NOVEMBER 2020

Air emissions and water pollution discharges from ships with scrubbers

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ICCT CONSULTING REPORT

ACKNOWLEDGEMENTS

We thank Environment and Climate Change Canada for funding this analysis. Thank you also to Environment and Climate Change Canada staff for reviewing earlier versions of this report.

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EXECUTIVE SUMMARY

Ships use scrubbers to comply with fuel sulfur standards by removing sulfur dioxide from the exhaust instead of using lower sulfur but more expensive fuels. Instead, ships with scrubbers can continue to use cheaper high-sulfur heavy fuel oil (HFO). The International Maritime Organization (IMO) allows the use of scrubbers as an equivalent compliance option because they are expected to reduce sulfur dioxide emissions by the same, or more, as using compliant fuels. However, when considering the total air pollution consequences of scrubbers, they may not be equivalent to using lower-sulfur fuels, such as marine gas oil (MGO). Additionally, while scrubbers are effective at reducing sulfur dioxide, the sulfur and other contaminants removed from the exhaust gas—including carcinogens such as polycyclic aromatic hydrocarbons (PAHs) and heavy metals—are dumped overboard in the form of washwater, also called discharge water. This happens even with so-called “closed-loop” scrubbers.

In this study, we estimated air and water emission factors for ships using HFO with scrubbers compared to other fuels based on the available literature and the methods of the *Fourth IMO Greenhouse Gas Study*. Regarding air emissions, we found that using scrubbers can substantially reduce sulfur dioxide emissions but carbon dioxide, particulate matter, and black carbon emissions were higher when using HFO with a scrubber than using MGO. For water pollutants, we found that scrubber discharges usually comply with IMO guidelines; however, compliance does not guarantee that scrubber discharges are safe. We found that all scrubbers (open-loop, closed-loop, and hybrid) discharge water that is more acidic and turbid than the surrounding water. Additionally, scrubbers emit nitrates, PAHs, and heavy metals, all of which can negatively affect water quality and marine life. Within Canada, this includes scrubber discharges in the Great Lakes, as well as British Columbia and the St. Lawrence Estuary, where endangered species like the Southern Resident killer whales and belugas already suffer from high levels of contamination, including from PAHs and heavy metals.

Based on this analysis, the ICCT makes the following recommendations. We recommend individual governments continue to take unilateral action to restrict or prohibit scrubber discharges from both open-loop and closed-loop systems. We also recommend that the IMO focus on harmonizing rules for scrubber discharges including where, when, and even if those discharges should be allowed, and to do so with urgency. The IMO should consider prohibiting the use of scrubbers as a compliance option for new build ships and work to phase out scrubbers installed on existing ships. This is because we found that using HFO with scrubbers is not equivalently effective at reducing air pollution compared to using lower sulfur fuels, such as MGO. Additionally, scrubbers of all kinds (open, closed, and hybrid) directly contribute to ocean acidification and water pollution, whereas lower sulfur fuels do not. Until then, we recommend that individual countries, including Canada, take immediate actions to protect their air and waters from scrubber emissions and discharges. These actions could include one or both of the following: (1) an immediate prohibition on using scrubbers to comply with the Canadian portion of the North American ECA because they are not equivalently effective at reducing air pollution as ECA-compliant fuels; (2) an immediate prohibition on all scrubber discharges in Canadian ports, internal waters, and territorial seas because they contribute to acidification and water pollution that can negatively affect marine life.

INTRODUCTION

In this report, the International Council on Clean Transportation (ICCT) provides expert advice to Environment and Climate Change Canada to enable them to update their Marine Emission Inventory Tool such that air and water pollution discharges from ships equipped with exhaust gas cleaning systems (EGCSs), also known as "scrubbers," can be estimated for ships operating in Canadian waters.

BACKGROUND

Ships use scrubbers as a way to comply with regional and global fuel sulfur standards by removing sulfur dioxide (SO_2) from the exhaust rather than using lower sulfur fuels. In the North American Emission Control Area (ECA), the maximum allowable fuel sulfur content is 0.10% by mass. The ECA extends 200 nautical miles from the U.S. and Canadian coasts and includes all Canadian waters south of 60°N latitude. The American and Canadian Arctic regions are not covered by the ECA. Outside ECAs, the maximum allowable sulfur content for marine fuels is 0.50% as of January 1, 2020. Before 2020, the maximum allowable sulfur content was 3.50%. This tightening of the global fuel sulfur cap drove dramatic increases in scrubber installations, and the rapid uptake of scrubber installations and orders in the lead-up to 2020 is illustrated in Figure 1.

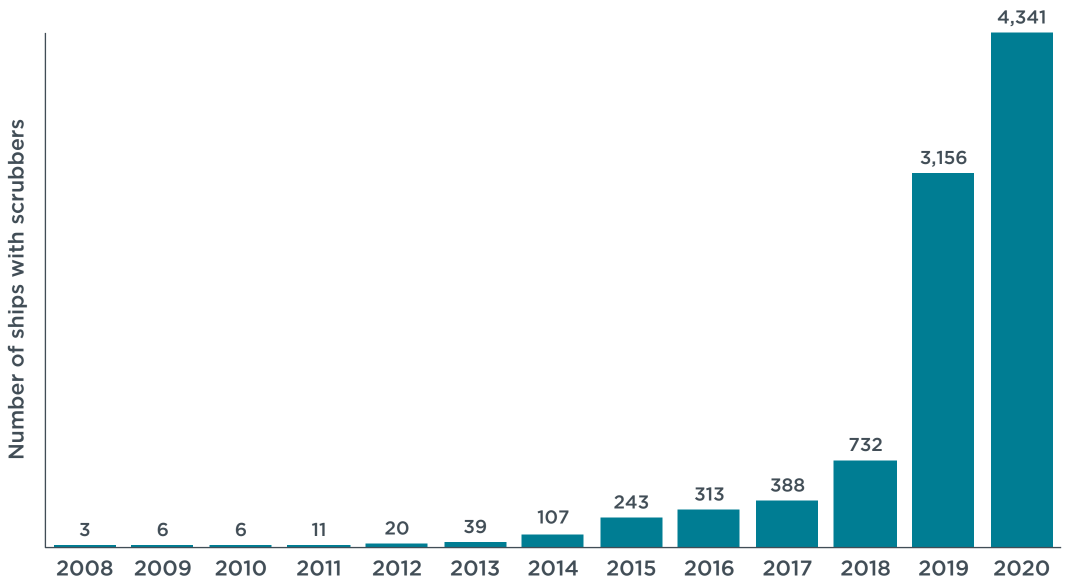


Figure 1. Number of ships with scrubbers by year. Source: DNV GL (2020)

While scrubbers are effective at reducing SO_2, the sulfur and other contaminants removed from the exhaust gas—including carcinogens such as polycyclic aromatic hydrocarbons (PAHs) and heavy metals—are dumped overboard in the form of washwater, also called discharge water. Many of these contaminants in the washwater, including heavy metals and many PAHs, do not biodegrade and therefore amass in the environment and the food web. This makes these pollutants of particular concern for marine mammals. When marine mammals are exposed to these contaminants, usually through their food, the contaminants accumulate in their organs or are stored in their fat reserves. In lean times when food is scarce, or during pregnancy, the fat reserves are used, re-exposing the animal to the contaminants. Heavy metals, which are known to bioaccumulate in the liver, bone marrow, and kidneys in marine mammals, have been linked to carcinogenic effects and immune suppression in marine mammals (Dosi, 2000; Kakuschke & Prange, 2007). On the east coast of North America in the St. Lawrence estuary system, high PAH concentrations in beluga whales corresponded with higher rates of digestive tract cancers and tumor production (Guise, Lagacé, & Béland, 1994; Martineau et al., 2002). On the west coast, the endangered Southern Resident killer whales, found in the inlets and sounds of British Columbia, have a population critically at risk with only 72 individuals remaining in 2020, according to the U.S. National Oceanic and Atmospheric Administration (NOAA) Fisheries Department (NOAA Fisheries, 2020). PAHs and trace metals are listed as direct impacts to the species in the Recovery Strategy in their Species at Risk Act designation, which notes that they are likely to be the most contaminated mammals in the world (Government of Canada, 2011; Ross, Ellis, Ikonomou, Barrett-Lennard, & Addison, 2000).

Georgeff, Mao, and Comer (2019) found that, in 2017, 30 scrubber-equipped ships emitted nearly 35 million tonnes of scrubber discharge water off the coast of British Columbia, including in and near critical habitats for threatened and endangered Northern and Southern Resident killer whales. Cruise ships were responsible for 90% of these discharges. The paper predicted that the International Maritime Organization (IMO) 2020 global fuel sulfur cap would result in 47 million tonnes of scrubber discharges in that area in 2020 as more ships, particularly container ships, bulk carriers, and roll-on/roll-off ferries, begin to use scrubbers. This figure includes ships that use open-loop scrubbers, which continuously discharge contaminated washwater, and from hybrid scrubbers than are operated in open-loop mode. No ships used closed-loop scrubbers in that area. Forthcoming research from the ICCT will also show that in addition to discharges off Canada's west coast, ships are also using scrubbers on the east coast, including in the St. Lawrence estuary, home to endangered beluga whales (Osipova, Georgeff, & Comer, forthcoming).

Some ships are using closed-loop scrubbers or hybrid scrubbers in closed-loop mode, mainly when operating near shore or in port. Closed-loop scrubbers recirculate the washwater, but a small volume of bleed-off water is still emitted. Unlike open-loop systems, closed-loop systems store scrubber sludge (also called residuals) on board for on-land disposal. Although closed-loop scrubbers can operate in zero-discharge mode for short periods (Kjølholt, Aakre, Jürgensen, & Lauridsen, 2012), they most often emit highly concentrated and highly contaminated bleed-off, making "closed loop" a bit of a misnomer. While closed-loop scrubbers do remove some solids, the sludge ultimately ends up in a landfill, usually as hazardous waste (Kjølholt et al., 2012). Open-loop scrubbers typically do not have water treatment systems to remove solids before discharge, contrary to many schematics of scrubbers in the literature. The water flow rate of open-loop systems is often too high to allow for onboard treatment (European Sustainable Shipping Forum, 2017). Instead, whatever sludge could be captured from open-loop systems remains suspended in the washwater and is discharged overboard.

In response to the rapid uptake and use of scrubbers to comply with the IMO's 2020 global fuel sulfur limit, and concerns about the cumulative effects that more ships using scrubbers discharging acids, PAHs, heavy metals, and other pollutants could have on the marine environment, many countries are limiting or prohibiting scrubber discharges in their exclusive economic zones (EEZs), territorial seas, internal waters, canals, and/or ports, as shown in Table 1. We note that Canada has no such restrictions, despite significant and growing scrubber discharges, including 5.1 million tonnes in critical habitat for threatened and endangered Northern and Southern Resident killer whales off the coast of British Columbia as of 2017 (Georgeff, 2020).

