THESIS FOR THE DEGREE OF LICENTIATE OF PHILOSOPHY

Navigating towards environmental impact assessment of shipping -The marine perspective-

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Navigating through maritime and marine sciences. Illustration by Anna Lunde Hermansson.

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ABSTRACT

The shipping sector exert multiple pressures on the environment, affecting climate change, human health and the marine environment. From a policy perspective, shipping is usually assessed based on the emissions to air (e.g. carbon dioxide (CO_2), sulphur and nitrogen oxides (SO_X and NO_X) and particles) with the focus on limiting impact on climate and human health. Shipping is generally not considered as a main contributor of other hazardous substances to the marine environment. At the same time, none of the Baltic Sea basins has achieved Good Environmental Status in accordance with the Marine Strategy Framework Directive goals. Therefore, this thesis aims to lay the foundations to enable environmental impact assessment of the shipping sector, following the DAPSIR approach. DAPSIR connects society, environment and policy within a structured framework where for example; *Driver* can be human needs, *Activity* is the shipping sector, *Pressures* are contaminants that enter the environment which may change the environmental *State* that result in *Impact* on both the environment (e.g. biodiversity loss) and human welfare. Finally, *Responses* represent the actions needed to reduce adverse effects.

One objective within this work is to quantify the contaminant loads of metals and polycyclic aromatic hydrocarbons (PAHs), from different ship-activities with a focus on scrubbers. A scrubber is installed on ships as an abatement technique to meet the requirements stated in the new regulations of sulphur content in marine fuels. In a scrubber, the ship exhausts are led through a spray of water and SO_X is easily dissolved and particles are scavenged. The scrubber system can be open (where seawater is pumped through the system continuously), closed (where water is recirculated with a small bleed-off) or hybrid (where the mode of operation can be shifted between open and closed). The scrubber technique has moved the emissions from air to water with unknown impacts.

Emission factors of metals and PAHs from usage of marine gas oils (MGOs) and heavy fuel oils (HFOs), with and without the use of scrubbers, where derived from an extensive literature review. The results show that HFO combustion with a scrubber result in much higher emission factors of metals and PAHs as compared to the use of MGO. These emission factors were then used to determine the relative load contribution from scrubbers compared to other ship-activities, coastal industries, atmospheric deposition and riverine input to the Baltic Sea. The comparison revealed that open loop scrubber discharge and release of biocides from antifouling paints are the two largest anthropogenic sources of several metals and PAHs, e.g. copper, vanadium and anthracene, to the Baltic Sea. In addition, the cumulative environmental risk assessment of 9 metals and 16 PAHs from near-ship atmospheric deposition, antifouling paint, bilge water discharge, closed and open loop scrubber water discharge show unacceptable risk in three out of four ports.

The total contaminant load from shipping and subsequent risks of adverse effects on the marine environment can be assessed with existing tools. The use of HFO and scrubbers result in high emissions, in absolute and relative terms, of metals and PAHs to both air and water. The result suggests that the use of scrubbers cannot offer a sustainable solution and the discharge of scrubber water should be prohibited to increase the probability of achieving Good Environmental Status in the Baltic Sea.

Keywords: ship pollution, marine environment, DAPSIR, metals, polycyclic aromatic hydrocarbons, scrubbers

SAMMANFATTNING

Sjöfartssektorn introducerar flera belastningar på miljön vilket har en påverkan på klimatförändringar, människors hälsa och den marina miljön. Ur ett policyperspektiv bedöms sjöfarten vanligtvis utifrån utsläppen till luft (t.ex. koldioxid (CO_2), svavel- och kväveoxider (SO_X och NO_X) och partiklar) med fokus på att begränsa klimat- och hälsoeffekter. Detta har lett till att sjöfarten inte ingår bland de största bidragande sektorerna för utsläpp av farliga ämnen till havsmiljön och det saknas kunskap om sjöfartens påverkan på havsmiljön på lokal och regional nivå. Samtidigt uppnår ingen del av Östersjön God Miljöstatus i enlighet med målen i marina direktivet (MSFD). Därför syftar denna avhandling till att lägga grunden för att möjliggöra miljökonsekvensanalys av sjöfartssektorn, enligt DAPSIR-metoden. DAPSIR kopplar samman samhälle, miljö och policy inom ett strukturerat ramverk där exempelvis; *Drivers* är drivkrafter som representerar mänskliga behov (t.ex. mat, varor), *Activities* är aktiviteter inom sjöfartssektorn, *Pressures* är belastningar från föroreningar som släpps ut i miljön som ett resultat av fartygsaktiviteter, vilket kan resultera i en förändring av miljötillstånd (*State*). Detta kan i sin tur resultera i påverkan (*Impact*) på både miljö (t.ex. förlust av biologisk mångfald, minskad motståndskraft) och mänsklig välfärd. Slutligen, *Respons* och åtgärder behövs för att reducera negativa effekter av vårt nyttjande.

Fokus för denna avhandling är att koppla samman aktivitet, belastning och (förändring av) miljötillstånd genom att först kvantifiera belastningar av metaller och polycykliska aromatiska kolväten (PAHer), från olika fartygsaktiviteter och speciellt från skrubbrar. Skrubbrar introducerades till sjöfartssektorn för att möta de nya reglerna om svavelhalt i bränslen. På ett fartyg utrustat med en skrubber leds avgaserna genom en vattensprej vilket gör att SO_X löser sig och partiklar fångas upp. Skrubbersystemet kan vara öppet (där havsvatten kontinuerligt pumpas genom systemet), stängt (där vattnet recirkuleras med ett mindre utsläpp) eller hybrid (där driften kan växlas mellan öppet och stängd drift). Skrubbertekniken har flyttat utsläppen från luft till vatten med okänd påverkan.

Emissionsfaktorer av PAHer och metaller från användning av marin diesel (MGOs) och tjockolja (HFOs), med och utan användning av skrubbers, samlades in genom en omfattande litteraturstudie. Emissionsfaktorer användes vidare för att bestämma den relativa belastningen från skrubbrar i förhållande till belastningar andra fartygsaktiviteter, kustnära industrier, atmosfärsdeposition och flodtillförsel till Östersjön. På mer lokal skala bedömdes även belastning och den kumulativa risken av input av metaller och PAHer från fartygsaktiviteter i hamnar.

Resultaten från denna avhandling visar att förbränning av HFO, med eller utan skrubbrar, resulterar i mycket högre emissionsfaktorer av metaller och PAHer jämfört med användningen av MGO. Utsläpp från öppna (*open loop*) skrubbrar samt frigöring av biocider från antifouling-färger utgör en väsentlig del av belastningen av t.ex. koppar, vanadin och antracen till Östersjön. Den relativa kumulativa risken för 9 metaller och 16 PAHer från fem föroreningskällor (dvs. atmosfärsdeposition, skrovfärg, länsvattenutsläpp samt skrubbervattenutsläpp från slutna och öppna system) nådde oacceptabla nivåer i tre av fyra hamnar som ingick i denna studie.

Avhandlingen visar att den totala föroreningsbelastningen från sjöfart och efterföljande risker för negativa effekter på den marina miljön kan bedömas. Användningen av HFO tillsammans med en skrubber resulterar i höga utsläpp, i absoluta och relativa termer, av metaller och PAHer till både luft och vatten. Resultatet tyder på att användningen av skrubbrar inte kan erbjuda en hållbar lösning och att utsläpp av skrubbervatten bör förbjudas för att öka sannolikheten för att uppnå god miljöstatus i Östersjön.

Nyckelord: föroreningar från sjöfart, marin miljö, DAPSIR, metaller, polycykliska aromatiska kolväten, skrubbrar

ACKNOWLEDGEMENT

In the true spirit of *last minute*, with only few minutes left until printing I find myself having one last thing to write – the acknowledgements. Last, but certainly not least I realise there are so many people I want to thank. This last couple of years have certainly been a journey and I want to share my appreciation to all of you who has been a part of it. I hope you know who you are, I certainly do!

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Finally, to Arvid – for your endless encouragement but, more importantly, for reminding me of all the other, non-work-related, stuff that I love. Looking forward to our future adventures together!

Second half starts now!

List of Publications

Paper I

Lunde Hermansson, A., Hassellöv, I.-M., Moldanova, J., & Ytreberg, E. (2021). Comparing emissions of polyaromatic hydrocarbons and metals from marine fuels and scrubbers. *Transportation Research Part D: Transport and Environment*, 97. https://doi.org/10.1016/j.trd.2021.102912

Authorship contribution CRediT Anna Lunde Hermansson: Methodology, Investigation, Writing - original draft, Writing - review & editing, Visualization.

Paper II

Ytreberg, E., Hansson, K., Lunde Hermansson, A., Parsmo, R., Lagerström, M., Jalkanen, J.-P., & Hassellöv, I.-M. (2022). Metal and PAH loads from ships and boats, relative other sources, in the Baltic Sea. *Marine Pollution Bulletin*, 182. https://doi.org/10.1016/j.marpolbul.2022.113904

Authorship contribution CRediT Anna Lunde Hermansson: Writing – review & editing, Visualization, Formal analysis.

Paper III

Lunde Hermansson, A., Hassellöv, I.-M., Jalkanen, J.-P., & Ytreberg, E. (2022). Cumulative risk assessment of metals and polycyclic aromatic hydrocarbons from ship emissions in ports. *Manuscript in preparation*. Planned submission to *Journal of Environmental Management.*

Authorship contribution CRediT Anna Lunde Hermansson: Methodology, Investigation, Writing - original draft, Writing - review & editing, Visualization, Formal analysis

LIST OF ADDITIONAL PUBLICATIONS AND REPORTS

Derivation of environmental quality standards in sediment, commissioned by the Swedish Agency for Marine and Water Management within the project: Update and development of new assessment criteria for metals

Lunde Hermansson, A., & Ytreberg, E. (2022). Zinc in sediment - an environmental quality standard overview. Chalmers Research. https://research.chalmers.se/en/publication/530951/file/530951_Fulltext.pdf

Lunde Hermansson, A., & Ytreberg, E. (2022). Arsenic in sediment - an environmental quality standard overview. Chalmers Research. https://research.chalmers.se/en/publication/530952/file/530952_Fulltext.pdf

Lagerström, M., Lunde Hermansson, A., & Ytreberg, E. (2021). Copper as a HELCOM core indicator. Chalmers Research. https://research.chalmers.se/en/publication/527564/file/527564_Fulltext.pdf

Deliverable to the Horizon 2020 project - EMERGE: Evaluation, control and Mitigation of the EnviRonmental impacts of shippinG Emissions

Ytreberg, E., A. Lunde Hermansson and I.-M. Hassellöv (2020). Deliverable 2.1 - Database and analysis on waste stream pollutant concentrations, and emission factors. EMERGE: Evaluation, control and Mitigation of the EnviRonmental impacts of shippinG Emissions, funded by European Union's Horizon 2020 research and innovation programme under grant agreement No 874990. pp: 1-37.

Governmental report commissioned by the Swedish Transport Agency and the Swedish Agency for Marine and Water Management

Hassellöv, I.-M., Lunde Hermansson, A. and Ytreberg, E. (2020) Current knowledge on impact on the marine environment of large-scale use of Exhaust Gas Cleaning Systems (scrubbers) in Swedish waters. Technical report.

