TEXTE
83/2021

Environmental Impacts of Exhaust Gas Cleaning Systems for Reduction of SOx on Ships – Analysis of status quo

Report compiled within the framework of the project ImpEx

German Environment Agency

Umwelt Bundesamt

TEXTE 83/2021

Ressortforschungsplan of the Federal Ministry for the
Enviroment, Nature Conservation and Nuclear Safety

Project No. (FKZ) 3719 57 101 0
Report No. FB000513/ZW,ENG

Environmental Impacts of Exhaust Gas Cleaning Systems for Reduction of SOx on Ships – Analysis of status quo

Report compiled within the framework of the project
ImpEx

by

Octavio Marin-Enriquez, Annika Krutwa, Katrin Ewert
Federal Maritime and Hydrographic Agency (BSH), Hamburg (Germany)

in cooperation with

Brigitte Behrends
Marena Ltd., Jever (Germany)

On behalf of the German Environment Agency

Imprint

Publisher
Umweltbundesamt
German Environment Agency

Wörlitzer Platz 1
06844 Dessau-Roßlau
Tel: +49 340-2103-0
Fax: +49 340-2103-2285
buergerservice@uba.de
Internet: www.umweltbundesamt.de/

/umweltbundesamt.de
/umweltbundesamt

Report performed by:
Bundesamt für Seeschifffahrt und Hydrographie
Federal Maritime and Hydrographic Agency
Bernhard-Nocht-Str. 78
20359 Hamburg

Report completed in:
November 2020

Edited by:
Section I 2.2 Air Pollution and Energy Saving in the Transport Sector
Katharina Koppe

Publication as pdf:
http://www.umweltbundesamt.de/publikationen

ISSN 1862-4804

Dessau-Roßlau, June 2021

Abstract: ImpEx – Environmental Impacts of Exhaust Gas Cleaning Systems for Reduction of SOx on Ships (Work package 1: Analysis of status quo)

In recent times, there is an increase in installations of Exhaust Gas Cleaning Systems (EGCS) on ships due to international regulations on sulphur content restrictions in marine fuels. EGCS reduce sulphur oxide emissions by cleaning exhausts but instead emit polluted acidic water to the marine environment.

The present report provides an overall review on the status quo of EGCS, with special focus on discharge water. It is based on a literature review and covers technical aspects, market analyses, regulatory framework and research activities related to this topic.

The market analyses indicate that the current number of ships with EGCS is above 3,000, representing more than 16.8% of the dead weight tons (DWT) of the global fleet. The future development of the EGCS market may be affected by the fluctuation of fuel prices, the uncertainty in fuel demand and availability, the modification of legal framework and the development of new technologies.

Several deficiencies were identified in the discharge water quality criteria established in the EGCS Guidelines of the International Maritime Organization (IMO). Further, prior research studies demonstrated an acidic pH and the presence of several pollutants such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), oil residues and nitrate in relevant concentrations in EGCS discharge water. In addition, ecotoxicological analyses indicated toxicity effects and that the single-pollutant approach alone is not sufficient for the environmental risk assessment of EGCS discharge water.

Thus, despite the current regulation, concerns regarding the impacts on the marine environment due to these emissions remain. Considering that, present and future studies should provide valuable input to the process of appropriate regulation.

Kurzbeschreibung: ImpEx – Umweltauswirkungen von Abgasreinigungssystemen zur Reduzierung von SOx auf Schiffen (Arbeitspaket 1: Status quo Analyse)

In den letzten Jahren hat die Anzahl von auf Schiffen installierten Abgasreinigungssystemen (EGCS) stetig zugenommen. Diese Entwicklung ist auf internationale Bestimmungen zur Beschränkung des Schwefelgehalts in Schiffskraftstoffen zurückzuführen. EGCS reduzieren Schwefeloxidemissionen, indem die Abgase gereinigt werden, leiten aber stattdessen verunreinigtes saures Wasser in die Meeresumwelt ein.

Der vorliegende Bericht gibt einen Gesamtüberblick über EGCS, mit besonderem Fokus auf die Abwasser-Problematik. Hierfür wurden umfassende Informationen aus der vorhandenen Literatur zusammengetragen. Der vorliegende Bericht beinhaltet technische Aspekte und eine Marktanalyse und behandelt rechtliche Rahmenbedingungen und Forschungsaktivitäten zu diesem Thema.

Die Marktanalyse zeigt, dass derzeit mehr als 3.000 Schiffe mit EGCS ausgerüstet sind, was über 16,8% der weltweiten Tragfähigkeit (DWT) entspricht. Die zukünftige Entwicklung des EGCS-Marktes kann durch Fluktuationen der Kraftstoffpreise, Ungewissheiten bei der Kraftstoffnachfrage und -verfügbarkeit, Änderungen der rechtlichen Rahmenbedingungen und die Entwicklungen neuer Technologien beeinflusst werden.

Mehrere Defizite wurden bei den in den EGCS-Richtlinien der Internationalen Seeschifffahrtsorganisation (IMO) festgelegten Qualitätskriterien für Abwässer festgestellt. Bisherige Untersuchungen zeigten einen sauren pH-Wert und das Vorkommen mehrerer Schadstoffe wie Schwermetalle, polyzyklische aromatische Kohlenwasserstoffe (PAK),

Ölrückstände und Nitrat in relevanten Konzentrationen im EGCS-Abwasser. Darüber hinaus wiesen ökotoxikologische Tests auf Toxizitätseffekte hin und dass der Single-Pollutant-Ansatz allein für die Umweltrisikobewertung von EGCS-Abwasser nicht geeignet ist.

Daher bestehen trotz der derzeitigen Regelung weiterhin Bedenken hinsichtlich der Auswirkungen auf die Meeresumwelt durch diese Emissionen. In Anbetracht dessen sollten gegenwärtige und zukünftige Studien einen wertvollen Beitrag zum Prozess einer angemessenen Regulierung leisten.

Table of content

List of figures

List of tables

List of abbreviations

AbwV	*Abwasserverordnung* (German Wastewater Directive)
BfG	*Bundesanstalt für Gewässerkunde* (German Federal Institute for Hydrology)
BOD	Biological oxygen demand
BOTU	Bleed-off treatment unit
BSH	*Bundesamt für Seeschifffahrt und Hydrographie* (German Federal Maritime and Hydrographic Agency)
BTEX	Benzene, toluene, ethylbenzene and xylene
BWMS	Ballast water management systems
CDNI	Strasbourg Convention on the Collection, Deposit and Reception of Waste during Navigation on the Rhine and Inland Waterways of 9 September 1996
CL	Closed loop
COVID-19	Coronavirus disease 2019
CO_2	Carbon dioxide
COD	Chemical oxygen demand
DWT	Dead weight tonnage (tonnes)
ECA(s)	Emission Control Area(s)
EEZ	Exclusive Economic Zone
EGCS	Exhaust Gas Cleaning System(s)
EGR	Exhaust Gas Recirculation
EQS	Environmental Quality Standards
EU	European Union
FNU	Formazin nephlometric units
GESAMP	Group of Experts on the Scientific Aspects of Marine Environmental Protection
GT	Gross tonnage
HFO	Heavy fuel oil
IMO	International Maritime Organization
MAMPEC-BW	Marine Antifoulant Model to Predict Environmental Concentrations (as amended for Ballast Water discharges)
MARPOL	International Convention for the Prevention of Pollution of Ships
MEPC	IMO Marine Environment Protection Committee
MGO	Marine gas oil
MSFD	Marine Strategy Framework Directive
Mt	Megatons
NOx	Nitrogen oxides
NTU	Nephlometric turbidity units
PAH	Polycyclic Aromatic Hydrocarbon(s)
pH	Defined as decimal logarithm of the reciprocal of the hydrogen ion activity

AbwV	*Abwasserverordnung* (German Wastewater Directive)
OL	Open loop
PCB	Polychlorinated biphenyls
PEC	Predicted Environmental Concentration
PNEC	Predicted No-Effect Concentration
POP	Particulate organic phosphorus
POC	Particulate organic carbon
PON	Particulate organic nitrogen
ppb	Part per billion
ppm	Part per million
PPR	IMO Sub-Committee on Pollution Prevention and Response
SECA	Sulphur Emission Control Area
SO_2	Sulphur dioxide
SOx	Sulphur oxides
SPE	Solid-phase extraction
THC	Total hydrocarbons
UBA	*Umweltbundesamt* (German Environment Agency)
UNCLOS	United Nations Convention on the Law of the Sea
WET	Whole effluent toxicity
WFD	Water Framework Directive
WHG	*Wasserhaushaltsgesetz* (Federal Water Act)
WHO	World Health Organization
WP	Work package

Summary

The present report provides an overall review on the status quo of Exhaust Gas Cleaning Systems (EGCS), with special focus on the environmental aspects of the discharge water. It is based on a literature review and covers technical aspects, market analyses, the regulatory framework and recent research activities related to this topic. The work was carried out within the project ImpEx (WP 1).

Open loop (OL), closed loop (CL) and hybrid EGCS have been installed on board ships since the introduction of international regulations on sulphur emissions from maritime traffic. EGCS discharge water has an acidic pH and contains several pollutants, such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), oil residues and nitrate. Thus, there are concerns regarding the impacts on the marine environment due to these emissions. The discharge volume depends on the type of system. In the case of OL systems, it is strongly dependent on the alkalinity of the surrounding water. In the past, 45 m^3/MWh was commonly assumed as average flowrate; recent studies, however, indicate average flowrates of around 90 m^3/MWh.

Notifications of approved EGCS on board ships from the Global Integrated Shipping Information System (GISIS) database of the International Maritime Organization (IMO) were used and complemented to generate a database about the current market penetration of this technology. This information was compared to market analyses carried out by private entities. The market analyses indicate that the current number of ships with EGCS is above 3,000, representing about 3.1% of the global fleet but more than 16.8% of global dead weight tons (DWT). OL systems dominate the market (>80%), followed by hybrid systems (~15%). EGCS are now strongly present on ship types other than ferries and cruise ships compared to numbers from 2019; bulk carriers, tankers and container ships are the top adopters of this technology.

The current COVID-19 pandemic has impaired the installation progress of EGCS, leading to uncertainties in short-term market estimations. A long-term prognosis shows a fuel market share of 10% for heavy fuel oil in combination with EGCS by 2050. The actual development of EGCS and other regulatory-compliant solutions may be affected by the fluctuation of fuel prices, the uncertainty in fuel demand and availability, the modification of legal framework (including regulations for other emissions besides sulphur oxide emissions) and the development of new technologies and energy sources.

The EGCS discharge water is internationally addressed by the EGCS Guidelines of the IMO that are referenced in the European law and consequently in the German law. However, in several ports and regions worldwide additional regional and local restrictions to EGCS discharge water were adopted. In this regard, work is currently ongoing within the IMO Marine Environment Protection Committee (MEPC) and its Sub-Committee on Pollution Prevention and Response (PPR) on harmonization of rules and guidance on the discharge of EGCS discharge water.

The EGCS Guidelines were recently reviewed and the revised version (“2020 EGCS Guidelines”) is expected to be adopted in the session 76 of the MEPC. The “2020 EGCS Guidelines” address some of the issues of the current version of the EGCS Guidelines (2015), such as the necessity of a definition of phenanthrene equivalent for measurement of PAHs (PAH_{phe}) and the lack of clarity for release of tank stored EGCS discharge water. However, the limit values set in the discharge criteria remain unchanged. This literature review could not establish any underlying documentation resulting in the determination of the limit values referenced by the IMO EGCS Guidelines, especially for turbidity and PAH_{phe}. Thus, it is questionable whether these criteria in fact ensures the protection of the marine environment. The current discharge criteria (for turbidity, PAH_{phe} and nitrates) does not represent any practical restriction for conventional OL

systems; except for pH, but dilution is allowed in that case so that effects on regional acidification are not prevented. In the case of CL systems, the turbidity limit value does represent a restriction; thus, water treatment prior discharge is required. Since 2008, the EGCS Guidelines ask for a review of the discharge criteria as soon as more data on the contents of the discharge water and its effects become available taking into account any advice given by GESAMP. Within that review, the use of PAH_{phe} as surrogate parameter for oil content should be clarified and the effectiveness of the turbidity criterion to prevent discharges of heavy metals should be addressed.

Finally, previous and current research activities were reviewed and summarized. Studies with sampling campaigns on board reported logistic challenges as well as missing and unsuitable sampling points. Results from chemical analyses of discharge water showed generally higher concentrations of pollutants in CL systems than in OL systems, despite a more efficient water treatment being applied. Vanadium and nickel are the metals with the highest enrichment in discharge water.

Studies focused on ecotoxicological analysis indicated that CL discharge water show higher toxicity than OL discharge water. However, when considering the flowrates, OL discharges represented a higher risk to marine ecosystems. Even the water treatment prior discharging in CL systems showed no significant reduction of toxicity effects. Results from whole effluent toxicity (WET) tests indicated species-specific responses to EGCS discharge water and demonstrated that the single-pollutant approach alone is not sufficient for the environmental risk assessments of EGCS discharge water. The latter might be explained by cumulative or even synergistic toxicity effects and by unknown pollutants present in EGCS discharge water. Environmental risk assessments, based on the ratio between Predicted Environmental Concentration and Predicted No-Effect Concentration (PEC/PNEC approach), presented different and opposing conclusions. The approach and methodology applied, considerations for determining PEC values and selected safety factors to establish PNEC values should be taken into account when evaluating the conclusions.

Other national and international research projects being carried out in parallel to the ImpEx project and covering the assessment of EGCS discharge water were identified and generally described. Possible synergies with these projects are sought.

Zusammenfassung

Der vorliegende Bericht präsentiert einen Überblick zum Status quo von Abgasreinigungsanlagen (EGCS, *Exhaust Gas Cleaning Systems*) mit besonderem Schwerpunkt auf den umweltrelevanten Aspekten der Abwassereinleitungen. Er basiert auf einer Literaturrecherche und deckt technische Aspekte, Marktanalysen, die rechtlichen Rahmenbedingungen und aktuelle Forschungsarbeiten im Zusammenhang mit dem Thema ab. Der Bericht wurde im Rahmen des Projektes ImpEx (AP1) erstellt.

Scrubber mit offenen (OL, *open loop*) und geschlossenen Systemen (CL, *closed loop*) sowie hybride EGCS sind seit der Einführung internationaler Regelungen zur Reduktion der Schwefelemissionen im Seeverkehr an Bord von Schiffen installiert worden. EGCS-Abwasser hat einen sauren pH-Wert und enthält verschiedene Schadstoffe, wie Schwermetalle, polyzyklische aromatische Kohlenwasserstoffe (PAKs), Ölrückstände und Nitrat. Daher gibt es Bedenken hinsichtlich der Auswirkungen dieser Emissionen auf die Meeresumwelt. Das Einleitvolumen hängt von der Art des Systems ab und wird zum Beispiel in OL-Systemen besonders von der Alkalinität des Umgebungswassers beeinflusst. In der Vergangenheit wurden gewöhnlich durchschnittliche Durchflussmengen von 45 m^3/MWh angegeben. Neuere Studien deuten jedoch auf durchschnittliche Durchflussraten von etwa 90 m^3/MWh.

Meldungen über genehmigte EGCS an Bord von Schiffen aus der GISIS (*Global Integrated Shipping Information System*) Datenbank wurden verwendet und ergänzt, um eine Datengrundlage zur aktuellen Marktdurchdringung dieser Technologie zu erstellen. Diese Informationen wurden mit Marktanalysen verglichen, die von privaten Unternehmen durchgeführt wurden. Aus der Marktanalyse geht hervor, dass derzeitig über 3.000 Schiffe mit EGCS ausgerüstet sind, was mehr als 3,1% der weltweiten Flotte, aber 16,8% der weltweiten Tragfähigkeit (DWT) entspricht. OL-Systeme dominieren den Markt (>80%), gefolgt von hybriden Systemen (~15%). EGCS waren anfangs v.a. in Fähren und Kreuzfahrtschiffen vertreten, aktuell sind andere Schiffstypen, wie Massengutfrachter, Tanker und Containerschiffe die Top-Anwender dieser Technologie.

Die aktuelle COVID-19-Pandemie hat Auswirkungen auf den weiteren Fortschritt von EGCS-Installationen, was zu Unsicherheiten bei den kurzfristigen Marktschätzungen führt. Eine Langzeitprognose zeigt bis 2050 einen Kraftstoffmarktanteil für Schweröl in Kombination mit EGCS von 10%. Die tatsächliche Entwicklung von EGCS und anderen regelkonformen Lösungen kann durch Fluktuationen der Kraftstoffpreise, Ungewissheiten bei der Kraftstoffnachfrage und -verfügbarkeit, Änderungen der rechtlichen Rahmenbedingungen (einschließlich der Vorschriften für weitere Emissionen außer Schwefeloxide) und die Entwicklungen neuer Technologien und Energieträger beeinflusst werden.

Im internationalen Kontext befassen sich die EGCS-Richtlinien der Internationalen Seeschifffahrtsorganisation (IMO, *International Maritime Organization*) mit EGCS-Abwasser. Die Richtlinien sind auch nacheuropäischem und deutschem Recht zu berücksichtigen. In mehreren Häfen und Regionen weltweit wurden jedoch zusätzlich regionale und lokale Einschränkungen für EGCS-Abwasser verabschiedet. In dieser Hinsicht wird derzeit im IMO Ausschuss zum Schutz der Meeresumwelt (MEPC, *Marine Environment Protection Committee*) und seinem Unterausschuss für die Verhütung und Bekämpfung der Umweltverschmutzung (PPR, *Pollution Prevention Response*) an einer Harmonisierung der Regeln und Leitlinien für die Einleitung von EGCS-Abwasser gearbeitet.