Table 1. Locations where scrubber discharges are restricted or prohibited as of September 2020

Country	Details
Argentina	Prohibits open-loop (OL) discharge water in internal waters, territorial seas, and EEZs
Australia	Ships using scrubbers must notify Australian Maritime Safety Authority before port arrival
Bahrain	Prohibits OL discharges in territorial seas and EEZs unless they can be proven to comply with the 2015 IMO guidelines
Belgium	Discharges prohibited in ports, internal waters, and within 3 nautical miles (nm) of shore
Bermuda	Prohibits OL discharges in territorial seas; closed-loop (CL) discharges allowed with prior approval
Brazil	Discharges prohibited at Vale bulk terminals/ports; discharges discouraged within 24 nm of shore
China	Prohibits OL discharges in internal rivers and Domestic Emission Control Areas
Egypt	Discharges prohibited in territorial seas, ports, and the Suez Canal
Estonia	Discharges prohibited in ports and estuaries unless the ship owner can demonstrate that the discharge does not cause significant adverse effects
Finland	Discharges prohibited in the port of Porvoo
France	Prohibits OL discharges in some ports and rivers, including Bordeaux, Port Jérôme-sur-Seine, River Seine, and Le Havre
Germany	Discharges prohibited in internal waterways
Gibraltar	Prohibits OL discharges in waters of Gibraltar
Hong Kong	Use of scrubbers requires an exemption
Ireland	Discharges prohibited in ports of Dublin, Waterford, and Cork
Latvia	Discharges prohibited in territorial seas and ports
Lithuania	Discharges prohibited in ports
Malaysia	Prohibits OL discharges in territorial seas except for ships transiting the Malacca Strait that are not bound for a Malaysian port
Norway	Prohibits OL discharges in World Heritage Fjords sea areas of Geirangerfjord and Nærøyfjord
Oman	Discharges prohibited in territorial seas
Pakistan	Prohibits OL discharges in the ports of Karachi and Bin Qasim
Panama	Prohibits OL discharges in the Panama Canal
Portugal	Prohibits OL discharges in port
Qatar	Discharges prohibited in territorial seas
Saudi Arabia	Prohibits OL discharges in port
Singapore	Prohibits OL discharges in port
Spain	Prohibits OL discharges in the ports of Algeciras, Cartagena, and Huelva
Sweden	Discharges prohibited in the ports of Brofjorden, Gävle, Norrköping, Umeå, Sundsvall, Skellefteå, and Stockholm
United Arab Emirates	Prohibits OL discharges in the port of Fujairah
USA	California: Prohibits the use of scrubbers to comply with fuel sulfur limits within 24 nm Connecticut: Discharges prohibited in ports and waters of the state Hawaii: Discharges allowed, but special reporting required

Sources: Damgaard (2020) and Standard Club (2020)

Given this trend toward unilateral action by individual countries, the EU-28 and European Commission (EC) in 2019 proposed that IMO's Marine Environment Protection Committee (MEPC) undertake a new output to "evaluate and harmonize the development of rules and guidance on the discharge of liquid effluents from EGCS, including conditions and areas under which liquid effluents from EGCS can be discharged, and to regulate as appropriate access for ships equipped with such systems on that basis" (MEPC 74/14/1, para. 2). In their submission proposing a new output on harmonizing rules and guidance for EGCS discharges, the EU and EC explain that the only guidelines for EGCSs that currently apply are the 2015 guidelines, but that they do not have additional protections for sensitive areas. They also state that "it is questionable if the current criteria are fit for purpose in the current scenario, where a significant uptake of scrubbers or other technologies that discharge effluent into the marine ecosystem is occurring" (MEPC 74/14/1, para. 27).

MEPC 74 approved this new output on harmonizing rules and guidance for EGCS discharges, and tasked the Pollution Prevention and Response (PPR) subcommittee to work on the issue, with a target completion year of 2021. PPR 7 refined the title and scope of the output, which is expected to be approved at MEPC 75 (November 16–20, 2020) and will likely be sent back to PPR 8 to continue working on the topic. This provides an opportunity to develop guidance on when, where, or even if discharges should be allowed. It is likely that this work will focus on guidance for discharges in ports, harbors, estuaries, and busy shipping lanes, but Friends of the Earth International et al. (PPR 7/12/4) suggested that near shore areas, polar regions, and areas of cultural and ecological sensitivity and significance should also be considered.

A HISTORY OF IMO'S SCRUBBER GUIDELINES

The IMO first decided to regulate sulfur oxides (SO_x) from ships in the 1997 Protocol to the International Convention for the Prevention of Pollution from Ships (MARPOL), which included MARPOL Annex VI. Annex VI entered into force in May 2005 and contains regulations that limit SO_x and nitrogen oxides (NO_x) from ship exhaust. Sulfur oxides are primarily controlled by limiting the sulfur content of fuels, with one limit globally and another inside Sulfur Emission Control Areas (SECAs). Originally, scrubbers were to be allowed only within SECAs. However, a few months after Annex VI entered into force, IMO began revising it. In the revision, the IMO agreed that the maximum fuel sulfur content of marine fuels and the maximum NO_x emissions from marine engines would become more stringent over time. Additionally, ships would be allowed to use scrubbers globally, not just in SECAs under an "equivalence" provision added as Regulation 4. The revisions also introduced ECAs, which set stronger limits for not only SO_x, but also NO_x. Currently, there are four ECAs (Table 2). These revisions to MARPOL Annex VI were adopted in 2008 and entered into force in July 2010.

Despite scrubbers being allowed as an alternative SO_x compliance option under Regulation 4 of MARPOL Annex VI, port and coastal states are free to unilaterally limit or prohibit the use of scrubbers in their jurisdictions. Today, scrubber discharges are limited or prohibited in the territorial seas, internal waters, ports, or canals of at least 29 countries (Table 1). Canada currently has no restrictions on scrubbers.

Table 2. Current Emission Control Areas

Region	Applied for	Adopted	Enforced
Baltic Sea	1995 (SECA) 2016 (ECA)	1997 (SECA) 2017 (ECA)	2006: 1.5% max S 2010: 1% max S 2015: 0.1% max S 2021: Tier III NO_x
North Sea	2000 (SECA) 2016 (ECA)	2005 (SECA) 2017 (ECA)	2007: 1.5% max S 2010: 1% max S 2015: 0.1% max S 2021: Tier III NO_x
North America (United States & Canada, except the Arctic)	2009 (ECA)	2010 (ECA)	2012: 1% S max 2015: 0.1% S max 2016: Tier III NO_x
United States Caribbean Sea (Puerto Rico & U.S. Virgin Islands)	2010 (ECA)	2011 (ECA)	2014: 1% S max 2015: 0.1% S max 2016: Tier III NO_x

The IMO has established EGCS guidelines[1] for certain pollutants and other parameters (e.g., pH and temperature) for scrubber discharge water, but these guidelines are voluntarily applied by flag states, do not cover all pollutants (heavy metals are not explicitly included; turbidity is used as a proxy), and lack rigorous scientific justification. Endres et al. (2018) concluded that despite the existing IMO guidelines, "there is still the

1 IMO proposed revised 2020 guidelines for scrubbers at the 7th session of its Pollution Prevention and Response Sub-Committee (PPR 7); while they have not yet been adopted by the Marine Environment Protection Committee, we expect them to be approved at MEPC 75. Nevertheless, the discharge criteria established in the 2015 guidelines, as found in IMO Resolution MEPC.259(68), remains unchanged. The text of the 2015 guidelines are available here: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/MEPC.259%2868%29.pdf

risk for acidification, eutrophication, and accumulation of PAHs, PM [particulate matter], and heavy metals in the marine environment" (p. 139).

The first IMO scrubber guidelines can be found in Resolution MEPC.130(53), adopted in 2005. IMO subsequently published 2008, 2009, and 2015 guidelines in Resolutions MEPC.170(57), MEPC.184(59), and MEPC.259(68). Draft 2020 guidelines have been proposed in Annex 9 of document PPR 7/22/Add.1 and are expected to be approved by MEPC 75 in November 2020.

Regarding air emissions, all guidelines require that scrubbers result in SO_2/carbon dioxide (CO_2) ratios that are less than or equal to those that would result from burning compliant fuels. These limits are based on sulfur content and are summarized in Table 3. Note that only the 0.50% and 0.10% values are relevant after January 1, 2020. As such, the rest have been grayed. While all scrubbers tend to easily meet these SO_2 limits, researchers have found that when accounting for total sulfur emissions (gaseous + particle phase), scrubbers may emit more total sulfur than compliant fuel (Johnson et al., 2017). The guidelines set no limits on any air pollutant other than SO_2.

Table 3. Air emissions limits for ships with scrubbers

Fuel sulfur content (% m/m)	SO_2 (ppm)/CO_2 (% v/v)
4.50	195.0
3.50	151.7
1.50	65.0
1.00	43.3
0.50	21.7
0.10	4.3

MEPC.130(53): 2005 GUIDELINES—THE FIRST SCRUBBER GUIDELINES

In the original scrubber guidelines, found in Resolution MEPC.130(53) and adopted by MEPC 53 on July 22, 2005, scrubbers were expected to be used solely inside of SECAs, as allowed under the Protocol of 1997, which entered into force on May 19, 2005. Under the original guidelines, scrubber washwater was to be monitored for pH and oil content, but no numeric discharge criteria were proposed for either parameter. Instead, section 17 states the following:

> *17. Wash Water*
>
> *EGCS-SO_X unit's wash water systems should:*
>
> > *(a) eliminate, or reduce to a level at which they are not harmful, hydrocarbons, carbon residue, ash, vanadium, other heavy metals, and other substances contained within EGCS-SO_X unit's wash water that may have an adverse impact on ecosystems if discharged overboard,*
> >
> > *(b) ensure that the approach adopted, to control wash water quality and residual waste is not achieved in a way that causes pollution in other areas or environmental media,*
> >
> > *(c) also taking into account guidelines to be developed by the Organization.*

Regarding scrubber residues (sludge), section 18.1 makes it clear that they should be disposed of on land and not discharged overboard or incinerated on board:

> *18.1 Residues generated by the EGCS-SO_X unit should be land disposed. Such residues should not be discharged to the sea or incinerated on board.*

MEPC.170(57): 2008 GUIDELINES—WHERE THE FIRST AND ONLY DISCHARGE CRITERIA WERE ESTABLISHED

In 2008, there were only three ships with scrubbers, according to DNV GL (2020). In the 2008 guidelines, found in Resolution MEPC.170(57), which were adopted by MEPC 57 on April 4, 2008, the first discharge criteria were set, but only when the "EGC System is operated in a *[sic]* ports, harbours, or estuaries" (section 10.1.1). It includes criteria for pH, PAH, turbidity/suspended particulate matter, and nitrates. Although subsequent guidelines have expanded the discharge limits to apply beyond ports, harbors, and estuaries, the discharge limits first established in these 2008 guidelines have never been revised to be more stringent.

The 2008 guidelines were adopted at MEPC 57, but the work on setting discharge criteria had begun in 2006. MEPC 55, which was held October 9–13, 2006, established a correspondence group on Washwater Criteria for Exhaust Gas-SO_x Cleaning Systems. In establishing these discharge criteria, the correspondence group considered proposals from the United Kingdom (MEPC 55/4/5) as well as Finland and Norway (MEPC 55/4/7).

The UK document proposed that discharge criteria be established for pH and oil concentration (measured as PAH). They proposed that the pH of the discharge plume should not exceed 0.2 pH units below the background water conditions at a distance of 1 meter from the ship. They also proposed a 30 ppb (approximately equal to 30 µg/L) limit for PAHs, associated with a 50 tonnes per megawatt hour (t/MWh) flow rate. The same UK document shows that the 2000 EU Water Framework Directive sets drinking water standards of 0.01 ppb for total PAH. The 1992 Australian Water Quality Guidelines set a 3 ppb limit. In the 1992 Convention on the Protection of the Marine Environment of the Baltic Area, the Baltic Marine Environment Protection Commission, better known as HELCOM, set a 15 ppb limit for PAHs. The UK document provides the results of a 2004 study of discharges from an open-loop scrubber fitted to a European ferry, the *Pride of Kent*. In that study, the authors found that the maximum PAH concentration was 24 ppb, and that was in the residue settling tank. Typical PAH concentrations were 3–4 ppb compared with <0.6 ppb at the inlet, they said. It is perplexing why the UK would propose a limit of 30 ppb PAH at 50 t/MWh flow rate for ships with scrubbers, a level unlikely to be exceeded, given that typical concentrations were between 3 and 4 ppb. Indeed, as we will show in the results, we found that ships rarely exceed the PAH limits, which under the current guidelines allow discharges of approximately 50 µg/L (~50 ppb) at a 45 t/MWh flow rate.