Pre-study commissioned by the Swedish Agency for Marine and Water Management within the project Better environmental performance in shipping and improved onboard practices

Lunde Hermansson, A. och Hassellöv, I.-M. (2020) Tankrengöring och dess påverkan på havsmiljön. Rapport nr 2020:6, Havsmiljöinstitutet. https://www.havsmiljoinstitutet.se/digitalAssets/1804/1804376_hermansson---hassello--v-tankrengo--ring-hmi-2020_6_rev_4mars-22.pdf

also translated to English in 2022: https://havsmiljoinstitutet.se/digitalAssets/1809/1809544_tank-cleaning-and-its-impact-on-the-marine-environment_sime-report-2022.6.pdf

CONTENTS

ABBREVIATIONS

AFS	International Convention on the Control of Harmful Antifouling Systems on Ships
BSAP	Baltic Sea Action Plan
BSPA	Baltic Sea Protected Areas
BWM	International Convention for the Control and Management of Ships' Ballast Water and Sediments
CO_2	Carbon dioxide
DAPSIR	Driver-Activity-Pressure-State-Impact-Response
DNV-GL	Det Norske Veritas - Germanischer Lloyd
EC	European Commission
ECA	Emission Control Area
EEA	European Environmental Agency
EEZ	Exclusive Economic Zone
EMSA	European Maritime Safety Agency
EU	European Union
EQS	Environmental Quality Standards
IEA	International Energy Agency
GES	Good Environmental Status
HELCOM	The Baltic Marine Environment Protection Commission
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
MAMPEC	Marine Antifoulant model to Predict Environmental Concentrations
MARPOL	International Convention for the Prevention of Pollution from Ships
MEC	Measured Environmental Concentration
MEPC	Marine Environment Protection Committee
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
MSFD	Marine Strategy Framework Directive
NaOH	Sodium hydroxide
NECA	Nitrogen Emission Control Area
NO_X	Nitrogen oxides
OSPAR	The Convention for the Protection of the Marine Environment of the North-East Atlantic
PAH	Polycyclic Aromatic Hydrocarbon
PEC	Predicted Environmental Concentration
PM	Particulate matter
PNEC	Predicted No Effect Concentration
PPR	Sub-Committee on Pollution Prevention and Response
PSSA	Particularly Sensitive Sea Area
RBSP	River Basin Specific Pollutants
RCR	Risk Characterization Ratio
SECA	Sulphur Emission Control Areas
SO_X	Sulphur oxides
STEAM	Ship Traffic Emission Assessment Model
ULSFO	Ultra-Low Sulphur Fuel Oils
UN	United Nations
UNCLOS	The United Nations Convention on the Law of the Sea
VLSFO	Very Low Sulphur Fuel Oils
WFD	Water Framework Directive

1 INTRODUCTION

Shipping is an important prerequisite for global trade and tourism (Stopford, 2008; Andersson et al., 2016). This is also reflected in the European Union (EU) Blue Economy report where shipping is represented as a key contributor within all established Blue Economy sectors, such as maritime transport, port activities and coastal tourism (EC et al., 2022). Although, some issues concerning the shipping industry's impact on the environment are mentioned in the EU report, the main focus is on the air pollutants such as sulphur and nitrogen oxides (SO_X and NO_X) and the strive for decarbonization, i.e. reducing the emissions of carbon dioxide (CO_2). However, shipping is also responsible for a large contribution of contaminants entering the marine environment via engine exhausts emissions and discharges from different onboard systems. These contaminants exert great pressures on an already threatened ocean.

Today, input of hazardous substances is identified as a main pressure on European Seas (EEA, 2019b) and focus is more often directed towards the reduction of hazardous compounds from land-based sources (EEA, 2019b; UN SDG 14). However, ships also give rise to substantial emissions of hazardous substances (e.g. Jalkanen et al., 2021; Lunde Hermansson et al., 2021). Yet ships' contributions are rarely included in the assessment, implying that the hazardous substance contribution from ships is overlooked. At the same time, almost 97% of the Baltic Sea area were classified as *problem areas* in an integrated status assessment by the European Environmental Agency (EEA, 2019b) and the goal of reaching Good Environmental Status by 2020 in the Baltic Sea area, in accordance with the Marine Strategy Framework Directive (MSFD), have not yet been met (EC, 2008, 2017; HELCOM, 2018c).

A collective assessment of the environmental risks associated to ship activities, both in terms of contaminant and contaminant sources, is necessary to get the complete perspective. This was also acknowledged by Moldanová et al. (2022) who proposed a structured approach, following the classical DPSIR framework, to assess different pressures related to shipping. DPSIR is a widely accepted conceptual framework to describe the connections between society (*Drivers*, *Pressures*), environment (*State, Impact*) and policy (*Response*). As a more recent addition, A for human *Activities* have been included to facilitate distinguishment between drivers and pressures (Borja et al., 2006; Atkins et al., 2011). Also, the DAPSIR framework is applied within marine management legislations (e.g. the Water Framework Directive (WFD) and MSFD) as well as regional sea conventions (e.g. HELCOM and OSPAR) to work towards ecosystem-based management (Borja et al., 2010). Thus, the overall research approach adopted within this thesis is based on the DAPSIR framework (Figure 1). The use of the different components (i.e. D-A-P-S-I-R) and the scope of DAPSIR have varied over time (Elliot et al 2017), within this thesis, all components are defined from the perspective of shipping and limited to effects and impacts on the marine environment.

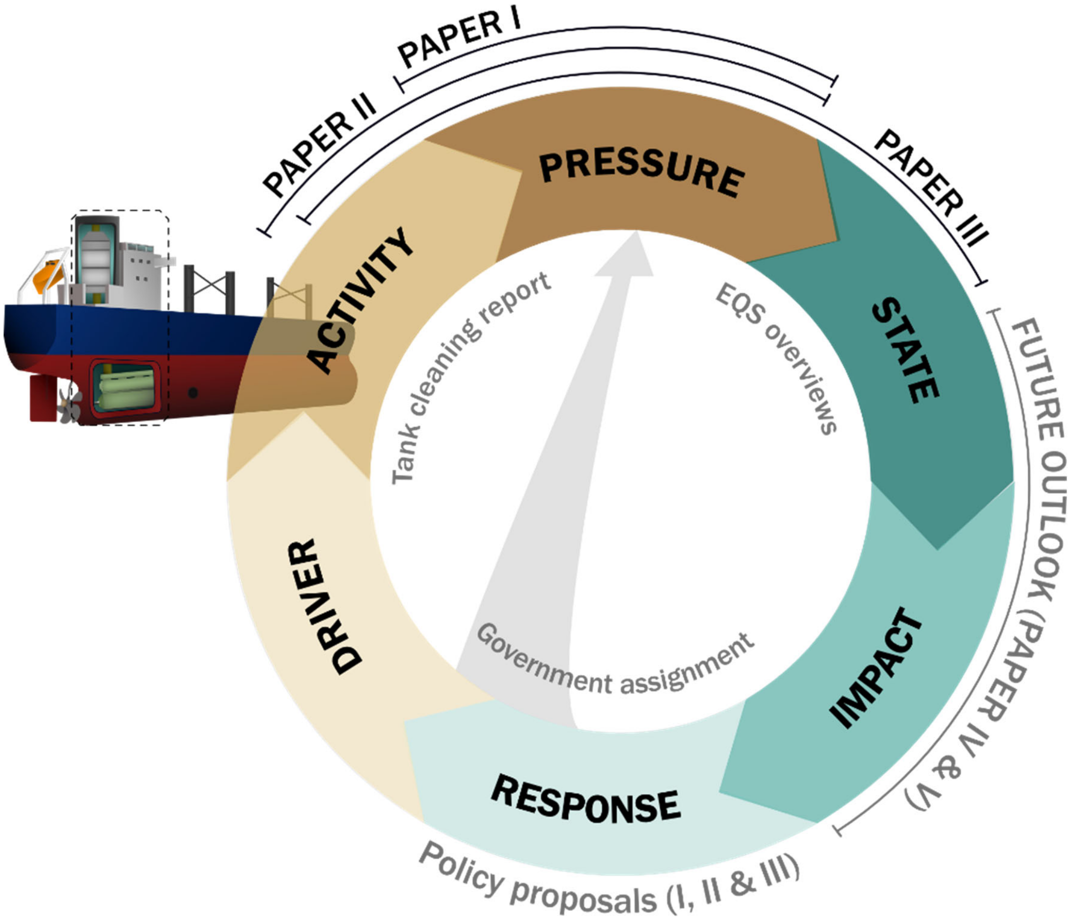


Figure 1: How the work behind this thesis fit within the DAPSIR framework. The bars indicate the parts of DAPSIR that correlate with the papers presented within this thesis and where to aim in future outlook. Also, reports related to the work is listed in the inner circle where tank cleaning refers to a pre-study on legal discharges of tank cleaning effluents (Lunde Hermansson and Hassellöv, 2020), EQS overview are three reports on sediment quality standards of copper, zinc and arsenic (Lagerström et al., 2021; Lunde Hermansson and Ytreberg, 2022b; Lunde Hermansson and Ytreberg, 2022a) and the Government assignment refer to a report on scrubber-use (Hassellöv et al., 2020b) that was also submitted as a supporting document to the Sub-Committee on Pollution Prevention and Response meeting (PPR 9) of IMO in 2022.

The *Drivers* are defined as (basic) *human needs* in accordance with Elliott et al. (2017) and in the case of shipping, this can for example be connected to human consumption (e.g. shipping of goods and food) or recreational needs (e.g. cruises). *Activities* are related to the operation of a ship and will depend on the type of ship, number of crew and passengers, and different onboard systems. Shipping is the main activity (also a sector) and the different sub-activities produce different *Pressures*, explained more in detail in section 2.1. When activities and pressures are known, a *State*, or change in state, can be assessed. Although the *Impact* component should focus on human welfare (Atkins et al., 2011; Elliott et al., 2017), within this thesis *Impact* will also include the marine environmental impact which can be assessed in terms of change in ecosystem functioning without an established link to human welfare. *Response* (and measures) permeates all work as the underpinning aim is to provide decision-support to stakeholders and policy makers when mitigating, regulating and planning the use and conservation of the marine environment. Response does not only act on the *Driver* component but can be directed towards the other components through specific regulations e.g. restriction of discharges from onboard systems (illustrated by grey arrow in Figure 1).

Within this thesis, Paper I focus on characterising emission factors of contaminants from ships operating with different marine bunker fuels (Lunde Hermansson et al., 2021) while Paper II is comparing the pressure of contaminants from different human activities, including shipping, in the Baltic Sea region (Ytreberg et al., 2022). Based on the results of Paper I and II, Paper III assesses how the pressure of contaminants from shipping may impact the marine environment, and more specifically degrade the environmental *State* in different Baltic ports.

The main *Activity*, and contaminant source, at the focus of this work is the exhaust gas cleaning systems, commonly known as scrubbers, and the emissions and discharges connected to the scrubber operation. Scrubbers are installed on ships to reduce the air emissions of SO_X and particulate matter (PM) to meet the new regulations of the International Maritime Organization (IMO, 2020). The regulations stipulate that the maximum sulphur content in fuels should not exceed 0.5% m/m (globally) and in sulphur emission control areas (SECAs), the limit is 0.1 % m/m. To meet the regulations, ships have to switch to more expensive low sulphur fuel oils or continue to use cheaper high sulphur fuel oils and install a scrubber that ensures air emissions of SO_X and PM at compliant levels, equivalent to low sulphur fuels.

