scrubber systems (operating in both OL and CL modes) showed higher PAH levels in outlet versus inlet water — an indication that scrubbers, as opposed to alternate sources, resulted in an elevated presence of PAHs in the water column (Achten et al., 2024). This aligns with modeled outputs from Hermansson et al. (2023), who estimated that scrubbers accounted for an average of 95% of PAH levels in two European ports.

For all 71 PAHs, Achten et al. (2024) measured median concentrations of 73.8 micrograms per liter (µg/L) and 109.7 µg/L for OL and CL systems, respectively. Concentrations of all 71 PAHs were three to four times higher than concentrations of the 16 EPA PAHs alone, highlighting the importance of testing beyond the EPA 16 in order to capture all possible toxic compounds. Concentrations of the 16 EPA PAHs were within a similar range of concentrations found by Teuchies et al. (2020), Du et al. (2022), and Thor et al. (2021). HMW PAHs were detected more frequently in CL samples (61 detections) compared to OL samples (21 detections), likely due to the volatilization of LMW PAHs during recirculation of wastewater in CL systems (Achten et al., 2024). **High HMW PAH levels were indicative of increased toxicity in CL discharge.** This was confirmed by a Yeast Dioxin Screening (YDS): a toxicity test used to determine whether the PAHs found in scrubber discharge react similarly to dioxin, a known carcinogen. The YDS found 12 PAHs, including three EPA PAHs (pyrene, fluoranthene and phenanthrene) to be toxic. One of the compounds, **dibenzothiophene, has been classified as hazardous to aquatic life by the European Chemicals Agency** (Achten et al., 2024). The fact that CL discharge water showed higher toxicity in all bioassays is reflected in the research of Marin-Enriquez et al. (2023) and Thor et al. (2021). Importantly, scrubber inlet samples — water that has not yet gone through the scrubber system — demonstrated no dioxin-like effects.

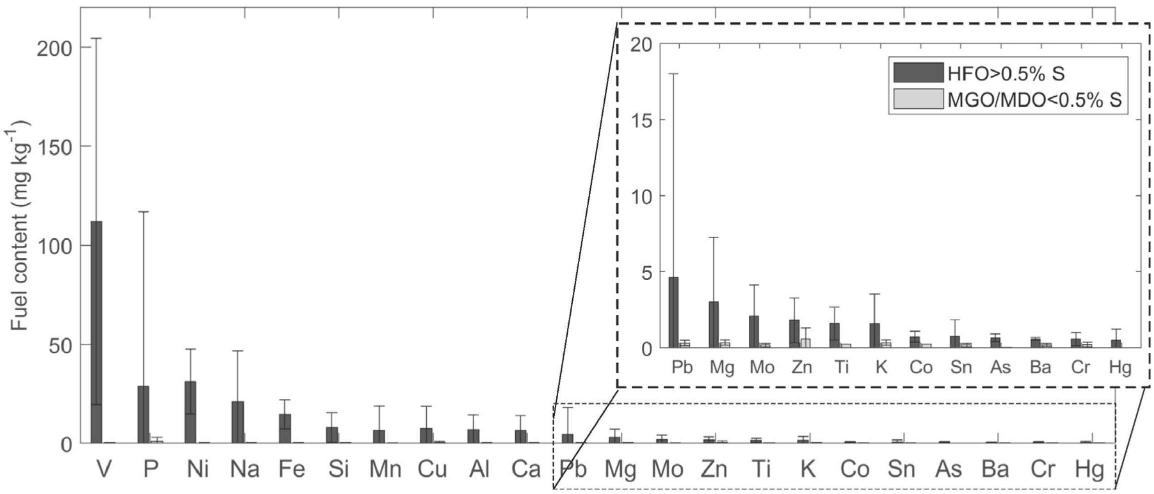
While not explicitly related to scrubber discharge, several studies explore the human health risks of exposure to PAHs accumulated in edible marine organisms. A recent study by Wang et al. (2023), for instance, analyzed PAH concentrations in 10 marine fish species from coastal areas of Guangdong, China. Researchers found that while the overall level of PAHs in fish could be categorized as “minimally polluted,” all species showed the capacity to bioaccumulate these hazardous compounds. **Carcinogenic risk assessments revealed that urban children faced the highest risk, with overall risk levels for certain populations classified as “cautionary.”** This highlights the heightened vulnerability of sensitive groups to dietary exposure to PAHs. The study identified three primary anthropogenic sources of PAHs in marine organisms: petroleum pollution, coal and biomass combustion and emissions from marine transport. Among these, **marine transport emissions — which could include scrubber discharge given the capture and release of atmospheric emissions by scrubber systems — accounted for the highest carcinogenic risk.** Notably, the actual daily intake of PAHs exceeded the acceptable daily intake for all population groups studied (Wang et al., 2023).



Potential pathways of PAHs from industrial sources (including marine transport emissions) to aquatic organisms to humans, within the risk assessment framework.
SOURCE: Wang et al., 2023.

Heavy metals

Unlike PAHs, which enter scrubber wastewater via unburned fuel, heavy metals originate from numerous sources in a vessel. Heavy metals such as vanadium (V) and nickel (Ni), and to a lesser degree copper (Cu), are often derived from residual fuel content (Teuchies et al., 2020). Anti-fouling paint and galvanic anodes used on vessel exteriors may increase zinc (Zn) and Cu levels in the water feeding the scrubber (i.e., inlet water) (Lunde Hermansson et al., 2021). Metals like Cu, Zn and chromium (Cr) can leach from piping, engine and scrubber system wear, as well as from increased corrosion caused by acidic scrubber water (Gadd, 2020). Other potential contributors include fuel additives and lubrication oils containing Zn (Lunde Hermansson et al., 2021; Teuchies et al., 2020). Arsenic (As), cadmium (Cd), iron (Fe), lead (Pb), mercury (Hg), selenium (Se) and thallium (Tl) have also been detected, though in trace amounts, in scrubber effluent (J. Faber et al., 2019; Lunde Hermansson et al., 2021). **Research points toward scrubbers introducing new metal sources compared to what may be released from a ship without a scrubber system, leading to an increased metal load in the environment** (Lunde Hermansson et al., 2021).



Comparison of average metal and element concentrations in heavy fuel oil (HFO) and marine gas oil/marine diesel oil (MGO/MDO), with error bars indicating standard deviation. SOURCE: Lunde Hermansson et al., 2021.

Ni and V are the most concentrated metals in scrubber discharge due to their presence in heavy fuel oil (Comer, 2020; Gadd, 2020). In a meta-analysis, **Comer et al. found average Ni and V levels to be about 40 times higher in CL systems** (V: 1500-19,700 µg/l; Ni: 410-3,470 µg/l) compared to OL systems (V: 140-308 µg/l; Ni: 40-73 µg/l). Conversely, **OL systems often have higher discharges of smaller amounts of metals like cadmium, mercury and lead** due to their more acidic discharge, which increases dissolved metal content (Comer, 2020).

Trace metals accumulate in the cells and tissue of marine organisms and are biomagnified through the trophic web to higher biotic levels (Endres et al., 2018). The bioavailability and toxicity of metals depend on various water characteristics, including pH, suspended matter concentration, dissolved organic carbon, hardness and mineral composition (M. Faber et al., 2021). While certain trace metals are essential to biological processes, others induce toxicity. Even essential metals become toxic at excessive concentrations. Due to their chemical and physical similarities, non-essential metals can mimic essential metals in aquatic species. These similarities allow non-essential metals to enter the body and disrupt biologically critical processes. Metals induce toxicity through several mechanisms, such as disrupting enzymatic functions, acting as redox catalysts in reactive oxygen species production, interfering with ion regulation and forming DNA and protein adducts (Gauthier et al., 2014).

To our knowledge, no human toxicological or health risk assessments of scrubber-related heavy metal releases have been conducted. Public health studies that examine the potential health impacts of exposure to heavy metals in aquatic systems do not include "source-apportionment" analyses

— that is, they do not identify the source of heavy metals entering marine ecosystems. That said, evidence is abundant regarding the toxicological mechanisms and health outcomes of heavy metal exposure more generally. Inhalation of vanadium compounds, for example, may lead to **respiratory issues, including airway irritation, coughing, wheezing and sore throat.** Animal studies have demonstrated that high concentrations can cause **lung lesions, inflammation and fibrosis.** Oral exposure in laboratory animals has been linked to gastrointestinal, hematological and developmental issues (ATSDR, 2012).

Nickel exposure is also associated with numerous health issues, including allergies, cardiovascular and kidney disorders, gastrointestinal diseases, lung fibrosis and cancers affecting the lungs and nasal passages. Although the precise mechanisms of nickel toxicity are not fully understood, evidence points to mitochondrial dysfunction and oxidative stress as significant contributors. Emerging studies indicate that **nickel exposure may lead to epigenetic changes, disrupting the genome and potentially playing a role in cancer-causing mechanisms** (Genchi et al., 2020).

Several studies point toward elevated health risks of metal-PAH mixtures from scrubber discharge. As Gauthier et al. (2014) underscore, **metal-PAH mixtures can result in "more-than-additive" co-toxicity, wherein the toxicity of the contaminant mixture exceeds the combined toxicity of its individual components.** The interaction between metals and PAHs affects cellular transport, alters metal bioavailability and inhibits detoxification processes (Gauthier et al., 2014). Gaps in current research on co-toxic mechanisms, however, lead to uncertainties about the human health impacts of exposure to substances such as metal-PAH mixtures from scrubber discharge.