The Norway and Finland document (MEPC 55/4/7) also proposed discharge criteria based on testing data from two ships, one ferry and one oil tanker, each outfitted with prototype open-loop scrubbers. The tests were conducted in 1991 and 1993. The minimum pH after the scrubber was recorded as 2.7. They assert that, due to dilution, even a pH of 0 would not result in a pH of less than 6.8, which is the most conservative

Predicted No Effect Concentration (PNEC[2]) they found in the literature, at a distance of at least 20 meters from the ship. The maximum PAH concentration in the scrubber washwater was 0.25 µg/L (~0.25 ppb), compared with the most conservative PNEC they could find in the literature, which was 3.3 µg/L. The Norway and Finland document suggests that, due to dilution effects, PAHs could be discharged at concentrations of approximately 6,200 µg/L while maneuvering or in transit, or more than 460 µg/L during quayside maneuvering and still not exceed the PNEC. Based on this, they recommend three tiers of criteria that port states could choose, with each level being 10 times more protective than the other. For pH, they suggested no limit. For PAH, they suggested a limit of 450, 45, or 5 µg/L (presumably rounded up from 4.5 µg/L), depending on the level of protection the port state would like to impose. They also proposed possible discharge criteria for heavy metals including nickel (Ni), vanadium (V), copper (Cu), lead (Pb), mercury (Hg), and cadmium (Cd) in units of µg/L, following the same tiered approach. However, individual heavy metal discharge criteria never made it into any scrubber guidelines because onboard monitoring is thought to be challenging. It should be understood that the modeling exercise presented in the Finland and Norway document, which showed no predicted adverse effects even at high pollution concentrations, is based on pollution discharges from one ship, whereas ports, harbors, estuaries, nearshore areas, and shipping lanes now experience scrubber discharge loads from multiple ships. Moreover, the number of ships with scrubbers is growing, as shown in Figure 1.

Ultimately, the correspondence group established by MEPC 55 did not propose specific discharge criteria limits. However, the group reported that most group members agreed that pH and oil concentration were two key performance parameters for scrubbers. The correspondence group suggested that a working group be established at MEPC 56 to finalize the discharge criteria.

At MEPC 56, which was held July 9–13, 2007, the Working Group on Air Pollution considered the report of the IMO Correspondence Group that MEPC 55 had established on Washwater Criteria for Exhaust Gas-SOx Cleaning Systems (their report is found in document MEPC 56/4/1) and developed a draft set of washwater discharge criteria for pH, oil (using PAHs as a proxy), heavy metals (using turbidity as a proxy), and nitrates. The report of the Working Group on Air Pollution (MEPC 56/WP.6) does not explain how it arrived at the discharge criteria for these parameters.

The criteria agreed to in the MEPC 56 Working Group on Air Pollution in the report are summarized in the annex to document BLG-WGAP 2/4. As stated in that document, MEPC 56 recommended a minimum outlet pH of 6.5 and a maximum difference between inlet and outlet of 2 pH units while the ship was at berth or at anchor in a port, harbor, or estuary. (In the eventual 2008 guidelines, this 2 pH difference would apply only to ships while maneuvering or in transit.) We note that because pH is a logarithmic scale, a difference of 2 pH units is equal to a 100-fold difference in acidity. They also suggested that, while underway in all areas, the pH should be maintained at a level that avoids acute effects on aquatic ecosystems, damage to antifouling systems, and accelerated corrosion of critical metal components. These considerations were lost in the eventual 2008 guidelines.

2 PNEC is the limit below which no adverse effects from exposure are measured.

For PAHs, MEPC 56 suggested a limit of 15 ppb at a discharge rate of 45 t/MWh. This would be weakened to 50 µg/L under the 2008 guidelines. For turbidity, they recommended a maximum of 25 formazin nephelometric units (FNU), which remained, although an alternative limit of 25 nephelometric turbidity units (NTU) was added under the 2008 guidelines. For nitrates, they suggested no nitrate limit for EGCS units designed to reduce oxides of nitrogen by less than "[10] per cent" (BLG-WGAP 2/4, annex 2, p. 2). Otherwise, they suggested that the discharge limit should be less than that associated with a "[10] per cent" removal of NO_x from the exhaust. No scrubbers are designed to remove NO_x, so no nitrate discharge limits for scrubbers would be needed had the first clause remained. This first clause would later be removed, and the second clause was weakened to allow 12% removal of NO_x or 60 mg/L of nitrates, whichever is greater, under the 2008 guidelines. The MEPC 56 Air Pollution Working Group advised MEPC not to adopt the draft 2008 guidelines yet and to instead send them to the second intersessional meeting of the Bulk Liquids and Gases Working Group on Air Pollution (BLG-WGAP 2) for further review and refinement.

BLG-WGAP 2 met from October 29, 2007, to November 2, 2007, in Berlin to work on the 2008 scrubber guidelines based on the draft washwater criteria developed by MEPC 56. BLG-WGAP 2 was instructed by MEPC 56 to finalize the draft revision to the 2005 guidelines found in MEPC.130(53), to finalize discharge criteria for EGCS from MEPC 56, and to include them in the draft amended 2008 guidelines. BLG-WGAP 2 did not finalize the draft washwater discharge criteria, so they were sent to BLG 12, which was held in February 2008, and they were also sent directly to MEPC 57, which was held in April 2008.

BLG 12 had for their consideration the draft discharge criteria from BLG-WGAP 2 in annex 6 to document BLG 12/6/Add.1. However, the discharge criteria BLG 12 ultimately recommended to MEPC 57 in document BLG 12/WP.6/Add.4 were weaker than those proposed by BLG-WGAP 2. The report of the BLG 12 Air Pollution Working Group (BLG 12/WP.6) contains no explanation or justification for this decision. The discharge criteria agreed to by BLG 12 were ultimately adopted, without revision, by MEPC 57 as the 2008 guidelines in Resolution MEPC.170(57) on April 4, 2008. Since then, the guidelines have been reviewed three times (2009, 2015, and 2020), and the discharge criteria have never been revised.

Below, for each parameter—pH, PAH, turbidity, and nitrates—we compare the recommendations of BLG-WGAP 2, as found in document MEPC 57/4/1, to the 2008 guidelines that MEPC 57 agreed to in Resolution MEPC.170(57). Table 4 details changes to the discharge criteria over time for these pollutants as well as heavy metals, compared with the number of ships with scrubbers installed during the year in which the revised guidelines were adopted. As the table shows, despite a review of the guidelines in 2009, 2015, and 2020, the discharge criteria that were initially established in the 2008 guidelines have never been revised and no numeric discharge criteria have ever been established for any heavy metal. Meanwhile, the number of ships with scrubbers has grown from three ships in 2008 to more than 4,300 ships in 2020.

Table 4. How IMO scrubber discharge criteria have changed over time, compared with the number of ships with scrubbers installed

Pollutant	MEPC.130(53): 2005 guidelines	MEPC 57/4/1: proposed discharge criteria from BLG-WGAP 2 for 2008 guidelines	MEPC.170(57): 2008 guidelines, as adopted by MEPC 57	MEPC.184(59): 2009 guidelines	MEPC.259(68): 2015 guidelines	PPR 7/22/ Add.1, Annex 9: Draft 2020 guidelines
pH	Eliminated or reduced "to a level at which they are not harmful."	pH ≥ 6.5 stationary; max Δ 2 pH units when moving	pH ≥ 6.5 stationary; max Δ 2 pH units when moving. OR pH ≥ 6.5 in the plume at 4 m while stationary	*Unchanged from 2008 guidelines*	*Unchanged from 2008 guidelines*	*Unchanged from 2008 guidelines*
PAH	Eliminated or reduced "to a level at which they are not harmful."	Max Δ 15 ppb PAH_{16} at 45 t/MWh	Max Δ 50 µg/L (~50 ppb) of PAH_{phe} at 45 t/MWh	*Unchanged from 2008 guidelines*	*Unchanged from 2008 guidelines*	*Unchanged from 2008 guidelines*
Turbidity	Eliminated or reduced "to a level at which they are not harmful."	Max Δ < 25 FNU or NTU; minimize suspended PM, including heavy metals and ash	Same as MEPC 57/4/1	*Unchanged from 2008 guidelines*	*Unchanged from 2008 guidelines*	*Unchanged from 2008 guidelines*
Nitrates	Eliminated or reduced "to a level at which they are not harmful."	Not > that associated with a [10%] removal of NO_x from the exhaust, or beyond [1] mg/L at 45 t/MWh, whichever is greater.	Not > that associated with a 12% removal of NO_x from the exhaust, or beyond 60 mg/L at 45 t/MWh, whichever is greater.	*Unchanged from 2008 guidelines*	*Unchanged from 2008 guidelines*	*Unchanged from 2008 guidelines*
Heavy metals	Eliminated or reduced "to a level at which they are not harmful."	No limits	No limits	No limits	No limits	No limits
Ships with scrubbers	2	3	3	6	243	4,341 installed or on order through 2020

pH

BLG-WGAP 2 recommended that scrubber washwater have a pH of not less than 6.5 while at berth, but when maneuvering and in transit the limit would be a maximum difference of 2 pH units between inlet and outlet. MEPC 57 agreed but kept an alternative compliance option introduced by BLG 12 that would allow setting the scrubber's overboard pH discharge limit based on whatever pH achieved a minimum pH of 6.5 in the plume at a distance of 4 meters from the overboard discharge point. This introduces myriad confounding factors. The overboard discharge limit, in this case, would depend on the alkalinity of the inlet water, wind, waves, depth, sampling location, and other parameters. Moreover, setting the overboard pH discharge limit based on achieving a minimum pH of 6.5 at 4 meters from the overboard discharge point *ensures* that the pH will be less than 6.5 at the overboard discharge point and is therefore less protective. Given that the pH of seawater is typically around 8.0, and that the pH scale is logarithmic, even achieving a pH of 6.5 means that the overboard discharge is 32 times more acidic than seawater. Additionally, ships typically mix the scrubber outlet water with "reaction water," which is usually ambient seawater, before discharging it overboard, artificially raising the pH before it is monitored, while emitting the same total amount of acids overboard.

Note that the U.S. Environmental Protection Agency (EPA) under its 2013 Vessel General Permit (VGP) requires a pH of no less than 6.0 at the overboard discharge point, or a maximum difference of 2 pH units during maneuvering and transit. However, the EPA does not allow the second provision (i.e., a pH of no less than 6.5 at 4 meters) because the minimum pH of 6.0 at the point of discharge is weaker than the IMO's minimum pH of 6.5 at overboard discharge and likely results in a pH greater than 6.5 at 4 meters. The EPA (2013) explains in its VGP fact sheet that allowing a minimum pH of 6.0 while disallowing the 4-meter provision is simpler, while essentially consistent with the IMO guidelines. However, in October 2020, the EPA issued a proposed rule that would harmonize its pH requirement with the IMO's 2015 guidelines (U.S. EPA, 2020). The EPA is accepting comments through November 2020.

PAH

BLG-WGAP 2 agreed that PAH was an appropriate indicator of oil content for scrubber washwater. They suggested that the U.S. EPA's 16 criteria PAHs (PAH_{16}) should be measured and that washwater criteria for PAH be further reviewed at BLG 12. At BLG 12, PAH_{16} was replaced with phenanthrene equivalence (PAH_{phe}) and the discharge limit was weakened. The original discharge limit was 15 ppb (approximately equal to 15 µg/L) of PAH_{16}; in other words, the sum total of EPA's 16 criteria PAHs. This was replaced with 50 µg/L of PAH_{phe}. Both limits were associated with a normalized washwater discharge rate of 45 t/MWh. Both the BLG-WGAP 2 recommendations and the 2008 guidelines explain that the PAH concentration should be measured downstream of any water treatment equipment, but upstream of any dilution or reactant dosing prior to discharge.