There are three different types of scrubber systems: open loop, closed loop and hybrid scrubbers (section 2.3). The process of the three systems is similar, exhausts are led through a fine spray of water and SO_X is easily dissolved in the water, forming sulphuric acid, while PM and contaminants are also scavenged. In the open loop system, with >80% of the market share (DNV-GL, 2021; Ytreberg et al., 2022), seawater is used as scrubber agent and after the scrubber process, the contaminated water is discharged directly back at sea (Figure 2). The closed loop system is instead recirculating freshwater, with an addition of base to improve SO_x uptake. In a closed loop system, considerably smaller volumes are discharged. The hybrid system can switch between open and closed loop mode to enable compliance with different local regulations. Despite fulfilling the requirements of reducing air emissions of SO_X, the scrubber technology introduces a new contaminant source, scrubber discharge water, that is highly acidified (pH around 3.9 ± 0.2) and enriched with contaminants such as metals and polycyclic aromatic hydrocarbons (PAHs) (Lunde Hermansson et al., 2021 (Paper I)). The main pressure covered within this thesis is thus the contaminant load of metals and PAHs related to the fuel consumption and the use of scrubbers. Also, near-ship atmospheric deposition, biocide release from antifouling paints and bilge water discharge are included for comparison (Paper III).

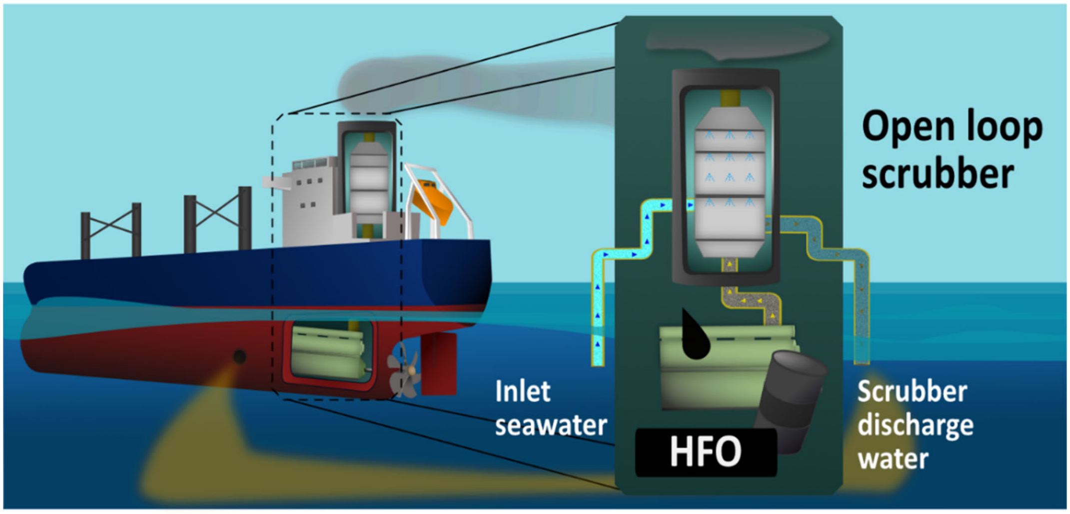


Figure 2: Simplified illustration of an open loop scrubber system where seawater is pumped into the scrubber and sprayed over the exhaust coming from the engine. The air emissions are then compliant with the IMO regulations with respect to SO_X and PM but the discharge water, that is highly acidified and enriched with metals and PAHs, is being discharged directly to sea.

In the Baltic Sea area, Osipova et al. (2021) estimated that the total volumes of discharged scrubber water amounted to almost 300 million tonnes in 2020. With an increasing share of the global fleet installing or opting to install scrubbers (Hassellöv et al., 2020a; DNV-GL, 2021; Ytreberg et al., 2022 (Paper II)), it is crucial to investigate the composition of this discharge water and the implications the discharges will have on the marine environment.

Several countries within and outside of Europe (e.g. Germany, Belgium, China) have already acted within their mandate and put a ban on the discharge of (open loop) scrubber water discharge. For several years, there has been a discussion within IMO on how to assess the risks and impacts associated to the discharge of scrubber water (Germany, 2018; Japan, 2019a; Austria et al., 2021) and recently, new guidelines were approved by the MEPC (2022).

To illustrate the different perceptions related to scrubber use; on the one side the EEA and the European Maritime Safety Agency (EMSA) are using a rather vague terminology when referring to scrubbers and their environmental impact (EMSA and EEA, 2021 (EMTER report)):

*"...effective controls **may** be needed to minimise the **potential** negative effects, **if any**, on the marine environment caused by the resulting overboard discharges."*

EMTER report p. 117

While, at the same time, in the latest World Ocean Assessment II (UN, 2021) the authors expresses their concern regarding shipping, and scrubbers explicitly, with the following sentence:

*“There is a general **knowledge gap** on the nature and impact of liquid input from ships, and the discharge of water from exhaust gas cleaning systems (scrubbers) is an **emerging source** of metals and polycyclic aromatic hydrocarbons.”*

WOA p. 103

The overall aim of this thesis is to fill parts of that gap by assessing the marine environmental risks associated to ship activities, focusing on scrubbers and the associated discharge of metals and PAHs to the marine environment. Also, the work aims to continue to fit the new knowledge within the framework of DAPSIR with clear connections to response, policy and current regulations (Figure 1). The specific objectives are to:

1) present emission factors of metals and PAHs in scrubber discharge water together with emission factors to air from combustion of different fuels (Lunde Hermansson et al., 2021 (Paper I)),
2) compare the loads of metals and PAHs from scrubber discharge water, relative other natural and anthropogenic sources, to the Baltic Sea area (Ytreberg et al., 2022 (Paper II)) and
3) assess the cumulative environmental risk associated to emissions of contaminants from shipping, by including several contaminants and contaminant sources simultaneously (Paper III)

The study area is the Baltic Sea, a shallow, semi-enclosed brackish sea area in northern Europe. The Baltic Sea has a large catchment area, resulting in a salinity gradient stretching from the Kattegat basin (S=25‰), to the Bothnian Bay (S=3‰) (Rodhe and Winsor, 2003). The northerly location, enclosure by land and strong seasonality create a unique and fragile ecosystem.

The Baltic Sea is exposed to several pressures from human activities which, together with the poor water exchange and high sensitivity (Stigebrandt, 2003; HELCOM, 2018c;a), makes it especially important to understand the potential impact the release of scrubber water can have on this environment.

2 BACKGROUND

Understanding the difficulties and challenges of assessing environmental impact from shipping and the potential socio-economic responses, requires interdisciplinary knowledge within marine, atmospheric and maritime sciences. This includes multiple disciplines from the in-depth knowledge of atmospheric and marine chemistry to the understanding of maritime industry and the economy of scale. Also, knowledge of the regulatory frameworks is paramount, not only with regards to shipping but also to marine management, conservation and utilization of ecosystem services provided by the marine environment. In order to do so, the potential ecotoxicological pathways of different contaminants and methods on how to assess environmental risk must also be included.

Therefore, the work requires the combination of in-depth knowledge, where different disciplines are working together, as well as the expansion of knowledge for individuals to understand and assess the scope of maritime and marine environmental sciences.

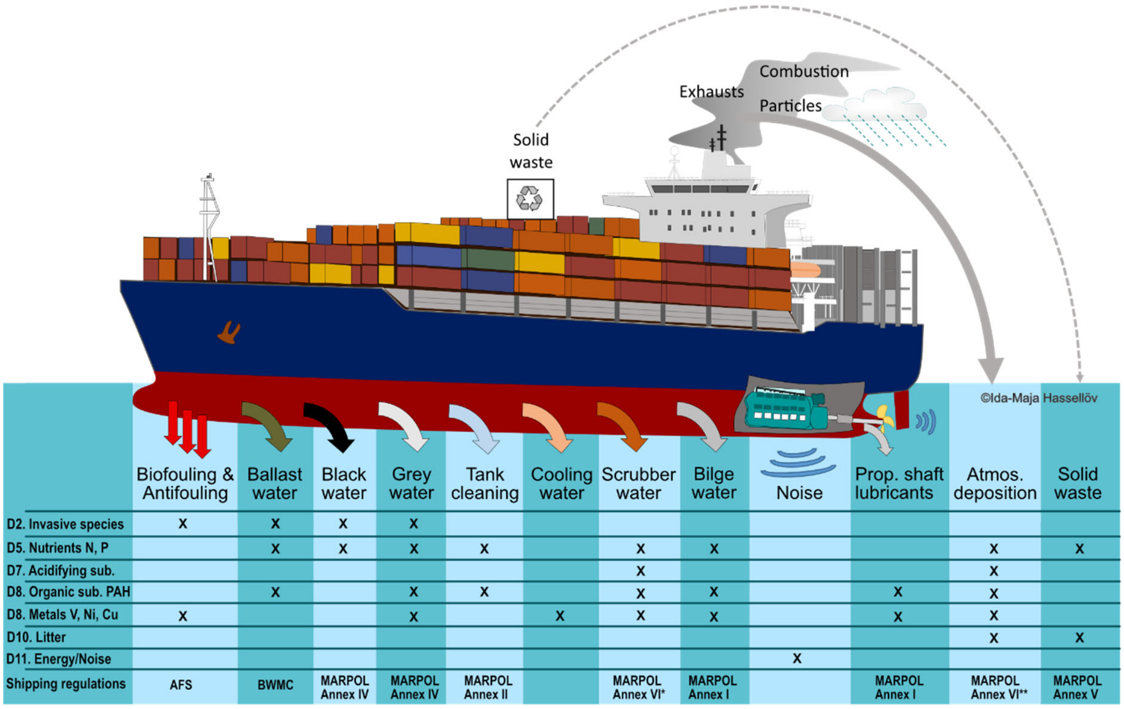
2.1 SHIP-SOURCE POLLUTION IN THE BALTIC SEA

At every given moment, around 1500 commercial ships are present in the Baltic Sea area (HELCOM, 2018a). Each ship can exert several different pressures on the environment including; emission of air pollutants, discharge of hazardous, eutrophying and acidifying substances, underwater noise/energy input and introduction of invasive species. Some of these pressures are summarised in Figure 3, also indicating the relevant shipping regulations (if any) and what descriptors (according to the MSFD) that can be impacted by the different contaminant sources.

The deposition of air pollutants, emitted from combustion, can result in immediate load of primary contaminants when the deposition occurs close to the ship. Alternatively, the deposition can be a result of secondary formation and degradation reactions during atmospheric dispersion and transportation (Eyring et al., 2010; Badeke et al., 2021). Monitoring of atmospheric ship emissions have historically focused on gases such as CO_2, SO_X and NO_X and the characterization of particles based on size (e.g. PM2.5, PM10). Although emission and deposition of some contaminants (cadmium, copper, mercury, lead and benzo[*a*]pyrene) are modelled within the Baltic Sea area, through the EMEP model (Gauss et al., 2020), ship-related emissions are not included in this analysis. There is thus a knowledge gap regarding metals and PAHs being emitted from ships and how much they contribute to the total environmental load (Lunde Hermansson et al., 2021 (Paper I)).