Nitrates and nitrites

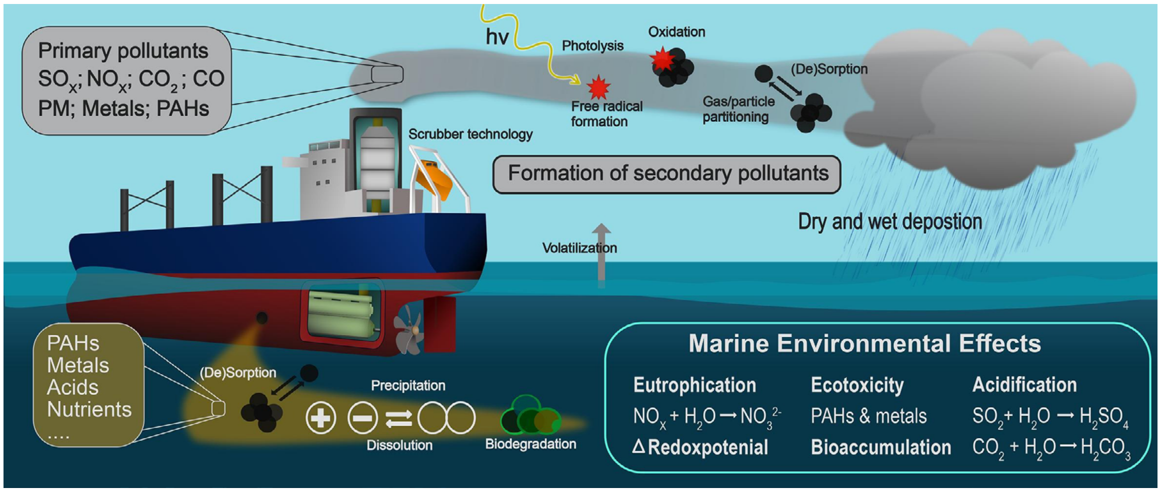
Scrubber discharge contains elevated nitrate and nitrite concentrations compared to seawater, primarily due to the dissolution of nitrogen oxides (NO_x) produced during combustion. Nitrates and nitrites are water-soluble forms of nitrogen that are readily taken up as nutrients by marine primary producers such as algae, leading to toxic algal blooms (Gadd, 2020). The presence of these compounds in scrubber discharge has raised concerns about potential environmental impacts, particularly in terms of nutrient loading and nutrient enrichment (Comer, 2020; Gadd, 2020; Ytreberg et al., 2021).

To mitigate concerns of eutrophication, IMO guidelines establish criteria for scrubber effluent wherein the discharge of nitrates should not exceed levels associated with a 12% removal of NO_x from the exhaust gases or 60 mg/L of nitrates normalized for an exhaust gas scrubber discharge rate of 45 tons/MWh, depending on which measurement is greater (Magnusson et al., 2018). The IMO guidelines focus solely on nitrates despite the presence of both nitrates and nitrites in the discharge, both of which impact marine ecosystems.

Studies on scrubber discharge have shown that nitrate concentrations in CL systems typically fall within the IMO guidelines, with median concentrations around 125,000 mg/MWh (Comer, 2020). Data for nitrates/nitrites in OL discharges remain limited, but **evidence suggests that CL concentrations are higher than OL** (Comer, 2020; Marin-Enriquez et al., 2023). That said, elevated nitrogen levels in scrubber discharge water have been linked to **increased biovolume in microplankton species,** suggesting potential ecological consequences in certain marine environments (Ytreberg et al., 2021).

Scrubbers also contaminate the air

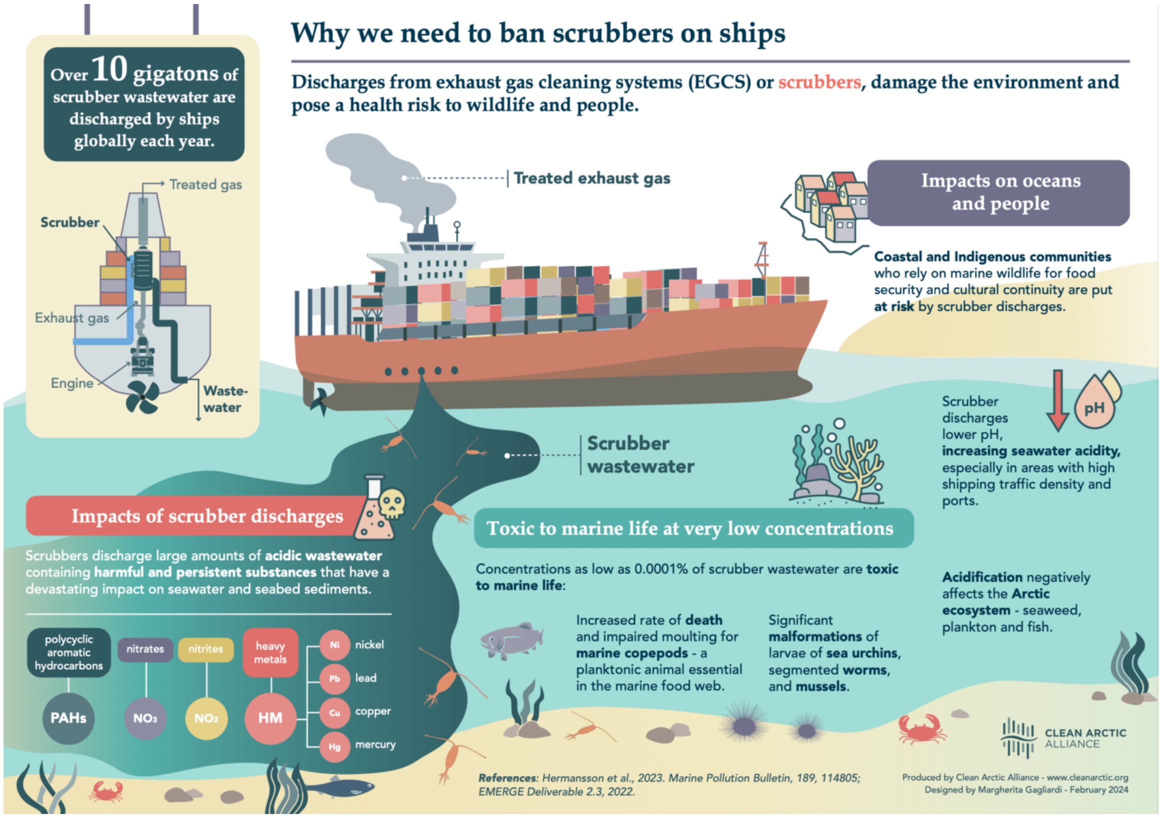
In addition to contaminating the water, ships that continue to burn HFO with a scrubber system emit more air pollutants than ships that use low-sulfur fuel alternatives. **While scrubbers may effectively reduce SO_x emissions, they are less efficient at removing other toxic compounds.** According to Comer (2022), **ships using HFO with scrubbers emit 70% more particulate matter and up to 4.5 times more black carbon** compared to ships running on marine gas oil (MGO). Lunde Hermansson, Hassellöv, et al. (2024) emphasize that even with scrubbers in operation, considerable amounts of PAHs are still emitted into the atmosphere. Scrubbers also incentivize the continued use of HFO in Sulfur Emission Control Areas (SECAs), **exacerbating air quality concerns in areas designated by the IMO to be safeguarded from such impacts** (Lunde Hermansson, Hassellöv, et al., 2024).



Emissions from ship smokestacks and scrubber discharge at the ocean-air boundary, including potential reaction pathways, transport mechanisms and impacts on the marine environment. SOURCE: Lunde Hermansson et al., 2021.

Community health impacts

Marine ecosystem disruption from scrubber use on maritime vessels raises significant health and environmental concerns for Indigenous and subsistence fishing communities, particularly in sensitive Arctic regions. As mentioned, toxic algal blooms linked to nutrient overload in marine environments can devastate marine populations, threatening the resilience of communities that rely on seafood. Elevated PAH and heavy metal loads in marine organisms also put seafood-dependent communities at higher risk of health complications (Clean Arctic Alliance, 2022).



Discharges from exhaust gas cleaning systems (EGCS) or scrubbers, damage the environment and pose a health risk to wildlife and people.

Over 10 gigatons of scrubber wastewater are discharged by ships globally each year.

Coastal and Indigenous communities who rely on marine wildlife for food security and cultural continuity are put **at risk** by scrubber discharges.

Scrubber discharges lower pH, **increasing seawater acidity,** especially in areas with high shipping traffic density and ports.

Scrubbers discharge large amounts of **acidic wastewater** containing **harmful and persistent substances** that have a devastating impact on seawater and seabed sediments.

Concentrations as low as 0.0001% of scrubber wastewater are **toxic to marine life**:

Increased rate of **death** and impaired moulting for **marine copepods** - a planktonic animal essential in the marine food web.

Significant **malformations** of larvae of **sea urchins,** segmented **worms,** and **mussels.**

Acidification negatively affects the **Arctic ecosystem** - seaweed, plankton and fish.

References: Hermansson et al., 2023. Marine Pollution Bulletin, 189, 114805; EMERGE Deliverable 2.3, 2022.