Turbidity

Both MEPC 57/4/1 and MEPC.170(57) set the limit at 25 NTU or FNU, although we found no justification for this limit. Additionally, "the discharge water treatment system should be designed to minimize suspended particulate matter, including heavy metals and ash," although there are no specific numeric limits associated with this. Also, open-loop systems do not typically have discharge water treatment systems.

Nitrates

For nitrates, BLG-WGAP 2 had draft limits in bracketed text associated with no more than a 10% removal of NO_x or 1 mg/L, whichever is greater. The bracketed text means the group could not agree on an exact limit and the "whichever is greater" language already sets a weaker standard than had it been phrased as "whichever is lower." During BLG-WGAP 2, the European Association of Internal Combustion Engine Manufacturers (EUROMOT) wanted to weaken the provision further by increasing the limit to that associated with a 20% removal of NO_x. Ultimately, BLG 12 agreed to somewhat weaken the draft limit from 10% to 12%, but also to dramatically increase the allowable nitrate concentration from 1 mg/L to 60 mg/L. Scrubber discharges can comply with the guidelines for nitrate concentrations under either limit. In practice, the concentration limit is easier to demonstrate compliance with, rather than trying to estimate what nitrate concentration would be associated with a 12% removal of NO_x. Additionally, because scrubbers are not designed to remove NO_x and, as we will show in the results, are expected to have no impact on NO_x emission factors, the relevant nitrate limit is 60 mg/L, because it is the greater of the two. The 2008 guidelines did not explain whether the nitrate limit was based on the discharge concentration or the difference between inlet and outlet concentrations. It was clarified in the draft 2020 guidelines that the limit is based on the latter. This clarification itself is a weakening of the nitrate limit, because seawater often contains nitrates. However, it is understandable that the guidelines would be interested in preventing additional nitrates from the scrubber system. We should note that washwater discharges contain both nitrates and nitrites; the IMO guidelines cover only nitrates. The United States, in its 2013 VGP, requires the sum of nitrates and nitrites to be less than 60 mg/L.

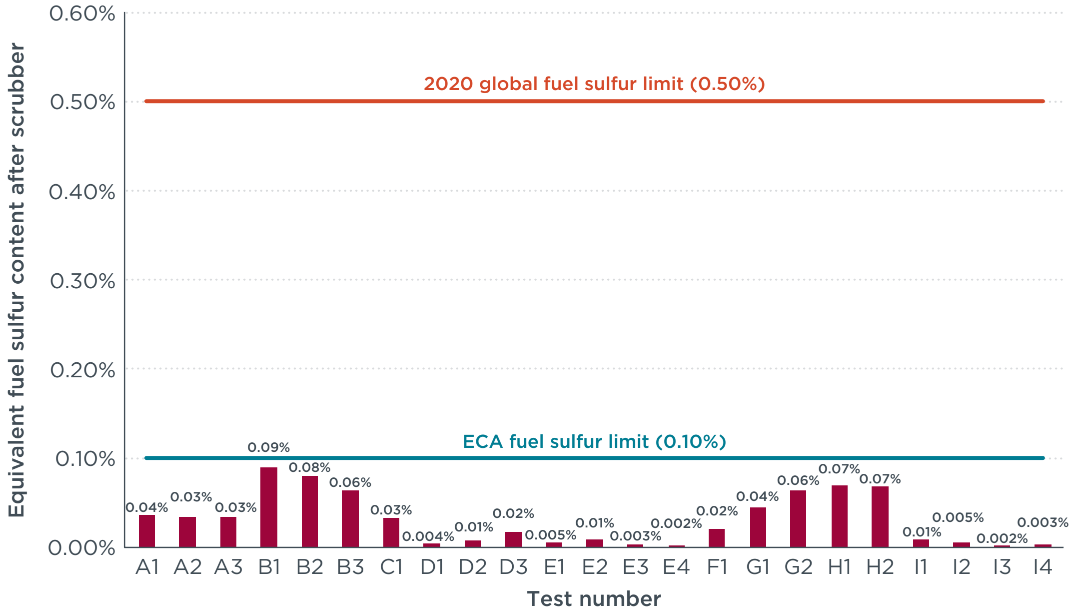
RESULTS

This section summarizes the air and water emissions associated with scrubbers based on a review of the available literature and our own calculations.

AIR EMISSIONS

We found eight studies representing 23 samples that contained information on air emissions from scrubbers (Fridell & Salo, 2016; Interlake Steamship Company, 2018; Johnson et al., 2017; Johnson, Miller, & Yang, 2018; Lehtoranta et al., 2019; Timonen et al., 2017; Wärtsilä, 2010; Winnes, Fridell, & Moldanová, 2020). We compared the emissions from ships with scrubbers to expected values for other marine fuels, based on the emission factors in the *Fourth IMO Greenhouse Gas Study* (Faber et al., 2020). A detailed spreadsheet containing information about ship type, engine, scrubber type, and emission factors is provided in the supplemental material.

We calculated the equivalent fuel sulfur content of ships with scrubbers based on the SO_2 emissions after the scrubber and the engine's specific fuel oil consumption (SFOC, measured in grams of fuel per kilowatt hour, g/kWh).[3] As shown in Figure 2, we found that all ships with scrubbers emitted SO_2 in amounts low enough to achieve equivalent fuel sulfur contents that were lower than both the 2020 global fuel sulfur limit of 0.50% and the ECA fuel sulfur limit of 0.10%. The original fuel sulfur content is presented in the table directly below the chart in the figure. While ships with scrubbers achieve lower SO_2 emissions than if they had used lower-sulfur fuels, other air pollutants are higher for ships with scrubbers than using ECA-compliant fuels, such as marine gas oil (MGO), as we explain next.



A	B	C	D	E	F	G	H	I
1.89%	2.50%	2.30%	2.77%	0.65%	1.90%	1.24%	1.35%	0.65%

Figure 2. Equivalent fuel sulfur content after the scrubber, with original fuel sulfur contents in the table.

3 Equivalent fuel sulfur content (% m/m) = $gSO_2/kWh \div (SFOC \times 0.97753 \times 2)$.

Table 5 shows the relative emissions in the exhaust for a ship using 2.60% sulfur heavy fuel oil (HFO) with a scrubber compared with other marine fuels, including 2.60% sulfur HFO without a scrubber, 0.50% sulfur very low sulfur fuel oil (VLSFO), 0.10% sulfur marine gas oil (MGO), and 0.07% sulfur MGO (global average fuel sulfur content as of 2019).

Table 5. Relative emissions change after the scrubber when using HFO (2.6% S) compared with other fuels

Comparison: 2.6% S HFO + scrubber versus...	SO_2	CO_2	PM_{10}	$PM_{2.5}$	NO_x	CO	BC (SSD)	BC (MSD)
HFO (2.6% S)	-98%	+2%	-79%	-79%	0%	-11%	-9%	-11%
VLSFO (0.50% S)	-90%	+4%	-59%	-59%	0%	-11%	unknown	unknown
MGO (0.10% S)	-52%	+4%	+61%	+61%	0%	-11%	+353%	+81%
MGO (0.07% S)	-31%	+4%	+69%	+69%	0%	-11%	+353%	+81%

We found that scrubbers can substantially reduce SO_x emissions, with average SO_2 emissions 31% lower than 0.07% sulfur MGO. Based on SO_2 emissions and fuel consumption, we calculated the equivalent fuel sulfur content, as shown in Figure 2. One must remember that scrubber SO_2 performance depends on a number of factors. The performance will vary based on the sulfur content of the fuel, engine power, engine load, scrubber water flow rate, and the alkalinity of the inlet or recirculating water. While all of the scrubbers tested meet the 0.10% ECA sulfur limit, it is possible that scrubber parameters may be adjusted to only just meet the relevant sulfur limits. For example, if a ship is operating outside of an ECA, the scrubber flow rate may be adjusted down to allow SO_2 emissions that would correspond to 0.50% sulfur fuel. In that case, the SO_2 emissions reductions from scrubbers compared with VLSFO and MGO would be overestimated when the ship is operating outside of ECAs. If scrubber operations are modified to allow higher sulfur emissions outside of ECAs, direct PM emissions would also increase. Therefore, although we found that using 2.6% sulfur HFO with a scrubber can reduce PM emissions compared with using 0.50% sulfur VLSFO, this reduction would be overestimated if scrubber parameters are adjusted to allow higher emissions outside of ECAs. Likewise, our finding that PM emissions for ships using 2.6% sulfur HFO with a scrubber were nearly 70% higher than MGO, on average, would be an underestimate, meaning that PM emissions from ships using HFO with scrubbers could be even higher on the high seas.

For climate pollutants, including CO_2 and black carbon (BC), using HFO with scrubbers results in higher emissions than MGO. Average CO_2 emissions were 4% higher using HFO with a scrubber compared with MGO. BC emissions using HFO with a scrubber were expected to be 81% higher than using 0.07% sulfur MGO in a medium-speed diesel (MSD) engine and more than 4.5 times higher than using MGO in a slow-speed diesel (SSD) engine. This is because both MSD and SSD engines emit substantially more BC emissions when using residual fuels such as HFO compared with distillate fuels like MGO (Comer, Olmer, Mao, Roy, & Rutherford, 2017; Faber et al., 2020; Olmer, Comer, Roy, Mao, & Rutherford, 2017). Therefore, even though the scrubber removes some BC from the exhaust (roughly 10%), ships using HFO with scrubbers still emit more BC than those using MGO.

Emissions of NO_x were sometimes lower and sometimes higher after the scrubber; however, based on the studies we reviewed, we found the average effect to be 0%. We do not expect scrubbers to have a significant direct impact on NO_x emissions because

NO_x formation is more sensitive to other parameters, including combustion temperature. We also found that scrubbers seem to somewhat reduce carbon monoxide (CO) emissions (-11% on average) across fuels. The mechanism by which scrubbers reduce CO emissions deserves further investigation. Based on these findings, Table 6 provides recommended emission factors for ships using HFO in combination with scrubbers.

Table 6. Recommended emission factors (g/kWh) for ships using HFO + scrubbers

Engine type	Engine age	SFOC (g/kWh)	Sulfur content	Carbon factor, Cf (gCO_2/g fuel)	Engine RPM	SO_2	CO_2	PM_{10}	$PM_{2.5}$	NO_x	CO	BC
SSD	<1984	209	2.60%	3.114	<130	0.19	650	0.30	0.28	18.2	0.48	0.04
SSD	1984-1999	188	2.60%	3.114	<130	0.17	586	0.30	0.27	18.2	0.48	0.03
SSD	2000-2010	178	2.60%	3.114	<130	0.16	554	0.30	0.27	17.1	0.48	0.03
SSD	2011-2015	178	2.60%	3.114	<130	0.16	554	0.30	0.27	14.5	0.48	0.03
SSD	2016+ outside ECA	178	2.60%	3.114	<130	0.16	554	0.30	0.27	14.5	0.48	0.03
SSD	2016+ in ECA	178	2.60%	3.114	<130	0.16	554	0.30	0.27	3.4	0.48	0.03
MSD	<1984	219	2.60%	3.114	720	0.20	681	0.30	0.28	14.1	0.48	0.09
MSD	1984-1999	198	2.60%	3.114	720	0.18	618	0.30	0.28	14.1	0.48	0.08
MSD	2000-2010	188	2.60%	3.114	720	0.17	586	0.30	0.27	12.1	0.48	0.08
MSD	2011-2015	188	2.60%	3.114	720	0.17	586	0.30	0.27	9.7	0.48	0.08
MSD	2016+ outside ECA	188	2.60%	3.114	720	0.17	586	0.30	0.27	9.7	0.48	0.08
MSD	2016+ in ECA	188	2.60%	3.114	720	0.17	586	0.30	0.27	2.4	0.48	0.08

In Table 7, we have estimated the expected life-cycle CO_2 emissions from ships using HFO with scrubbers compared with other fuels. We have taken into account the relative energy density and carbon factor (Cf) of each fuel based on the *Fourth IMO Greenhouse Gas Study* (Faber et al., 2020). We have also shown how SFOC changes based on fuel type and whether or not a scrubber is used. We assumed an SSD engine built in the year 2001 or newer. These SFOCs are consistent with the *Fourth IMO Greenhouse Gas Study*. We have added a 2% fuel consumption increase for HFO with scrubbers compared with HFO without scrubbers, consistent with our findings in Table 5, which show that using HFO with a scrubber emits 2% more CO_2 emissions than HFO without a scrubber. For VLSFO, we assume that it is an 80/20 blend of MGO and HFO to achieve a maximum 0.50% sulfur content.