From a marine perspective, there are several other contaminant sources to consider. Some are related to operations on most ships (e.g. release of antifouling biocides and ballast water exchange) while others are more ship specific (e.g. discharge of scrubber water or tank cleaning effluents) (Jalkanen et al., 2021; Moldanová et al., 2022). Antifouling paint is perhaps the contaminant source that has received most attention, as biocides are released from the hull paint to prevent biofouling (Andersson et al., 2016). Studies show that thousands of tonnes of copper and zinc are continuously released to the environment (Jalkanen et al., 2021; Ytreberg et al., 2022) and that maritime shipping contributes to >40% of the total copper load within the Baltic Sea area (Ytreberg et al., 2022 (Paper II)). To avoid biofouling in the cooling water piping system and the sea chest, these are often equipped with antifouling systems that continuously release antifouling biocides such as copper and zinc (Growcott et al., 2016). To what extent the cooling water systems releases biocides remains to be further investigated.

Another issue related to biofouling is the introduction and spreading of invasive species, this can also occur in conjunction with ballast water operations when ships adjust the buoyancy and trim with seawater. Ballast water discharge is regulated to reduce the spreading of invasive species but the techniques used for cleaning ballast water can also introduce new chemicals to the environment (Andersson et al., 2016). Ballast water discharge has been identified as one of the main sources of invasive species in European waters (Katsanevakis et al., 2013).



	Biofouling & Antifouling	Ballast water	Black water	Grey water	Tank cleaning	Cooling water	Scrubber water	Bilge water	Noise	Prop. shaft lubricants	Atmos. deposition	Solid waste
D2. Invasive species	x	x	x	x								
D5. Nutrients N, P		x	x	x	x		x	x			x	x
D7. Acidifying sub.							x				x	
D8. Organic sub. PAH		x		x	x		x	x		x	x	
D8. Metals V, Ni, Cu	x			x		x	x	x		x	x	
D10. Litter											x	x
D11. Energy/Noise									x			
Shipping regulations	AFS	BWMC	MARPOL Annex IV	MARPOL Annex IV	MARPOL Annex II		MARPOL Annex VI*	MARPOL Annex I		MARPOL Annex I	MARPOL Annex VI**	MARPOL Annex V

Figure 3: Illustration of several potential contaminant sources from an operating ship, adapted from Jalkanen et al. (2021). The different sources exert pressures on the marine environment and can have impact in several of the descriptors (D) defined by the Marine Strategy Framework Directive (MSFD). Finally, the regulations connected to the contamination sources are listed on the bottom row. AFS and BWMC refers to the conventions on antifouling systems and ballast water management control. For further description of regulations, see section 2.2.

The daily life on a ship also generates waste water such as black water, i.e. sewage, and grey water, i.e. waste water from kitchen facilities, laundry facilities and cabins (e.g. showers), that is sometimes discharged overboard contributing to eutrophication and input of hazardous compounds (Ytreberg et al., 2020b). The volumes produced are often related to the number of people onboard and a large cruise vessel will generate more wastewater than a tanker with a small crew. Tankers, i.e. liquid bulk carriers, on the other hand can use large amounts of wash water when they clean their holding tanks between unloading and loading of cargo. The contaminated wash water can then be legally discharged into the sea in accordance with applicable regulations (MARPOL Annex II).

A mix of metals and organic contaminants, such as PAHs, can be derived to oils and fuels used on the ship, where operational discharges contribute to the daily contaminant load. For example, propeller shaft lubricants leak continuously (2-6 litres per day (Andersson et al., 2016)); bilge water that consists of oily residues and condensed water from the machinery space, is discharged legally (exception in Finnish waters) as long as the oil content is less than 15 ppm (MARPOL Annex I); and scrubber water, becoming enriched with both metals and PAHs as exhausts are led through a fine spray of water, can be discharged by hundreds to thousands of m^3 daily from a single ship (more details in section 2.3).

Moreover, the operation of the ship results in underwater noise pollution that is included as one of the indicators in the MSFD (Descriptor 11). Studies on underwater noise have proven to impact marine life (Popper and Hawkins, 2019; Duarte et al., 2021). Also, the potential disruption of the natural bio(geo)chemical state in the water column and sediment due to wake formation (Nylund et al., 2021) and resuspension of sediments are other pressures connected to ship operations in need of more research.

To summarise, a single ship has several different sources of pollutants that all exert pressures on the marine environment. For most of the sources, there are conventions that regulate the use and emission, but, as will be described in section 2.3, the discharge of scrubber water is only covered by guidelines of recommendatory nature.

2.2 SHIPPING-RELATED REGULATIONS AND CONVENTIONS TO PROTECT THE MARINE ENVIRONMENT FROM CONTAMINATION

There are several legal instruments and commitments in place to protect the marine environment. The International Maritime Organization (IMO) and the European Commission (EC) have the primary control in terms of shipping regulations (by IMO) and the protection of the marine environment (by EC). This is then implemented by regional sea conventions and national laws.

From the European Commission, The Water Framework Directive (WFD, 2000/60/EC and 2013/39/EU) and the Marine Strategy Framework Directive (MSFD, 2008/56/EC) are the main governing documents. The MSFD constitutes a framework where Member States shall apply an ecosystem-based approach with the aim of achieving (and maintaining) Good Environmental Status (GES).

Marine strategies shall apply an ecosystem-based approach to the management of human activities, ensuring that the collective pressure of such activities is kept within levels compatible with the achievement of good environmental status and that the capacity of marine ecosystems to respond to human-induced changes is not compromised, while enabling the sustainable use of marine goods and services by present and future generations

MSFD, EC (2008)

The MSFD assessment is based on eleven qualitative descriptors where two are especially relevant with regards to the contaminants covered in this thesis:

i) Descriptor 8: Contaminants are at a level not giving rise to pollution effects and
ii) Descriptor 9: Contaminants in fish and other seafood for human consumption do not exceed levels established by Community legislation or other relevant standards

The WFD is covering waters within 1 nautical mile from the baseline and is geographically overlapping with the MSFD in the coastal areas. The WFD also sets goals of achieving Good Status (chemical and ecological; Figure 4) which then ties back to the GES goal of MSFD (Figure 4). The chemical status is assessed by comparing measured environmental concentrations to threshold values, i.e. environmental quality standards (EQSs), of 33 priority substances listed in the annexes of the directive. Also, EU Member States that identify substances as pollutants of concern, can add these as River Basin Specific Pollutants (RBSP) with national EQSs and include them when assessing the ecological status of WFD (Figure 4). The threshold values of the priority substances of the WFD are also valid for the MSFD. Failure of reaching Good chemical status implies that GES cannot be achieved.

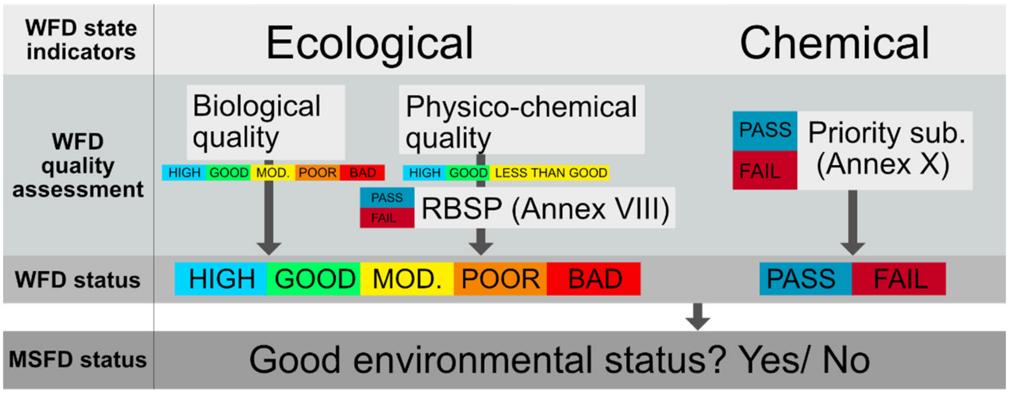


Figure 4: The connection between the Water Framework Directive (WFD) and the aim to reach Good Environmental Status (GES) according to the Marine Strategy Framework Directive (MSFD). Both Good Ecological Status and Good Chemical Status must be reached in order to fulfil GES. RBSP=River Basin Specific Pollutants.

The regional sea conventions act to implement the strategies and goals of the MSFD and WFD. The regional sea convention of the Baltic Sea area is the *Convention on the Protection of the Marine Environment in the Baltic Sea Area* (the Helsinki-convention, HELCOM) that has implemented a strategic programme (Baltic Sea Action Plan) to achieve GES. Two of the four main segments of the action plan are directly linked to the use of scrubbers where the segment *Hazardous substance and litter* has a main goal of a *Baltic Sea unaffected by hazardous substances and litter* and the segment *Sea-based activities* should be *environmentally sustainable*.

Marine protected areas, e.g. Natura 2000 and Baltic Sea Protected Areas (BSPAs), are designated sites with high nature values where human activities can be partly or fully restricted to ensure conservation. According to the Aichi Target 11 under the Convention on Biological Diversity, 10% of the European coastal and marine areas should be conserved through *effectively and equitably managed, ecologically representative and well-connected systems* by 2020. The ambition has now further increased in the EU Biodiversity Strategy (EC, 2020) and the *30 by 30* initiative (Dinerstein et al., 2019; UNOC, 2022) where 30% of sea areas should be legally protected by 2030.

The IMO has the responsibility to ensure safety and security of shipping and to prevent pollution, both atmospheric and marine, from ships. The IMO is a specialized UN agency that shall provide the regulatory framework for the global shipping industry, including environmental performance. The Marine Environment Protection Committee (MEPC) is the senior technical body of marine pollution issues within the IMO and they address the control and prevention of ship-source pollution covered by the International Convention for the Prevention of Pollution from Ships (MARPOL).

MARPOL is one of the key conventions within IMO. It consists of six annexes (Annex I-VI) where each annex covers the regulations connected to different aspects of ship operations (oil, liquid bulk, packaged goods, sewage, garbage and air pollution). One of the aspects covered is the prevention, or at least minimization, of pollution from the specific ship operations. Areas that have been identified as more sensitive, both related to the oceanographic and ecological condition and the ship traffic intensity, can be classified as *Special Areas*. The designation of *Special Areas* is connected to the different annexes within MARPOL and requires a higher level of protection by more stringent rules and/or mandatory practices. The Baltic Sea area is defined as *Special Area* under four of the six annexes (Table 1). Designated *Special Areas* within Annex VI on air pollutants are referred to as emission control areas (ECAs) where the emissions of SO_X (SECA) and NO_X (NECA) are more strictly regulated than outside ECAs.

In addition to *Special Areas*, *Particularly Sensitive Sea Areas* (PSSAs) are recognized as being ecologically, socio-economically or scientifically significant areas in need of special protection. Unlike the *Special Area* designation, the PSSA classification will not necessarily result in regulatory measures but can be used as argument for higher protection. The Baltic Sea is also classified as a PSSA.

Table 1: Indicating which of the annexes (MARPOL Annex I-VI) where the Baltic Sea is classified as a *Special Area.*

	Annex I	**Annex II**	**Annex III**	**Annex IV**	**Annex V**	**Annex VI**
Name of regulation	Regulations for the Prevention of Pollution by Oil	Regulations for the Control of Pollution by Noxious Liquid Substances in Bulk	Prevention of Pollution by Harmful Substances Carried by Sea in Packaged Form	Prevention of Pollution by Sewage from Ships	Prevention of Pollution by Garbage from Ships	Prevention of Air Pollution from Ships
Special area Baltic Sea	Yes	No	No	Yes	Yes	Yes

IMO has also adopted the International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM Convention), the International Convention on the Control of Harmful Antifouling Systems on Ships (AFS convention) and the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (London Convention and protocol).