In diesem Zusammenhang wurden die EGCS-Richtlinien kürzlich überarbeitet, und die überarbeitete Fassung ("2020 EGCS-Richtlinien") wird voraussichtlich auf der Sitzung 76 des

IMO-Ausschusses MEPC angenommen werden. Die "2020 EGCS-Richtlinien" greifen einige der in der aktuellen Version der EGCS-Richtlinien als ergänzungswürdig erarbeiteten Punkte auf, wie z.B. die Notwendigkeit einer Definition des Phenanthren-Äquivalents für die Messung von PAKs (PAK_{phe}) und die mangelnde Klarheit für Einleitung von in Tanks gespeichertem EGCS-Abwasser. Die in den Einleitkriterien festgelegten Grenzwerte bleiben jedoch unverändert. Im Rahmen dieser Literaturrecherche konnte mangels entsprechender Dokumentation nicht nachvollzogen werden, wie die Grenzwerte in den EGCS-Guidelines, insbesondere für Trübung und PAH_{phe}, zustande gekommen sind. Es ist daher fraglich, ob diese Kriterien tatsächlich den Schutz der Meeresumwelt gewährleistet. Die vorliegenden Einleitkriterien (für Trübung, PAK_{phe} und Nitrate) stellen keine praktische Einschränkung für herkömmliche OL-Systemen dar, mit Ausnahme des pH-Wertes. Allerdings ist in diesem Fall eine Verdünnung zulässig, so dass Auswirkungen auf die Ozeanversauerung nicht verhindert werden. Bei CL-Systemen hingegen stellt der Trübungsgrenzwert eine Einschränkung dar, so dass eine Wasseraufbereitung vor der Einleitung erforderlich ist.

Seit 2008 fordern die EGCS-Richtlinien unter Berücksichtigung der Empfehlungen von GESAMP eine Überprüfung der Einleitkriterien, sobald mehr Daten über die Inhaltsstoffe des Abwassers und deren Auswirkungen verfügbar sind. Im Rahmen dieser Überprüfung sollte die Verwendung von PAK_{phe} als Ersatzparameter für den Ölgehalt geklärt und die Wirksamkeit des Trübungskriteriums zur Verhinderung von Schwermetalleinleitungen untersucht werden.

Schließlich wurden frühere und aktuelle Forschungsarbeiten betrachtet und zusammengefasst. Studien mit Probenahmekampagnen an Bord berichteten über logistische Herausforderungen sowie über fehlende und ungeeignete Probenahmestellen. Die Ergebnisse chemischer Analysen von Abwasser zeigten im Allgemeinen höhere Schadstoffkonzentrationen in CL-Systemen als in OL-Systemen trotz der effizienteren Wasseraufbereitung. Vanadium und Nickel sind die Metalle mit der höchsten Anreicherung im Abwasser.

Studien, die sich auf ökotoxikologische Analysen konzentrieren, wiesen darauf hin, dass CL-Abwasser eine höhere Toxizität als OL-Abwasser aufweist; trotz der Wasserbehandlung vor der Einleitung zeigte sich keine signifikante Reduzierung der Toxizitätseffekte in den CL-Systemen. Betrachtet man die Durchflussmengen, so stellen OL-Abflüsse ein höheres Risiko für marine Ökosysteme dar. Ergebnisse von Tests zur Gesamttoxizität des Abwassers (WET, *Whole Effluent Toxicity*) ergaben artspezifische Reaktionen auf EGCS-Abwasser und zeigten, dass der *Single-Pollutant-Ansatz* allein für die Umweltverträglichkeitsprüfung bezüglich EGCS-Abwasser nicht geeignet ist. Kumulative oder sogar synergistische Toxizitätseffekte und nicht identifizierte Schadstoffe im EGCS-Abwasser könnten die Ergebnisse erklären. Umweltrisikobewertungen, die auf dem Verhältnis zwischen der vorausgesagten Konzentration des Stoffes, welche in der Umwelt erwartet wird und der vorausgesagten Konzentration des Stoffes, bis zu der keine (toxische) Auswirkungen auf die Umwelt auftreten, basieren (PEC/PNEC-Ansatz), führten zu unterschiedlichen und gegensätzlichen Schlussfolgerungen. Der angewandte Ansatz und die Methodik, Überlegungen zur Bestimmung der PEC-Werte und ausgewählte Sicherheitsfaktoren zur Festlegung der PNEC-Werte sollten bei der Bewertung der Schlussfolgerungen berücksichtigt werden.

Weitere nationale und internationale Forschungsprojekte, die parallel zum ImpEx-Projekt durchgeführt werden und sich mit der Bewertung von EGCS-Abwasser befassen, wurden identifiziert und allgemein beschrieben. Mögliche Synergien mit diesen Projekten werden angestrebt.

1 Introduction

In order to reduce sulphur oxides (SOx) and particulate matter emissions from sea-going ships, regulation 14 of Annex VI of the International Convention for the Prevention of Pollution of Ships (MARPOL) sets out sulphur limits in fuel oil used on board ships. As an alternative, EGCS (commonly referred to as “scrubber”) may be operated on board to reach at least equivalent SOx emission reductions, while still using non-compliant fuels, as allowed under regulation 4 of MARPOL Annex VI. The implementation of the sulphur limit in Emission Control Areas (ECAs) (0.1%) in 2015 and, more recently, of the global sulphur limit (0.5%) in 2020 has boosted the development of the market of EGCS in the maritime sector.

Before the entry into force of MARPOL Annex VI in 2005, the use of EGCS on board ships as an equivalent method for the compliance with Regulation 14 has been discussed at the MEPC and other subcommittees of the IMO. Environmental concerns regarding the release of EGCS discharge water have been a subject of discussion. In section 10 of the Guidelines for Exhaust Gas Cleaning Systems (EGCS Guidelines) discharge criteria have been defined generally intended to prevent acute effects occurring in the aquatic environment (GESAMP, 2009). Since the EGCS Guidelines of 2008, it has been noted that the discharge *“criteria should be revised in the future as more data becomes available on the contents of the discharge and its effects, taking into account any advice given by GESAMP”* (MEPC, 2008a; MEPC, 2009; MEPC, 2015). Attending the need to generate information about the EGCS discharge water, the German Federal Maritime and Hydrographic Agency (BSH) carried out on behalf of the German Environment Agency (UBA) a project (2016-2019) that included a sampling campaign on board five vessels equipped with EGCS, chemical characterization of water samples as well as an emission and distribution modelling of EGCS discharge water in the Baltic Sea and North Sea. The project report concluded that further research is needed for a better quantification and evaluation of the total impact on the marine environment of this abatement technology (Schmolke et al., 2020). Concerning that matter and to address specific questions arisen from the mentioned project, a follow-up project (ImpEx – Environmental Impacts of Exhaust Gas Cleaning Systems for Reduction of SOx on Ships, 2020–2023) is conducted on behalf of UBA by a consortium of German federal agencies, state authorities and institutions. The project ImpEx shall contribute to a factual discussion on the concerns from EGCS discharge water in marine environment. The here presented results of WP 1 of the project include an overall review on the status quo of EGCS, with special focus on the environmental aspects of the discharge water. It is based on a literature review and covers technical aspects, market analyses, the regulatory framework and recent research activities related to this topic. Further information about the project is presented in Table 6.

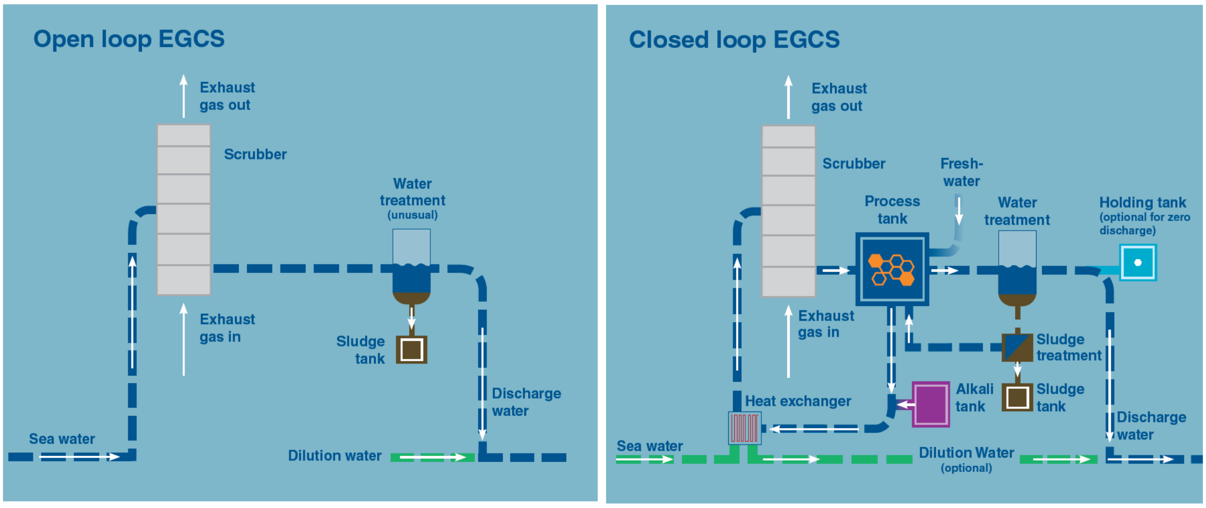
2 Technical description of the EGCS technology

There are several information sources from classification societies, governmental authorities, research institutes and manufacturers describing the fundamentals and operation of the EGCS technology on board ships. Especially EGCSA (2012), ABS (2019), Lloyd's Register (2012), Kjølholt et al. (2012) and US EPA (2011) offer an extensive technical description of EGCS. This report does not aim to describe into detail the EGCS technology. Thus, only a general description is presented in this chapter. Aspects related to the water management are discussed more extensively.

EGCS, also called scrubber, is an established technology in the land-based industry sector for air pollution abatement (e.g. flue gas from combustion plants) and for recovery of valuable products from a gas stream. Depending on the medium used for removal of the target compounds, EGCS can be classified as dry and wet; the first type uses packed bed granulated chemicals and the latter a liquid stream (typically water) as absorption medium.

In the maritime industry, wet EGCS dominate the market, while for dry EGCS just one manufacturer (EGCSA, 2012) and four installations (DNV GL, 2020) are reported. The reasons for the low acceptability are among others, the requirement for extensive space for dry EGCS installations which cannot be met by many ships and the huge amount of solid waste produced (gypsum). Wet EGCS are divided in open (OL) and closed loop (CL) EGCS, depending on the mode of operation; if the installation can be operated in both modes it is called hybrid EGCS. Figure 1 depicts the differences in the water management between open loop and closed loop EGCS. Independently of the type of system, water is pumped into an absorption tower and sprayed into the exhaust gas stream. In the absorption tower, SO_2 is transferred from the gas to the liquid phase and subsequently oxidized to sulphate species. The SO_2 removal efficiency for every system depends on several factors (e.g. amount and quality of water, system design, temperature, initial SO_2 concentration, and chemical addition) that affect diffusivity and equilibrium solubility (US EPA, 2002). Removal efficiency can be above 98% (Fridell and Salo, 2014; Lloyd's Register, 2012). This process is called flue gas desulphurisation or SO_x scrubbing.

Figure 1: Process flow for the two modes of operation of wet EGCS: open loop (left) and closed loop (right)



Source: BSH (2020).

2.1 Open loop EGCS

An OL system, also commonly referred to as seawater system, requires high amounts of seawater (~45 m^3/MWh) and relies on its natural alkalinity for the scrubbing process (Lloyd's Register, 2012). The water is directly discharged back to the sea, in some cases with prior treatment for solids removal or dilution with seawater to increase the pH. The energy consumption of OL systems is 1-3% of the engine power output (US EPA, 2011).

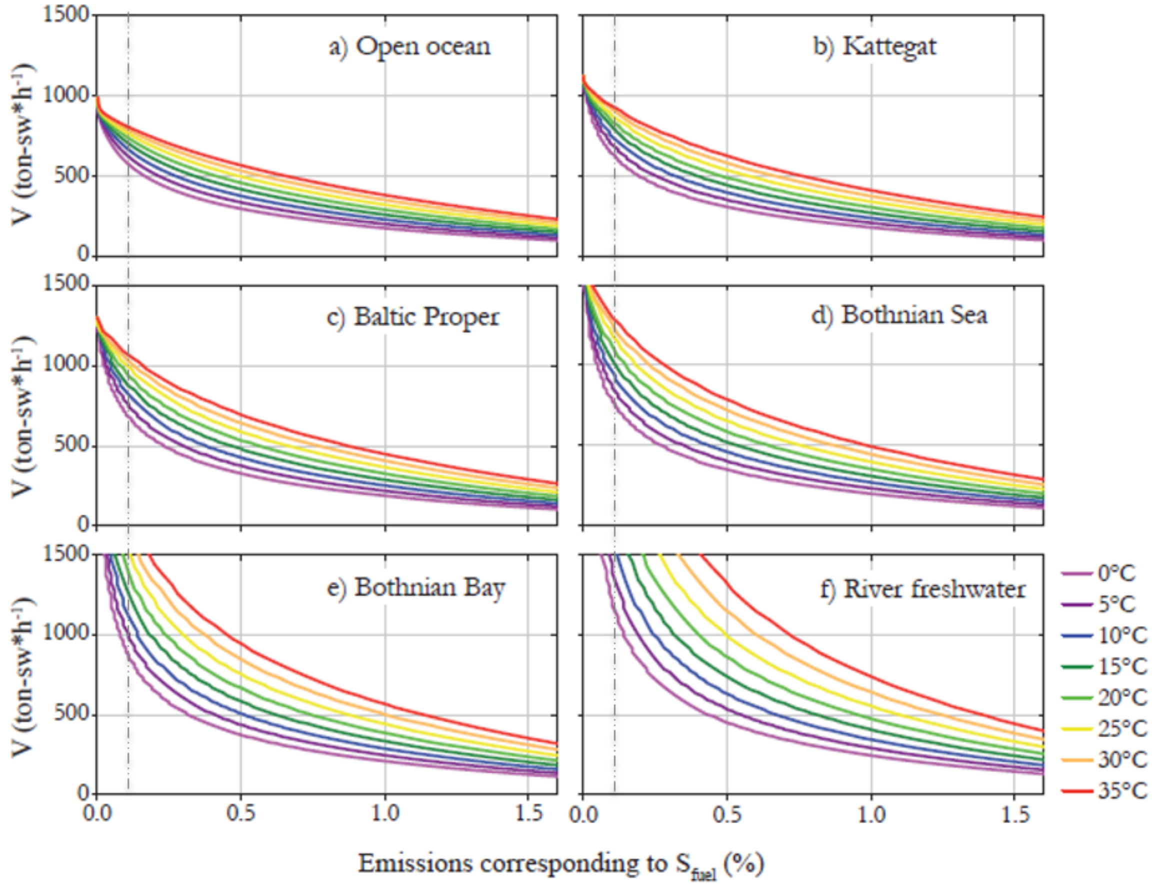
Although in most of the literature 45 m^3/MWh is given as the typical flowrate for OL systems, the required flowrate varies significantly as a function of the physical-chemical properties of the water (temperature, alkalinity and salinity), the desired SOx removal efficiency (Hassellöv and Turner, 2007) and the effectiveness of the water-gas contact (system design) (EGCSA, 2012). Hassellöv and Turner (2007) mentioned that the initial factor determining the SOx uptake capacity is the alkalinity or buffering capacity of the water. Once it is consumed, the factor enabling further uptake is the solubility of sulphur dioxide, which decreases with higher temperature and salinity (ionic strength). They calculated the water volume required to reach a determined level of reduced emission as a function of temperature for six different waterbodies (see Figure 2). For the calculations, combustion of fuel with 3% sulphur content, engine power of 12 MW and specific fuel consumption of 185 kg/MWh were assumed. For instance, to achieve emissions equivalent to combustion of fuel with 0.1% sulphur content and water temperature of 15 °C, a water flowrate of around 56 m^3/MWh would be required in open sea and 80 m^3/MWh in the Bothnian Sea. Buhaug et al. (2006) indicated a water consumption in the range of 40-100 m^3/MWh. Based on an extensive literature review, Teuchies et al. (2020) and Hassellöv et al. (2020) reported an average flowrate of 87 ± 50 m^3/MWh and 90 ± 14 m^3/MWh, respectively. In the sampling campaign of the previous UBA/BSH study (Schmolke et al., 2020) water flowrates under stable conditions from around 60 to 140 m^3/MWh were recorded.