Combustion emissions in grams of CO_2 per kilowatt-hour out (gCO_2/kWh out) are calculated by multiplying Cf (gCO_2/g fuel) by SFOC (g fuel/kWh out).

Upstream emissions (gCO_2/kWh out) are calculated as follows:

$$U_{out} = U_{in} \times \frac{EC}{1000} \times SFOC$$

U_{out} = upstream emissions (gCO_2/kWh out)

U_{in} = upstream emissions (gCO_2/MJ in) from GREET (Argonne National Laboratory, 2019), which is 13.5 for MGO and 10.7 for HFO; VLSFO is assumed to be 12.9, reflecting an 80/20 mix of MGO and HFO.

EC = energy content (kJ in/g fuel) as found in Table 7; dividing by 1,000 converts to units of MJ in/g fuel

SFOC = specific fuel oil consumption (g fuel/kWh out), which is listed by fuel in Table 7

As shown in Table 7, the expected combustion emissions for ships with HFO and scrubbers are higher than using MGO, while the upstream emissions are lower. Adding the two together, we find that the total well-to-wake (WtWa) emissions for a ship using HFO with a scrubber are expected to be 1.1% higher than using MGO.

Table 7. Life-cycle CO_2 emissions for ships using HFO + scrubbers relative to other fuels

				(gCO_2/kWh out)			
Fuel	**Energy content (kJ/g fuel)**	**Cf (gCO_2/g fuel)**	**SFOC (g fuel/kWh out)**	**Combustion**	**Upstream**	**Well-to-wake (WtWa)**	**WtWa relative to MGO**
MGO	42.7	3.206	165	529	95	624	0.0%
VLSFO	42.2	3.188	167	532	91	624	-0.1%
HFO	40.2	3.114	175	545	75	620	-0.6%
HFO + scrubber	40.2	3.114	178	554	77	631	+1.1%

WATER POLLUTANTS

We reviewed 17 studies and found that only 10 had enough information to assess whether scrubber discharges were complying with IMO guidelines. We evaluated each study based on whether it included relevant information on the ship, fuel sulfur content, scrubber type, engines, engine operating parameters, discharge water flow rate, and transparency of results, as shown in Table 8.

Many industry-funded studies such as Faber et al. (2019) and Carnival (2019) lacked the necessary information to determine the total mass of pollution discharges and to assess whether they satisfied IMO guidelines. For example, in Faber et al. (2019), 253 samples were analyzed, but only generalized information on ship types and engine loads at berth were provided. No flow rate was reported, which makes it impossible to determine if the discharges comply with the IMO guidelines. Nevertheless, Faber et al. (2019) improperly compared unadjusted per-liter concentrations of PAHs and other pollutants to the discharge criteria in the 2015 IMO guidelines; this was improper because they did not normalize the pollutant concentrations to a specific washwater flow rate. The IMO guidelines limit PAH concentrations to 50 µg/L at a normalized washwater flow rate of 45 t/MWh. Faber et al. (2019) explained that the PAH concentrations in their study “were not normalized” (p. 38). They used this to argue that the samples that had PAH concentrations greater than 50 µg/L may still comply with the guidelines, when exactly the opposite could be true. Without normalizing the pollutant concentrations to a specific washwater flow rate, no conclusions can be drawn regarding compliance with, or exceedance of, IMO guidelines.

We omitted three other studies that were at least partially funded by industry. One from Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT, 2018), as well as Wärtsilä (2010) and Koski, Stedmon, and Trapp (2017). While the MLIT (2018) study included information for many of the evaluation criteria, we could not fully understand the experimental set-up and therefore excluded it. From what we can understand, MLIT (2018) evaluated the characteristics of scrubber discharge water generated in the lab using a 257 kW, medium-speed laboratory engine and a hybrid scrubber. While MLIT (2018) provided measured values for certain discharge criteria, it was not clear if they related to open-loop or closed-loop operations, or what engine power and flow rate were associated with those values. Wärtsilä (2010) did not report measured values for any discharge criteria. Koski et al. (2017) did not provide information on the associated flow rate, making it impossible to calculate the total mass of pollutants discharged.

Government-funded studies typically contained more details, although some government-funded studies did not include enough information, including U.S. EPA (2011), which did not contain information on fuel type, sulfur content, or flow rate. Additionally, Ytreberg et al. (2019), which was funded by the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning, focused on how microplankton respond to scrubber discharge water exposures, rather than evaluating scrubber performance against IMO's discharge criteria and tests were done using discharges generated by a small laboratory engine rather than from a ship, hence ship identification information is not applicable. With these exceptions, government-funded studies were the most useful for this analysis. In some cases, such as Teuchies, Cox, Van Itterbeeck, Meyseman and Blust (2020), which was funded by the independent municipal Antwerp Port Authority, the study included detailed supplemental material containing raw data that was made publicly available. Except for Teuchies et al. (2020), the downside is that the government-funded studies often were limited in scope. Only a handful were able to measure more than one ship, and almost all measured a ship in European waters.

Table 8. Evaluation of the quality of sources containing information on scrubber discharges

Source	Includes ship ID information (e.g., IMO number)?*	Includes fuel type and sulfur content?	Includes scrubber type?	Includes engine power?	Includes flow rate?	Includes raw data?	Grade (% based on a max score of 12)	Enough information to be used in this study?	Funding source
Hansen (2012)	2	2	2	2	2	2	100%	Y	Government
Kjølholt et al. (2012)	2	2	2	2	2	2	100%	Y	Government
Ushakov, Senersen, Einang, & Ask (2019)	2	2	2	2	2	2	100%	Y	Government
Zhu et al. (2016)	2	2	2	2	2	2	100%	Y	Government
Ytreberg et al. (2019)	n/a	2	2	2	2	2	100%	N	Government
Magnusson, Thor, & Grandberg (2018)	2	2	2	0	2	2	83%	Y	Government/ Industry
Teuchies et al. (2020)	0	2	2	2	2	2	83%	Y	Government
Winnes et al. (2018)	2	2	2	2	0	2	83%	Y	Government
Buhaug, Fløgstad, & Bakke (2006)	2	1	2	2	0	2	75%	Y	Government/ Industry
Germany (2018)	0	2	2	0	2	2	67%	Y	Government
Hufnagl, Liebezeit, & Behrends (2005)	2	1	2	1	0	2	67%	Y	Industry
Koski, Stedmon, & Trapp (2017)	2	2	2	0	0	2	67%	N	Government/ Industry
MLIT (2018)	0	2	2	2	1	1	67%	N	Government/ Industry
US EPA (2011)	2	0	2	2	1	1	67%	N	Government
Wärstilä (2010)	2	2	2	2	0	0	67%	N	Industry
Faber et al. (2019)	0	0	2	0	0	1	25%	N	Industry
Carnival (2019)	0	0	1	0	0	1	17%	N	Industry

*Grading scale for all criteria: 2 = all relevant data provided; 1 = some relevant data provided; 0 = no relevant data provided.

We identified 10 studies containing a total of 112 discharge samples that were of high enough quality to compare scrubber discharges to the discharge criteria in the IMO guidelines. In this section, we compare reported values from the literature against the discharge criteria for pH, PAH, turbidity, and nitrates contained in the draft 2020 guidelines, which can be found in document PPR 7/22/Add.1, annex 9. These are the same as the limits first established in the 2008 guidelines, which are found in Resolution MEPC.170(57).

pH

Ten studies representing 63 samples contained usable information on pH. The pH was measured at the overboard discharge point for all but one sample (test number 111). Twenty-seven samples were from closed-loop scrubbers, and 36 were from open-loop or hybrid scrubbers operating in open-loop mode. The pH was higher (less acidic) for closed-loop systems because the pH can be more directly controlled using alkaline materials, such as caustic soda, before discharging (Figure 3). The median pH for closed-loop systems was 7.59, while it was 5.63 for open-loop systems.

Of the 27 samples from scrubbers operating in closed-loop mode, all but seven had a pH ≥ 6.5, which would comply with the IMO guidelines for when the ship is stationary. All but four samples had a pH ≥ 6.0, which would comply with the EPA's 2013 VGP. It was not always clear in the literature if the ships were stationary, maneuvering, or in transit during the sampling. Nevertheless, all but one of the closed-loop samples also had a delta pH of less than 2, which would comply with both the IMO guidelines and the EPA 2013 VGP for ships that are maneuvering or in transit.

The pH was lower (more acidic) for open-loop systems, because the buffering solution is seawater, which has variable alkalinity. The pH also depends on the amount of reaction water, which is usually ambient seawater, mixed in before monitoring. As a result, only six out of 36 samples from open-loop scrubbers had a pH of ≥ 6.5, while 14 had a pH ≥ 6.0. Only 13 of 36 samples had a delta pH of less than 2, meaning that, had the ship been moving, 23 of 36 samples would have failed to comply with the IMO guidelines. Only one measurement in one study reported pH from a sample taken 4 meters away from the overboard discharge point (Ushakov et al., 2020); that was reported to have a pH of 6.52, which is high enough to comply with both the IMO guidelines and the EPA VGP.

Overall, closed-looped scrubbers performed the best in terms of pH, with 74% of samples having a pH ≥ 6.5 and 85% ≥ 6.0. Additionally, 96% of closed-loop samples had a delta pH < 2. Open-loop scrubbers, on the other hand, performed poorly, with only 17% of samples having a pH ≥ 6.5 and 39% having a pH of ≥ 6.0. Only 36% of open-loop samples had a delta pH less than 2. This is despite the practice of diluting the discharge with additional seawater before monitoring. Blending scrubber discharge water with ambient seawater prior to dumping it into the sea does not change how much acid is added to the surrounding waters; it merely raises the pH before it is monitored for comparison with the guidelines. Port State control officers may need to consider how to ensure that ships are complying with the delta 2 pH limit during maneuvering and transit of waters under their jurisdiction.