On a global level, the United Nations Sustainable Development Goal (UN SDG) number 14 require that we should *Conserve and sustainably use the oceans, seas and marine resources for sustainable development*, where significantly reduce pollution is included as one of the targets. Also, The United Nations Convention on the Law of the Sea (UNCLOS) include obligations to protect and preserve the marine environment (Article 192) and explicitly stipulate that States have *Duty not to transfer damage or hazards or transform one type of pollution into another* (Article 195).

2.3 EXHAUST GAS CLEANING SYSTEMS, SCRUBBERS

The global sulphur cap aimed at improving air quality and protect human health and has been amended to MARPOL Annex VI on *Prevention of Air Pollution from Ships* (Regulation 14). On the 1st of January 2020, the new regulations were implemented, reducing the maximum allowable sulphur content in fuels on ships operating outside of SECAs to 0.5% m/m (mass by mass). Within SECAs, the sulphur limit was 0.1% m/m since January 2015 which remained the same after the implementation of the new global sulphur cap. The sulphur cap resulted in a shift to fuels with lower sulphur content, i.e. the distillate marine gas oils (MGO) or hybrid fuels such as very/ultra-low sulphur fuel oils (VLSFO and ULSFO).

However, according to *MARPOL Annex VI Reg. 4,* compliance methods and alternatives (i.e. *Equivalents*) can be allowed as long as they offer emission reductions in line with the standards set forth within the annex such as regulation 14 on SO_X emissions. Scrubbers proved to be a compliant method to remove SO_X from the exhaust, fulfilling the *Equivalents* requirements in MARPOL Annex VI. Installing a scrubber thus offered ship owners to continue to run their ships on cheaper high sulphur residual fuels while still being compliant. Compliancy is assessed with respect to SO_X emissions to the atmosphere, while other criteria of the produced scrubber water, e.g. pH, turbidity and phenanthrene equivalents (a measure of PAH content), directed towards the marine environment are only covered by guidelines of recommendatory nature provided by the MEPC. The 2015 *Guidelines for exhaust gas cleaning systems* (MEPC.259(68)) was updated in 2021 (MEPC.340(77)) and, in connection to this, Japan (2019b) proposed a framework to assess the risk and impact from scrubber water discharge. After input by several Member States within the European Union (Austria et al., 2021), the MEPC recently approved a new guideline document to help Member States to assess the risks associated to discharge of scrubber water and provide decision support (MEPC, 2022). According to the guidelines;

The adoption of restrictions or a ban on discharge water from EGCSs should be considered in areas where any of the following indicative criteria are fulfilled:

> *1. environmental objectives in the areas are not met, e.g.* ***good chemical status, good ecological status or good environmental status*** *are not achieved under applicable legislation;*
>
> *2. the discharge of EGCS effluents represents an* ***additional risk*** *of deteriorating the environment and the resiliency of the climate system;*
>
> *3. the EGCS discharge water* ***conflicts with the conventions*** *and regulations formulated to protect the marine environment (see UNCLOS Article 195, etc.); and*
>
> *4. the EGCS discharge effluent represents an increase in the costs of management of dredged materials in ports.*

Paragraph 7.4 MEPC (2022)

There are different types of scrubber systems on the market (Figure 5). The most common one is the open loop system where large volumes of seawater (100-1000s m^3h^{-1}) (Ytreberg et al., 2020a; Lunde Hermansson et al., 2021) is being pumped into the scrubber, where the exhaust are led through a spray of water, scavenging SO_x and other contaminants. The acidified and contaminated water is then being discharged directly back to the sea. The closed loop system instead uses freshwater, with the addition of base (often sodium hydroxide (NaOH)) to buffer the acid formation and improve the uptake efficiency of SO_X. As the water is recirculated, the sludge (containing much of the contaminants) is separated and can be collected for onshore disposal. Despite the name, the closed loop discharge volumes are estimated to approximately 0.2-0.5 m^3/h (Ytreberg et al., 2020a; Lunde Hermansson et al., 2021). There are also hybrid systems where the operator can switch between open and closed loop mode depending on the local requirements, then the closed loop mode can also run with seawater.

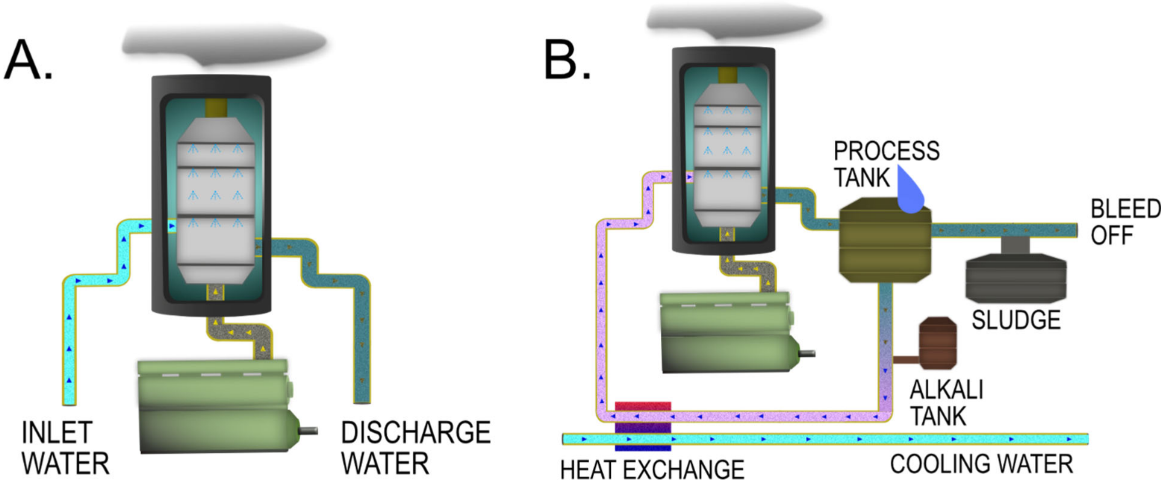


Figure 5: Illustration of open (A) and closed (B) loop scrubber systems. Adopted from DNV-GL (2021).

In 2015, the same year as the implementation of the 0.1% sulphur limit within ECAs, there were less than 100 ships equipped with scrubbers globally (Ytreberg et al., 2021; Ytreberg et al., 2022). As of last year, almost 3500 ships were registered as being equipped with a scrubber on the IMO GISIS database (Jalkanen et al., 2021) and according to DNV, the total number of ships with scrubbers in operation and on order exceeds 4500 (DNV-GL, 2021). For comparison, in the Baltic Sea area there were approximately 50 ships equipped with scrubbers in 2015 and >450 in 2020.

Although ships with scrubbers only represent approximately 5% of the current fleet with respect to number of ships (DNV-GL, 2021), the latest report by the International Energy Agency (IEA, 2021), forecasted that high sulphur fuel oils, in combination with scrubbers, will represent approximately 25% of the total bunker fuel demand in year 2026. This would suggest that ships equipped with scrubbers belong to the larger size-classes of the fleet with the largest fuel oil consumption. According to other studies, the share of the fleet equipped with scrubbers represented approximately 15% of gross tonnage in 2019 (Dulière et al., 2020; Teuchies et al., 2020) and could reach 35% according to Clarkson's World Fleet Register. In an OSPAR report on scrubbers (Jalkanen et al., 2022) it was also reported that ships equipped with scrubbers is most common in the category of ships with highest fuel consumption.

In some countries (e.g. China, Germany, Belgium), a national ban on open loop scrubber water discharge has been implemented within the inner national waters (Nepia, 2021). On an even more local scale, ports (e.g. port of Gothenburg, Petro port in Stenungsund and port of Trelleborg in Sweden) and other areas (e.g. some of the Norwegian fjords) have local restrictions where scrubber water discharge is prohibited (Nepia, 2021).

3 KEY CONCEPTS AND RESEARCH APPROACH

This thesis is focusing on the *Activity*, *Pressure* and *State* component of the DAPSIR cycle. Activities and pressures are more covered in Paper I and II while Paper III attempts to assess the change in State. The methodologies are described in detail in the respective papers and an overview of the workflow is illustrated in Figure 6.

In order to assess the contaminant load of metals and PAHs due to the use of scrubbers, and to compare emissions from conventional fuels such as heavy fuel oils (HFOs) and marine gas oils (MGOs), an extensive review on all available literature was conducted (Lunde Hermansson et al., 2021 (Paper I)). The emission factors were then used to calculate the relative load contribution from scrubbers in the Baltic Sea region (Ytreberg et al., 2022 (Paper II)) and to estimate the cumulative risk of several contaminant sources in ports (Paper III).

Both Paper II and Paper III are based on the use of real-time Automatic Identification System (AIS) data, with corresponding ship information (e.g. the vessels passenger capacity, main engine power, gross tonnage, vessel size, hull surface area etc.). The Ship Traffic Emission Assessment Model (STEAM) was used, together with the emission factors of metals and PAHs (Lunde Hermansson et al., 2021), to calculate the contaminant load within a specified area, e.g. the entire Baltic Sea or a specific port. In Paper III, the contaminant loads derived from STEAM, the hydrodynamic properties of ports and the chemical properties of the contaminants were used in the Marine Antifoulant Model to Predict Environmental Concentrations (MAMPEC). MAMPEC has previously been used for assessing antifouling paint and ballast water systems (Deltares; Van Hattum et al., 2002) and has also been proposed as the preferred tool when assessing risks, and potential restrictions, of scrubber water discharge (MEPC, 2022). MAMPEC is a two dimensional hydrodynamic and chemical fate model that assumes steady-state when calculating predicted environmental concentrations (PECs) in the water and sediment compartment of the defined environment and its surroundings (Van Hattum et al., 2002). MAMPEC is divided into three modules, the *Environment* module, the *Compound* module and the *Emission* module.

In the *Environment module*, the port is translated into a box model (Paper III Supplementary material A), with a constant depth and one opening to the surrounding environment. Also, all the properties of the water column (e.g. temperature, salinity, chlorophyll-a, suspended particulate matter (SPM)) as well as wind speed, water exchange and sedimentation rate are defined with constants.