2.2 Closed loop EGCS

A CL system, also commonly referred to as freshwater system, employs typically freshwater treated with an alkaline substance (e.g. caustic soda) to adjust the pH level. After the washing process in the spray tower, the water is passed into a process (or recirculation) tank. There, a small portion of the water is taken from the tank bottom, where the scrubbing products are settled, pumped out and discharged after being treated for solids removal. The water treatment units are typically hydrocyclones, centrifugal separators or dissolved air flotation, sometimes in combination with flocculants. The amount of water being discharged (bleed-off) is significantly lower (0.1 - 0.3 m^3/MWh) than the water volume discharged from OL systems. Teuchies et al. (2020) reported an average discharge rate of 0.47 ± 0.25 m^3/MWh. Alternatively, bleed-off can be stored in a holding tank and properly discharged. That temporarily zero discharge mode is very convenient in regions with existing restrictions for EGCS water discharge. Residuals removed from the water treatment are called sludge and must be properly disposed ashore. The amount of sludge generated may range from 0.1 to 0.9 kg/MWh (EGCSA, 2012; Lloyd's Register, 2012; US EPA, 2011; Den Boer and Hoen, 2015). Stena Teknik (Asplind, 2018) reported an amount of sludge disposal equivalent to around 1% of the burnt fuel. From the process tank, most of the water is recirculated (~20 m^3/MWh) and, after addition of an alkaline solution for pH control and cooling by a seawater heat exchanger to prevent losses by evaporation, is pumped back to the absorption tower. Depending on the amount of water losses, freshwater (make-up water) is added to the system. The energy consumption of CL systems is reported to be about 0.5-1% of the engine power output. The rate of consumption of caustic soda ranges between 6-18 L/MWh and is directly proportional to SO_2 in flue gas; typical ratio is 1.25 kg caustic soda per 1 kg SO_2 or 6 L/MWh·%S (EGCSA, 2012; Lloyd's Register, 2012; US EPA, 2011;

Den Boer and Hoen, 2015). Lahtinen (2016) measured a specific consumption of 50% alkali about 10 kg/MWh·%S in a small test EGCS and around 6 kg/MWh·%S in a commercial EGCS.

Figure 2: Required water volume flowrates as a function of the achieved level of reduced emission for six different natural waters at different temperatures



Assumptions: combustion of fuel with 3% sulphur content, engine power of 12 MW and specific fuel consumption of 185 kg/MWh. Thus, the values on the Y-axis 500, 1000 and 1500 t/h correspond approx. to specific flowrates of 41.7, 83.3 and 125 m^3/MWh, respectively.
Source: Hassellöv and Turner (2007).

2.3 Hybrid EGCS

Hybrid systems can be operated in either OL or CL modes. This require special arrangements that make the system more complex than OL or CL systems individually. The OL mode is typically employed in open sea, where the alkalinity is sufficient for efficient SOx removal (EGCSA, 2012). The CL mode, on the other hand, is commonly operated only in sensitive areas with local regulative restrictions (in zero discharge mode) or in waters with insufficient alkalinity or with poor quality (to protect the systems) (Lloyd’s Register, 2012; Woodfall, 2020). Manufacturers also offer OL systems “hybrid ready”, designed to facilitate future upgrades.

2.4 Discharge water composition

The EGCS discharge water is characterized by low pH, elevated temperature, increased chemical oxygen demand (COD) and decreased dissolved oxygen concentration (US EPA, 2011). It does not only contain removed sulphur oxides but also pollutants present in exhaust gas, including PAHs, oil residues, heavy metals and nitrate (Endres et al., 2018). The specific composition of the

EGCS discharge water depends on several variables including EGCS design and operation, fuel and lube oil composition, engine load and conditions (quality of combustion), water treatment, water background concentrations and chemicals added. These variables can be grouped, so that three different pollutants sources are identified: the exhaust gas, the inlet water and the EGCS itself including the water processing (US EPA, 2011). For example, the corrosion of the system material may contribute to the presence of metals in the discharge water (Den Boer and Hoen, 2015). Another factor affecting the concentration of pollutants is the water flowrate. In ports, harbours and estuaries, where the continuous engine power is considerably lower, some systems operate with reduced flow and some ships do not use EGCS at all in ports. Other systems operated at constant flow will obviously discharge a cleaner effluent (MEPC, 2008b), or more correctly, diluted pollutant concentrations at such conditions. At the end, the pollutants load discharge might be more relevant to evaluate environmental impacts than their discharge concentration. There are concerns about the environmental impact of EGCS, because of the amounts and components of the EGCS discharge water (Lange et. al, 2015).

2.5 Current developments on the EGCS technology

EGCS experts and manufacturers (Riviera and EGCSA, 2020) have expressed that the technology is already mature. However, current research and development activities are being carried out, for instance, to enhance particulate removal and CO_2 capture from the exhaust gas (Riviera and EGCSA, 2020; IOW, 2020). In the treatment of EGCS discharge water, there is still room for improvements, so that new filter and membrane types are being tested (Riviera and EGCSA, 2020). For instance, the Flensburg University of Applied Sciences is currently carrying out a project to test a membrane plant for the treatment of bleed-off in CL systems (HS Flensburg, 2020). Actually, most of the current developments on scrubber water treatment are focused on bleed-off from CL systems. The relatively great volume flowrates from OL systems make the technical feasibility of water treatment very complex. In fact, water treatment units in OL systems are uncommon. In this regard, the company Prime Lake has completed a pilot test using electro-aeration for elimination of harmful contaminants in water from OL systems (Hakirevic, 2020).

3 Market analysis

Recent studies about the EGCS market for the maritime industry have been identified and reported in Table 1. Various studies such as DNV GL (2020), Lloyd's List (Bockmann, 2020) and Clarksons Research (2019) relied mainly on surveys by EGCS manufacturers for the data collection. As in the work of Schmolke et al. (2020), information from GISIS was retrieved in order to have data from an official and independent information source. GISIS is a public on-line platform developed by the IMO Secretariat in compliance with the decision by IMO Members requesting public access to sets of data provided by the Maritime Administrations and collected by the IMO Secretariat (IMO, 2017). IMO has included in GISIS a section regarding the approval of equivalence compliance methods by ships (Regulation 4.2 of MARPOL Annex VI), and administrations are required to make entries into the database. This public information served as a source to create a new database about the installed and approved EGCS worldwide. Data of notifications made by 9 November 2020 were collected, including notifying party, IMO number, approval date and details of the EGCS (manufacturer, model and type). The database was complemented with data (such as ship name, ship type and year of construction) from the IHS Markit database (2020).

For comparison purposes, the prognosis of the study of EnSys Energy and Navigistics Consulting (2016) is included in Table 1 as MEPC 70/INF.9. This prognosis assumed that the ships, for whom the installation and operation of an EGCS is economically advantageous, acquire an EGCS.

Table 1: Total number of ships with EGCS as reported by different information sources

Number of ships	EGCS-stand	Information source [i]	Information stand [ii]
9,247	Installed (prognosed)	MEPC 70/INF.9	31/12/2019
2,753 (+ 580)	Installed (+ on-order)	Lloyd's List	14/02/2020
3,137	Installed	DNV GL (Veracity Platform)	31/12/2019
2,808 [iii]	Installed + on-order	Clarksons Research	04/06/2019
2,788	Installed and approved	GISIS (IMO Platform)	9/11/2020

i) MEPC 70/INF.9 (EnSys Energy and Navigistics Consulting, 2016); Lloyd's List (Bockmann, 2020); DNV GL (DNV GL, 2020); Clarksons Research (2019); GISIS (IMO, 2020)

ii) It refers to the date by which the numbers are given and not necessarily the date of consultation. This is the case for the information reported from MEPC 70/INF.9 and DNV GL. The date given for GISIS refers to the date at which the data was collected; all notifications given by that date were considered.

iii) Number excludes some orders not yet linked to individual ships, which might increase the number up to ~4,000.

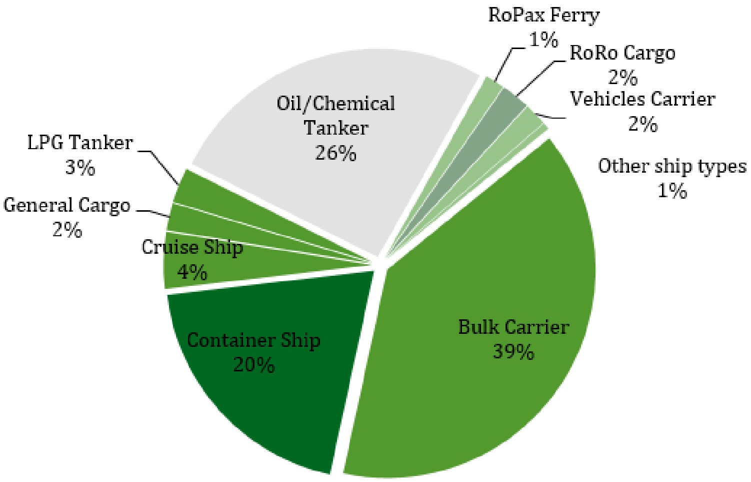
When comparing the numbers from Table 1, it is noticeable that the prognosis from MEPC 70/INF.9 overestimated the number of installations. On the other hand, the number of notifications collected from GISIS are below the numbers given by the market studies. This might be because not all member States have yet submitted information to GISIS, or the notifications are delayed. However, it seems that data by GISIS will soon meet the numbers of the market studies. GISIS entries have been observed regularly during the last year, and in recent months the number of notifications has increased significantly.

Based on the data presented in Table 1 and the remarks noted above, it could be assumed that the current actual number of ships with EGCS is above 3,000. This number represents 3.1% of the global fleet[1]. The share of the global DWT and GT are more significant: about 16.8%[2] and about 16.3%[3], respectively.

DNV GL (2020) specifies that, from the installation projects, 28% are newbuildings and 72% retrofits. Newbuildings are being actually fitted more intensively than existing ships. According to Clarksons Research (2019), 2.3% (12.2% GT) of the existing ships are or will be EGCS-fitted, while 14.5% (33.1% GT) of the orderbook will be EGCS-fitted. This corresponds with the fact that retrofitting on existing ships is more challenging; thus, such an investment should be considered for large ships with several operational years left (Lahtinen, 2016).

Figure 3 shows the market share by ship type. Bulk carriers, tankers and container ships are the top adopters of the EGCS-technology. That is clearly a different figure when compared with the data (Figure 5 in Schmolke et al., 2020) prior to the Global Sulphur Cap 2020, where the cruise ships together with RoPax and RoRo vessels dominated the market and were pointed out as first adopters after the implementation of the 0.1% sulphur limit in ECAs. Cruise ships are to be considered a special case, with 62% (GT) of its global current fleet being EGCS-fitted, but only 25% (GT) of the orderbook (Clarksons Research, 2019), perhaps due to the adoption of alternative compliance fuels.

Figure 3: EGCS market share by ship type



As of 9 November 2020: 2,788 ships. Source: Raw information obtained from GISIS (IMO, 2017).

Regarding market share by type of system, Figure 4 shows clearly a dominance of OL systems with above 80% of the market, followed by hybrid systems with ~15%. The three biggest market suppliers are Wärtsilä, Alfa Laval and EcoSpray, which cover around one third of the EGCS market (see Appedix A.1). This agrees with DNV GL (2020) that places the same companies as market leaders with a similar market share.

---

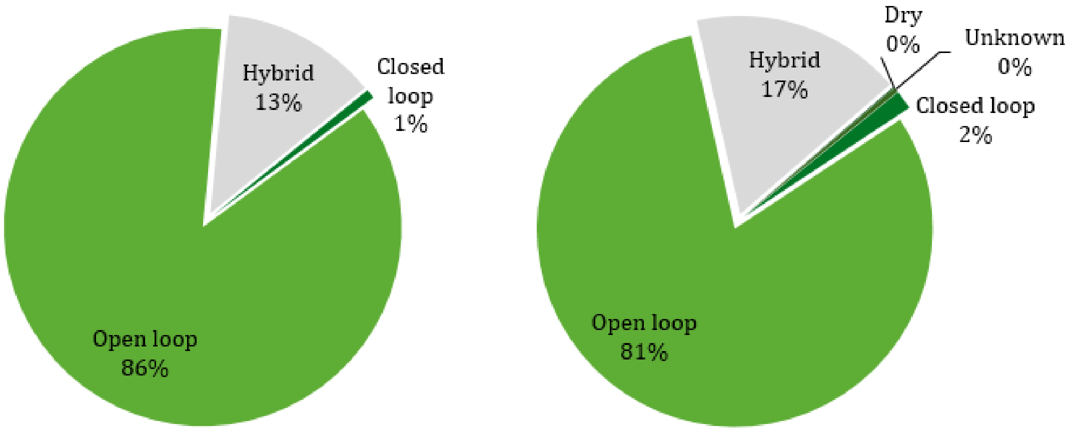
[1] UNCTAD (2020) reports 96,295 propelled seagoing merchant vessels of 100 GT and above in 2019.

[2] . The 2,788 EGCS-fitted ships reported in the GISIS database account for 332.2 million DWT. That number divided by the global DWT (1,976.5 million DWT as of UNCTAD, 2020) results in 16.8%.

[3] The 2,788 EGCS-fitted ships reported in the GISIS database account for 218.1 million GT. This number divided by the global GT (1,341.4 million GT as of UNCTAD, 2020) results in 16.3%.

Figure 4: EGCS market share by type of EGCS

Information from GISIS (left) and from DNV GL (right)

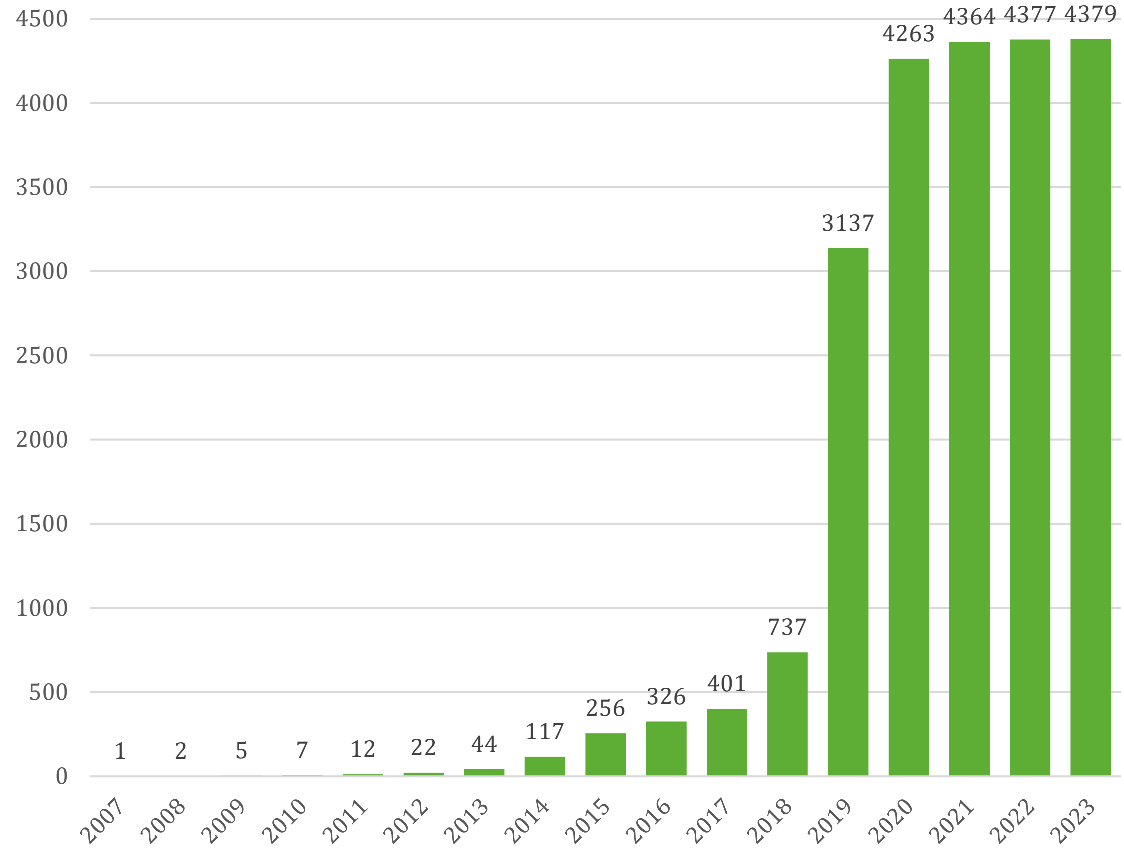


Left: Information as of 3 March 2020: 1,513 ships. Notifications without information about the type of EGCS are not considered. The detailed information of notifications submitted in the period 3 March – 9 November 2020 (1,275 notifications) has not been processed. Source: Raw information obtained from GISIS (IMO, 2017).
Right: Information as of 8 May 2020. Source: DNV GL, 2020.

4 Forecast of EGCS application and alternative compliant solutions

The database from DNV GL (2020) presents the number of ships EGCS-fitted for the coming years. Figure 5 shows 4,379 ships EGCS-fitted by 2023. Clarksons Research (2019) counted up to ~4,000 ships (including further additions pending) and estimated that by end 2020 up to 15% of the world fleet by tonnage capacity will be EGCS-fitted.

Figure 5: Total number of ships with EGCS (in operation and on-order)



Source: DNV GL (2020), retrieved on 07/05/2020 from https://afi.dnvgl.com/.

Those short-term prognoses which are based on confirmed orders, could present modifications due to the current COVID-19 pandemic and low fuel oil prices in the market. These factors have led to postponement and cancellation of EGCS installations. First, the outbreak of the virus in China and the Asiatic region stopped the work in the shipyards, where most of the installation works were scheduled. Secondly, the economic impact of the COVID-19 pandemic has also affected the shipping industry. As a response, the shipping companies have taken several measures including the postponement or cancellation of EGCS installations. In addition to that, or perhaps one reason to support that decision is the current low cost gap between (non-compliant) residual fuels and (compliant) low-sulphur fuels, originated by the current market crisis caused by the COVID-19 pandemic. That cost gap is a determining factor on the economic viability for the adoption of EGCS. A gap above 200 USD per ton might ensure a fast return of investment. At the beginning of the year 2020, that cost gap reached values above 300 USD per ton; in May 2020 it was only ~60 USD per ton (Ship&Bunker, 2020)[4].