Produced by Clean Arctic Alliance - www.cleanarctic.org
Designed by Margherita Gagliardi - February 2024

Schematic illustration of chemicals released from scrubber systems and their potential impacts on marine ecosystems. SOURCE: Clean Arctic Alliance, 2024.

The continued reliance of the shipping industry on HFO poses further environmental and health risks to coastal and port communities. Ships that burn HFO, even with a scrubber, release black carbon (BC) emissions (Kuittinen et al., 2024). Fine BC particles can enter the bloodstream and affect vital organs, contributing to respiratory diseases and premature death (Clean Arctic Alliance, 2022). Given these risks, the Clean Arctic Alliance has called for an IMO ban on scrubber discharge in Arctic waters to protect marine biodiversity and the communities that depend on marine resources.

Future considerations

While critical knowledge gaps remain, the significance of our existing understanding of scrubber pollution cannot be overstated. That said, gaps highlight the need for a deeper examination of emerging evidence, particularly regarding the complex interactions and compounded risks associated with scrubber discharge. For instance, studies suggest that the toxicity of scrubber discharge as a mixture may be higher than the sum of its components, underlining the importance of evaluating discharges holistically rather than focusing on individual pollutants (Achten et al., 2024;

Gauthier et al., 2014; Koski et al., 2017; Lunde Hermansson, Hassellöv, et al., 2024). Also understudied is evidence that the acidic nature of scrubber discharge water may increase metal bioavailability and remobilize metals from sediments, further exacerbating ecological and human harm (Teuchies et al., 2020). Expanding risk assessment frameworks to include the synergistic effects of multiple pollutants from scrubber use is crucial for a comprehensive understanding of their impact on human and environmental health.

The economics of scrubbers

Are scrubber bans justified, or too costly to industry?

Pacific Environment commissioned Energy and Environmental Research Associates, LLC (ERRA) to undertake an analysis of scrubber economics. EERA applied its Regulatory Assessment of Technology and Emissions from Supply Chains (RATES) model to describe the economic costs of using scrubbers. ***Source note:*** *Charts and graphs in this section were provided by EERA unless otherwise noted.*

The analysis found that the short payback period indicates that the return on scrubber investment is quickly realized, and most operators have already recouped their initial costs. **Ninety-five percent of ships recovered the installation cost within five years, possibly even as quickly as one year for vessels with frequent operations using scrubbers.**

While scrubbers may remain more cost-effective than distillate fuels, the discharge of scrubber waste causes significant harm to marine ecosystems, which shifts the economic burden to other stakeholders, with damages quantified in the millions. This analysis suggests that **shipowners would not face significant financial losses on capital expenses if scrubbers were banned.** If scrubbers were phased out, the bulk of the financial burden from the initial capital expense would have already been alleviated within that time frame.

Payback periods decrease with increasing engine size. Larger vessels have shorter payback periods due to higher fuel consumption and lower capital expenditures per kW.

Findings align with other studies, showing that the majority of ships equipped with scrubbers have recovered their installation costs, or would do so during a phase-out period, making scrubber removal financially viable for most operators.

Model parameters and inputs

Using the input parameters shown below, EERA's RATES model provided estimates of the cumulative hourly costs. The following figure shows cumulative cost trajectories over time for open and closed-loop scrubbers on large vessels. Capital expenditure (CAPEX) costs are assumed to be incurred in hour zero, and operating expenditures (OPEX) and fuel costs are ongoing and increase monotonically. Where the curves intersect shows the point in time at which the costs of scrubbers fall below marine diesel oil (MDO) and the initial capital costs are recouped relative to simply using distillate fuels. After the point of intersection the scrubber scenarios are lower cost, and the operator can theoretically extract a higher profit due to lower fuel costs. Results are presented in terms of operating hours, i.e., hours at sea, with operating days noted, and not total days of vessel life, which can also include periods at berth, under maintenance, etc. when scrubbers are not in use.

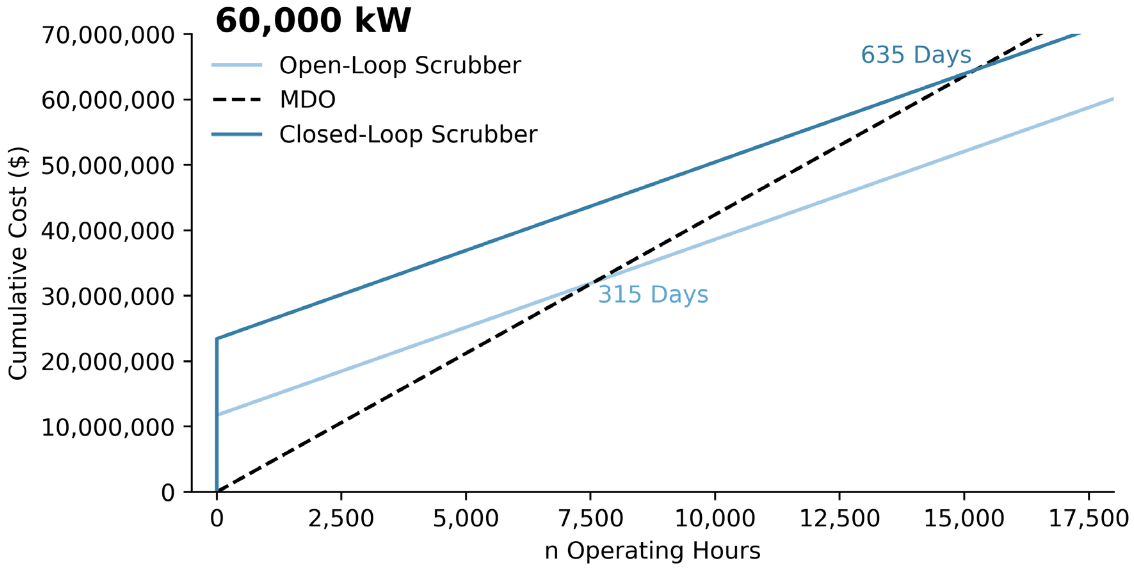
Input parameters for RATES modeling of total costs and breakeven periods:

Name	Parameter	Source
Speed	Container ship: 16.3 kts Tanker: 11.4 kts General Cargo: 11.4 kts Fishing: 7.5 kts	Fourth IMO GHG Study, Table 35.
Design Speed	Container ship: 23.9 kts Tanker: 15.1 kts General Cargo: 14.0 kts Fishing: 11.7 kts	Fourth IMO GHG Study, Table 35.
BSFC	Uniform distribution 175 to 195 g/kWh	Fourth IMO GHG Study
Scrubber Cost Open-Loop CAPEX ($/kW)	Triangular distribution [low, mode, high] Small (< MW): 358, 731, 1,618 Medium (6 - 15 MW): 220, 320, 641 Large (> 15 MW): 54, 193, 350	Lunde Hermansson, Hassellöv, et al. (2024), adjusted to 2024 USD
Scrubber Cost Closed-Loop CAPEX ($/kW)	Triangular distribution [low, mode, high] Small (< MW): 842, 1,371, 2,038 Medium (6 - 15 MW): 310, 447, 512 Large (> 15 MW): 162, 445, 548	Lunde Hermansson, Hassellöv, et al. (2024), adjusted to 2024 USD
Scrubber Cost OPEX ($/kW)	Triangular distribution [low, mode, high] Open-Loop: 0.6, 0.8, 0.9 Closed-Loop: 8.9, 11, 12.8	Lunde Hermansson, Hassellöv, et al. (2024)
Parasitic Load (%)	Triangular distribution [low, mode, high] 0, 1, 3	Carr and Corbett (2015)
Fuel Price ($/MT)	Triangular distribution [low, mode, high] HFO: 523.11, 550.66, 584.90 ΔMGO: 257.49, 304.02, 402.92	EERA Analysis of Ship and Bunker for 2024

Results: Scrubber breakeven period

The capital expenditure (CAPEX) costs are pictured by the vertical line at time T = 0. Operating costs (fuel + system operation) increase linearly from there. Open- and closed-loop scrubbers are both assumed to operate using HFO as the base fuel and MDO as the alternate Emission Control Area (ECA)-compliant fuel. The slope of the curve is flatter for the scrubber scenarios, reflecting lower daily operating costs due to lower price HFO plus OPEX. The curve is steeper for MDO, indicating higher daily operating costs due to the higher price of MDO fuels. The MDO and scrubber lines intersect at the point at which modeled costs are equivalent, the so-called breakeven point, or return period. For a 60,000 kW engine, we estimate the open-loop breakeven period to be around 315 days of operation and 635 days for a closed-loop system. The return period defines the time taken to recoup the initial capital investment, relative to MDO consumption. To the right of those intersection points, where the MDO line is above the scrubber line, the cumulative costs of operating the vessel using the scrubber system are lower than operating on MDO.