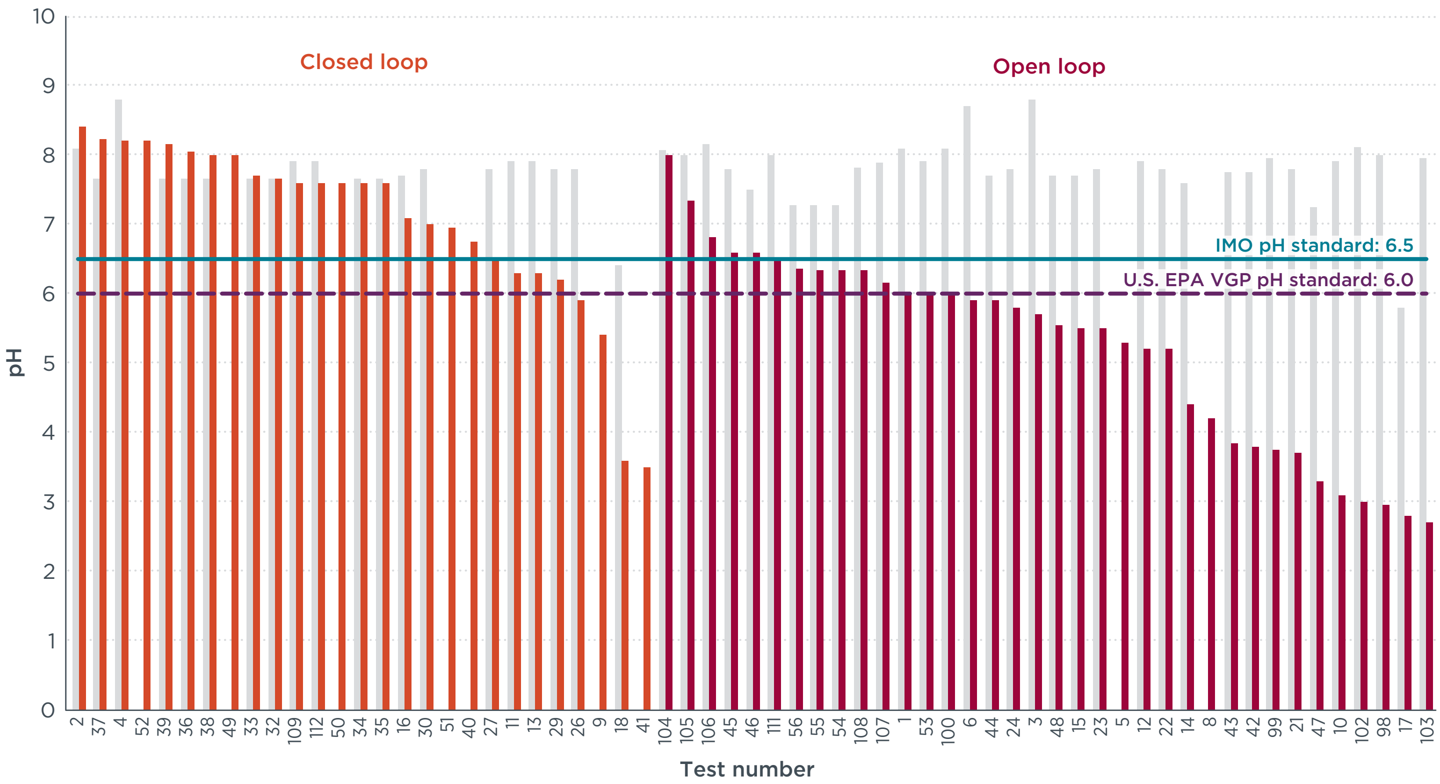


Figure 3. pH in scrubber discharge water. Gray bars show pH values before entering the scrubber system; orange and red bars show pH values after scrubbing process for closed- and open-loop scrubbers, respectively. Blue line indicates a pH of 6.5, consistent with IMO guidelines, and the purple dashed line is equal to a pH of 6.0, consistent with EPA 2013 VGP.

PAHs

Four studies representing 60 samples contained usable information on PAHs. Ten samples were from closed-loop scrubbers, and 50 were from open-loop scrubbers or hybrid scrubbers operating in open-loop mode (Germany, 2018; Kjølholt et al., 2012; Teuchies et al., 2020; Ushakov et al., 2020). Nearly all samples were below the PAH_{phe} limit. At 50 µg/L and 45 t/MWh, the maximum allowable discharge under the IMO guidelines is equivalent to 2,250,000 µg/MWh. As shown in Figure 4, 93% of samples complied with the IMO guidelines (note the log scale). Open-loop scrubbers emitted greater amounts of PAH_{phe} compared with closed-loop systems, oftentimes an order of magnitude higher. The median PAH_{phe} value for closed-loop systems was 6,630 µg/MWh, while it was 118,760 µg/MWh for open-loop systems.

Only four samples exceeded the discharge criteria for PAH_{phe}, and they were from open-loop scrubber measurements taken on board ships by Germany's Federal Maritime and Hydrographic Agency (Germany, 2018). The report, which tested washwater using onboard monitoring systems and additional in-situ measurements on board five ships, noted discrepancies between the two methods. It found that the onboard monitoring data showed lower PAH_{phe} values than the in-situ data. Worryingly, it also found that the onboard monitoring system seemed to be malfunctioning for two of the five ships, where PAH outlet concentrations were lower than inlet concentrations. This is highly unlikely, given that seawater has very low ambient concentrations of PAHs, so this suggested to the researchers that it was a calibration problem. While the onboard monitoring never found exceedances of the PAH_{phe} limits, the in-situ measurements showed that PAH_{phe} concentrations were greater than 50 µg/L in seven out of nine tests (two tests for each of four ships, plus one test for the fifth), but this was without normalizing the results to 45 t/MWh, which is what the guidelines are based on. We normalized them and found that four test points were above the discharge criteria, as shown in Figure 4.

The remaining studies that recorded open-loop discharges (Kjølholt et al., 2012; Teuchies et al., 2020; Ushakov et al., 2020) found PAH_{phe} emissions ranging from 7,000 to 1,600,000 µg/MWh, with an average of 900,000 µg/MWh. The large range indicates that open-loop PAH_{phe} discharges are inconsistent.

The two studies that reported closed-loop scrubber PAH_{phe} data (Germany, 2018; Teuchies et al., 2020) recorded PAH_{phe} discharges from the bleed-off water to be below the IMO guideline limits, within the range of 1,800 to 24,000 µg/MWh. Germany (2018) tested one ship with a closed-loop scrubber and, like the open-loop scrubbers they evaluated, noted significant discrepancies between the ship's onboard monitoring and the in-situ measurements for the closed-loop PAH_{phe} data. The in-situ PAH_{phe} measurements were as much as 33 times higher than those reported by the onboard monitoring system. Teuchies et al. (2020) compared their closed-loop PAH_{phe} measurements with the water quality standards of the European Water Framework Directive and noted that "the concentrations of most PAHs and all metals in closed loop bleed-off largely exceeded their WQS [water quality standards] and are expected to be acutely toxic for most aquatic organisms" (Teuchies et al., 2020, p. 7).

As previously mentioned, the current IMO guidelines are based on PAH_{phe}. Phenanthrene, which is a molecule of three fused benzene rings and is classified as a low molecular weight PAH of 178 g/mol, is one of 16 PAHs that is customarily analyzed. Out of the 16 PAHs, the molecular weights range from 128 g/mol for 2-ring naphthalene, to 276 g/mol for 6-ring Benzo[g,h,i]perylene. The tendency to bioaccumulate and to resist biodegradation generally increases with increasing molecular weight (Adeniji, Okoh, & Okoh, 2018). Selecting phenanthrene as the surrogate for all PAHs in discharge water has unclear origins. According to the U.S. EPA, the IMO's basis for selecting PAH_{phe} seems to be based on the fact that phenanthrene was found to be the most abundant PAH in the analysis of washwater during trials on the vessel *Pride of Kent,* which is reviewed in this report as Hufnagl et al. (2005). Recall that the United Kingdom used the *Pride of Kent* data in the submission to MEPC 55 that suggested a 30 ppb (~30 µg/L) limit for PAHs.

The U.S. EPA seems to find the IMO guidelines inadequate, given that monitoring 16 criteria PAHs is required in the 2013 EPA VGP. Bosch et al. (2009) critiqued the idea of "phenanthrene equivalents" as a proxy for measuring hydrocarbon emissions (i.e., oil), stating that the concept needs to be explained or replaced, due to the unknown amounts of other PAHs being emitted. Additionally, PAHs, phenanthrene and otherwise, are difficult to analyze on board. In some studies, discharge water samples were taken from the site and chemically analyzed in a lab. The onboard measurements depend on the measurement of the phenanthrene fluorescent intensity, and the results of that are dependent on the solubility of PAH_{phe} and proper calibration of the instrument (Tomioka & Hashima, 2019). Germany (2018) suggested higher calibration and maintenance frequency of the systems for onboard measurements after seeing the large discrepancies in detail between onboard and laboratory analyses.

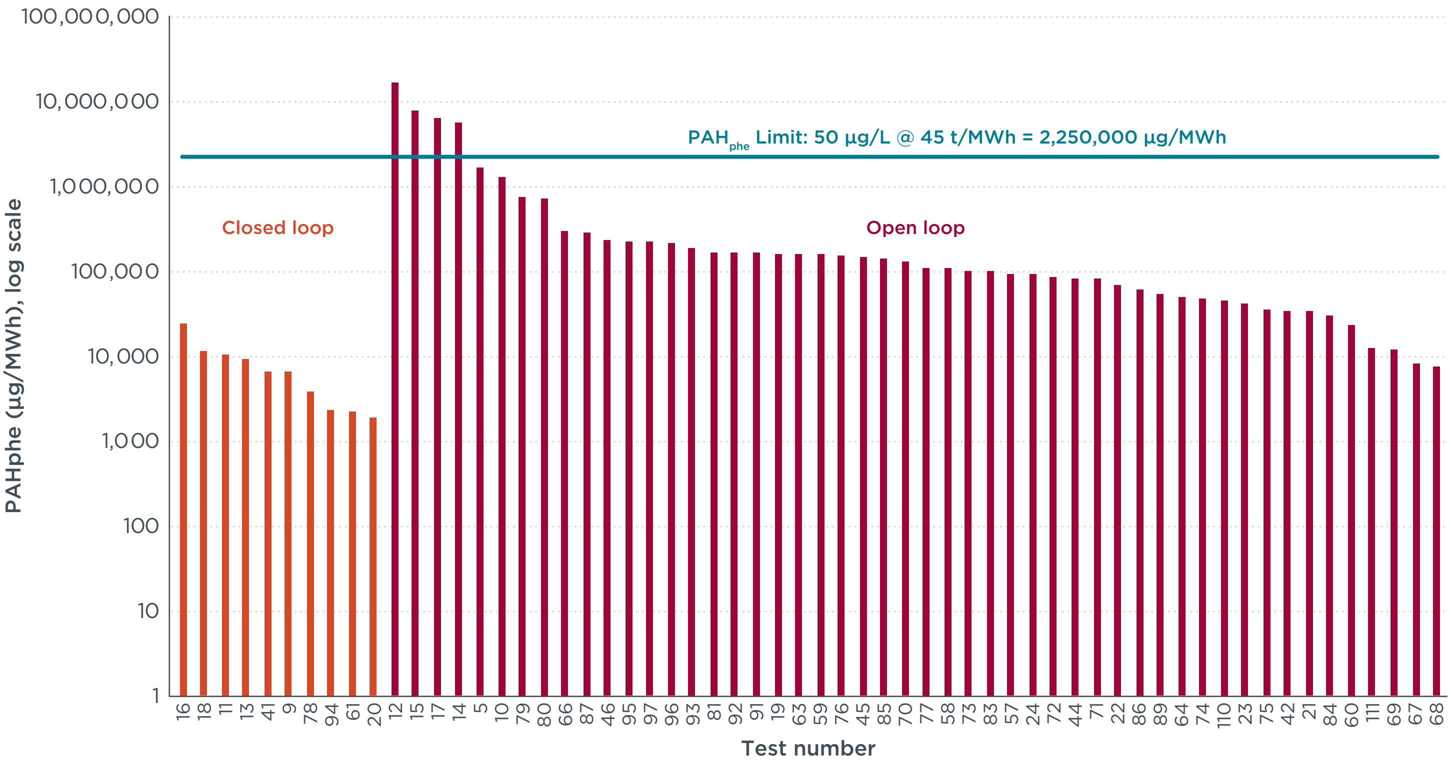


Figure 4. PAH_{phe} in scrubber discharge water.