A long-term prognosis for the EGCS market after the first years of implementation of the Global Sulphur Cap is very uncertain, because there are many factors affecting the decision of the ship owners: fluctuating fuel prices, uncertainty in fuel demand and availability, modification of legal framework and development of new technologies (Schmolke et al., 2020). Here it is worth introducing other compliance options to Regulation 14 of the MARPOL Annex VI. Besides the use of heavy fuel oil in combination with EGCS, alternative compliance solutions can be divided into (DNV GL, 2019a):

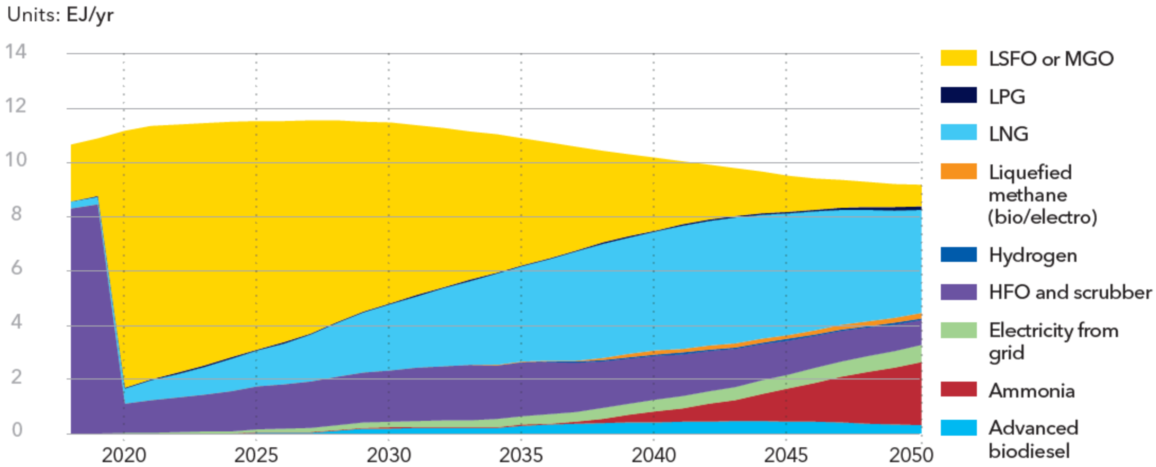
- Marine gas oil (MGO) or distillates,
- New compliant low-sulphur fuels (LSFO),
- Liquefied natural gas (LNG) and
- Other alternative fuels, such as methanol, biofuels, liquefied petroleum gas (LPG), battery propulsion and fuel cells powered by hydrogen.

Other environmental IMO regulations (e.g. NOx regulation) also have an impact in the marine fuel market and the development of new technologies. For instance, LNG is gaining a more favourable position as an alternative for complying with SOx (DNV GL, 2019a) and NOx regulations (Ushakov et al., 2019). On the other hand, other alternative fuels will gain attention to reach the IMO greenhouse gases (GHG)-reduction targets if policy measures and incentives are introduced; otherwise, it is predicted that the current fuel mix will prevail but with LNG taking a greater share of it (DNV GL, 2019b). To this regard, DNV GL (2019b) explored three different IMO ambition pathways based on different assumptions on regulations for reducing GHG emissions and made a prognosis on the marine fuel market for the period 2018 – 2050. Figure 6 shows the results for the pathway with main focus on design requirements. It is noticeable a strong decrease on the share of HFO in combination with EGCS before 2020 and after that a relatively constant share with slight fluctuations. For the year 2050, the energy share of HFO and EGCS is projected to be 10%. The same study predicts the energy share of HFO and EGCS in newbuildings to be from around 30% in 2020 to moderately decrease to <20% by 2034. This implies that more orders of EGCS are to be expected during the next years. However, this conclusion should be considered with some caution as it is based on a prognosis with different assumptions (without taking into account other emerging fuels such as methanol) for the abovementioned factors that are unsettling the fuel market.

---

[4] „Global 20 Ports Average“ bunker prices on 15 May 2020 were 181.40 (IFO380), 243.00 (VLSFO) and 297.00 (MGO) USD per ton, as retrieved from https://shipandbunker.com/prices

Figure 6: **Energy use and projected fuel mix 2018 – 2050 for the simulated IMO ambitions pathway with main focus on design requirements**



EJ/yr, exajoules per year; LSFO, low-sulphur fuel oil; MGO, marine gas oil; LPG, liquefied petroleum gas; LNG, liquefied natural gas; HFO, heavy fuel oil; Advanced biodiesel, produced by advanced processes from non-food feedstocks.
Source: DNV GL (2019b).

5 Legal framework

Sulphur oxide emissions from sea-going ships are regulated in Regulation 14 of the revised MARPOL Annex VI by specifying a progressive reduction on the sulphur content in fuels used on board. Regulation 14.1 set the limit values worldwide for fuels sulphur content; since 1 January 2020 the global limit is 0.5% m/m, known as the Global Sulphur Cap 2020. Regulation 14.4 set even lower limit values in designated special areas (ECAs – Emission Control Areas); since 1 January 2015 the ECA limit is 0.1% m/m (MEPC, 2008c). The Baltic Sea, North Sea, American Caribbean Sea and North America are currently defined as sulphur ECAs (IMO, 2020).

At the same time, Regulation 4.1 of MARPOL Annex VI (MEPC, 2008c) allows for *"any fitting, material, appliance or apparatus to be fitted in a ship or other procedures, alternative fuel oils, or compliance methods used as an alternative to that required by this Annex if such (…) are at least as effective in terms of emissions reductions as that required by this Annex, including any of the standards set forth in regulations 13 and 14"*. EGCS are recognized as an equivalent compliance method according to Regulation 4 of MARPOL Annex VI, capable of fulfilling the aforementioned standards of Regulation 14 while still allowing for the use of non-compliant fuel.

Regulation 14 of MARPOL Annex VI is basically a measure to control sulphur emissions by establishing fuel quality standards. By using compliant fuel, the formation of SOx is prevented (to a certain extent), addressing the source of the problem. By use of EGCS (allowed by Regulation 4 of Annex VI), the formation of SOx is not avoided. Instead, the formed SOx are transferred from the exhaust gas to washwater. Depending on the type of EGCS, different waste streams are generated, which might contain pollutants of concern that end up in the marine environment by direct discharge to water bodies (see chapter 2).

For ships using EGCS (and non-compliant fuel), Regulation 14 of MARPOL Annex VI cannot be monitored directly (by fuel sulphur content analysis). Instead, SOx and CO_2 emissions in exhaust gas must be measured and using the emission ratio SO_2 (ppm)/CO_2 (%v/v) can be indirectly compared to the limits set in Regulation 14. Apart from this, due to the occurrence of EGCS discharge water and other waste streams, additional regulations are required to control their discharge and disposal. In other words, both emission streams to the air and to water bodies are of concern and regulated in several laws and directives. This chapter recapitulates briefly some international, European and national German regulations that apply to the control of EGCS discharge water.

5.1 International regulations for EGCS discharge water

The 1982 United Nations Convention on the Law of the Sea (UNCLOS) contains in Part XII (Articles 192-237) the fundamental international provisions for protection and preservation of the marine environment. The General Provisions (Articles 192-196) shall be regarded for the acceptance of discharge of EGCS discharge water (Proelß and Schatz, 2019). Of particular relevance is Article 195 specifying: "*In taking measures to prevent, reduce and control pollution of the marine environment, States shall act so as not to transfer, directly or indirectly, damage or hazards from one area to another or transform one type of pollution into another*".

The water and waste discharges from EGCS are predominantly addressed at international level by MARPOL Annex VI and its linked guidelines. The 53rd session of the MEPC developed the guidelines for EGCS (Resolution MEPC.130(53), MEPC (2005)) that included the requirements for the design, testing, survey and certification of EGCS. These guidelines were last updated in 2015 (Resolution MEPC.259(68), commonly known as "2015 EGCS Guidelines", MEPC (2015)). Although these guidelines are not legally binding, administrations of the contracting Member

States are effectively bound to consider them according to Regulation 4.3 of MARPOL Annex VI when approving the use of EGCS as an equivalent.

The focus of the “2015 EGCS Guidelines” is the SOx air emissions compliance. However, Regulation 4.4 of MARPOL Annex VI states that *“equivalent methods shall endeavour not to impair or damage the environment, human health, property, or resources”*. Based on that and on the environmental concerns of the EGCS discharge water, several requirements for the release of EGCS discharge water were developed and described under paragraph 10 of the “2015 EGCS Guidelines”. These include discharge criteria, continuous monitoring, data recording and adequate disposal of residues (sludge) ashore. The EGCS discharge water limit values for relevant parameters are summarised in Table 2.

Table 2: Discharge water quality criteria as described in section 10.1 of the “2015 EGCS Guidelines” (Resolution MEPC.259 (68))

Parameter	Discharge criteria
pH	≥ 6.5 (but ΔpH ≤ 2 during maneuvering and transit is allowed) or, ≥ 6.5 (measured in four meters distance from the point of discharge)
PAH	≤ 50 µg/L PAH_{phe} (normalized at 45 t_{water}/MWh) above the inlet water concentration and measured after any water treatment equipment but prior any water dilution or other reactant dosing unit.
Turbidity/Suspended Particle Matter	≤ 25 FNU (or 25 NTU) above the inlet water concentration and measured after any water treatment equipment but prior any water dilution or other reactant dosing unit.
Nitrates	≤ 60 mg/L (normalized at 45 t_{water}/MWh) at discharge or ≤ associated with 12% removal of NO_x from the exhaust, whichever is greater.
Water additives and other substances	Special assessment, and, if necessary, additional discharge criteria should be established.

The “2015 EGCS Guidelines” were revised by the IMO PPR. During PPR 7 (February 2020) a draft of an updated version (“2020 EGCS Guidelines”) was finalized with a view to adoption and approval by MEPC 75. Due to the COVID-19 pandemic, MEPC 75 was postponed (initially planned for April 2020) and the agenda was shortened, so that the revised EGCS Guidelines could not be adopted as planned. Relevant changes, as proposed by the “2020 EGCS Guidelines”, for the EGCS discharge water requirements are as follows:

- Use and definition of new term “*discharge water*” instead of “*washwater discharge*”.
- Use and definition of new term “*EGCS residue*” instead of “*washwater residue*”.
- Definition of “*12-hour period*” used for monitoring of several parameters.
- Definition of “*phenanthrene equivalent*” for measurement of PAHs.
- Nitrates discharge data is to be presented as the difference between concentrations in the inlet water and in the discharge water.
- Establishment of requirements for discharge water from temporary storage.
- Establishment of permissible deviations of the discharge water monitoring equipment.

- Maintenance and servicing of the washwater and discharge water monitoring systems and ancillary components should be recorded in the EGCS Record Book.
- Specification of design guidance for water sampling points/valves (representative and accessible location).
- A guidance for voluntary discharge water data collection is included. This guidance had as basis the submission PPR 5/11.

No modifications were made to the limit values described in section 10.1 of the “2015 EGCS Guidelines”. The discharge water quality criteria, however, should be reviewed in the future as more data become available, including relevant research and development results, on the content of discharge water and its effects, taking into consideration any advice given by the Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP). To this regard, MEPC 74 requested GESAMP to establish a Task Team to assess the available evidence related to the environmental impact of EGCS discharge water, including the studies and analyses submitted to IMO Committees (PPR and MEPC), other analyses and results from research projects, as well as the results of available simulations for predicting the environmental concentrations of target substances (MEPC, 2019). The first findings of the work of the GESAMP Task Team on EGCS were reported to PPR 7 in document PPR 7/INF.23 and are presented in chapter 7 of this report.

The draft of the “2020 EGCS Guidelines” also indicates that in case of a breakdown of the EGCS or associated equipment, corrective actions should be recorded and the relevant flag and port State's Administration should be notified, in accordance with MEPC.1/Circ.883/Rev.1. The referred circular is a proposed draft to update and supersede MEPC.1/Circ.883 with a view to adoption and approval by MEPC 75. This circular defines an EGCS malfunction as “*any condition that leads to an emission exceedance, with the exception of the short-term temporary emission exceedance cases (…) or an interim indication of ongoing compliance in the case of sensor failure*”. According to this circular, identification and remediation of malfunctions should be initiated following the trouble-shooting process specified by the EGCS manufacturer. The short-term exceedances refer only to the air emission (emission ratio: SO_2 (ppm)/CO_2 (%v/v)) and not to the water emission (discharge water quality criteria). For the interim indication of ongoing compliance in the case of sensor failure, including instrumentation for the monitoring of discharge water (pH, PAH and turbidity), the required documentation and actions are determined based on the assumption that all monitored parameters keep certain interrelation.

5.2 European regulations for EGCS discharge water

On European level, several regulations apply to EGCS discharge water. The EU Sulphur Directive (Directive (EU) 2016/802, 2016) regulates the SOx emissions from ships. It implements the MARPOL Annex VI (with regards to SOx). The limit values for sulphur content in fuels are established in accordance with MARPOL Annex VI. In Article 8, the use of Emission Abatement Methods (e.g. EGCS) as alternative methods for compliance is permitted. For their approval, Article 9 refers to the Guidelines developed by the IMO.

Another main instrument applicable to EGCS discharges under European law is the EU Directive on port reception facilities for the delivery of waste from ships (Directive (EU) 2019/883, 2019), which includes both sludge and bleed-off water in its scope. This Directive indicates that Member States should:

- continue to work at IMO level for a comprehensive consideration of the environmental impacts of wastewater discharges from OL-EGCS, including for measures to counter possible impacts and
- be encouraged to take appropriate measures in accordance with the EU Water Framework Directive (WFD, Directive 2000/60/EC, 2000), including discharge bans for wastewater from OL-EGCS.

Actually, Proelß and Schatz (2019) suggest that the WFD and the EU Marine Strategy Framework Directive (MSFD, Directive 2008/56/EC, 2008), which contain general European environmental protection objectives, might be considered for the regulation of EGCS discharge water.

The European Sustainable Shipping Forum (ESSF) was established to implement the Sulphur Directive; the ESSF Subgroup on Emission Abatement Methods (formerly Air Emissions from Ships) evaluates the use of EGCS. The ESSF Subgroup worked on the amendment of the 2015 guidelines for EGCS and submitted the outcome to the IMO (PPR 5/11).

5.3 National German regulations for EGCS discharge water

In the German national law, the relevant provisions of MARPOL Annex VI and the EU Sulphur Directive are implemented in the Regulations on Environmentally Sustainable Behaviour in Maritime Shipping (*See-Umweltverhaltensverordnung*) para. 13: "*Compliance with the requirements for Low Sulphur Marine Fuel*". In particular, paragraph 13.5 refers to the approval of equivalent compliance methods according to Regulation 4 of MARPOL Annex VI; and paragraph 13.7 prohibits the discharge of EGCS discharge water in sea-waterways as well as in the Exclusive Economic Zone (EEZ) unless it has been demonstrated that the EGCS discharge water has no significant adverse effects on human health and the environment. At present, such a proof may be presented, for instance, in form of a valid approval as well as a documentation of the proper operation of the system. If using caustic soda, pH should not be higher than 8.0, according to the EU Sulphur Directive.

For inland waterways the regulations of the Strasbourg Convention on the Collection, Deposit and Reception of Waste during Navigation on the Rhine and Inland Waterways of 9 September 1996 (CDNI) and the Federal Water Act (*Wasserhaushaltsgesetz*, WHG) are applicable. For the latter, the discharge of EGCS discharge water constitutes a use of water within the scope of paragraph 9.1.4 WHG which must be subject to prior authorization according to paragraph 8.1. Nevertheless, EGCS discharge water is also considered a type of "*wastewater*" within the scope of paragraph 54.1.1 WHG, therefore its discharge is generally prohibited by paragraph 57.1 WHG if not covered by an acquired permission. According to Article 3.1 of the CDNI, the discharge of ship-generated waste by all ships, including seagoing ships, is prohibited. While EGCS discharge water is not explicitly referred to within the CDNI, it can be classified as a form of "*other waste generated from the operation of a vessel*" under the CDNI, according to the German legal conception. Thus, the CDNI establishes an absolute prohibition for discharges of EGCS discharge water in German inland waterways with the exception of the German part of Lake Constance and the Rhine section North of Rheinfelden (BSH, 2018).

5.4 Discharge bans and harmonization approaches

Due to the abovementioned EGCS discharge water composition (see chapter 2.4), there are environmental concerns regarding the discharge of EGCS discharge water. In some countries and regions, the discharge criteria of the EGCS Guidelines do not meet local or national standards.

Many ports are already impacted by different kinds of industrial discharges from a variety of sources. At present, there is no internationally regulated procedure from the IMO to designate special areas or a distance to the nearest land for the prohibition of EGCS discharge water as there are for other discharges such as wastewater, waste, NOx and SOx. For this reason, national authorities or individual ports have decided to implement restrictions on the EGCS discharge water so-called "scrubber bans". For instance, the Maritime and Port Authority of Singapore (MPA, 2018) commented about the local ban on discharges that the aim is to protect the marine environment and ensure that port waters are clean and not contaminated. A summary of the current countries and ports applying special restrictions or prohibition for EGCS discharge water is presented by EGCSA (2019), BRITANNIA P&I (2020) and North (2020).