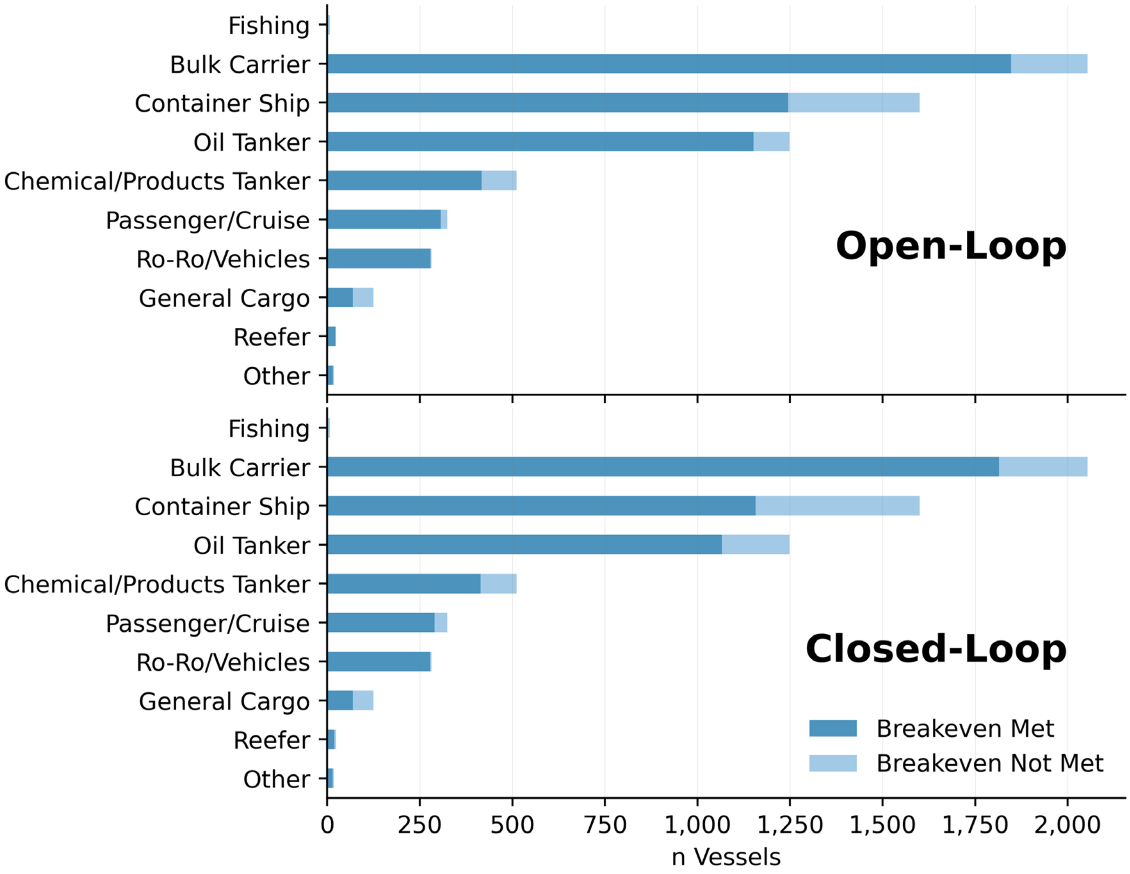
RATES cost curves for open- and closed-loop scrubbers relative to MDO (60,000 kW vessel) are shown in this graph:



Using the RATES model we also calculated the breakeven period for each operational vessel in the dataset. Because it is not known from the IHS data whether the vessel has an open, closed or hybrid-type system, we calculate results for both open- and closed-loop systems, to provide the bounding conditions corresponding to the shortest and longest breakeven periods.

As noted, only around 1.1% of vessels have closed-loop scrubbers installed, and so breakeven periods are likely to be much closer to the open-loop estimates.

This graph shows the number of vessels that have reached breakeven for open-loop (top) and closed-loop (bottom) systems:



As scrubber install date is not available from IHS, we conservatively assume for vessels built prior to 2020 that the install date was Jan. 1, 2020. For vessels with scrubbers built after the IMO 2020 regulation went into effect, we assume that the scrubber install date is the same as the vessel built date. As expected, the breakeven periods are longer for closed-loop systems due to higher initial CAPEX and ongoing OPEX costs, but that does not change the breakeven rates dramatically. If we assume all systems are closed-loop, with the highest cost and longest breakeven time, **nearly 75% of all container ships have reached their estimated breakeven period, and nearly all bulk carrier (88.4%), oil tanker (85.3%), passenger cruise (89.5%) and ro-ro (98.6%) vessels have also reached estimated breakeven.**

The table below shows summary statistics for the modeled return or breakeven periods in the scrubber vessel fleet. The return period is the length of time for the vessel to recoup its capital investment relative to MDO. Statistics provided include the mean and standard deviation (Std.), median value and the minimum and maximum values returned by the model. Fishing vessels show the longest return periods (time to recoup initial investment), as those are typically the smallest vessels. **Container ships, chemical/products tankers, bulk carriers, oil tankers, passenger/cruise, reefers and ro-ros all show an average return period of less than 550 days of operation.**

This table presents summary statistics of breakeven periods (days) for vessels with open-loop scrubbers.*

	Count	Mean	Std.	Min.	Median	Max.
Bulk Carrier	2,053	463	246	264	555	7,300
Chemical/Products Tanker	512	548	191	242	486	1,181
Container Ship	1,600	512	169	390	438	1,947
Fishing	7	1,797	701	1,043	2,312	2,408
General Cargo	125	749	331	236	513	1,234
Oil Tanker	1,249	447	256	292	329	7,300
Other	18	274	141	137	268	648
Passenger/ Cruise	324	372	149	319	348	1,650
Reefer	24	216	165	129	135	637
Ro-Ro/ Vehicles**	282	337	129	216	241	1,113

* **Key for Statistical Measures:** These descriptions elucidate key statistical terms in the table above:
Mean: The average value
Standard Deviation (Std.): The measure of how spread out the values are from the mean
Minimum (min.): The smallest observed value in the sample
Median (50%): The middle value, dividing the data in half
Maximum (max.): The largest value observed in the sample

** **Roll-on/Roll-off vessels are designed to carry wheeled cargo, such as cars and trucks, that can be driven on and off the ship via ramps**

Note that these model estimates incorporate a set of assumptions (laid out above in Model Parameters and Inputs) that could affect the individual vessel return periods. Scrubber CAPEX and OPEX costs are not known for every vessel and so we make assumptions based on the best available CAPEX and OPEX estimates in the literature. Furthermore, fuel prices are variable. While we have been careful to document the assumed prices, if the price delta between MDO and HFO were to grow or shrink, we would expect to see return periods behave inversely, by shortening or lengthening, respectively. This analysis incorporates variation in the data input parameters to the model, but uses measures of central tendency to report representative results. We also assume a constant operating speed for each vessel type based on average data reported in the IMO's 4th Greenhouse Gas Study (GHG4). In reality, vessel speeds adjust frequently in operation and may not be directly aligned with fleetwide averages. There are also a variety of factors that contribute to variation in capital costs, many of which are unobservable due to company-held information.

With these caveats considered, the results from the RATES modeling indicate that return periods are generally on the order of two to five years operating, and are in good agreement with peer-reviewed results from Lunde Hermansson, Hassellöv, et al. (2024), and others discussed below.

Scrubbers have been financially advantageous for shipowners compared to using more expensive fuels to meet compliance to date. By the end of 2022, more than 50% of ships equipped with scrubbers had recovered their installation costs and over 95% of ships with the open-loop scrubber systems broke even within five years of installation. However, the discharge of scrubber waste has caused significant environmental damage, particularly in the Baltic Sea where the cost of this harm was estimated at over $707 million between 2014 and 2022 (approximately $88.4 million per year), assuming $1.04 USD/EUR (Lunde Hermansson, Hassellöv, et al., 2024).

This highlights the trade-off between economic savings for shipowners and the environmental costs of their operations. There is support for limiting the use of scrubbers, although industry representatives have expressed concerns about economic uncertainty facing the industry and have pointed out that companies have made significant investments in EGCS technology in good faith, following the provisions of MARPOL Annex VI (IMO, 2023).

Ship & Bunker's economic insights in February 2024 estimated that scrubber installation costs ranged from $2 to 8 million, with two to three weeks of downtime to retrofit. Fleet-wide investments reported by Eagle

Bulk, estimated at $100 million, had an expected payback period of two years, which is aligned with our breakeven estimates (Glander International Bunkering, 2024). A report from BRS Shipbrokers published in November 2024 states that the cost of installing a scrubber on a capesize vessel (i.e., a large bulk carrier typically ranging from 150,000-200,000 DWT) was approximately $1.3 million in 2020, with an installation time of four to six weeks, but that installation costs have since decreased to around $800,000, making scrubbers even more cost-effective in the short-term compared to low-sulfur fuels (Chambers, 2024).

However, the alternative fuels market now also presents another layer of consideration, as they offer the potential to meet regulatory measures and align with IMO and national climate targets. Under emissions fees like the European Union's Emissions Trading System (EU ETS), the long-term costs of scrubbers may rise as they do not mitigate greenhouse gas emissions, whereas alternative fuels with lower carbon footprints may become increasingly competitive. These factors contribute to a more comprehensive cost analysis, factoring in both economic savings and environmental goals.

Some manufacturers are working to upgrade scrubber systems to include carbon capture features, which could extend the lifespan of scrubbers as a viable option for shipowners (Wärtsilä Corporation, 2023). While announcements have been made regarding these developments, these technologies are primarily in the pilot/demonstration phase and have yet to be commercialized at scale. If new carbon capture scrubber systems are successfully developed, existing scrubbers would likely need to be replaced or retrofitted to realize the benefits. By incorporating carbon capture systems, these upgraded scrubbers could not only remove SO_x from exhaust gases but also capture CO_2 emissions, helping to reduce greenhouse gas emissions, extending compliance and lowering paid carbon levies. However, carbon capture systems could be expensive, have significant rate requirements and may not achieve the industry-claimed reduction rates (Ballout et al., 2024; IEEFA, n.d.).