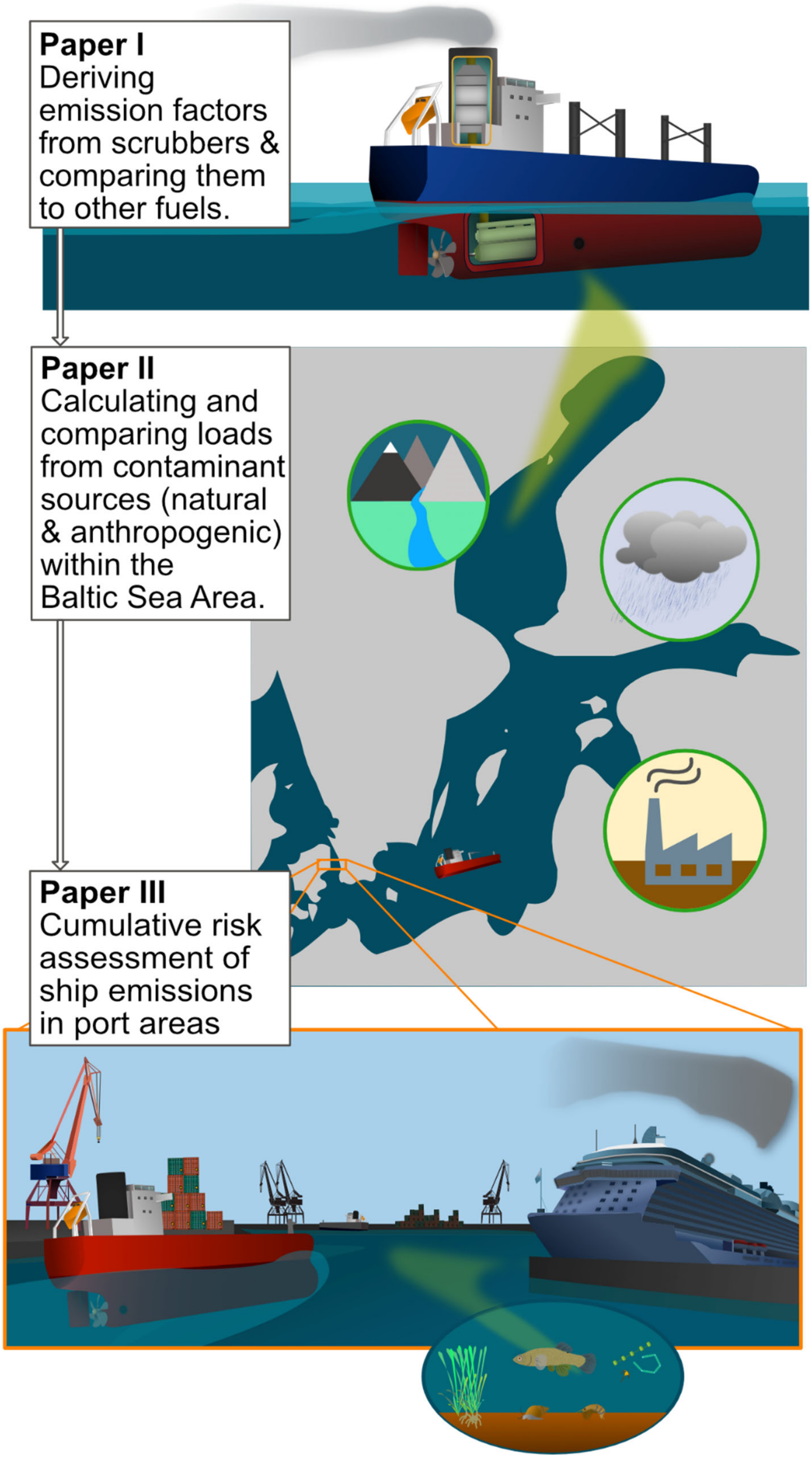


Figure 6: The different concepts and output used in the different papers and how they connect to one another.

In the *Compound module*, the chemical properties are also assigned with constant values although properties such as solubility, vapor pressure and partitioning coefficients are dependent on and vary with temperature, salinity and concentration of suspended particulate matter (e.g. Turner and Millward, 2002; Allison and Allison, 2005; Atkinson and Arey, 2007). Published degradation rates for organic compounds are highly variable (e.g. Arey and Atkinson, 2003; de Bruyn et al., 2012), reflecting the uncertainty of these parameters. In MAMPEC, the degradations rates are also represented by a fixed value.

Finally, the *Emission* module is used to compute daily loads (g/day) of the different contaminants to the specific environment of interest. The uncertainties with the *Emission module* are connected to the uncertainties of STEAM and the choice of emission factors. The STEAM pressure data does not provide any information on uncertainty estimates for the volumes and loads reported. The discharge of bilge water and scrubber water are functions of operational engine load (Paper III) and the open and closed loop scrubber discharge rate is defined as 90 m^3/MWh and 0.45 m^3/MWh as recommended by Ytreberg et al. (2020a) and Ytreberg et al. (2021). The confidence interval of open loop scrubber discharge showed a ±14% variation and for closed loop it was ±50% (Lunde Hermansson et al., 2021). For the other activities, no uncertainty could be determined.

In Paper III, change in *State* is assessed as an added risk to the environment. Risk is conventionally assessed quantitatively by comparing the predicted (or measured) environmental concentration (P(M)ECs) of a single substance (i) to the predicted no effect concentration (PNEC) of that same substance (Backhaus and Faust, 2012). If P(M)EC is larger than PNEC, then the P(M)EC/PNEC ratio, i.e. the risk characterisation ratio (RCR), will be larger than 1, implying an unacceptable risk to the environment (Eq. 1).

$$\mathrm{RCR} = \frac{\mathrm{P(M)EC_i}}{\mathrm{PNEC_i}} \qquad (1)$$

Measured environmental concentrations (MECs) are obtained from actual measurements within the area of interest. Predicted environmental concentrations (PECs), on the other hand, are estimated from more or less sophisticated hydrodynamic and chemical fate models (e.g. MAMPEC) where a single discharge or a continuous daily contaminant load is used as model input and the physico-chemical properties of the compound and environment determine the predicted concentration.

PNECs represent threshold values at which no effect on the ecosystem is expected. These threshold values are normally derived from ecotoxicological tests, where different species, representing a variety of trophic levels, are exposed to different concentrations. For the 33 priority substances within the WFD, threshold values, i.e. environmental quality standards (EQSs), have been derived for the water compartment (sometimes also sediment and biota). Regional sea conventions can also agree on regional indicators, e.g. copper in sediment within the HELCOM area (Lagerström et al., 2021), and nations can mandate for more compounds to be included as RBSP, providing them with national threshold levels.

There are three main issues connected to the derivation and use of PNEC values that have been identified within the scope of this work. The first issue is the challenges and uncertainties connected to the derivation of PNEC. This was also identified by Vorkamp and Sanderson (2016), who compared EQS values, derived by different EU member states, for hundreds of chemicals in freshwater. They concluded that an EQS value in one country could be >100 times larger than an EQS value in another country, although the available ecotoxicological data is limited and general guidelines (e.g. the EC Technical Guidance Document No. 27; TGD 27 (EC, 2018)) of how to derive EQS values exist (Vorkamp and Sanderson, 2016). One of the main reasons for the discrepancy was identified to be the year of derivation, many of the threshold values were derived prior to the development of guidance documents.

The second issue is the determination of an assessment factor that should account for the uncertainties in the threshold value from the ecotoxicological tests. The assessment factor should ensure that the threshold value that was protective of single species based on single substance exposure in laboratory tests is also protective of the entire ecosystem. The value of the assessment factor is determined from the number of test species and data points, the use of deterministic or probabilistic approach together with supporting information such as mesocosm studies (EC, 2018). This allows for some room of interpretation and can partly explain the discrepancies in derived threshold values.

The third issue is the lack of available ecotoxicological data. For many of the compounds, there might be some available test results but these can be difficult to retrieve as industry and business do not have a requirement to share exposure results publicly. It is thus difficult to assess the reliability and relevance of those studies and evaluate if they should be included in the EQS derivation following the TGD 27 (EC, 2018). Also, ecotoxicological studies must sometimes be omitted from the PNEC derivation as they fail to fulfil the reliability and relevance assessment, i.e. CRED analysis (Moermond et al., 2016). In a Joint Research Centre (JRC) workshop, it was proposed that industry should be required to share their data concerning exposure and application of chemicals (Drakvik et al., 2020), but so far this has not been implemented.

In a natural environment, with several different substances potentially causing adverse effects on the environment, there is a need to account for the cumulative effects. There are different approaches available to account for mixture toxicities and to calculate a total RCR for a complex solution (Backhaus and Faust, 2012; Nys et al., 2017). Although a simplification, a 1st Tier conservative approach is to sum all of the individual PEC/PNEC values and estimate the RCR_{sum} for the mixture (Eq. 2)(Backhaus and Faust, 2012).

$$\mathrm{RCR_{sum}} = \sum \frac{\mathrm{P(M)EC_i}}{\mathrm{PNEC_i}} \qquad (2)$$

This approach is also in accordance with the new guidelines for risk and impact assessments of the discharge water from scrubbers (MEPC, 2022) stating that:

The cumulative effects of mixtures should be taken into account and a PEC/PNEC summation approach is recommended where PEC/PNEC ratios of all mixture components (PAHs and metals) are summed up to a final Risk Quotient.

On a regulatory level, the EQS values are based on single substances, not accounting for the mixture effects (Kienzler et al., 2016). Several studies have shown that the ecotoxicological tests of mixtures result in higher toxicities than would be expected from the single compound concentrations (Koski et al., 2017; Nys et al., 2017; Thor et al., 2021). Today, there is little knowledge on the synergistic and potentially antagonistic effects of mixtures (Rudén, 2019). As species in the marine environment are exposed to complex mixtures rather than single compounds with only one effect (Kienzler et al., 2016), it has been suggested to apply a precautionary approach and to add an additional assessment factor to account for mixture effects, i.e. a mixture assessment factor (MAF) (Drakvik et al., 2020). The MAF can, as a lower Tier assessment be assigned a simple fixed factor. Rudén (2019) proposed an allocation factor of 10 for single substance risk assessments due to the fact that a chemical is not released into a pristine environment.

In this work, the individual RCRs are summarised to account for the cumulative toxicity of a mixture and the result provide an added RCR_{sum} to the marine environment which can be used to assess the *State* change. However, no additional assessment factors have been assigned to the individual PNEC values and the background concentrations are not included.

4 RESULTS AND DISCUSSION

The DAPSIR framework allows for a structured approach to assess the impact of the shipping sector. To understand the *Impact*, the pathways from *Driver* to *Activity* to *Pressure* to *State change* must be connected. Therefore, the focus in Paper I was to quantify the pressure and collect and compile the emission factors of metals and PAHs connected to the combustion of conventional fuels and the use of scrubbers. The study shows that the use of scrubbers, allowing for HFO combustion, results in atmospheric emissions and discharges of metals and PAHs to the marine environment (Lunde Hermansson et al., 2021 (Paper I)). The compiled data also revealed that HFO combustion, with or without a scrubber, generates higher emission factors of all included metals and PAHs as compared to MGO combustion (Lunde Hermansson et al., 2021 (Paper I)). The result from Paper I feed into the *Pressure* component of DAPSIR (Figure 1) and, in Paper II, enabled for comparison between the metal and PAH load from different activities such as the use of scrubbers, the application of other onboard systems and loads from additional sectors (e.g. industries as point sources and riverine input).

The relative load of metals and PAHs from ships operating with scrubbers within the Baltic Sea area is large (Ytreberg et al., 2022 (Paper II)). For example, shipping and the use of open loop scrubbers accounted for at least 8.5% of the total load of anthracene, a core indicator within the HELCOM area (HELCOM, 2018b), and 18% of the total load of vanadium within the Swedish Exclusive Economic Zone (EEZ). Ships and leisure boats also account for a large share of the copper load (almost 40% of total load) and zinc load (almost 8% of total load), primarily from antifouling paints (Ytreberg et al., 2022 (Paper II)). In remote off-shore areas, where shipping is the main anthropogenic activity, the relative contribution is probably even larger than the numbers in Ytreberg et al. (2022) (Paper II) suggests.

The results of Paper III can be used to indicate the relative load contribution from the different activities and the cumulative risk contribution. The added RCR, i.e. *State change*, in port environments was modelled as a function of the contaminant load of metals and PAHs from ship-activities. The ship-source contamination of metals and PAHs from bilge water discharge, near-ship atmospheric deposition, release of biocides from antifouling paint and scrubber water discharge, results in unacceptable risk in Baltic Sea ports (Paper III). In accordance with Paper II, open loop scrubber water discharge and antifouling paint account for the highest contribution to the cumulative risk. Also, important to note is that the contribution of antifouling paint can be attributed most ships while open loop scrubbers are only used by a smaller share of the fleet. The approach in Paper III can provide information when assessing the *State* and *State* *change* in the environment and, more importantly, reveal the individual contributions from different *Activities* and *Pressures*.