Recently, the EU Committee on Transport and Tourism submitted a motion for a European Parliament resolution to prohibit the use of heavy fuel oil and water discharges from EGCS into the sea (Delli, 2020). According to Argus Media, the European Parliament's environment committee voted for a "phase-out", rather than simple prohibition of OL-EGCS (Manifold Times, 2020). The proposal is still to be subject to the parliamentary procedure.

In order to address the issue of different and unilateral local rules, MEPC 74 proposed a new output on “*Evaluation and harmonization of rules and guidance on the discharge of discharge water from EGCS into aquatic environment, including conditions and areas*” (MEPC, 2019). In this regard, Member States and organizations of the related IMO Committees (MEPC and PPR) have submitted several documents. Many Member States, together with various stakeholders, requested the consideration of scientific and evidence-based data for the development of future regulatory measures (MEPC, 2019). At the same time, there are diverse proposals for the harmonization of rules. Japan (2019) suggested the development of guidelines to provide recommended procedures for environmental impact assessments and criteria that Member States should follow when setting local or regional regulations on discharge of EGCS discharge water into sensitive waters. China et al. (2019) recalled precedents on MARPOL regulations on how to manage and allow discharges of pollutants below threshold limits and under stipulated conditions, as for instance, when the ship is at a certain distance from the nearest land and/or is proceeding en route at a certain speed. This new output is planned to be concluded during PPR 8 in 2021.

6 Deficiencies of the EGCS discharge guidelines

This chapter analyses the current deficiencies on the discharge water quality criteria as presented in the "2015 EGCS Guidelines" as well as the drafted "2020 EGCS Guidelines". This literature review could not establish any underlying documentation resulting in the determination of the limit values referenced by the IMO EGCS Guidelines, especially for turbidity and PAH_{phe}. Thus, it is questionable whether the criteria in section 10 of the EGCS Guidelines ensures the protection of the marine environment in the short and long term from acute and chronic effects. In fact, the discharge criteria have been defined generally intended to prevent acute effects occurring in the aquatic environment (GESAMP, 2009) and is supposed to be revised as more data becomes available on the contents of the discharge and its effects, taking into account any advice given by GESAMP (MEPC, 2008a; MEPC, 2009; MEPC, 2015). US EPA (2011) indicated that the guidelines limits may be inadequate for metals and PAHs.

6.1 pH criteria

The current "2015 EGCS Guidelines" and the drafted review allow to select one of the two following requirements for the EGCS discharge water:

1. pH ≥ 6.5 at the discharge, but during manoeuvring and transit a ΔpH ≤ 2 (difference between inlet and overboard discharge) is allowed, or
2. pH limit value for the discharge that ensures achieve pH ≥ 6.5 at a distance of 4 m from the overboard discharge point with the ship stationary. The overboard pH discharge limit can be determined either by means of direct measurement, or by using a calculation-based methodology.

The first point indicates two cases setting more stringent pH criteria in port than during manoeuvring or in transit (ΔpH ≤ 2 indicates a minimum of roughly 5.0 – 6.3, assuming seawater pH ranges 7.0 – 8.3) (GESAMP, 2009). Dilution is allowed in order to achieve these requirements. This measure, while supposed to prevent acute harmful effects to the ecosystem, does not prevent acidification effects in the long term. Dulière et al. (2020) modelled the acidification effects of EGCS discharge water obtaining high effects (equivalent to 10 to 50 years acidification effects due to climate change) in areas of high traffic density as well as in the vicinity of large harbours and recommended to follow the precautionary principle.

In the report of the Correspondence Group (MEPC 56/4/1, United States, 2007) to develop the first discharge criteria, it was suggested not permitting the discharge of EGCS discharge water in those ports, harbours and estuaries where pH is a concern, instead of only restricting pH. United Kingdom (2006) proposed that the pH at the point of discharge should not deviate more than 0.2 units below the pH at the sea water inlet. Lange et al. (2015) proposed that the pH in the discharge should be no more than 0.5 units below the value of the surrounding water.

In addition, the assumption of 2.2 mmol/L for alkalinity and 8.2 for pH in the calculation method, allowed under the second requirement, may not be conservative because EGCS discharges may occurred in waters with lower pH and lower buffer capacity.

6.2 PAHs and oil content

The current "2015 EGCS Guidelines" and the drafted review set a normalized limit for PAHs given in phenanthrene equivalents for the difference between the inlet and discharge concentrations: 2.25 g PAH_{phe}/MWh. In the drafted "2020 EGCS Guidelines", however, the limit value for discharge water from temporary storage is fixed in 50 µg PAH_{phe}/L regardless the specific flowrate. In the EGCS Guidelines, oil content is not used as discharge criteria, as is the case for bilge water discharges, because oil discharge monitoring systems are based on UV-light scattering technology, which is not sensitive enough for the oil concentrations in EGCS discharge water. The regulation of PAH discharges to indirectly restrict oil discharges was originally proposed by United Kingdom (2006) because:

1. It has been demonstrated that the monitoring of PAHs provides a direct surrogate to the monitoring of oil content.
2. The instruments available to monitor PAHs have resolutions to parts per billion (ppb) levels and are insensitive to interference from the varying nature of sea water.

United Kingdom (2006) assessed other regulations restricting oil discharges (such as MARPOL Annex I), typical amounts of other sources of oil discharges (such as oil platforms, bilge water and air emissions from ships) and currently available technology for water treatment; and considered reasonable to set the maximum content of oil in EGCS discharge water at 1 ppm. Relating the oil content to PAHs leads to a recommendation to set the maximum continuous PAHs concentration at 15 ppb (µg/L). This is based upon a specific flowrate of 45 m^3/MWh as originally suggested and was also drafted for the EGCS Guidelines (BLG 12/6/Add. 1). The limit value of 15 ppb PAH was related to the US EPA PAH_{16} according to US EPA Method 610. After reviewing the documents submitted to IMO for the development of the EGCS Guidelines, it remains uncertain how the current limit of 50 ppb was selected (refer to BLG 12/17 Annex 6, where the recommendation of the working group in BLG 12/6/Add. 1 was modified).

Norway and Finland (2006) suggested to set tiered limit values for total hydrocarbons and PAHs (see Table 3) in closed waters and no restrictions in the open sea, as proposed in the study of Buhaug et al. (2006). At a certain point (United States, 2007) limit values of 15 ppm and 5 ppm for oil discharges where suggested for a ship when moving and stationary, respectively. Those values were suggested taking as basis the MARPOL Annex I criteria (15 ppm for bilge water). The proposed limit values would lead to unacceptable high emissions if considering that the bilge water discharges from a ship can range 0.01 – 13 m^3/d (CE Delft and CHEW, 2017), while a medium size ship with an OL system would discharge ~13000 m^3/d EGCS discharge water.

Table 3: Proposed tiered limit values for total hydrocarbons and PAHs in EGCS discharge water as in document MEPC 55/4/7 and typical concentrations found in EGCS discharge water

Compound	Tier 1	Tier 2	Tier 3	Measured concentrations [i)]
THC (ppm)	4.5	0.45	0.045	0.10 – 0.39 [ii)]
PAH (µg/L)	450	45	5	0.5 – 24 [iii)]

THC, total hydrocarbons (in this report comparable to oil content); PAH, polycyclic aromatic hydrocarbons. Limit values are based in a specific flowrate of 44 m^3/MWh.

Source: adapted from Norway and Finland (2006).

i) As reviewed from different research works and summarized in Table A-4. The values presented correspond to the range of concentrations found in OL systems and are not normalized to 44 m^3/MWh.

ii) In Table A-4 given as "Oil content" and includes measurements of THC and hydrocarbon oil index (depending of the study)

iii) Here, the measurements of PAH_{EPA16} are considered. It is unclear which PAH are considered for the proposed limit values.

In fact, the oil content in EGCS discharge water from OL systems is in the range 0.1 – 0.4 mg/L (see Table 3, THC range), far below 15 ppm. PAH_{EPA16} concentrations range 0.5 – 24 µg/L (see

Table 3) and PAH_{phe} values from the on-line monitoring systems recorded during the sampling campaign by Schmolke et al. (2020) were all below the limit value 50 µg PAH_{phe}/L. For instance, air emission measurements (Fridell and Salo, 2014; Winnes et al., 2018) from ships burning residual fuel oil showed PAH_{EPA16} emission factors upstream the EGCS in the range 1.4 – 1.7 g/MWh. If all the PAHs would end up in the EGCS discharge water and assuming 45 m^3/MWh as specific flowrate, the concentration of PAH_{EPA16} in the discharge water would be in the range 31 – 38 µg/L. This cannot be the case, since the scrubbing removal efficiency of PAH is around 50%, as shown by the air emission measurements downstream the EGCS (0.77 g PAH_{EPA16}/MWh) by Winnes et al. (2018). In the case of CL systems, the limits could be reached even without using the bleed-off treatment unit (Lahtinen, 2016). Thus, the current set limit value for PAHs does not represent any challenge for current EGCS, so that treatment of EGCS discharge water may not be required for compliance.

It is important to establish limit values to protect the receiving waters from the high amounts of PAHs and oil residues discharged. Linders et al. (2019) made a simple calculation for a worst-case scenario assuming all ships EGCS-fitted and determined that the total emissions of PAHs (59 Mt) would be 10 times higher than the worldwide PAHs emissions from all sources.

Furthermore, a deficiency of the current “2015 EGCS Guidelines” is the missing definition for phenanthrene equivalents. Actually, this is a term or measuring unit established and used only for these Guidelines. In the review of the documentation submitted to the relevant IMO Committees, no document was found justifying the use of phenanthrene as surrogate parameter. Nevertheless, it is known that phenanthrene was chosen as surrogate parameter for PAH due to its high concentration in discharge water, its high solubility and its lower volatility compared to naphthalene. Other PAHs are insoluble or too toxic, which might pose a health risk during calibration of the sensors. Further information regarding the use of phenanthrene equivalents as a unit for the measurement of PAHs is presented by EGCSA (2012). However, the relation of phenanthrene equivalents to PAH_{EPA16} or oil content remains unclear (US EPA, 2011). One manufacturer of a PAH_{phe} online sensor requires the application of a factor of 6.2 to account for all PAH_{EPA16}, when calibrating the sensor with phenanthrene only (TriOS Mess- und Datentechnik, n.d.). The optical sensors for PAH_{phe} are only capable to measure dissolved compounds; particulate phase is not measured and creates interferences, so that it is advisable to report PAH_{phe} turbidity-corrected (TriOS Mess- und Datentechnik, n.d.). In practice, depending on manufacturer and ship operator, PAH_{phe} is reported as the raw measurement, turbidity-corrected and/or with multiplication factor (e.g. 6.2 for PAH_{EPA16}).

The PAH_{phe} concept creates confusion by stakeholders in the discussions as well; studies tried to compare PAH_{phe} measurements to PAH_{EPA16} or understood PAH_{phe} as a parameter that considers the toxic equivalence factors for different compounds (Linders et al., 2019). It should be mentioned that the drafted revision of the EGCS Guidelines (as noted in chapter 5.1) will introduce a definition for the phenanthrene equivalents based on the wavelengths of excitation and detection employed by the optical measuring devices. Nevertheless, the reliability of the measurements remains a pending topic as stated in chapter 7.4 and reported by US EPA (2011) and Linders et al. (2019).

6.3 Turbidity, suspended solids and heavy metals

The current “2015 EGCS Guidelines” and the drafted review set a maximum limit value of 25 FNU (or NTU) for turbidity for the difference between the inlet and discharge concentrations.

The turbidity discharge criterion is intended to minimize the release of suspended particulate matter, including heavy metals and ash. Bosch et al. (2009) mentioned that turbidity was taken as monitoring value because it is a simple method for on-line analysis; however, they remarked that:

1. Turbidity is not a direct method of determining the number of exhaust particles that end up in the EGCS discharge water.
2. There is no direct correlation between turbidity and particle concentration.
3. Turbidity is strongly dependent on the particles size in the water (smaller particles are likely to have significantly less influence on the measured turbidity than larger ones).
4. Studies are required to find a correlation between turbidity and concentrations of suspended solids, metals and ash in the EGCS discharge water before this criterion can be considered a surrogate of those pollutants.

As highlighted in chapter 7.4, no research works were found examining the relation between turbidity, suspended solids, organic pollutants and metals. It is crucial to work on determining whether turbidity can be used as a surrogate parameter to protect receiving waters from metals discharges. Even though the turbidity values in the EGCS discharge water are far below the limits of the EGCS Guidelines, a considerable amount of metals is released that could pose a risk to the environment (US EPA, 2011). Further, the majority of the metals are found in the dissolved fraction (and not in particulate form), presumably due to the acidic conditions and high levels of chloride in the water (see chapter 7.4).

This limit value does not represent any challenge for OL systems and can be complied without water treatment (see Table A-4). On the other hand, because the set limit value is not normalized, for CL systems it represents a restriction and water treatment (no dilution) prior discharge is required. To this regard, Lahtinen (2016), commented that because turbidity limit is not related to the specific flowrate (limit value is not normalized), the same criteria are valid for small and large volume flows with totally different impacts on receiving waters. In practice, most of the CL systems are equipped with a water treatment unit for the bleed-off, while OL systems normally do not include water treatment and if included, treating only a part of the discharge flow leading to lower treatment efficiency than in CL systems. After comparing pollutant concentrations and volume discharge flows in OL and CL systems, Teuchies et al. (2020) reported lower total discharge of pollutants from CL operation than from OL operation (6 times for metals and 183 times for PAHs).

Local conditions and regulations for metals should be also considered. Table 4 presents a review on local regulations on wastewater for discharge of metals (Lahtinen, 2016), proposed limit values for EGCS discharge water (Norway and Finland, 2006) and measured metal concentrations found in the reviewed research studies (summarized in Table A-4). Based on information presented in Table 4 and the uncertainties in turbidity as a surrogate parameter, it might be convenient to established limit values for metals of environmental concern in EGCS discharge water, for instance for vanadium, nickel, copper and zinc, to safeguard the environmental protection of the receiving waters.

Table 4: Limit values for metals from wastewaters set in local regulations, proposed limit values for EGCS discharge water as in document MEPC 55/4/7 and typical metal concentrations found in EGCS discharge water

Compound (µg/L)	Proposed limit values [a)]			Local limit values [b)]				Measured concentrations [c)]	
	Tier 1	Tier 2	Tier 3	HSY	SV P95	ADEC1	ADEC2	OL	CL
Chromium	NA	NA	NA	100	50	-	-	<0.9 – 31	9 – 14 000
Copper	-	40	4	2 000	200	87	130	1 – 260	10 – 2 400

Compound (µg/L)	Proposed limit values a)			Local limit values b)				Measured concentrations c)	
	Tier 1	Tier 2	Tier 3	HSY	SV P95	ADEC1	ADEC2	OL	CL
Lead	-	-	-	500	50	-	-	0.09 – 120	0.16 – 3.8
Nickel	-	30	3	500	50	43	43	6 – 440	220 – 6 600
Vanadium	-	-	150	NA	NA	NA	NA	12 – 860	2 800 – 25 000
Zinc	NA	NA	NA	3 000	200	360	360	2 - 450	40 – 2 400

Legends:

HSY – HSY Helsinki Region Environmental Services Authority

SV P95 – Guidelines according to Svenskt vatten's Publication P95

ADEC1 – The Alaska Department of Environmental Conservation. These limits concern discharge of treated sewage and treated grey water. There are technology based effluent limits. The presented values are from limits category "Other Treatment System". These effluent limits apply to wastewater discharge while docked, anchored, or moving at a speed below 6 knots.

ADEC2 – Similar to ADEC1. These effluent limits apply to wastewater discharge while underway travelling at a speed of 6 knots or greater.

OL – Open loop EGCS

CL – Closed loop EGCS

NA – Not applicable. Compound is not considered in the proposed or existing regulation.

Sources: a) Adapted from Norway and Finland (2006); b) Adapted from Lahtinen (2016); c) As reviewed from different research works and summarized in Table A-4.

6.4 Nitrates

The current "2015 EGCS Guidelines" specify the following requirements for the EGCS discharge water, being applicable whichever the greater value is:

1. Nitrates concentration ≤ that associated with a 12% removal of NOx from the exhaust, or
2. Nitrates concentration ≤ 60 mg/L normalized to a specific flowrate of 45 m^3/MWh.

This criterion does not take into account the contribution of the current environmental concentrations. However, in the drafted review of the "2020 EGCS Guidelines" the considerations of the inlet water are taken into account.

While the inclusion of a discharge criterion for nitrates in the EGCS Guidelines seems to be a measure to prevent eutrophication and, to a certain extent, acidification effects, the definition of the limit values may take into account other factors. In document BLG 12/6/11 (Finland, 2007) an explanation for the origin of the mentioned discharge criteria was found. Finland (2007) explains that "*with the nitrate clause the intention of the IMO is to address cleaning devices designed to remove NOx, not to complicate the introduction of normal SOx-scrubbers*". To this regard, GESAMP (2009) understood the nitrates criterion as "*intended to cover the event of a hypothetical scrubber (…) also removing extensive amounts of NOx beyond the soluble* NO_2 *fraction likely to be partly removed*". The maximum allowed NOx removal (12%) from the diesel engine exhaust was taken as this is considered the maximum amount of NOx that can be dissolved in washwater by normal EGCS and the concentration (60 mg/L) was derived from that number (Finland, 2007). This means that unless the EGCS has special features for NOx removal, the nitrate limit value would not be exceeded by a conventional EGCS, designed only for SOx removal. In the reviewed IMO documentation, no information or study was found presenting an environmental assessment to demonstrate that the release of EGCS discharge water with nitrate concentration below the set limit does not impair the marine environment.