Fuel availability and price

Results: Scrubber breakeven period

This section explores **how the introduction of changes in regulation by the IMO in 2020 impacted fuel usage patterns** and highlights price differences between HFO, marine gas oil (MGO) and very low sulfur fuel oil (VLSFO).

MGO is typically composed of lighter fractions than other marine fuels like HFO, making it cleaner and more refined. It is often used in situations where emissions need to be minimized, such as in ports or Emission Control Areas. MGO complies with recent regulations aimed at reducing sulfur emissions from ships, as it has a lower sulfur content compared to heavier marine fuels. VLSFO is a type of marine fuel oil designed to meet IMO low sulfur requirements and is typically a blend that includes residual oil; the blends must meet ISO 8217 with a sulfur content no greater than 0.5%.

Prior to IMO 2020, the U.S. Energy Information Administration (EIA) had forecasted a drastic reduction in high sulfur fuel oil (HSFO) consumption, from 58% in 2019 to 3% in 2020, and anticipated only minimal uptake of scrubbers. HSFO and HFO are often used interchangeably, as both refer to types of residual fuel oils. HSFO is a sub-category of HFO, specifically identified by its higher sulfur levels.

EIA forecasted that the most significant price impacts would occur in 2020, with shifts in petroleum product pricing beginning as early as mid-2019. They projected that HSFO, which accounted for 58% of U.S. ocean-going bunker fuel consumption in 2019, would drop sharply to 3% in 2020. Moreover, they anticipated scrubber installations would be minimal and only drive a partial recovery in HSFO consumption (EIA, 2019).

Before the implementation of IMO 2020, the shipping and bunker industries expressed concerns about the potential for the regulations to disrupt fuel markets. The reduction in allowable sulfur content from 3.5% to 0.5% raised fears of uncertain supply, shortages and price spikes for compliant fuels (EIA, 2019). Other compliance pathways, such as scrubber uptake, were said to introduce further uncertainty by potentially sustaining high-sulfur fuel oil (HSFO) demand, adding complexity to the decisions faced by refineries. Given that the maritime sector represents a substantial portion of global fuel oil demand, stakeholders scrutinized the refiners' ability to meet the surge in demand for low-sulfur fuels without ripple effects in the broader energy markets (EIA, 2018; Sand, 2019; Wood Mackenzie, 2019).

IMO introduced the Fuel Oil Non-Availability Report (FONAR) to help ease concerns over non-compliance with the 2020 sulfur regulations, designed to reduce the risk of penalties, as long as operators can provide evidence of their efforts to obtain compliance. When ships are unable to obtain a compliant fuel for circumstances beyond their control, such as fuel shortages, the FONAR provides documentation to explain the efforts and allows them to continue their voyage without the immediate threat of fines (DNV, 2019).

In the first quarter of 2020, Breakbulk, an industry news group, engaged stakeholders to assess the early impact of IMO 2020. Companies reported concerns over fluctuating bunker adjustment factors and difficulties quantifying the sulfur cap's cost impact. Carriers, facing these costs, felt justified in passing them on to customers, though it remained uncertain if they could fully recover or profit. This uncertainty, combined with challenges like limited access to loans, raised concerns about the industry's financial health. While some companies had planned proactively, stakeholders noted that the full impact would only become clear as the market adjusted over time (Fields and Burrows, 2020).

In practice, the implementation of IMO 2020 went very smoothly, largely due to the long lead times for the regulation to go into effect and adequate preparation by stakeholders, including fuel producers. In 2020, the first year of the new regulations, "just 55 cases of 0.50% compliant fuel being unavailable had been reported" (IMO, 2021). Fuel producers were able to ramp up 0.50% fuel production to meet demand at tolerable prices, and global markets absorbed the shift without major effect. Forbes reported that while energy costs are a significant part of shipping expenses, the market adjusted, and the availability of multiple compliance options, including scrubbers, avoided disruptions (Blackmon, 2020).

Thus, contrary to fears, the market was able to adjust to IMO 2020 and avoid disruptions.

It is beyond the scope of this work to definitively determine whether or not there would be enough fuel available to accommodate up to around 116 million metric tonnes of additional distillate fuel if scrubbers were subject to additional regional or international bans. The distillate demand from the shipping sector would more than double, and the additional induced demand would be equivalent to around 8-9% of current global distillate production for all uses. Meeting this induced demand would require major effort and investment. However, with adequate lead times, planning and preparation, the industry was able to meet the significant demands of IMO 2020, demonstrating that they were able to produce sufficient fuel to meet demand at economically viable prices.

Uncertainty about whether there would be an adequate supply of distillate fuels to accommodate demand if scrubbers were banned has been suggested as a reason to continue the status quo. However, the industry's success adapting to the IMO 2020 regulations indicates that markets and suppliers can adjust as needed in response to changing conditions when given adequate lead times and preparation.

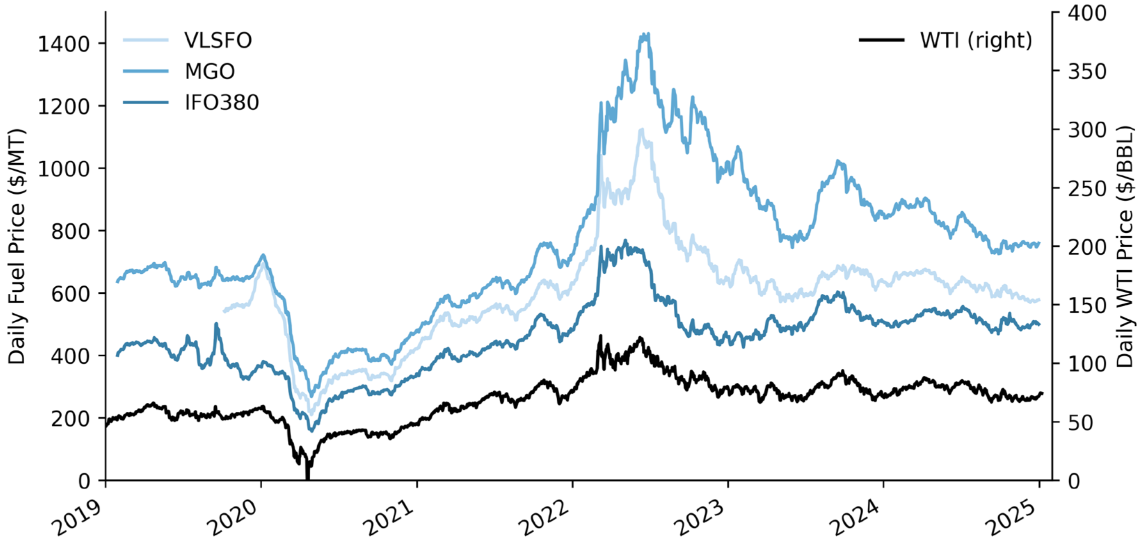
Price stability and volatility

Marine fuel prices have remained relatively stable for the past 18 months, consistent with recent stability in Brent crude trading prices (EIA, 2025). MGO and VLSFO are both sold at a premium over HFO (IFO380) (USDA, 2025).

The weekly mean price for HFO over the past 18 months is $549.9 per metric ton (MT) and the difference between MGO versus HFO is $316.7 per MT. The weekly mean price difference for VLSFO over that period was $121.5 per MT. On average for that period, MGO is 1.58 times and VLSFO is 1.22 times the HFO price.

In 2022, the bunker industry experienced record prices and margins as the **Russia-Ukraine War fueled global oil supply concerns.** In response, nations, shipping and bunker companies announced plans to reduce reliance on Russian business. HSFO demand rose during the year, accompanied by rising interest in scrubber technology, as price trends widened the gap between HSFO and VLSFO (Jordan, 2023). Historically, high fuel prices have not interfered with trade or increased the cost of goods significantly for consumers.

This graph shows global average bunker prices for VLSFO, MGO, IFO380 (HFO) and West Texas Intermediate (WTI) Crude over the last six years.



Onshore reception capacity for scrubber waste

This section examines the capacity of ports worldwide to handle scrubber waste, exploring the infrastructure and facilities available for receiving scrubber residues. It highlights variations in disposal capabilities across different regions and the challenges posed by limited reception facilities in certain areas.

Questions have been raised about whether onshore capacity would be adequate to receive waste from closed-loop and hybrid scrubbers, in the event that open-loop scrubbers were banned and hybrid scrubbers were limited to operating in closed-loop mode. Data is insufficient and incomplete, but ports and terminals are required to provide reception and disposal services for "scrubber sludge," the discharge product of closed-loop EGCS.

Key findings of onshore reception

- **IMO mandates that ports provide facilities and arrange for disposal services to address waste management from scrubber use. Remote or less industrialized ports may be exempt.**

- **707 ports/terminals report their scrubber waste reception capabilities in the Global Integrated Shipping Information System (GISIS) database, but many ports, including U.S. ports, do not voluntarily provide such information.**

- **The U.S. Coast Guard (USCG) classifies scrubber residues as non-hazardous waste, managing them under oily residue facilities, suggesting the U.S. may not treat scrubber residues as a distinct waste category.**

- **135 U.S. ports report oily residues reception, including facilities in Alaska and Hawaii.**

- **Only five (non-U.S.) ports have been reported by stakeholders as unable to handle scrubber sludge since 2018, suggesting major U.S. ports likely provide adequate facilities.**

The sludge byproduct must be collected on board and disposed of at appropriate reception facilities, which ports and terminals are required to provide under MARPOL Annex VI, Regulation 17, entered into force on May 19, 2005. These disposal mandates were developed alongside the implementation of ECAs to support stricter air pollution regulations, recognizing the need to address the waste management challenges associated with the increased use of scrubbers, an approved method to comply with SO_x emission limits (ABS, 2018).