In addition to metals and PAHs and their potential ecotoxicological adverse effects, there are more aspects connected to the discharge of scrubber water that also need to be addressed to fully grasp the impact of scrubber use. Several additional substances, detected in scrubber water, might have adverse effects on marine organisms (further discussed in section 4.1), the discharge water might contain eutrophying compounds (Ytreberg et al., 2019) and the input of strong acids (as sulphuric acid) can have impact and locally contribute to ocean acidification and decrease the buffer capacity, i.e. the alkalinity (Hassellöv et al., 2013; Turner et al., 2018).

Several studies conclude that the addition of strong acids from scrubbers, can have large effects, especially in near-coastal areas and areas of high shipping intensity prone to stratification, e.g. the Baltic Sea area (Hassellöv et al., 2013; Stips et al., 2016; Turner et al., 2018). This is also concluded by a recent report by Dulière et al. (2020), stating that ship traffic contribute to ocean acidification in the North Sea area, especially in shipping routes and harbours. Although the change in pH due to scrubber water discharge might be small, the addition of strong acids will result in consumption of alkalinity which will reduce the ocean capacity of CO_2 uptake (Turner et al., 2018). Addition of strong acids could also be problematic in areas where the saturation state of calcium carbonate ($CaCO_3$) is close to 1, e.g. the Baltic Sea, where undersaturation of $CaCO_3$ would affect the occurrence of calcifying organisms (Tyrrell et al., 2008).

4.1 ASSESSING STATE CHANGE WITH PEC AND PNEC

When assessing the state or risk by comparing PECs and PNECs, there are several uncertainties that must be considered, both in terms of model estimates of the concentrations in the environment (i.e. PEC) and the derivation of safe threshold values (i.e. PNECs). For example, the MAMPEC model assume steady-state and non-changing conditions when deriving PECs and the absolute no-effect threshold values are based on single-species and single-compound studies under laboratory conditions. The main issue is that the risk of a highly dynamic system is assessed based on relatively static models and assumptions.

Within this work, several additions have been made to MAMPEC to adopt the assessment to scrubber water discharge. For the calculation of PEC, two new port environments (Port of Copenhagen and Port of Gdynia) and 25 new compounds have been parametrised and added to the *Environment* and *Compound* modules of MAMPEC (Paper III).

The emission factors of metals and PAHs from the use of different fuels and the use of open and closed loop scrubbers show a wide range (Lunde Hermansson et al., 2021 (Paper I)). This implies that the calculated PEC, that is assumed to linearly correlate to the contaminant load in MAMPEC, will also show a wide range depending on the emission factors used. In the scenario of more worst-case character, where the 95% upper level of the concentrations of open loop scrubber water was used instead of average concentrations, the scrubbers' relative contribution to the RCR_{sum} as well as the total cumulative risk in the port increased (Paper III).

As an initial estimate, the combination of STEAM and MAMPEC provides an indication of what pressures the different activities within an area might exert on the environment. There are however several aspects of the assessment that can be improved. Within this thesis and Paper III, the added environmental risk is assessed. For a more holistic assessment, background concentrations, long-range transport of contaminants and land-based activities should also be included. This requires more data and more sophisticated models to estimate PECs. The updated chemical fate and transportation model should allow for dynamic scenarios where the contaminant loads, environmental conditions and the fate of the contaminants are allowed to change. A sensitivity analysis would improve the understanding of the different parameters and their influence of model results and provide important supporting information in order to present the results in a transparent way. Ideally, the results from models should be validated with in-situ measurements. Few studies have attempted to validate the results from MAMPEC but in Lagerström et al. (2020) they observed good agreement between modelled and measured concentrations of copper in a Swedish marina if the release rate, i.e. the load, was adjusted to previously measured data within the investigated area.

For many compounds, there are no derived PNEC values, and these compounds cannot be assessed with the proposed method of calculating RCR and the cumulative risk (RCR_{sum}). This is problematic as the usual suspects within (marine) environmental risk assessment (Cd, Hg, Pb and BaP) do not cover substances that are highly relevant with respect to shipping and the use of scrubbers, e.g. vanadium, chromium and alkylated PAHs. Some threshold values have been derived by national EPAs or governmental agencies, but if they are not implemented in the legal framework (e.g. WFD or MSFD), these thresholds have little legal relevance and exceedance does not necessarily imply management action. Several relevant substances are thus excluded from the environmental risk assessment. The issue is partly addressed by HELCOM who state within their recent action plan (HELCOM, 2021) that they should:

Develop national programmes with a particular focus on hazardous substances which are not adequately regulated by other policies (HL2) and to *identify emerging pollutants of high concern (HL9).*

Similar efforts were requested by the EEA (2019a) who proposed a wider variety of substances to be monitored in order to provide earlier warnings.

An additional problem, identified when applying the DAPSIR approach, is the mismatch between how state is assessed in theory (e.g. comparison of derived threshold values in the water column) and in practice (e.g. field campaigns to measure contaminant concentration in sediment). As a first step, determining appropriate indicators, for the most appropriate compartment (e.g. water, sediment or biota) with the possibility of monitoring, could improve the efficiency of the *State* assessment.

In previous assessments of environmental risk connected to antifouling paints or ballast water, the different activities were assessed one at the time without adding any other ship-based activities (Zipperle et al., 2011; ECHA, 2017). This implies that the marine environmental risks, associated to ship-activities, are underestimated. The results of Paper III show exactly this, if the assessment is limited to one activity and/or one substance the conclusion might be that there is an acceptable risk ($RCR_{sum}<1$). However, adding up the RCR of the 9 metals and 16 PAHs from several activities result in an unacceptable risk ($RCR_{sum}>1$) in the environment.

4.2 Reflections on sustainable shipping and the connections to marine ecosystem services

In the report *The Ocean Economy in 2030* (OECD, 2016), it is stated that *for many, the ocean is the new economic frontier* and that ocean economy contributes significantly to the global economy, even outperforming the global economic growth rate by 2030. One key actor of ocean economy is the shipping industry, both as an industry on its own and as a prerequisite for the development of other ocean-based sectors (Virdin et al., 2021). The marine ecosystems provide input to ocean industries such as ecosystem services and raw material while, at the same time, being at risk of becoming adversely affected by the industry activities (OECD, 2016). These potentially competing interests put a lot of responsibility on policy makers and marine spatial planning (MSP) to ensure that ocean industrialization does not conflict with the ecological and social dimensions of the sustainable development goals (Virdin et al., 2021).

Handling all commercial shipping under the same *shipping industry umbrella* and assume that all the sub-sectors have the same internal drivers and impact is a simplification. This becomes apparent when categorising the different ecosystem services that can be directly or indirectly impacted by the pressures related to commercial ship operations and primarily the discharge of scrubber water (Table 2). The impact on the ecosystem services might be the same, e.g. reduced biodiversity due to release of toxic substances, but how that affect the sub-sectors of the shipping industry might vary. As an example, the operation of a container vessel does not depend on biodiversity or pristine areas to function, the water is a transportation route. On the other hand, for a cruise line company, the degradation of marine environments could negatively affect the customer and thus the revenue of the business.

Table 2: Examples of ecosystem services that can be impacted by the discharge of scrubber discharge water. Inspired by Atkins et al. (2011).

Category	**Ecosystem service**	**Impact**
Production services	Food provision - extraction of estuarine/marine organisms for human consumption.	Toxic compounds result in reduced biomass and affect food safety.
Regulation services	Gas and climate regulation - balance and maintenance of the atmosphere.	Higher emission of CO_2 and input of strong acids result in decreased buffer capacity of seawater and potential degassing of CO_2.
	Disturbance prevention - flood and storm protection by biogenic structures.	Mortality and loss of oyster and mussel banks can reduce storm and wave protection in coastal zones.
Cultural services	Cultural heritage and identity - value associated with the estuarine/marine environment itself.	A polluted and exploited ocean may lose its cultural value.
	Leisure and recreation - refreshment and stimulation of the human body and mind through the perusal and study of, and engagement with, the estuarine/marine environment.	Destruction of pristine areas by pollution will have negative impact on recreational activities.
Overarching support services	Resilience and resistance - life support by the marine environment and its response to pressures.	Load of toxic, eutrophying and acidifying compounds will reduce the resilience of the seas.
	Biologically mediated habitat - habitat provided by living estuarine/marine organisms.	Increased toxicity will impact the ecosystems and species distribution.

However, most parts of the shipping industry are not reliant on other ecosystem services than the oceans providing a mean of floatation and transportation. This means that the arguments for conserving the marine environment or reducing pressures might need to be rephrased, and potentially enforced, in order to achieve change.

Drivers are not only derived from human *needs* but also from human *wants (Elliott et al., 2017)*. In order to reach sustainability within the shipping industry, which is largely driven by *the needs and wants* of society (e.g. trade, food, cruise), more focus should be directed towards the change in behaviour within society and enable consumers to take more informed and responsible decisions. This would require a much higher degree of transparency so that the full impacts of different choices are revealed.

To improve the transparency, the scientific community should aim for more transdisciplinary work to avoid tunnel vision and erase borders between scientific silos while actively communicating findings to policy makers and society. Policy makers must dare to take action and make, sometimes uncomfortable, decisions such as limit the use of fossil fuels or at least prohibit discharge of scrubber water. Also, the policymakers should put more pressure on the shipping industry to report and share data so that the environmental impact from shipping can be properly assessed. When it comes to environmental impact, the burden of evidence, to prove that an activity does not result in adverse effects, should be put on the shipping industry rather than the public society. A precautionary approach should also be applied while evidence is collected.

4.3 SHOULD DISCHARGE OF SCRUBBER WATER BECOME PROHIBITED?

Based on the result within this thesis, a question would be whether or not the discharge of scrubber water should be prohibited. Based on the discharge of metals and PAHs (*Pressures*) from scrubbers (*Activity*) and the effect on *State* (e.g. RCRs), the overall assessment suggests that an appropriate *Measure* (*Response*) would be to ban the discharge of scrubber water. This would substantially reduce the load of metals and PAHs to the marine environment (Paper II) and be an important step in reducing the shipping sector's pressures and the succeeding environmental impact.

A continued use of scrubbers implies a continued use of HFO. HFO emission contain higher concentrations of metals and PAHs (Lunde Hermansson et al., 2021) and the operation of the scrubber results in a higher fuel consumption of approximately 2% (Bengtsson et al., 2011; Stripple and Zhang, 2019; Faber et al., 2020). The use of scrubbers would thus increase the CO_2 emissions rather than decreasing them, contradicting the ambition of the IMO to reduce the greenhouse gas emissions with 50% by 2050. The scrubber manufacturers and oil refineries claim that desulphurization processes in the refinery result in 1-25% higher CO_2 emissions compared to running a scrubber with HFO (Faber et al., 2020). However, comparing the total fuel cycle for MGO and HFO, the CO_2 emissions increase by <0.5% (Corbett and Winebrake, 2008) or even decrease when using MGO (Bengtsson et al., 2011). When HFO is compared to VLSFO, the well to wake assessment show that the CO_2 equivalents increase with approximately 5% (Comer and Osipova, 2021). Further, other potential pathways of how the use of scrubbers may impact the CO_2 offset are not included in the assessment by Faber et al. (2020). For example, the addition of sulphuric acid to the ocean will decrease the ocean uptake capacity of CO_2. In addition, the addition of toxic compounds can degrade ecosystems that would otherwise provide export of carbon to the seafloor through the biological carbon pump.