Turbidity

Six studies representing 17 samples contained usable information on the turbidity of scrubber discharge water. Eight samples were from closed-loop scrubbers, and nine from open-loop or hybrid scrubbers operating in open-loop mode. The median turbidity for closed-loop systems was 9.9 NTU and it was 1.1 NTU for open-loop systems.

Closed-loop discharges had higher turbidity than open-loop discharges. It may be that there is higher turbidity in the closed-loop bleed-off water because it is more highly concentrated than open-loop discharges. It could also be that because water is recirculated, it becomes more turbid over time, despite water treatment designed to remove suspended solids as sludge.

The turbidity measurement units (FNU and NTU) both measure turbidity based on light scattering, although FNU uses infrared light and NTU uses white light. Two studies, Hansen (2012) and Ushakov et al. (2020), measured turbidity using FNU (see test numbers 100 for Hansen and 110 and 111 for Ushakov et al.). The one sample that measured above the IMO guideline's discharge criteria of 25 came from Germany (2018), which found an increase of 26.6 NTU from inlet water to outlet water for a closed-loop scrubber. Magnusson et al. (2018) found that the water treatment system used to collect residues from the closed-loop system they tested reduced turbidity in the discharge 96%, but even then the overboard discharge was at least 7.3 NTU higher than the surrounding seawater. Because no zeros were recorded, every discharge increased turbidity compared with the ambient seawater.

The IMO guidelines state that "the discharge water treatment system should be designed to minimize suspended particulate matter, including heavy metals and ash"

(PPR 7/22/Add.1, annex 9, p. 21). In practice, while closed-loop scrubbers intentionally separate out suspended particulate matter and store it onboard as sludge for on-land disposal, open-loop systems typically do not. A survey of scrubber manufacturers showed that open-loop systems typically do not collect sludge, implying that suspended particulate matter, including heavy metals and ash, are discharged overboard and not actually passed through a water treatment system (European Sustainable Shipping Forum, 2017). If solids were separated out, turbidity would be reduced, and heavy metals could be reduced as well because they can be attached to suspended solids. However, because the discharge water has a lower pH, metals can more easily dissolve into the water, rather than being held in the sediments. This was seen in a study by Wärtsilä (2010), which found high concentration of metals even though turbidity was well below the IMO discharge criteria. The U.S. EPA (2011) noted that there is no correlation between turbidity and particle concentration. Ushakov et al. (2020) questioned the scientific significance of measuring turbidity. They noted that the measured values depend on the scattering of light and the light source used, which can be influenced by seawater organics. Smaller particles in the discharge water would have low influence on the turbidity and could be missed, even though they may be contributing to pollution. Lastly, bubbles were a common source of interference in several studies, including Zhu et al. (2016), U.S. EPA (2011), and Wärtsilä (2010).

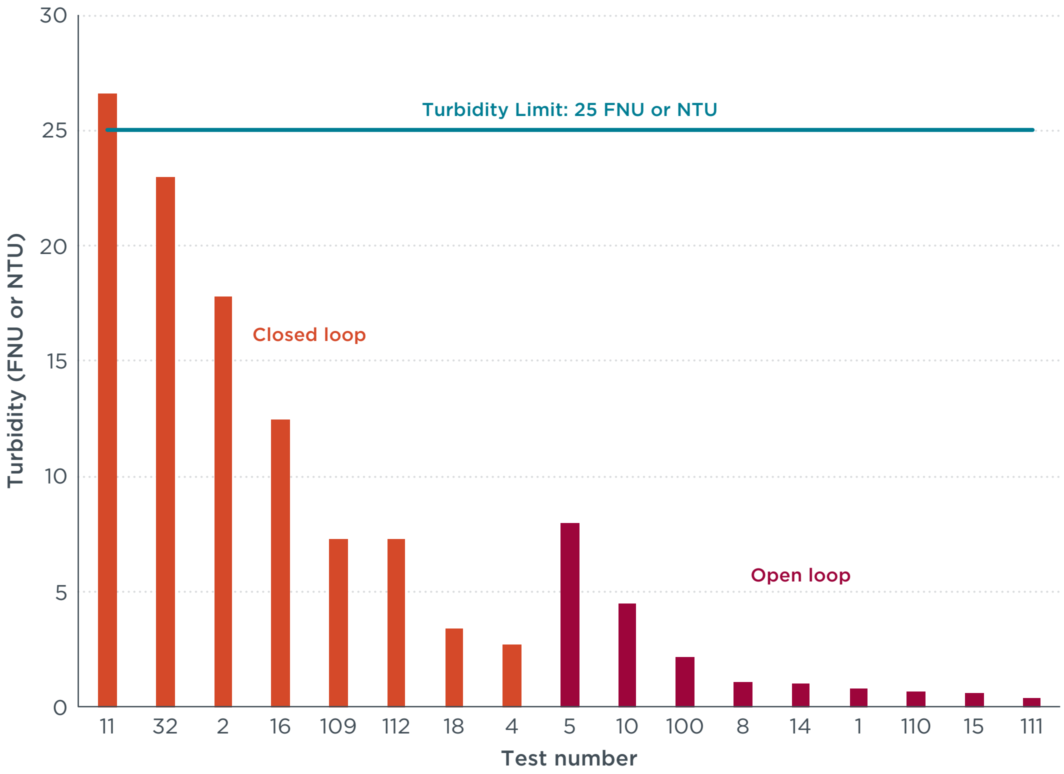


Figure 5. Turbidity in scrubber discharge water.

Nitrates

Four studies representing seven samples reported nitrates (Germany, 2018; Kjølholt et al., 2012; Magnusson et al., 2018; Zhu et al., 2016), and all but one were from closed-loop systems. No samples exceeded the IMO guidelines discharge criteria for nitrates, which at 60 mg/L at 45 t/MWh is equivalent to 2,700,000 mg/MWh. Given that there was only one value associated with open-loop discharges, it is not possible to compare discharge values between closed-loop and open-loop systems in detail. The median closed-loop discharge was approximately 125,000 mg/MWh. The sole open-loop discharge is 19,800 mg/MWh.

Nitrates and nitrites are essential for marine primary production, but an excess can accelerate eutrophication. Washwater discharges contain both nitrates and nitrites; however, the IMO guidelines cover only nitrates. The United States, in its 2013 VGP, requires ships to meet the same standard as the IMO guideline for nitrates, but it is the sum of nitrates and nitrites. Nevertheless, we have shown that scrubber discharges do not usually contain enough nitrates to exceed the limit in the IMO guidelines.

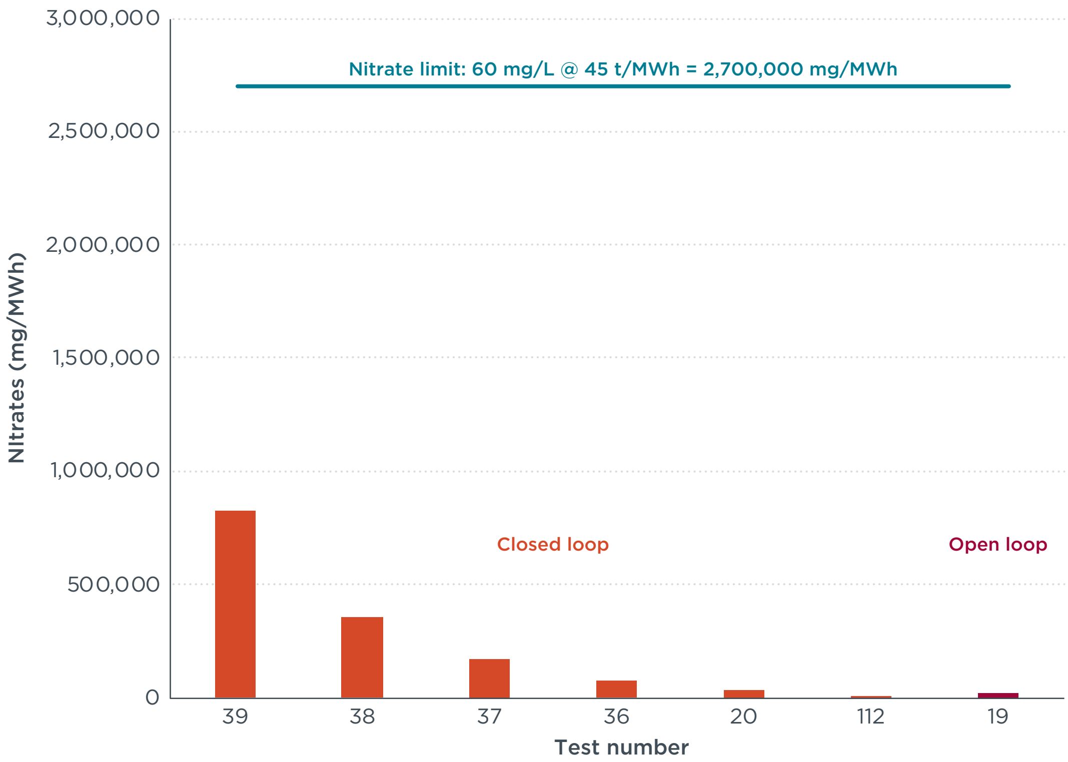
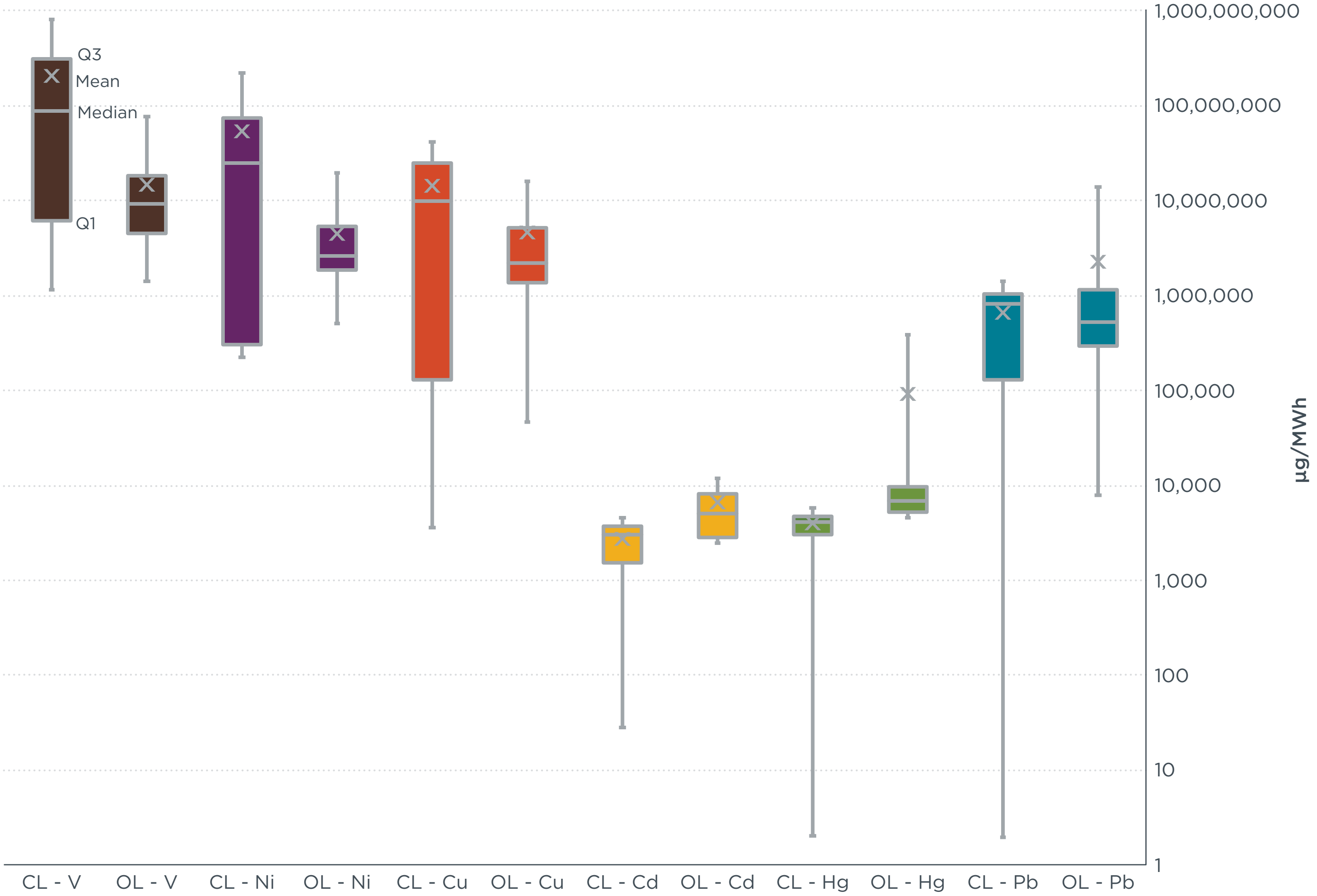


Figure 6. Nitrates in scrubber discharge water.