Ships must contact the port to arrange disposal, with costs varying for liquid versus solid sludge. Scrubber residues cannot be incinerated onboard and must be disposed of ashore per MARPOL Annex VI Regulation 16. By 2015, all major ports were expected to have adequate reception facilities, but shipowners were advised to confirm availability at trading ports to avoid deviations. If facilities were found to be inadequate, ship owners were required to notify the IMO (ABS, 2018).

According to MARPOL Regulation 17, ports and terminals are required to provide reception services, and if they don't, they must inform the IMO and stakeholders through the Global Integrated Shipping Information System (GISIS) website (IMO, 2025b). EERA's evaluation of the GISIS database indicates insufficient enforcement of public reporting. Compliance may instead be achieved through direct, private reporting to the IMO, which is not accessible to non-IMO stakeholders or vessel operators. To facilitate compliance with the IMO requirement in the United States, the U.S. Coast Guard (USCG) published Navigation and Vessel Inspection Circular (NVIC) No. 03-04 to inform the shipping industry of the interim procedures the U.S. adopted for U.S. flag vessels and foreign vessels operating in U.S. waters (U.S. Coast Guard, 2004).

Certain U.S. ports, particularly those in remote or less industrialized regions, may be exempt from receiving scrubber waste under Regulation 17. This could include ports in Alaska and Hawaii, as well as other smaller or isolated locations such as Caribbean islands, the Pacific islands and rural ports along the U.S. mainland. The IMO recognizes reasonable limitations to receiving these wastes, as is communicated by the Australian Maritime Safety Authority:

Regulation 17.2 recognises that reception facilities for exhaust gas cleaning system residues and ozone depleting substances may be impossible in some ports. If a particular port or terminal of a Party is remotely located from, or lacking in, the industrial infrastructure necessary to manage and process those substances referred to in Regulation 17.1 and therefore cannot accept such substances, then the Party shall inform the Organization of any such port or terminal so that this information may be circulated to all Parties and Member States of the Organization for their information and any appropriate action (AMSA, 2014).

According to the GISIS database, 707 port/terminal facilities report on their capability to receive "Exhaust gas-cleaning residues" (Annex VI). It is clear that this is the number of ports that are voluntarily sharing their compliance and not necessarily the entirety of ports that provide these services. When ports voluntarily report, they can (but are not required to) provide details such as: type of facility (ship-to-truck, -barge, -shore), minimum/maximum quantity (m^3), maximum discharge rate (m^3/h), availability (times), minimum prior notice required (hours), service provided details and other additional information. Most shipowners prefer to discharge scrubber sludge ship-to-shore rather than ship-to-truck, but ports must be equipped to handle it (Alfa Laval, 2019).

For the United States, no ports have voluntarily reported in the GISIS system about their scrubber waste reception. Thereby, there is no information about their sludge reception capacities. Moreover, for all other types of waste, it appears that California ports — such as the Ports of Long Beach, Los Angeles, Oakland, San Diego, San Francisco, etc. — have not voluntarily updated their waste facilities in the GISIS public system since 2014.

Disposal of Noxious Liquid Substances (NLS), Ozone-Depleting Substances (ODS) and EGCS residues is mandated under the same IMO framework, requiring specialized facilities for each type of waste. While the ODS/EGCS disposal process uses a shared Certificate of Adequacy (COA) application (Form CG-5401D) to report reception capabilities and identify EPA-authorized facilities, separate reporting boxes for ODS and EGCS residues highlight the unique treatment needs of each (U.S. Coast Guard, 2022). Though licenses are not required to issue a COA, collecting this data supports inspectors in verifying compliance with Annex VI and applicable environmental regulations.

The USCG states that scrubber residues are generally treated as non-hazardous waste unless testing indicates otherwise, and can be collected by facilities handling oily residues from bunker oil combustion (U.S. Coast Guard, 2024). Considering this detail, an additional look at the GISIS system for “Oily residues (sludge)” waste reception identifies 407 U.S. facilities that belong to approximately 135 ports.

Exploring the “Reported cases of alleged inadequacy” of shipowners sharing an inability to dispose of their EGCS waste at a respective port, only five cases regarding lack of capability to receive scrubber discharge were reported after March 2018. (This does not appear to include the port/terminals’ mandatory self-reporting — only violations noted by other stakeholders.) These ports included San Lorenzo, Honduras; San Jose, Guatemala; Itaguai, Brazil; Sangkulirang Kalimantan, Indonesia; and Zhoushan, China. Thus, it can be inferred until otherwise disputed that major U.S. ports are providing adequate disposal facilities for these wastes.

International **developments**

IMO leaves it up to Member States to regulate toxic scrubber discharge

The issue of how to deal with discharge of scrubber wastewater into the marine environment has been on the agenda of the IMO for years, and discussions are ongoing as of the date of this report. The Marine Environment Protection Committee’s (MEPC) **Pollution Prevention and Response Subcommittee (PPR 12),** meeting in London Jan. 27-31, 2025, will again discuss how to evaluate and harmonize its rules and guidance on scrubber discharges.

Currently, the IMO has adopted voluntary “guidance” to industry concerning scrubber use. Updated Guidelines for Exhaust Gas Cleaning Systems (MEPC.34(77)) were adopted in 2021, and Guidelines for Risk and Impact Assessments of the Discharge Water from Exhaust Gas Cleaning Systems (MEPC.1/Circ.899) were adopted in 2022, and the methodology and application of IMO guidance on EGCS is the subject of ongoing discussions. Although there have been growing calls to formally regulate or ban the use of scrubbers, **industry objections and questions about impacts, measurement protocols and enforcement have stalled regulatory action.**

Lacking sufficient Member State consensus to move forward with regulations to limit or ban the use of EGCS, IMO has indicated it is up to the Member States to regulate scrubbers within their jurisdictions, if they so desire.

Recognizing the documented harms from scrubbers, numerous locations — most recently the countries of Denmark, Sweden and Finland — have banned or announced upcoming bans on scrubber discharge in their territorial waters, and numerous other ports, communities and countries also have put some form of scrubber ban in place.

What follows is a summary of the most recent activities at the IMO with regard to EGCS, where the following trends have emerged:

- While declining to take regulatory action, the **IMO has invited Member States to submit proposals for EGCS regulations.** Although **no proposals for regulations have yet been submitted,** there have been submittals regarding further studies on scrubber effluent, proposals for how to direct the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) on further scrubber studies and submittals on how to determine representative emission factors.

- The IMO will continue to work on establishing **representative emission factors** for EGCS by establishing a GESAMP Task Team.

- IMO will work to develop a **database** of local, national or regional locations with EGCS regulations in place for the use of mariners.

- IMO also has concluded that, while there is a question of the **legality (under UNCLOS or MARPOL) of using EGCS for alternative compliance** — in other words, to substitute one form of pollution (exhaust gas in the air) with another (scrubber effluent discharge into the marine environment) — **it is up to Member States to determine the legality for their waters.** IMO recognizes that Member States have, and will continue to, regulate/ban scrubbers/scrubber discharge and requests that the IMO is kept informed of such regulations.

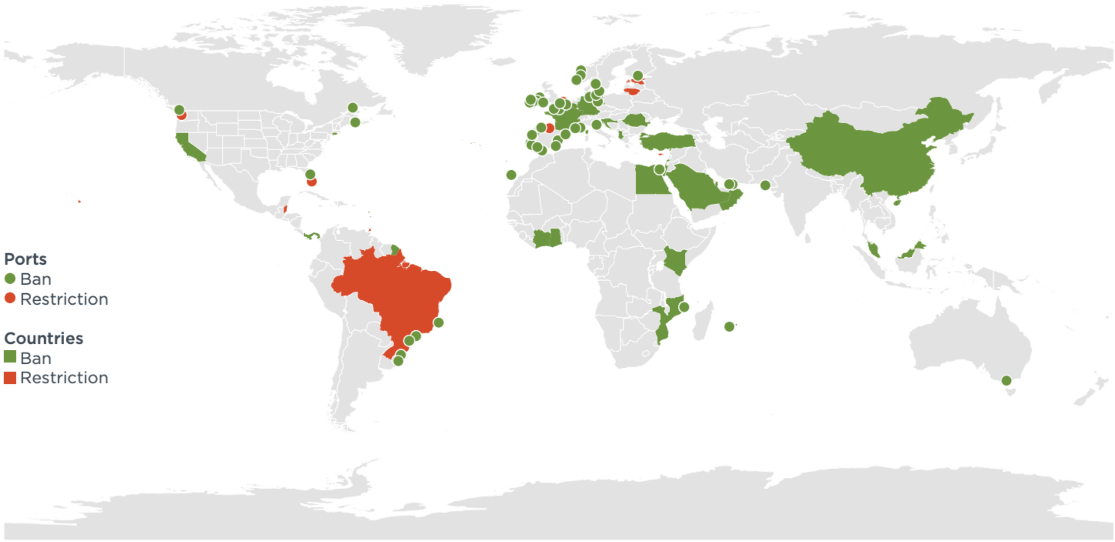
IMO guidelines lacking

Despite concerns, the IMO has only implemented scrubber discharge guidelines rather than enforceable regulations. Current guidelines specify limits for pH (a minimum of 6.5 at four meters from the discharge point), PAHs (a maximum of 50 micrograms per liter, or µg/L, as phenanthrene equivalents at a flow rate of 45 m^3/MWh), and turbidity (no more than 25 nephelometric turbidity units, or NTU, above the inlet water levels) (Teuchies et al., 2020).