Den Boer and Hoen (2015) describes that NOx emissions from diesel engine exhaust gas typically consist of 90–95% nitrogen monoxide, which is insoluble in water, while the nitrogen dioxide fraction is soluble in water. Therefore, during the scrubbing process only 5–10% of the NOx from the exhaust can be removed (Den Boer and Hoen, 2015; United Kingdom, 2006).

In the report of the GESAMP Task Team (Linders et al. 2019), it is stated that most of the reviewed studies confirm the limited capacity of EGCS to remove NOx from the exhaust and show nitrates concentrations well below the EGCS Guidelines. The report concludes that the potential for significant increase of primary production and eutrophication appears to be low (in alignment with the conclusion of US EPA, 2011) and notes that part of the exhaust NOx emissions would end up in the sea, independent of the use of an EGCS.

Table A-4 shows nitrate concentrations for EGCS discharge water from OL systems in the range <0.033 – 22.3 mg/L and from CL systems <4.4 – 290 mg/L. It should also be considered that due to the application of the IMO regulations for NOx reduction (Regulation 13 of MARPOL Annex VI), the concentrations in the EGCS discharge water might be expected to be much lower, because the NOx removal takes place before SOx removal.

In order to compare the nitrate discharge criterion (60 mg/L, normalized to a specific flowrate of 45 m^3/MWh) to other land-based regulations, the German Wastewater Directive (*Abwasserverordnung*, AbwV) was considered. There, total nitrogen is regulated for municipal wastewater (13 – 18 mg/L, equivalent to 57 – 80 mg NO_3/L) and industrial waters, but is not regulated for discharge waters from scrubbing of flue gases from combustion plants.

6.5 Water additives and other substances

The current "2015 EGCS Guidelines" and the drafted "2020 EGCS Guidelines" consider a regulation for EGCS making use of chemicals, additives, preparations or relevant chemicals created in situ. According to the Guidelines, in such cases an additional assessment is required, and could take into account the "Procedure for approval of ballast water management systems that make use of active substances (G9)" (resolution MEPC.169(57)), to determine if additional discharge criteria are required. Those water additives and other substances could be alkali solutions for pH control or coagulants and flocculants for the removal of suspended solids in the water treatment. That would cover mainly CL systems.

6.6 Sampling points and sampling procedures

The current "2015 EGCS Guidelines" contain neither any requirement for sampling points for EGCS discharge water nor guidance for sampling procedures. The drafted review now contains a brief text passage indicating that the location of sampling points should ensure representativeness of the sampled water as well as a detailed guidance for sampling and analysis of EGCS discharge water as an annex.

6.7 Inconsistency of regulations for closed loop systems

The current "2015 EGCS Guidelines" are more stringent for CL systems in some aspects than for OL systems. As mentioned above, the turbidity limit value is fixed and independent of the specific flowrate. This leads to CL systems to be designed with efficient water treatment units to reach compliant turbidity values. The limit value for PAH_{phe} is normalized, except for specific discharges in the range 0-1 m^3/MWh, where the threshold is set at 2,250 µg/L. This would apply to CL systems (0.1 – 0.3 m^3/MWh), and implies more stringent values than for OL systems. Nevertheless, the limit value for PAHs does not imply an actual restriction for both type of EGCS systems.

Another deficiency is pointed out by Lahtinen (2016). For the thresholds considering the inlet values, the definition of “inlet water” is rather unclear for CL systems; it may be understood as fresh feed water into the system or as washwater in recirculation in the system and entering the scrubber tower. A further issue linked to the consideration of the inlet values, but also to the normalization of thresholds, is the temporary storage by CL systems. In such case, it is nearly impossible to determine the applicable limit value. To this regard, the revised EGCS Guidelines introduces fixed thresholds (pH, PAHs and turbidity) for discharges from temporary storage, without consideration of inlet values and specific flowrates. Again, it poses more stringent values for CL systems (especially regarding PAHs: $PAH_{phe} \leq 50$ µg/L).

7 Research studies on EGCS discharge water

Due to the environmental concerns regarding EGCS discharge water and the call from the IMO to provide data about its contents and effects, several research studies have been conducted focusing on a specific issue or multiple aspects of the EGCS discharge water. Table A-3 summarizes the research activities identified during the literature review and indicates which relevant aspects on the discussions were covered.

The following chapters (7.1, 7.2 and 7.3) describe in detail the approach and results of some of the research studies listed in Table A-3. The review is focused on recent studies that cover sampling campaign, chemical composition, ecotoxicological effects or environmental risk assessment of EGCS discharge water, which are planned activities in project ImpEx. It serves as a basis and assists in considering the further processing and evaluation of the field campaigns, laboratory analyses and obtained data according to the current research and, where appropriate, to create synergies.

Chapter 7.5 presents research studies currently being carried out. Additionally, the reports by Stips et al. (2016), Heywood and Kasseris (2019), Linders et al. (2019) and Kasseris et al. (2020) summarized an extensive compilation of previous studies. Special attention must be given to the report of the GESAMP Task Team on EGCS (Linders et al., 2019), submitted to PPR 7 as document PPR 7/INF.23, which serves as basis for the planning and the methodological approach of the ImpEx project. The conclusions and recommendations of the work of the GESAMP Task Team include:

- A preliminary risk assessment based on the available information is currently not possible (uncertainties and data gaps).
- A clear procedure for conducting a risk assessment of pollutants, using the Marine Antifoulant Model to Predict Environmental Concentrations as amended for Ballast Water discharges (MAMPEC-BW) as a tool for environmental exposure assessment, was recommended.
- A database with data on physical-chemical properties, (eco)toxicological effects, fate and behaviour of relevant components needs to be developed.
- Data collection on chemical substances should focus on PAH_{EPA16} (possibly alkyl-PAHs), trace metals (arsenic, chromium, copper, nickel, and vanadium) and suspended solids.
- In available studies, uncertainties were identified in the methodology as well as in the organisation and performance of the measurements.
- Harmonised sampling and analysis procedures are necessary for comparability of data.
- The following aspects must be taken into account for the risk assessment:
  - ecotoxicological risks to marine pelagic and sediment dwelling organisms,
  - direct (skin contact) and indirect (seafood consumption) routes of exposure for humans and,

  - potential global impacts such as acidification and eutrophication.
- WET tests of samples, from representative areas, using internationally recognised methods are recommended to provide information on cumulative toxicity.

7.1 Chemical composition of EGCS discharge water

This chapter compiles the main research work on the chemical characterization of EGCS discharge water. The approach of the studies and the main findings related to chemical composition are presented in the following text (starting with the latest). Table A-4 shows an overview of the chemical composition of EGCS discharge water based on the results of recent research studies that carried out sampling campaigns on board ships during a sea voyage.

Schmolke et al. (2020) (in Table A-4 presented as BSH) from the German Federal Maritime and Hydrographic Agency (BSH) carried out a study on behalf of the German Environment Agency (UBA). Here, five ships were sampled during a sea voyage in the North and Baltic Sea regions. The ships included three cruise ships, one vehicle carrier and one RoRo vessel. Three of them were equipped with hybrid EGCS, so that both operation modes were sampled, and the other two with OL system. The OL results presented in Table A-4 correspond to the sampling point in the outlet (after dilution, if existing). Two particularities of this study are the parallel measurement of turbidity, PAH_{phe} and pH on board and comparison with the on-line monitoring data, and the determination of some additional PAHs[5] (no part of the priority PAH_{EPA16} list). Some of the main findings and discussions highlighted in the report are:

- Complete loss of alkalinity in most of the samples.
- Presence of metals mainly in dissolved form.
- Significant enrichment of vanadium and nickel.
- Elevated concentrations of copper and zinc in some inlet samples.
- PAHs in most of inlet samples below the detection limits (PAH_{EPA16}: <LOD – 0.3 µg/L).
- In OL discharge water, PAHs with 2-3 rings had a high contribution, especially naphthalene and its measured derivatives, and 4-6 rings PAHs had a low contribution to the total PAHs concentration; while an increase in the PAHs with 4-6 rings was observed in CL discharge water.
- The five additionally measured PAHs represent a significant fraction of the total PAHs measured (PAH_{EPA16} + additional PAHs).
- CL discharge water from the ship equipped with a hydrocyclone contained significantly less suspended solids than CL discharge water from the ships applying other treatment technologies.
- Discrepancy between the on-line monitoring data and the parallel on-board measurements for turbidity, pH and PAH_{phe}.

---

[5] Five additional PAH analyzed: 2-methyl-naphthalene, 2-methyl-naphthalene, dibenzothiophene, benzo-[e]pyrene and perylene.

- Identification of a correlation between the PAH_{phe} parallel on-board measurements with the laboratory results for PAH_{EPA16} and oil content (hydrocarbon oil index, HOI) in the OL discharge water samples. The dataset, however, is insufficient to conduct any robust statistical analyses. Thus further investigations are required. No correlation was found with the on-board monitoring data.

The study reports, among several limitations during the sampling campaign, missing sampling points or unsuitable design (material and piping size) of sampling points. The issues found with the on-line monitoring systems are stressed in that research work and will be further examined in the present project (AP 2.2).

An important part of this research study is the dispersion modelling based on the results of the chemical characterization (see chapter 7.3). Additionally, water samples from the sampling campaign were provided to the German Federal Institute for Hydrology (BfG) to conduct a separate study about ecotoxicological effects of EGCS discharge (see Kathmann et al. (2020) in chapter 7.2).

Carnival Corp. & plc and DNV GL (2019) (in Table A-4 presented as CCL) carried out a study, where Carnival Corporation was responsible for the organization of the sampling campaign and DNV GL for the compilation, review and analysis of the laboratory results. In this project, 53 ships operating with OL systems were sampled. Since a detailed project report is not available (only a presentation), not all details of this database are known, e.g. information about the ships, EGCS systems and sampling conditions. In a follow-up project (Faber et al., 2019), it is mentioned that the samples were collected from cruise ships, bulk carriers and ferries being in service in different locations in the Caribbean, the eastern Pacific, the Tasman Sea, the Strait of Malacca, the Atlantic Ocean, the North Sea and the Baltic region. The results presented in Table A-4 correspond to the average values excluding statistical outliers more than three standard deviations from the mean in the sampling point prior to any dilution (here called "Gross post-EGCS"). Besides the values shown in Table A-4, the scope of the parameters included others such as hydrocarbons (C_{10}-C_{40}), suspended solids, pH, BOD, COD and chromium VI, but their results are not reported. The enrichment of the pollutants in the seawater was calculated ("Net post-EGCS" = "Gross post-EGCS" – inlet). These values were compared to the current IMO requirements, wastewater land-based point standards (German Wastewater Ordinance and EU Industrial Emissions Directive) and stricter quality standards (EU Water Framework Directive and WHO Drinking Water Guidelines). The authors concluded:

- Phenanthrene and sum of PAH_{EPA16} average gross post-EGCS concentrations were far below the IMO limit value for PAH_{phe}. The same was observed for nitrate concentrations.
- Concentrations of the tested (and possible to compare) parameters in all samples were below the wastewater land-based point standards.
- Net post-EGCS average concentrations (excluding statistical outliers) of the tested (and possible to compare) parameters were below the stricter quality standards.

When reviewing the net post-EGCS metal concentration values, only for chromium, copper, nickel, vanadium and zinc an enrichment is clearly noticed. The aim of this work was to gain information about the EGCS discharge water quality and the presence of pollutants. However, as commented above, there is a related research project using the resulted database to conduct a pollutant accumulation modelling and an environmental risk assessment (see Faber et al., 2019 in chapter 7.3).

Ushakov et al. (2019) (in Table A-4 presented as NORW) carried out a study financed by SFI Smart Maritime and the Norwegian NOx-Fund. The samples were taken on board a LPG tanker (Clipper Harald) being at berth and operating auxiliary engines. The ship was equipped with an OL-EGCS, including water treatment (residence tank and cyclonic separation), and low-pressure exhaust gas recirculation (EGR). The study focused on the performance evaluation of the application of the combined air pollution abatement technologies (EGR and EGCS) expected to be adopted by ships to comply with the SOx (SECA) and NOx (Tier III) requirements. Increased generation of particulate matter due to the application of EGR (deteriorated combustion) was expected and confirmed with the exhaust gas analysis, which might affect the EGCS discharge water composition. Water samples were taken at the inlet, after the absorption tower and after the water treatment; the analysis results from the latter are presented in Table A-4. Some of the main findings and discussions highlighted in the study are:

- Water treatment efficiency for hydrocarbon fractions resulted in the range 45 – 55%, for metals around 10% and for PAHs below 15%.
- The majority of the measured PAHs are not carcinogenic.
- Only phenanthrene, fluoranthene and pyrene showed values above the Norwegian Environmental Quality Standards (EQS).
- For arsenic, copper, molybdenum and lead high concentrations in the inlet were measured, typical for high-traffic harbour areas. The concentrations of those compounds were actually lower (10 – 30%) in the discharge water.
- Significant enrichment of vanadium and nickel in discharge water is of high concern, their concentration exceeded by a factor of 26 and 5 the national EQS. These compounds originate from the fuel.
- Zinc also showed an increase in discharge water and its concentration exceeded by a factor of 2.2 the national EQS. This compound may originate from lube oil.
- Turbidity, nitrate and pH (assuming sufficient dilution) resulted compliant to the IMO requirements.
- Turbidity is pointed out as a very simple and robust proxy parameter for suspended solids. However, its accuracy and significance are scientifically questioned due to the measurement uncertainties caused by organics in seawater and different sizes of particulate matter.
- Nitrate and nitrite concentrations were below the detection limit. It is concluded that only a minor part of NOx ended up in the discharge water.

The study reported for the first sampling campaign abnormal concentrations of copper, zinc and lead not explained by the fuel analysis and are probably caused by the valves and piping material of the sampling points. Those results were not further considered, and the components were replaced by stainless steel. The authors questioned the current water discharges from other systems (e.g. engine cooling, ballast and other supporting systems) that could be possibly contaminated.

Magnusson et al. (2018) (in Table A-4 presented as IVL) from the Swedish Environmental Research Institute (IVL) carried out a study as part of the project “Scrubber: Closing the loop” coordinated by Stena Teknik and funded by the EU. In this project, three ships (Stena Britannica, Stena Forerunner and Stena Transporter) were sampled during a sea voyage. Since those ships usually cover a route between Great Britain and the Netherlands, it is assumed that the sampling was conducted in the North Sea region. The ships included two RoPax and one RoRo vessel; two of them equipped with CL system and one with OL system. A particularity of this study was the analysis of hydrocarbons both aliphatic and aromatic for different size fractions and eleven alkyl-PAHs. One of the focus of this study was to assess the removal efficiency of the bleed-off treatment unit (BOTU) by analysing samples taken before and after the treatment unit of a CL system. To this regard, the authors concluded that:

- Turbidity is reduced by 96% but still higher than the inlet seawater.
- Overall reduction of total hydrocarbons was around 97%, observing higher efficiency in the removal of heavy fractions than the lighter ones.
- Aliphatic hydrocarbons with >C_{16} were removed by >99%. However, the short chains (>C_8 – C_{12}) showed a significant increase.
- Aromatic hydrocarbons with three rings or more were removed in the range 90% – >99%. For instance, PAH_{EPA16} with 4-6 rings were reduced with an efficiency >99%.
- Most metals concentrations were reduced (~60% – 95%). However, copper and mercury concentrations were higher after the treatment unit, which could not be explained.

Presence of alkyl-PAHs was determined. Concentrations of the sum of the eleven measured alkyl-PAHs in discharge water resulted in 27 and 138 µg/L from OL and CL, respectively. Other important parts of this study are the ecotoxicological assays (see chapter 7.2) and the derived environmental risk assessment (see chapter 7.3). In addition to this study (Task 2), IVL published other reports focused on air emissions measurements (Task 1), cost benefit analysis (Task 3) and a life cycle assessment (Task 4) as part of the aforementioned project.

EGCSA and Euroshore (2018) (in Table A-4 presented as CESA) carried out a joint sampling campaign on board 20 ships in the North and Baltic Sea region and two ships in the Mediterranean Sea to gain information about the EGCS discharge water composition from OL and CL systems. The sampled ships included RoRo/RoPax (11), cruise ships (3), oil tankers (3), vehicle carriers (2), multi-purpose (1), RoRo container (1) and container ship (1). Samples were taken at a point prior to any dilution and analysed for the determination of the parameters shown in Table A-4 and benzene, toluene, ethylbenzene and xylene (BTEX). Results were normalized to 45 m^3/h discharge water flowrate and compared to limit values. Some of the main findings and discussions highlighted in the report regarding the discharge water are:

- In all samples the PAH_{EPA16} concentration was below 43 µg/L and average of 12 µg/L.
- Naphthalene (47%), phenanthrene (25%) and fluorene (8%) were the three dominant species in the PAH_{EPA16} composition. That is comparable to crude oil and

residual fuel oil compositions, which might indicate the predominance of petrogenic PAHs.