Heavy metals

We evaluated discharges of six heavy metals: vanadium, nickel, copper, cadmium, mercury, and lead. We found seven studies, representing 58 samples, that had reported values for at least one of these metals. Vanadium, which is found in HFO, was the most studied metal with 58 samples, 46 being from open-loop mode. As shown in Figure 7, vanadium had the highest average discharges of the metals studied, with closed-loop systems emitting more than open-loop, but the open-loop discharge values showed less variability. Nickel and copper displayed similar patterns of higher, more varying average values in closed-loop mode, but vanadium was discharged at significantly higher amounts than nickel and copper (note the log scale). Other metals, such as cadmium, mercury, and lead, were observed in smaller amounts, but had higher average discharges from open-loop scrubbers than closed loop. Open-loop discharges are more acidic, which could lead to larger amounts of dissolved heavy metals in the discharge water.

However, it appears that per MWh, closed-loop systems contribute greater mass of heavy metals than open-loop systems. With that said, additional work is needed to fully understand why closed-loop discharges exhibit greater variability. Currently there are no IMO guidelines for any heavy metal.



	CL - V	OL - V	CL - Ni	OL - Ni	CL - Cu	OL - Cu	CL - Cd	OL - Cd	CL - Hg	OL - Hg	CL - Pb	OL - Pb
Q1	6.2E+06	4.5E+06	3.1E+05	1.8E+06	1.3E+05	1.4E+06	1.5E+03	2.9E+03	3.0E+03	5.3E+03	1.3E+05	2.9E+05
Median	8.9E+07	9.3E+06	2.5E+07	2.6E+06	1.0E+07	2.2E+06	3.0E+03	5.0E+03	4.1E+03	6.8E+03	8.2E+05	5.2E+05
Q3	3.1E+08	1.8E+07	7.3E+07	5.3E+06	2.5E+07	5.2E+06	3.8E+03	8.3E+03	4.7E+03	9.8E+03	1.0E+06	1.1E+06
Mean	2.1E+08	1.5E+07	5.4E+07	4.4E+06	1.4E+07	4.5E+06	2.5E+03	6.1E+03	3.5E+03	8.4E+04	6.5E+05	2.2E+06

Figure 7. Heavy metal discharges (µg/MWh) for closed-loop (CL) and open-loop (OL) scrubbers, with values in the table. The box shows the interquartile range. The whiskers show the minimum and maximum values. The median and mean is marked by the X and the median is the horizontal line inside each box.

Table 9 includes recommended scrubber discharge water emission factors for each pollutant. They are based on rounded median values from the results presented in this section. Some emission factors are more certain than others. We found more data on pH, PAHs, and heavy metals, but less on turbidity and nitrates. The open-loop nitrate emission factor is based on one measurement and should be considered the least certain. On the other hand, the PAH_{phe} open-loop emission factor is based on 50 samples and should be considered the most certain. These emission factors can be used to get an understanding of the magnitude of water pollution from scrubbers, as well as trends over time. They will be particularly useful if paired with geospatial ship activity data so that the location and amount of discharges can be estimated. This could help determine the amount of pollution in ports, harbors, estuaries, rivers, critical habitats for marine life, Marine Protected Areas, Particularly Sensitive Sea Areas, and other areas of interest.

Table 9. Recommended scrubber discharge water emission factors

					Heavy metals (µg/MWh)					
Scrubber mode	**pH**	**PAH_{phe} (µg/MWh)**	**Turbidity (NTU)**	**Nitrates (mg/MWh)**	**Vanadium**	**Nickel**	**Copper**	**Cadmium**	**Mercury**	**Lead**
Closed loop	7.6	6,600	10	125,000	88,850,000	24,540,000	9,990,000	3,000	4,000	818,000
Open loop	5.6	119,000	1	20,000	9,310,000	2,590,000	2,180,000	5,000	7,000	519,000

CONCLUSIONS

This report assessed the impacts of scrubbers on air emissions and water pollution. Regarding air emissions, we found that scrubbers can substantially reduce SO_2 emissions, with emissions from ships using 2.6% sulfur HFO with a scrubber averaging 31% lower than 0.07% sulfur MGO. We also found that scrubbers seem to somewhat reduce CO emissions (-11% on average), although the mechanism by which this occurs deserves further investigation. For other pollutants, including CO_2, PM, and BC, using HFO with scrubbers results in higher emissions than MGO. Average CO_2 emissions were 4% higher using HFO with a scrubber compared with MGO. On a life-cycle basis, well-to-wake CO_2 emissions are expected to be 1.1% higher than using MGO. PM emissions from using HFO with a scrubber were approximately 70% higher than MGO, on average. BC emissions using HFO with a scrubber were expected to be 81% higher than using MGO in an MSD engine and more than four times higher than using MGO in an SSD engine. Emissions of NO_x were sometimes lower and sometimes higher after the scrubber; however, based on the studies reviewed, we found the average effect to be 0%. We do not expect scrubbers to have a significant direct impact on NO_x emissions because NO_x formation is more sensitive to other parameters, including combustion temperature.

Regarding water pollutants, we found that all scrubbers—open loop, closed loop, and hybrid—discharge water that is more acidic and turbid than the surrounding water. Additionally, all scrubbers emit nitrates, PAHs, and heavy metals. The acids that scrubbers emit contribute to ocean acidification. Discharge from open-loop scrubbers was typically more acidic than bleed-off water discharges from closed-loop systems. Turbid water degrades water quality and the suspended PM in turbid water can contain PAHs and heavy metals. We found that closed-loop bleed-off water was more turbid than open-loop discharges. We did not have enough information to determine which system—open or closed—emits more nitrates. Discharging nitrates contributes to acidification and can lead to eutrophication.

The amount of pollution that is discharged, as well as its ecological impacts, will depend on the characteristics of the inlet and receiving waters. Ships use scrubbers not only on the open ocean, but also in places with brackish and fresh water; in Canada, these include the St. Lawrence and Fraser estuaries, as well as the Great Lakes. Brackish and fresh waters are less alkaline than sea water, and this can affect the performance of the scrubbers. These waters may also already be contaminated by PAHs and heavy metals, meaning scrubber discharges will add additional pollution burdens to marine life. PAHs are carcinogenic and heavy metals are toxic, and both can accumulate in the water, sediments, and marine life. They bioaccumulate up the food chain and have been linked to cancer and immune system suppression in marine mammals including in killer whales and belugas. Open-loop systems emit substantially more PAHs than closed-loop systems, often orders of magnitude higher, whereas closed-loop systems tended to emit more heavy metals; this is an unexpected finding, given that closed-loop systems are meant to collect PM, which could include heavy metals, in onboard sludge tanks. One possible explanation is that the recirculating water collects more heavy metals before it is discharged as bleed-off. However, we found that the variability in closed-loop heavy metal discharges was greater than open-loop systems. Therefore, more work is needed to fully understand if open-loop or closed-loop systems emit different amounts of heavy metals.

In general, scrubber discharges from both open-loop and closed-loop systems usually comply with IMO guidelines. However, we question whether complying with the IMO guidelines should be taken as evidence that scrubbers are doing no harm to the aquatic environment. We discovered that the discharge criteria set out in IMO's guidelines were weakened at the very first opportunity. The first IMO scrubber guidelines were set in 2005 and did not include numeric discharge criteria but did state that pollutants should be eliminated or reduced to a level at which they are not harmful. Since then, the guidelines have only been weakened. The first numeric discharge criteria for pH, PAHs, turbidity, and nitrates were included in the 2008 guidelines, which were adopted by MEPC 57. The pH, PAH, and nitrate discharge criteria that were ultimately agreed to by MEPC 57 based on the outcomes of BLG 12 were substantially weaker than those proposed by the second intersessional BLG Working Group on Air Pollution (BLG-WGAP 2). Neither BLG 12 nor MEPC 57 gave any explanation for why these criteria were weakened from those proposed by the intersessional working group.

One could consider these results and conclude that the IMO guidelines simply need to be reviewed again and strengthened. However, we would argue that history has shown that the IMO guidelines were established at a limit that ensures that scrubber technologies can meet them. Given opportunities to strengthen the discharge criteria in 2009, 2015, and 2020, IMO member states declined, citing too little scientific evidence to revise them. The result is that the discharge criteria have not been strengthened since they were established. Meanwhile, the number of ships with scrubbers has grown exponentially, from three ships in 2008 to more than 4,300 in 2020. The guidelines ignore the cumulative effects of many ships operating and discharging in heavily trafficked areas, something to be expected given this rapid increase in the number of ships with scrubbers. Given that the IMO completed its most recent review of the guidelines at PPR 7 in 2020 and that MEPC will likely adopt them without further revision, we do not expect another opportunity to review and revise the discharge criteria at the IMO level for at least several years. During that time, thousands of ships will continue to use scrubbers that are designed to discharge acids, nitrates, solid particles, PAHs, and heavy metals to the marine environment, including in ports, harbors, estuaries, near shore areas, and busy shipping lanes where the combined effects could rapidly accumulate. This includes places like the Great Lakes, as well as British Columbia and the St. Lawrence estuary, where endangered species like the Southern Resident killer whale and belugas already suffer from high levels of contamination, including from PAHs and heavy metals.

The ICCT recommends that individual governments continue to take unilateral action to restrict or prohibit scrubber discharges from both open-loop and closed loop systems. We also recommend that the IMO focus on harmonizing rules for scrubber discharges including where, when, and even if those discharges should be allowed, and to do so with urgency. The IMO should consider prohibiting the use of scrubbers as a compliance option for newbuild ships and work to phase out scrubbers installed on existing ships. This is because we have found that using HFO with scrubbers is not equivalently effective at reducing air pollution compared to using lower sulfur fuels, such as MGO. Additionally, scrubbers of all kinds (open, closed, and hybrid) directly contribute to ocean acidification and water pollution, whereas lower sulfur fuels do not. Until then, we recommend that individual countries, including Canada, take immediate actions to protect their air and waters from scrubber emissions and discharges. These actions could include one or both of the following: (1) an immediate prohibition on using scrubbers to comply with the Canadian portion of the North American ECA because they are not equivalently effective at reducing air pollution as ECA-compliant fuels; (2) an immediate prohibition on all scrubber discharges in Canadian ports, internal waters, and territorial seas because they contribute to acidification and water pollution that can negatively affect marine life.

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