No criteria for metals are included in the IMO's scrubber discharge guidelines, leaving significant gaps in addressing the risks posed by scrubber discharge.

Jurisdictions banning or regulating scrubbers

Due to environmental concerns, ship scrubber discharge — particularly from OL systems — is subject to bans and restrictions in various regions worldwide. In a 2023 report, ICCT identified **93 measures across 45 countries regulating the use of ship scrubbers, with most restrictions taking the form of outright bans** (Osipova et al., 2023). These measures are primarily implemented at the port level, reflecting efforts by local authorities to mitigate marine pollution in populated areas.



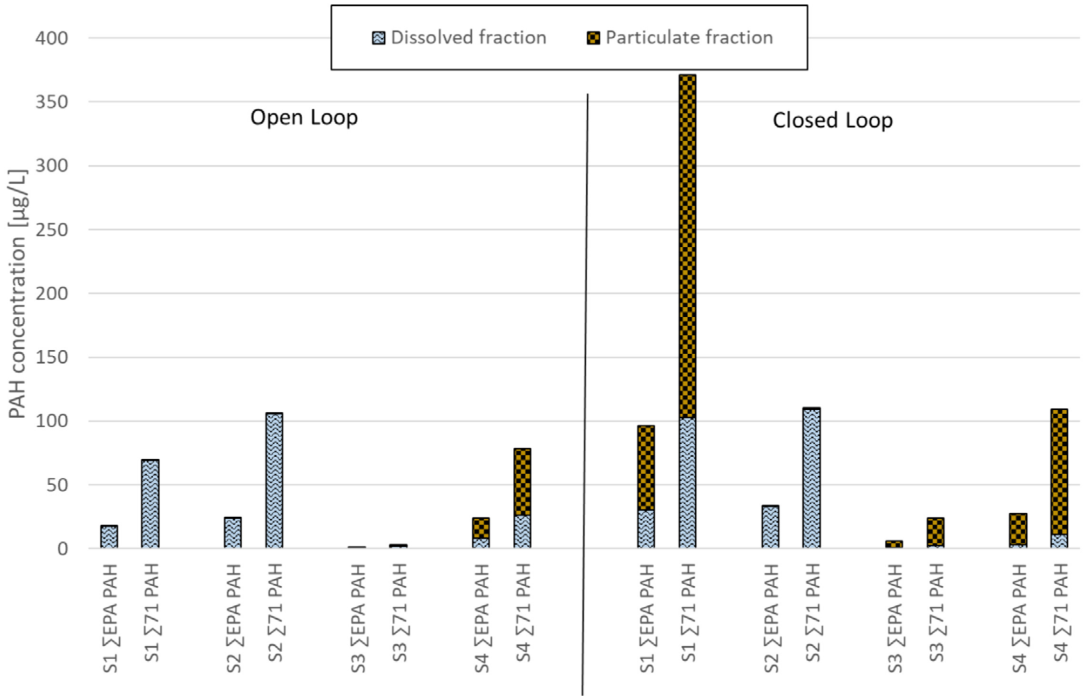
Ports and countries with bans or restrictions on scrubber discharge. SOURCE: Osipova et al., 2023.

New science since August

In August 2024, Pacific Environment published the report *Ship pollution:* ***From air to ocean:*** *The science on pollution scrubbers and why EPA should ban scrubber discharge*, which summarized 26 scientific studies depicting the harms from scrubbers used on ocean-going vessels. **Below is an Annotated Bibliography of additional recent studies.**

Achten, C., Marin-Enriquez, O., Behrends, B., Kupich, S., Lutter, A., Korth, R., & Andersson, J. T. (2024). Polycyclic aromatic compounds including non-target and 71 target polycyclic aromatic hydrocarbons in scrubber discharge water and their environmental impact. Marine Pollution Bulletin, 208, 116790. https://doi.org/10.1016/j.marpolbul.2024.116790.

Achten et al. (2024) assessed the concentrations, distribution and potential ecotoxicity of 71 PAHs, including the 16 EPA priority PAHs and their alkylated species. Water samples from hybrid ship scrubber systems (operating in both OL and CL modes) showed higher PAH levels in outlet versus inlet water — an indication that scrubbers, as opposed to alternate sources, resulted in an elevated presence of PAHs in the water column. For all 71 PAHs, Achten et al. measured median concentrations of 73.8 micrograms per liter (µg/L) and 109.7 µg/L for OL and CL systems, respectively — three to four times higher than concentrations of the EPA PAHs alone. HMW PAHs were detected more frequently in CL samples (61 detections) compared to OL samples (21 detections), likely due to the volatilization of LMW PAHs during recirculation of wastewater in CL systems.



Sum of EPA PAH and sum of 71 PAH concentrations in OL and CL scrubber discharge water samples, including dissolved and particulate fractions from the four studied ships. SOURCE: Achten et al., 2024.

Chircop, A. (2024). Pollution Substitution? Scrubber Discharges and the Law of the Sea: An Essay in Honor of Ted L. McDorman. Ocean Development & International Law, 55(4), 606–613. https://doi.org/10.1080/00908320.2024.2413602.

Chircop examines the environmental and legal implications of using exhaust gas cleaning systems on ships to comply with international sulfur emission regulations. Chircop argues that while scrubbers reduce air pollution by removing sulfur oxides from exhaust gases, they introduce a new form of marine pollution through the discharge of acidic and toxic discharge into the sea. The study highlights the presence of harmful substances such as polycyclic aromatic hydrocarbons (PAHs) in the discharged water, raising concerns about the effectiveness of scrubbers as an environmentally sustainable solution.

Chircop's primary focus is on the inconsistency of scrubber discharge with the rules and standards set forth by the United Nations Convention on the Law of the Sea (UNCLOS) and the International Convention for the Prevention of Pollution from Ships (MARPOL), a special convention of UNCLOS. Chircop contends that the authorization of scrubbers as an alternative compliance mechanism by national maritime administrations may conflict with UNCLOS provisions aimed at protecting and preserving the marine environment. The paper calls for a reevaluation of current policies to ensure that measures intended to reduce air pollution do not inadvertently harm marine ecosystems.

Kourkoutmani, P., Genitsaris, S., Demertzioglou, M., Stefanidou, N., Voutsa, D., Ntziachristos, L., Moustaka-Gouni, M., & Michaloudi, E. (2024). Effects from maritime scrubber effluent on coastal metazooplankton. Marine Biology, 172(1), 2. https://doi.org/10.1007/s00227-024-04562-8.