- Average normalized concentration of benzo[a]pyrene (0.06 µg/L) was below the WHO Guidelines limit for drinking-water quality.
- BTEX were found mostly below the detection limit and the maximum measured concentrations were 2 µg/L for benzene and toluene, below the WHO Guidelines limits for drinking-water quality.
- Vanadium was the most prevalent metal in samples.
- Contribution of copper and zinc probably from corrosion protection anodes and marine growth prevention systems, independently from EGCS systems.
- Nitrate normalized concentrations were compliant to the IMO requirement (<60 mg/L). Baseline nitrate levels in inlet seawater contributed significantly to concentrations found in OL discharge water. When subtracting that contribution, the average nitrate accumulation resulted in 7 mg/L. Nitrite levels are negligible. The authors suggested:
    - When reporting for compliance of nitrate levels, inlet concentration should be subtracted.
    - Remove the requirement for nitrate measurement from the EGCS Guidelines.

The study states the essential challenges to keep cleanliness during sampling and to find suitable sampling points.

Koski et al. (2017) (in Table A-4 presented as DTU) from the Technical University of Denmark carried out a study funded by the Danish Maritime Fond. This project was actually focused on the ecotoxicological effects of EGCS discharge water on coastal plankton (see chapter 7.2) but included a special assessment of the influence of some relevant metals contained in discharge water. Thus, metals were analysed on samples taken from an OL system on board a RoRo vessel (Magnolia Seaways) during a voyage in the open North Sea. The results were compared to metal levels in the Copenhagen harbour (sampled and analysed within the project) and in open sea. Some of the main findings and discussions highlighted in the report regarding the metal concentrations are:

- Vanadium, nickel and lead showed a strong and similar increase due to the scrubbing process. All three elements were strongly correlated with concentrations ranking EGCS discharge water > inlet water > Copenhagen harbour.
- High concentrations of copper in discharge water were observed, but the highest values were measured in the inlet samples. Those values were far above the copper levels in the open sea and Copenhagen harbour. This could be explained by the use of copper as antifouling agent in ship paints and pipe construction.
- Higher concentrations of chromium were detected in inlet water and EGCS discharge water.

- Zinc concentrations were in a similar range in the inlet samples, EGCS discharge water and harbour samples. A similar pattern was observed for arsenic. Cadmium resulted below detection limit in all locations.
- All average metal concentrations in the inlet resulted above the levels reported for the open sea.

Kjølholt et al. (2012) (in Table A-4 presented as COWI) from the consulting group COWI A/S carried out a study on behalf of the Danish Environmental Protection Agency. In this project, discharge water (from OL and CL) and sludge (from CL) from the hybrid EGCS on board the RoRo vessel Ficaria Seaways was analysed to assess the impacts of EGCS discharge water on the marine environment and to evaluate the options for sludge treatment and disposal. The ship is in service in the Kattegat area and North Sea. Some of the main findings and discussions highlighted in the report regarding the chemical characterization of the discharge water are:

- Vanadium and nickel were significantly enriched in both operation modes.
- Higher concentrations of copper and zinc were presumably caused from the material of the sampling point, since both metals were not detected in the fuel oil.
- Enrichment of sulphur in the discharge water was detected even in OL mode.
- Concentrations of PAH and total hydrocarbons (THC) were low in OL mode. In CL mode higher concentrations were observed.
- COD outlet concentrations (46 – 56 mg/L) in OL mode were slightly above the inlet concentration (44 mg/L). Higher levels (440 – 490 mg/L) are reported in the CL mode despite the partial reduction during water treatment (centrifugation).
- There was a significant reduction of suspended solids in water treatment (centrifugation) step in CL mode.
- The level of some pollutants in EGCS discharge water exceeded the compared EQS.

The OL results shown in Table A-4 are from samples taken downstream the scrubber tower (no dilution water). In the CL mode, the system was operated in a non-steady state (discontinuous) way. The water was initially recirculated and pollutant-enrichment was measured during two hours. The values presented in Table A-4 correspond to the samples taken after that time. Measurements of suspended solids at time intervals of 20 minutes demonstrated, however, that the saturation point was not reached after these two hours.

A particularity of this study was the analysis of the sludge from the CL operation. There, pollutants were found in a more concentrated form than in the discharge water. Additionally, dioxin/furans were found in a relatively low concentration and PCBs were not detected. Based on the presence of vanadium, nickel and THC, sludge should be classified as hazardous waste.

Additionally, the potential impact of EGCS discharge water to the marine environment was evaluated by using a simplified dispersion modelling in two areas (Kattegat Sea and Aarhus Bight) under different scenarios. Pollutant levels were generally found far below EQS, but in ports pollutant concentrations may be close or even slightly exceed levels of concern. The prohibition of EGCS discharge water in ports is suggested as precautionary approach.

Other studies including chemical analyses of EGCS discharge water samples taken on board are:

- Hansen (2012) from a hybrid system on board the RoRo Ficaria Seaways,
- US EPA (2011) from an OL system on board the cruise ship MS Zaandam,
- Wärtsilä (2010) from a CL system on board the tanker MT Suula and
- Hufnagl et al. (2005) from an OL system on board the RoPax Pride of Kent.

The first study in the list was conducted on board the same ship as the above described study of Kjølholt et al. (2012) and was also financed by the Danish EPA. The results of the measurements on the discharge water are reported less extensively. The author questioned the reliability of the on-line monitoring for PAH_{phe} on board, in the same way as Wärtsilä (2010). In the last three (older) listed studies, the samples were taken during operation of auxiliary engines. No further description about them is presented in this report as there are more recent and more extensive studies published.

7.2 Ecotoxicological effects of EGCS discharge water

This chapter compiles the main research work on ecotoxicological effects of EGCS discharge water. The approach of the studies and the main findings are presented below. Table A-5 contains an overview of their analysis, results and tested water.

Kathmann et al. (2019) carried out an assessment of both adverse acute (on luminescent bacteria and marine algae) and potentially chronic effects (dioxin-like activity and mutagenicity) caused by discharge water from OL and CL systems. OL discharge water tested positive for dioxin-like activity and mutagenicity, whereas no significant inhibition effects were shown in the *in vivo* assays. CL discharge water exerted stronger effects across all bioassays.

An evaluation on the effects of the water treatment in CL systems showed no significant reduction of toxicity. The treatment step itself is pointed out as a source of toxicity; for instance, incomplete removal of flocculants could be a possible explanation. The analyses were performed with filtered samples indicating that only water soluble compounds caused the observed effects, which might explain the absence of biological effect reduction despite efficient PAH removal. The results probably underestimate the full risk potential of the samples to marine organisms.

Toxicity could only partially be explained by the measured contaminants. This indicates that either mixture toxicity has to be taken into account or that toxic compounds (such as nitroarenes and substituted PAHs, especially nitro-PAHs) are present in the sample that were not captured by the applied chemical analysis. The authors concluded that further identification of pollutants in EGCS discharge water is required and technical measures should be re-evaluated to efficiently treat discharge water before its release.

Ytreberg et al. (2019) assessed how EGCS discharge water affects microplankton species (laboratory experiments) as well as a natural community of pelagic microplankton originating from the Baltic Sea (field experiment).

During the field experiment significant increases in chlorophyll a, particulate organic phosphorus (POP), carbon (POC) and nitrogen (PON) were observed when the plankton community was exposed to 10% EGCS discharge water for 13 days. The effects could be explained by stimulated algal growth due to the increased nitrate concentrations in the EGCS discharge water. Therefore, the authors mentioned that the additional load of nitrate from discharge water may have considerable effects on the growth of pelagic microplankton, especially in eutrophicated environments such as the Baltic Sea.

Furthermore, a significant increase in bacterial biomass was reported. The reasons for this might be a higher availability of dissolved organic matter due to cell lysis, the presence of black carbon as carbon source or pulsed addition of sulphuric acid. The biotic effects were consistent with the results of the complementary laboratory experiments, where primary productivity was observed to be stimulated at the beginning of the experiments.

The filamentous cyanobacteria *N. spumigena* showed negative responses in photosynthetic activity and the chain-forming diatom *M.* cf. *arctica* showed increased primary productivity at the end of the experiment, implying species-specific responses to EGCS discharge water. It is also discussed that potential adverse effects of metals in the EGCS discharge water may have been masked by the culture media.

Magnusson et al. (2018) tested acute toxicity using Microtox bioassay (on luminescent bacteria) and chronic toxicity through experimental studies with zooplanktonic copepods and bottom-dwelling blue mussels.

The acute toxicity was only slightly less after than before the treatment unit (as measured with Microtox bioassay method) despite the high reduction of hydrocarbons and metals in the water treatment. The authors explained this by the relatively low reduction of low molecular aromatic hydrocarbons, known for their acute toxicity, and by the high concentrations of copper and mercury in effluent water compared to water feeding into the unit.

The aim of the chronic toxicity tests was to identify the lowest concentration of EGCS discharge water where a statistically significant effect was detected. Copepods resulted to be more sensitive than blue mussels. Since neither pH nor alkalinity differed from the clean seawater at the effect concentrations, it was concluded that the observed effects on copepods were primarily caused by toxic compounds present in the EGCS discharge water rather than by acidification. It should be noted that in both CL and OL exposures, the lowest tested concentrations (0.04-0.1% CL and 1.0% OL water) resulted in toxic effects on the juvenile copepods. Thus, it cannot be excluded that even lower concentrations would have been harmful to the tested zooplankton species. On the assays with blue mussels, byssus strength was the only endpoint measured showing a significant effect.

The pollutant concentrations at the EGCS discharge water exposure level with observed detrimental effects were far below the toxic threshold values reported in the literature, suggesting that the constituents of the mixture might act with cumulative and synergistic effects. Thus, the authors stressed the importance of conducting risk assessment based on the whole effluent than a single pollutant approach.

MLIT (2018) conducted acute WET tests with OL-EGCS discharge water according to standardized test methods using three species of marine organisms at different trophic levels: fish (3rd trophic level), crustacean (2nd trophic level), and algae (1st trophic level). They followed the approach of the GESAMP group for the evaluation of ballast water management systems (BWMS) using active substances proposed in IMO document BWM.2/Circ.13/Rev.4 (MEPC, 2017).

In the algal toxicity test, no growth inhibition was observed in the concentration range of 0.01%–32.0%, even slight growth stimulation is reported at some concentrations. In the crustacean toxicity test, the acute effects were expressed immediately; the cumulative mortality was the same after 24 hours and at the end of the test period (96 hours). The same observation was reported in the fish toxicity test. Furthermore, possible influence of low dissolved oxygen concentrations at the higher exposure concentrations was observed: in the crustacean test some organisms stayed at the water surface, while in the fish test abnormal swimming (surface swimming) and nose raising was observed immediately after transferring the organisms to the test solution.

Based on the results of the tests with these three marine organisms, the study concluded that by diluting the EGCS discharge water to about 1/8 no obvious acute effect on the indicator organisms was observed. The authors also identified low pH and low dissolved oxygen concentration as predominant factors of the observed toxicity effects. It should be noted that both dissolved oxygen and pH were not adjusted to the recommended values in the standard methods during the preparation of the samples for the tests.

Koski et al. (2017) investigated the lethal and sub-lethal effects of OL-EGCS discharge water exposure on a common neritic copepod, focusing on threshold (metal) concentrations, exposure pathways and potential synergistic effects of the discharge water constituents. Additionally, collected organisms from a harbour were analysed for toxic effects due bioaccumulation of heavy metals caused by EGCS discharge water.

The direct exposure to discharge water increased adult copepod mortality and reduced feeding at metal concentrations which were orders of magnitude lower than the single lethal concentrations reported in the literature, suggesting synergistic effects on plankton productivity and bioaccumulation of metals. In contrast, reproduction was not influenced by dietary uptake of contaminants. The authors suggested the uptake route of metals as possible explanation to the higher sensitivity of feeding and survival, since vanadium, nickel and lead were mainly taken up directly from the water and therefore had a minor effect on reproduction.

The results of the analysis on the collected plankton indicated that some of the substances present in EGCS discharge water might bioaccumulate in the food chain. The high concentrations of vanadium on plankton remained unexplained. The authors prioritize further investigations to determine the sources and effects of vanadium and other metals, considering the current needs for management of different industrial and maritime activities in coastal waters.

No detrimental effects were observed at 1% EGCS discharge water exposure, suggesting that by ensuring a rapid dilution of discharges, the impact of EGCS discharge water can be kept minimal and comparable to that from atmospheric deposition, before EGCS technology was implemented.

The algal growth as a response to EGCS discharge water was measured as well. The authors observed at 100% discharge water exposure complete inhibition of algal growth, although half of the cells remained through the experiment; at 10% discharge water exposure, however, an increase in cell growth was reported.

7.3 Environmental risk assessment (PEC/PNEC approach)

The quotient between Predicted Environmental Concentration and Predicted No-Effect Concentration (PEC/PNEC) is employed typically in the environmental risk assessment of substances or mixtures. If the PEC/PNEC quotient is greater than 1, the substance is of environmental concern, while when the quotient is below 1, there is no significant risk expected based on the current knowledge. This approach has been found to be used in some research works for the assessment of EGCS discharge water. Table 5 summarizes the methodology and conclusions of the studies of Faber et al. (2019), Magnusson et al. (2018), Behrends (in preparation), Kasseris et al. (2020) and MLIT (2018). All studies covered EGCS discharge water from OL systems, only the IVL study (Magnusson et al., 2018) assessed also CL systems. Similarly, most of the studies used a whole effluent approach, while the CE Delft study (Faber et al., 2019) employed only a single-substance approach. However, for a complete risk assessment, it is recommended to sum up the PEC/PNEC quotient of every single substance to account for additive toxicity.

As aforementioned (chapter 7.2), the single-substance approach alone seems to be inadequate for an environmental risk assessment of the complex mixture of EGCS discharge water. This is because there is a potential risk of toxic effects arising from cumulative or synergistic toxicity. In order to assess the risks of effects of complex mixture in the environment, other approaches are proposed in the literature (ECETOC, 2001). One practical method is the simple summation of PEC/PNEC quotients of the substances in the mixture. This approach is considered conservative and could be used as a first-tier when applying concentration addition (European Union, 2012). Ushakov et al. (2019) employed this approach but with the EQS of the Norwegian Environment Agency as PNEC and the pollutant concentrations at discharge as PEC.

Table 5 shows diverging conclusions from the reviewed studies. Therefore, the methodology should be considered in detail when reviewing and comparing the studies. Especially the applied safety factors for the PNEC values have a drastic impact on the PEC/PNEC quotient.

Table 5: Research studies assessing EGCS discharge water using the PEC/PNEC approach

Research study	PEC (estimated or modelled dilution)	PNEC (required dilution)	PEC/PNEC	Conclusions of the studies
CE Delft	Mean equilibrium water concentrations modelled with MAMPEC using average measured data [i].	Based on MAC-EQS and AA-EQS of the Directive 2013/39/EU for single pollutants included in the list of priority substances [ii].	~0.06 [iii]	The impacts of using OL-EGCS are small in relation to the agreed water quality standards for 2021. Local hydrodynamic circumstances as well as background concentrations of priority substances should be taken into account when assessing the impacts of the use of EGCS-OL in a specific port.
IVL	Dilution factors were estimated based on a simple approach that considered the water displacement caused by the ship [iv]. OL: 6.3×10^{-5} CL: $1.5 - 1.9 \times 10^{-6}$	Based on WET tests carried out within the study. OL: 1×10^{-5} CL: $0.4 - 1 \times 10^{-6}$	OL: 6.3 CL: 1.9-3.8	The values indicate a risk for harmful effects on the marine organisms in the area around the shipping lanes. The water from the OL system was found to be more toxic than the waters from the two CL systems.
Marena	Equilibrium water and sediment concentrations of ten PAHs and five heavy metals modelled with MAMPEC using average (Hassellöv et al., 2020) and maximum concentrations (Faber et al., 2019) [i].	PNEC for PAHs are taken from European Union (2008) and for metals from Linders et al. (2019).	Using average conc. [v]: 0.58 - 3.14 Using maximum conc. (two PAHs and three metals) [v]: 11 - 60	The application of the additive toxicity approach leads to PEC/PNEC around 1 with the average discharge concentrations and discharge into a pristine environment, which indicates an environmental risk. Application of the maximum concentrations and/or background concentrations all result in a PEC/PNEC >1.

Research study	PEC (estimated or modelled dilution)	PNEC (required dilution)	PEC/PNEC	Conclusions of the studies
MIT	Steady-state concentrations resulted from near-field dispersion modelling in busy open waters and cumulative equilibrium concentrations from far-field dispersion modelling in enclosed waters.	Based on the results of MLIT (2018) and Koski et al. (2017): 2×10^{-4}	Near-field: <1 (with values >1 from sensitivity analysis) Far-field: >1	It is a plausible hypothesis that there is no likely risk of acute toxicity effects from short-term exposure in target organisms. However, for higher traffic zones, bays and ports, the study points to the likelihood that the presumed safe concentration threshold may be exceeded, indicating a clear cause for ecological concern.
MLIT	Dilution factors resulted from a numerical fluid simulation. After 1 min: 2×10^{-4} After 2 min: 1×10^{-4}	Based on WET tests carried out within the study and GESAMP BWWG safety factor. Short term: 2×10^{-3} Long term: 2×10^{-4}	<1	Any short- or long- term effects on marine organisms cannot be caused by the use of OL-EGCS. The risks for both the marine environment and the marine aquatic organisms are in the acceptable range.