According to the MEPC guidelines, the risk of scrubber water discharge should be assessed using MAMPEC and that the PEC that should be used in the assessment is the PEC calculated for the surrounding environment (MEPC, 2022). This is problematic as the surrounding area is not defined at all within MAMPEC and, if applied, it is assumed that there is only one port affecting the entire surroundings, not accounting for other potential input loads. As showed in Paper

III, this would allow for almost 90 million m^3 of open loop scrubber water to be discharged within the port of Copenhagen annually, corresponding to nearly half of the total open loop scrubber water discharge within the entire Baltic Sea area in 2018. This presents a potential conflict between new guidelines for ship activities, such as the MEPC (2022) and the already existing governing regulations for the marine environment such as the WFD and MSFD.

The MEPC guidelines also provide decision support on when a ban/restriction of discharge of scrubber water is motivated (Section 2.3 (Paragraph 7.4 in MEPC, 2022)) and this, on the other hand, is more aligned with the already existing regulations and conventions (e.g. WFD, MSFD, UNCLOS). Based on the work covered in this thesis, the initial analysis shows that at least three of four points are fulfilled to motivate a ban on discharge of scrubber water in the Baltic Sea area. For example;

1) none of the subbasins within the Baltic Sea area achieves Good Environmental Status (HELCOM, 2018c; EEA, 2019b) thus fulfilling the first point;
2) Based on the assessment of the cumulative risk in ports (Paper III), the discharge of scrubber water would add to the total risk, fulfilling point 2; and
3) the discharge of scrubber water conflicts with UNCLOS Article 195 (section 2.2) as the pollution has clearly been transferred from one type of pollution into another (Lunde Hermansson et al., 2021 (Paper I)), fulfilling point 3.

Considering the results presented within this thesis and attached papers, the criteria set up in MEPC (2022) and the potentially high damage cost associated to scrubber-use presented by Ytreberg et al. (2021), the use of open loop scrubbers cannot be a sustainable solution. Previous studies have suggested that a switch to closed loop scrubbers would reduce the environmental load from scrubbers significantly (Lunde Hermansson et al., 2021; Ytreberg et al., 2022). However, the ship would continue to run on HFO with higher emission factors of both metals and PAHs as compared to MGO (Lunde Hermansson et al., 2021). In addition, the operation of a closed loop system requires addition of a strong base and in a life cycle and cost assessment (Andersson et al., 2020), it was estimated that a ship equipped with a closed loop scrubber system would consume more than 2500 L of NaOH per day. NaOH is very reactive and corrosive and for a ship to carry large volumes onboard implies an additional risk to the crew as well as higher costs. Also, a closed loop system collects sludge from the recirculated water and can produce 600 L sludge per day (Andersson et al., 2020) that has to be delivered in port. Analysis show that the sludge contain very high concentration of metals and PAHs (Hansen, 2012; Magnusson et al., 2018) and should be disposed of correctly.

Further, closed loop scrubber systems are not entirely closed (Figure 5). Although the bleed-off volumes are much smaller than the volumes of open loop scrubber water discharge, the concentrations of metals and PAHs are higher (Ytreberg et al., 2020a; Lunde Hermansson et al., 2021; Ytreberg et al., 2021) and the discharge can be expected to have local effects on the marine environment. Finally, the checklist above, from MEPC (2022), is also valid for closed loop scrubbers as none of the Baltic Sea basins reach Good Environmental Status, the use of closed loop scrubbers would result in an added risk to the environment and the discharge of scrubber water conflicts with Article 195 of UNCLOS.

5 CONCLUSIONS

Shipping plays a vital role in the global economy and is a prerequisite for the availability of many of the goods expected in our daily life. Therefore, the assessment of the environmental impact from shipping must improve so that better decisions are made in the future, ensuring that all aspects of shipping are sustainable.

The DAPSIR framework works well to structure and align the environmental risk assessment from ship activities. Within this thesis, the main focus has been on the links between *Activity*, *Pressure* and *State* components of the DAPSIR framework, and with a particular focus on the use of scrubbers and emissions of metals and PAHs. More work and knowledge are needed to construct and improve the DAPSIR analysis for shipping, especially to connect the change in *State* to the *Impact* component and all the way to *Response*.

The discharge of scrubber water result in high emissions of metals and PAHs, the emissions are not removed (as was the intention by stricter regulation as of MARPOL Annex VI) but rather moved from the atmosphere to the oceans. The significance becomes more apparent when the contaminant load of metal and PAHs from scrubbers are compared to other contaminant sources, where scrubbers are responsible for a large share of for example vanadium and anthracene entering the marine environment. Further, environmental risk assessments in ports, based solely on ship-activities within the port, showed that three out of four ports reach unacceptable risk. Also, using the surrounding area outside the harbour, following the MEPC guidelines, will not provide protective restrictions on emissions and contaminant loads.

Today, none of the Baltic Sea basins achieve Good Environmental Status according to MSFD and additional input of contaminants will hinder the achievement of fulfilling descriptor 8 and 9. To meet the EU's goal of *clean, healthy and productive seas*, where clean also implies non-toxic, there is no room for adding more contaminants to an already affected ocean. Ocean governance should not only be about preserving and maintaining the marine environment, but also to improve its environmental status and resilience.

6 FUTURE OUTLOOK

In order to completely assess the shipping sector's effects on the marine environment, the causal relationships of pressure, state and impact must be established, preferably with measurable (quantitative) data. The socio-economic aspect of DAPSIR, e.g. the driver and responses, can also be better understood if we improve our understanding of the complex processes within the marine environment and the ecosystem functions and services the ocean can provide. This would allow for better informed marine strategies, supported by e.g. cost-benefit analysis, and ensure that the marine environment and its abiotic and biotic assets are protected sufficiently.

Some of the actions needed to improve and extend the assessments of ship activities include:

- Improving the knowledge and reducing the uncertainties of the assessment of *Pressures* from onboard activities. Metal and PAH concentration in scrubber water and the power-based emission factors are relatively well covered (Paper I). However, metal and PAH emission to air is less investigated for historically important fuels (e.g. HFO and MGO) and emission factors of metals and PAHs for some of the dominating fuels of today (e.g. VLSFO and ULSFO) are missing completely. There is a need to improve the knowledge base in order to propose appropriate *Measures*;

- Sophisticated models will be key in order to understand how contaminants enter, spread and which compartments (water, sediment, biota) that might be affected. This requires development of chemical fate, distribution and transportation models that can reflect the spatiotemporal (4D) dynamics of the sea. The output from the models will be important to identify hotspots, both in terms of direct contaminant load and accumulation after time, and to understand how *Measures* can be used to improve the environmental *State* ;

- Include more substances (i.e. ship-related metals and PAHs) and their ambient concentrations in the mapping of the environmental conditions, anthropogenic activities and vulnerability of the marine environment. The 9 metals and 16 PAHs covered in this thesis only constitute a limited selection of the many contaminants found in scrubber water and more efforts should be made to include other relevant substances. A complete assessment of the environmental *State* and *State change* is a prerequisite to understand the local, regional and even global *Impact* from different *Activities* and *Pressures*;

- Find cause-effect relationships to connect *State change* to *Impact*. This can be related to the environmental load of contaminants and should also include other anthropogenic pressures, both exogenic, such as climate change, and endogenic, e.g. noise pollution. Within this work, it will also be important to reflect on the aspects of scale, both in time and space, e.g. what effects are we expecting from different substances? How long will it take before we see the effects in the environment? Are there life-stages or areas that are more sensitive?

- Once the *Impact* on the marine environment is properly estimated, the results can feed into the assessment of *Impact* on human *Welfare*. This will be important in the cost-benefit analysis and in the communication with policy makers and the public when motivating and assessing *Response* and potential *Measures*.

- Moreover, related to all points above, elaborate sensitivity analysis and assessment of uncertainties should be prioritized. As different stakeholders use different terminologies, where uncertainty can strengthen confidence in the results for a researcher but appear as a weakness for a politician or industry, it will be important to present results in a transparent and clear way. Then, better evaluations of the results can be provided and the areas in need for improvement are more efficiently identified.

To fully utilize the DAPSIR-structured analysis with respect to scrubber-use, more knowledge on the other *Pressures* and their effect on *State* change and *Impacts* (e.g. air emission, ocean acidification) should be included. To address one of the knowledge gaps identified in Paper I, i.e. the lack of simultaneous and harmonised evaluation of air and water emissions of metals and PAHs, field campaigns on vessels equipped with a scrubber are needed. These data, in combination with compilation and comparison of emissions factors to air and water (Paper I), are important in order to understand to what extent substances other than SO_X, are scavenged by the scrubber and what is remained in the exhaust. Also, more efforts should be made to improve the understanding of strong acid addition into the marine environment, both locally in terms of adverse effects on marine organisms and regionally in terms of affecting the buffer capacity of the ocean.

Prior to evaluation of *Impact*, *State change* should be related to environmental background concentrations and further connected to effects in the marine environment. As a next step, the focus will move more towards the *Impact* in DAPSIR where the aim is to better understand the dose-response relationship of scrubber water on single species as well as ecosystems. As scrubber water is a complex mixture of metals, PAHs and other unknown contaminants, the results from standardised ecotoxicological tests might need additional interpretation before the dose-response relationship can be established. For this, we will need to apply a more multi-faceted approach and combine ecotoxicological data of single substances found in scrubber water and compare to whole effluent testing of scrubber water exposure. Also, multivariate analysis relating toxicity response to the different constituents of scrubber water, including acidity, will hopefully provide important information of the toxicity potential and the mixture components driving the toxicity. Even though we have knowledge of some of the constituents of scrubber water, it still remains to be investigated to what extent marine organisms and ocean state will be impacted. Such future work will hopefully also provide valuable input to the field of mixture toxicity assessments and how to assess the combined toxicity from many different sources at the same time.

To connect the results from ecotoxicological tests to marine ecosystems, and to assess the impact from the use of scrubbers and other activities, there must be a connection between ship activity and the transportation and fate of contaminants. For this, distribution and chemical fate models will be an important tool. Ideally, this could then be coupled with ecological models (e.g. ecological pathway models on ecosystem levels), where the environment vulnerability, including background concentrations and other contaminant sources, and value, e.g. ecosystem services, could be added to the analysis. This could also be an appropriate strategy to partly account for the spatiotemporal variation (e.g. spawning season, seasonality regimes of varying wind and stratification and migration of different species) found in the marine environment.

Modelling efforts should not be limited to the effects of metals and PAHs but also include effects of strong acid addition and eutrophication. The more knowledge gained, the more activities and pressures can be added to the assessment. Hopefully, methodologies for an impact assessment, where *Activity*, *Pressure* and *State change* are accounted for, can be developed as a first step to assess the atmospheric and marine environmental *Impact* from shipping. A collective impact assessment could also explore the cost-benefit relationships of different fuels, abatement methods or mitigation strategies. If successful, this will be an important tool for policy makers and highlight the necessity in including the shipping sector and its environmental impact in all decision-making.

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