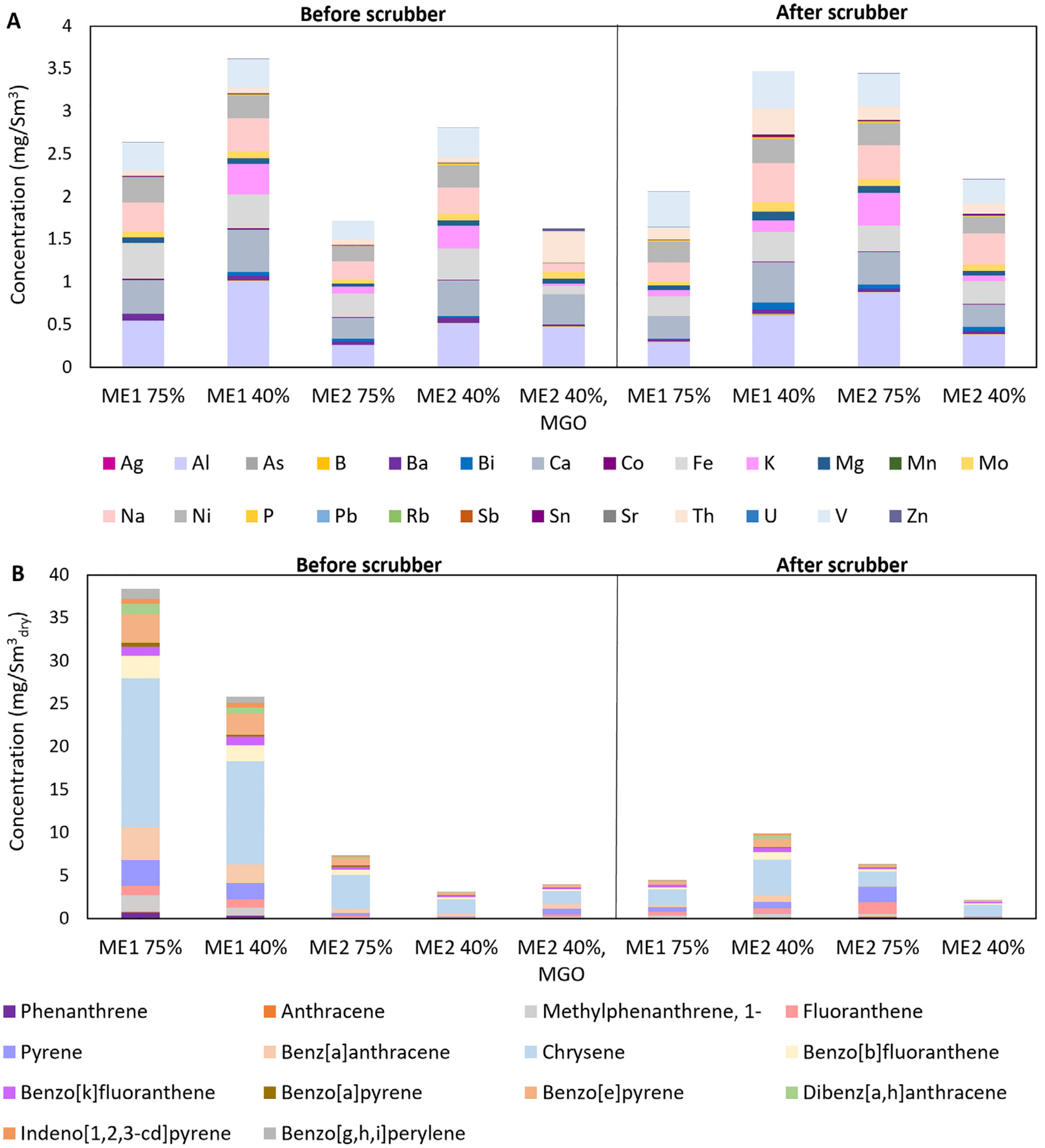
This study examines the impact of exhaust gas cleaning system (EGCS) effluent on coastal metazoan zooplankton (metazooplankton) communities in Thessaloniki Bay of the Eastern Mediterranean Sea. Researchers conducted experiments on metazooplankton exposed to three conditions: low concentrations of scrubber effluent, high concentrations of scrubber effluent and a control with no effluent. The pH of the scrubber discharge was 2.95, whereas the baseline seawater pH of Thessaloniki Bay was measured at 8.06 — this resulted in pHs of 7.90 and 7.18 in the low-concentration and high-concentration mixtures, respectively. After 6 days, the samples were sieved and specimens transferred to a stereoscope to be analyzed for swimming activity, given evidence that PAHs can have narcotic effects on copepods.

The findings indicated that low concentrations of scrubber effluent did not significantly affect metazooplankton populations, while high concentrations led to a notable decrease. Species-specific responses were observed, with the copepod Oithona exhibiting positive growth rates across all treatments. Overall, the study suggests that low levels of scrubber effluent may not adversely affect coastal metazooplankton communities, aligning with previous research on bacterioplankton and phytoplankton responses.

Kuittinen, N., Timonen, H., Karjalainen, P., Murtonen, T., Vesala, H., Bloss, M., Honkanen, M., Lehtoranta, K., Aakko-Saksa, P., & Rönkkö, T. (2024). In-depth characterization of exhaust particles performed on-board a modern cruise ship applying a scrubber. Science of The Total Environment, 946, 174052. https://doi.org/10.1016/j.scitotenv.2024.174052.

This study provides a comprehensive analysis of the chemical composition and physical properties of exhaust particles emitted by a cruise ship equipped with a hybrid scrubber operating in OL mode in the Baltic and North Sea Emission Control Area (ECA). Measurements were taken both upstream and downstream of the scrubber for the ship's two engines — one with selective catalytic reduction (SCR) for NO_x removal and both with scrubbers — under varying engine loads (75% and 45%) and fuel types, including HFO and MGO.

The scrubber effectively reduced overall particle concentrations, including non-volatile particles, though its efficiency varied with particle size. Notably, there was no significant reduction in particles larger than 50 nm, which typically include black carbon and, in the case of HFO combustion, metal-containing particles. SO2 was effectively removed, as was NO_x by the SCR. Tar particles from incomplete combustion were found in HFO samples both upstream and downstream from the scrubber. The effect of the scrubber on metal concentrations was unclear, with some metals (Al, Ca, K, Na, Ni, Th and V) increasing and others (Ba, Co, Pb and Sb) decreasing. The scrubber was found to have reduced concentrations of PAHs in exhaust gas.

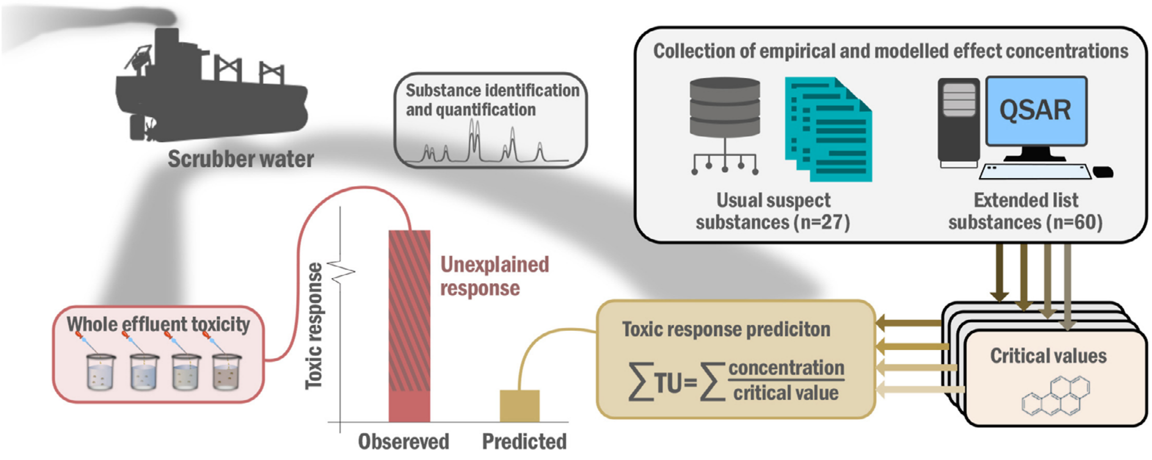


Metal (A) and PAH (B) concentrations in exhaust particles analyzed from filter samples taken before and after the scrubber. SOURCE: Kuittinen et al., 2024.

Lunde Hermansson, A., Gustavsson, M., Hassellöv, I.-M., Svedberg, P., García-Gómez, E., Gros, M., Petrović, M., & Ytreberg, E. (2024). Applying quantitative structure-activity relationship (QSAR) models to extend the mixture toxicity prediction of scrubber water. Environmental Pollution (Barking, Essex: 1987), 366, 125557. https://doi.org/10.1016/j.envpol.2024.125557.

Lunde Hermansson, Gustavsson, et al. (2024a) evaluate the effectiveness of Quantitative Structure-Activity Relationship (QSAR) models in predicting the toxicity of scrubber water from ships. The authors applied QSAR models to calculate toxic units (TUs) for all measured constituents of scrubber water or scrubber sludge, focusing on substances lacking experimental ecotoxicological data, such as many alkylated PAHs. Modeled results are compared to experimentally measured toxic effect concentrations in three organisms (fish, crustaceans and algae).

The findings indicate that, while QSAR models can supplement experimental data to enhance mixture toxicity predictions, the predicted ecotoxicological response of the analyzed substances still underestimates the toxicity observed in whole effluent toxicity (WET) tests. Even with the inclusion of alkylated PAHs in the predictions, nearly 80% of the measured toxicity remains unexplained. This suggests the presence of additional toxic substances or synergistic effects not accounted for in the models. The study underscores the need for comprehensive chemical screening and toxicity assessments beyond the commonly analyzed PAHs and metals to evaluate the environmental risks associated with scrubber water discharges accurately.



Schematic representation of QSAR analysis. SOURCE: Lunde Hermansson, Gustavsson et al., 2024a.

The case for **action now**

Damage from scrubber discharge justifies regulatory action

Guided by the **precautionary principle,** the IMO and other regulatory agencies must adopt proactive measures to mitigate risks from scrubber pollution, prioritizing preventive action over reactive responses to environmental and health disasters. If policymakers account for the substantial environmental and human health costs of unrestricted scrubber use, and recognize the economic, ecological and human health consequences of inaction, **they will find the adequate justification** to ban scrubber discharge into the marine environment.

The costs to industry of banning scrubbers are insignificant compared to the harm to the oceans, marine resources, human health and communities.

Failing to act to ban scrubbers **allows their use to continue increasing** and **enables those companies that have already recouped their capital investments to make profit off continued use of polluting and hazardous HFO.**

As the analysis above shows, most of the capital investments in scrubbers have already been repaid. **Limiting industry's future profits by requiring use of cleaner fuels is justified in the public interest** when balanced against the significant health and environmental harms from scrubber discharge.

IMO Member States must find consensus to adopt and enforce legally-binding regulations banning scrubber use, or requiring ships to use cleaner burning MGO/distillate fuels so they don't need to rely on scrubbers, which allow the continued use of HFO.

Until IMO institutes a global ban on scrubbers, **national governments, states, communities and ports should independently ban the discharge of scrubber waste within their jurisdictional waters** and stop approving scrubbers as an alternative compliance method for ships registered under their flags.

Without a ban on the use of scrubbers and the discharge of scrubber wastewater — or a mandate to use cleaner distillate fuels — **ecosystems, ocean resources and coastal communities will continue to be threatened and human health risks will increase.**

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