Sources: CE Delft, Faber et al. (2019); IVL, Magnusson et al. (2018); Marena, Behrends (in preparation); MIT, Kasseris et al. (2020); MLIT, MLIT (2018).

Legends: PEC, Predicted Environmental Concentration; PNEC, Predicted No-Effect Concentration; MAC-EQS, Maximum Allowable-Environmental Quality Standard; AA-EQS, Annual Average-Environmental Quality Standard. Limit values are based in a specific flowrate of 44 m^3/MWh.

i) 291 washwater samples from 53 different ships (Carnival Corp. & plc and DNV GL, 2019). See chapter 7.1.

ii) Regarded substances included cadmium, lead, mercury, nickel, anthracene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(g,h,i)perylene, fluoranthene and naphthalene.

iii) Refers to fluoranthene, which resulted with the highest single pollutant quotient: modelled mean equilibrium concentration as a percentage of the 2021 allowable annual average concentration as laid down in Directive 2013/39/EU for Inland Surface Waters. See Figure 25 in Faber et al. (2019).

iv) As proposed by a scientific advisory panel set out to assist the Alaska Department of Environmental Conservation effect of discharges of wastewater from cruise ships (Loehr et al. 2003).

v) The additive toxicity approach was used by adding the risk factors of the single PAHs and metals including dissolved, suspended and sedimentation risk factors. The calculations were done for two harbours: GESAMP BW harbour (lower risk value) and Baltic harbour (higher risk value).

7.4 General observations from the review of research studies

7.4.1 Sampling campaigns and sampling procedures

Based on the results of the abovementioned studies the following general observations and conclusions can be stated regarding sampling campaigns and sampling procedures:

- Different types of ships have been sampled, especially a higher number of RoRo/RoPax vessels and cruise ships in the Baltic and North Sea region. These ship types started to apply EGCS for compliance with the (S)ECA requirements.
- Sampling campaigns may face many logistic and organizational challenges for taking samples under the desired operation conditions and for delivering them on time.

- Particularly, missing and unsuitable sampling points are reported.

7.4.2 Chemical composition

Based on the results of the abovementioned studies the following general observations and conclusions can be stated regarding the chemical composition of EGCS discharge water:

- Trace metals are mainly found in dissolved form. This could be explained by acidic conditions and high levels of chloride in the water. Removal efficiency of metals relying only on mechanical treatment is therefore limited.
- Significant enrichment of vanadium and nickel in discharge water is observed. Both metals are found in residual fuel oils in high concentrations.
- Copper and zinc were also found in relevant concentrations in water samples (even in inlet samples). The materials of the sampling pipe, corrosion protection and antifouling systems may explain those irregularities.
- Nitrate levels in discharge water were generally found below the IMO discharge limit concentration and strongly dependent of the inlet water levels. Nitrite levels in OL samples were considered negligible.
- Oil concentration in OL discharge water was below 1 ppm, while oil in CL discharge water ranged between 2 –21 ppm (see Table A-4).
- Relation between oil content and PAH_{phe} was assessed only by one research study. That study found a correlation between the parallel measurements of PAH_{phe} and laboratory results for oil content (HOI) and PAH_{EPA16}. The PAH_{phe} values from the on-line monitoring data did not show a correlation with oil nor PAH_{EPA16}. The use of PAH_{phe} as a proxy parameter for oil content in EGCS discharge water should be further examined.
- Relation between turbidity, suspended solids, organic pollutants and metals was not assessed by any research work. The use of turbidity as criteria and proxy parameter for pollutants in EGCS discharge water should be examined.
- PAH_{EPA16} concentrations in discharge water were generally found below the IMO limit value given in PAH_{phe} (this comparison is actually not consistent but serves to illustrate the PAH levels in EGCS discharge water).
- Naphthalene, phenanthrene and fluorene represented the highest fractions of the PAH_{EPA16}. PAHs with more rings were found in much lower levels, mainly below the detection limits. In CL discharge water samples, however, their presence was more notable even though the water treatment unit could remove them very efficiently.
- Petrogenic PAHs (fuel related) were more dominant in the discharge water rather than pyrogenic PAHs (combustion related).

- Alkyl-PAHs were also present in the discharge water in significant levels. It is known that alkyl-PAHs, nitro-PAHs and other derivatives are found in much higher levels and some of them are more toxic than the parent-PAHs and $\mathrm{PAH}_{\mathrm{EPA16}}$ (Linders et al., 2019).
- Results from the on-line monitoring on board presented irregularities and discrepancies when compared to laboratory or *in situ* parallel measurements.
- Water treatment after scrubbing reach different levels of efficiency depending on the substances and applied technology. Particulate-associated and compounds with higher molecular weight were efficiently removed. The use of flocculant agents and their poor removal might influence the discharge water composition and toxicity negatively.
- Pollutant levels in discharge water were compared to limit values in international and local regulations:
    - Discharge water was generally compliant with IMO requirements and other limit values from land-based discharge regulations.
    - For some substances, concentrations exceeded the comparably stricter EQS. However, they do not apply to single-source discharges, since dilution, environmental fate and current environmental concentration should also be considered.
    - Directive 2010/75/EU and other regulations do not include limit values for vanadium, which is the metal with the highest concentration in the discharge water.

7.4.3 Ecotoxicological effects

Based on the results of the abovementioned studies the following general observations and conclusions can be stated regarding ecotoxicological effects of EGCS discharge water:

- CL discharge water exhibited higher toxicity effects than OL discharge water. CL systems require lower water flows and the water is recirculated; thus, pollutants are present in a more “concentrated” form. When considering the higher water flows resulting in a higher mass flow of pollutants, however, OL discharges represent a higher risk to marine ecosystems.
- Water treatment prior discharging in CL systems showed no significant reduction of toxicity effects.
- The single pollutant approach alone is not adequate for the environmental risk assessment of EGCS discharge water. Toxicity effects were observed in equivalent concentrations far below the reported toxicity thresholds for substances present in EGCS discharge water. This issue can be explained by:
    - The occurrence of pollutants or toxic compounds in the EGCS discharge water that have not been analysed and identified yet.

  - Cumulative or even synergetic toxicity effects in the EGCS discharge water. This implies that the joint effect of the mixture of all components in the discharged water is larger than the effect of the individual components, also known as “cocktail effect”.

- Both, adverse and stimulating response were observed in different types of organisms. This proves the different sensibility of organisms and implies species-specific responses to EGCS discharge water:
  - Algal growth was stimulated or not affected during exposure to EGCS discharge water.
  - Acute effects on luminescent bacteria were reported; while in a mesocosm experiment an increase in total bacterial biomass was observed.
  - Fish, crustacean and copepod species showed some mortality at specific exposure concentrations.
  - Mussels showed only effects on byssus strength.
- Different views regarding the effects of the pH of the observed toxicity effects are found in the studies. Low dissolved oxygen concentration is also mentioned as a toxicity factor. Both parameters might reach normal values immediately after dilution with surrounding water.
- To our knowledge, fish egg tests have not yet been conducted. This assay is typically conducted in Germany for the control and monitoring of industrial water discharges. The German Wastewater Directive (AbwV) Annex 47 “Scrubbing of flue gases from combustion plants” specifies a limit value for toxicity on fish eggs (G_{Ei} = 2) as requirement for washing water discharges.

7.4.4 Environmental risk assessment

From the review of previous studies focused on the environmental risk assessment of EGCS discharge water, it is observed that the conclusions are different and even opposing. Those differences could be explained by:

- the approach and methodology applied,
- considerations for determining PEC values and
- selected safety factors to establish PNEC values.

7.5 Current parallel projects covering EGCS discharge water

Four current research projects with the focus on EGCS discharge water were identified, where similar activities and analyses to those of the ImpEx project are planned. Therefore, contact with the project team members of these projects has already been established in order to exchange knowledge, experiences and results and thus to generate synergy effects. Further details about EMERGE, SAARUS, ShipTRASE, a Swedish project and ImpEx are exhibited in Table 6.

Table 6: Identified parallel projects covering EGCS discharge water and ImpEx

Project	**EMERGE** [i)]	**SAARUS** [ii)]	**ShipTRASE** [iii)]	**Swedish project** [iv)]	**ImpEx**
Name	Evaluation, control and mitigation of the environmental impacts of shipping emissions	Optimization of scrubber exhaust gas scrubbing technology to reduce environmentally harmful ship emissions (*Optimierung der Scrubber-Abgaswäsche Technologie zur Reduktion umweltschädlicher Schiffsemissionen*)	Global shipping: Linking policy and economics to biogeochemical cycling and air-sea interaction	Unknown	Environmental impacts of exhaust gas cleaning systems for reduction of SOx on ships.
Period	2020 - 2024	2019 - 2022	Jun 2020 – May 2023	Jan 2020 – Oct 2020	Jan 2020 – Jan 2023
Conducted by	▪ FMI - Finnish Meteorological Institute (coordination) ▪ IVL - Swedish Environmental Research Institute ▪ Chalmers University of Technology ▪ Other 15 organizations, including a total of 10 countries.	▪ Saacke GmbH (coordination) ▪ IOW - Leibniz-Institute for Baltic Sea Research in Warnemünde (water treatment) ▪ GEA Westfalia Separator Group GmbH (water treatment) ▪ Further research institutes, universities and manufacturers (engine, filter technology and air/particles)	Interdisciplinary and international collaboration with researchers from Sweden, Germany and France. The German project partners are: ▪ GEOMAR Helmholtz Centre for Ocean Research Kiel (Coordination of German consortium) ▪ CAU - Walther-Schücking-Institute for International Law at Kiel University ▪ Maritime Cluster Northern Germany	▪ Swedish Transport Agency ▪ Swedish Agency for Marine and Water Management	▪ BSH - Federal Maritime and Hydrographic Agency (coordination) ▪ BfG - German Federal Institute of Hydrology ▪ HU - Hamburg Institute for Hygiene and Environment ▪ Marena Ltd. ▪ UBA - German Environment Agency ▪ WWU - University of Munster
Financed by	European Commission (Horizon 2020)	German Federal Ministry for Economic Affairs and Energy (BMWi)	The Belmont Forum, Future Earth and JPI Oceans	Ordered from the Swedish Government	German Environment Agency (UBA)

Project	**EMERGE** [i)]	**SAARUS** [ii)]	**ShipTRASE** [iii)]	**Swedish project** [iv)]	**ImpEx**
Aim	▪ To comprehensively quantify and evaluate the effects of a range of potential emission reduction solutions for shipping in Europe, and ▪ to develop more effective strategies and measures to reduce the environmental impacts of shipping	To reduce ship-based emissions through optimized and extended EGCS to protect the atmospheric and maritime environment. Specific goals related to EGCS discharge water: ▪ Compliance with environmental standards in the field of water policy (2008/105/EC) and the WFD ▪ Turbidity value < 25 NTU	To analyse the ecological, economic and legal aspects of both short and long-term measures to reduce ship emissions and corresponding control mechanisms.	To draw conclusions about environmental and economic effects of EGCS discharge water based on recompilation of information and to review the "2015 EGCS Guidelines"..	To support the international discussions on the regulation of discharge water from EGCS. Hereby the scientific results obtained in the framework of the project, which take the concerns of marine environmental protection into account, shall contribute to a factual discussion.
Activities	Related to EGCS discharge water: ▪ Chemical characterization ▪ Ecotoxicological tests ▪ Modelling of environmental concentrations The project addresses both air and water emissions, including other waste streams such as wastewater, oil leaks, antifouling paint residues, food waste nutrients).	Related to EGCS discharge water: ▪ Treatment of water on board ▪ Analysis of the particles for organic pollutants (e.g. PAHs), metal residues, elementary composition and ecotoxicological hazard potential	The effects of EGCS discharge water and LNG on the uppermost water layers (e.g. in the trace gas cycling) will be investigated in the laboratory and compared to conventional ship propulsion emissions.	▪ Literature review on EGCS discharge water composition, ecotoxicological and economic effects ▪ Ecotoxicological studies (if time and resources are enough) ▪ Review of the legal framework regarding EGCS discharge water and water discharges.	▪ Review status quo (this report) ▪ Sampling campaign on board ships ▪ Chemical characterization ▪ Ecotoxicological tests ▪ Environmental risk assessment ▪ Workshops and committee work

i) EMERGE (nd) and Kukkonen et al. (2019)

ii) SAACKE GmbH (2020) and IOW (2020)

iii) GEOMAR (2020) and personal communication with project leader Marandino (2020)

iv) Havochvatten (2020) and personal communication with project team members Petrini (2020), Lindgren (2020) and Vallhagen (2020)

8 Outlook

The present review on the status quo of EGCS as part of the project ImpEx (WP 1), with special focus on the environmental aspects of the discharge water, covered technical aspects, market analysis, the regulatory framework and recent research activities related to this topic. The collated information and main findings will serve as guidance for the upcoming work packages within the project ImpEx, while the open issues for discussion will be addressed.

The next project activity is a sampling campaign on board ships including parallel measurements to the water online monitoring, as this was found to be a crucial issue. The water samples will be chemically and ecotoxicological characterized. The chemical analysis will include quantitative determination of heavy metals, oil content, PAH_{EPA16}, alkyl PAHs and a qualitative determination of further substances by GC-MS screening. The ecotoxicological assays will include WET and *in vitro* tests. The results will serve as basis for the realization of an environmental risk assessment and will be presented in workshops and the relevant committees.

The technical aspects of EGCS such as the type of system, differences in the technologies (especially for water treatment units) and volume flowrates will be taken into account for the evaluation of the results from the chemical and ecotoxicological analysis.

The current status and forthcoming developments on the technology, market and regulatory framework were compiled in this review. Changes in these areas are expected in the short term and will be followed for the duration of the project.

The present review and future results from the ImpEx project are planned to be considered for a non-conservative dispersion modelling, including biogeochemical processes, within a potential follow-up UBA project.

9 List of references

ABS (2019): Practical Considerations for the Installation and Operation of Exhaust Gas Cleaning Systems

Asplind, B. (2018): Technical description of the scrubber installation project. Stena Teknik. Webinar on “How to handle Scrubber Waste” An Exchange of Best Practice. https://www.youtube.com/watch?v=kd9ISJRUKgM&feature=youtu.be

Behrends, B.; Liebezeit, G. (2003): Reducing SO2 and NOX emissions from Ships by a seawater scrubber. BP Marine Report

Bockmann, M.W. (2020): Chinese owners and leasing banks dominate scrubber investment. Lloyd’s List Maritime Intelligence. https://lloydslist.maritimeintelligence.informa.com/LL1131043/Chinese-owners-and-leasing-banks-dominate-scrubber-investment

Bosch, P.; Coenen, P.; Fridell, E.; Stefan, A; Palmer, T.; Holland, M. (2009): Cost Benefit Analysis to Support the Impact Assessment accompanying the revision of Directive 1999/32/EC on the Sulphur Content of certain Liquid Fuels. Final report ED45756 by AEA to the European Commision

BRITANNIA P&I (2020): LIST OF JURISDICTIONS RESTRICTING OR BANNING SCRUBBER WASH WATER DISCHARGES. https://britanniapandi.com/blog/2020/01/27/list-of-jurisdictions-restricting-or-banning-scrubber-wash-water-discharges/ (30/04/2020)

BSH (2018): Einleitbedingungen von Waschwasser aus Abgasreinigungssystemen (Scrubber) in deutschen Gewässern (Discharge requirements for washwater from Exhaust Gas Cleaning Systems (Scrubber) in German waters). https://www.bsh.de/DE/THEMEN/Schifffahrt/Umwelt_und_Schifffahrt/MARPOL/_Module/Akkordeon/Anlage_6/Einleitbedingungen_Waschwasser.html (26/06/2020)

Buhaug, Ø.; Fløgstad, H.; Bakke, T. (2006): MARULS WP3 – Washwater Criteria for seawater exhaust gas-SOx scrubbers. MARINTEK. Report No. 260001.30.01. Submitted to MEPC 56 as document MEPC 56/INF.5

Carnival Corp. & plc and DNV GL (2019): Compilation and Assessment of Lab Samples from EGCS Washwater Discharge on Carnival ships. http://media.corporate-ir.net/media_files/IROL/14/140690/Carnival-DNVGL_Washwater_Analysis_2018.pdf

China, Malaysia, Singapore and United Arab States (2019): Factors to be considered when assessing the impact of washwater discharge from exhaust gas cleaning system (EGCS) operating in ports and coastal areas. Submitted to PPR 7 as document PPR 7/12/1

CE-Delft and CHEW (2017): The Management of Ship-Generated Waste On-board Ships. Publication code 16.7I85.130. Project EMSA/OP/02/2016

Clarksons Research (2019): Scrubber Count Update & IMO 2020 Market Impact Assessment [Presentation slides]

Delli, K. (2020): Draft report on technical and operational measures for more efficient and cleaner maritime transport (2019/2193(INI)). Committee on Transport and Tourism. Submitted on 8/10/2020. https://www.europarl.europa.eu/doceo/document/TRAN-PR-658855_EN.pdf

Den Boer, E.; Hoen, M. (2015): Scrubbers - An economic and ecological assessment. CE Delft, Delft

Directive 2000/60/EC (2000): Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy (Water Framework Directive). https://eur-lex.europa.eu/eli/dir/2000/60/oj

Directive 2008/56/EC (2008): Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive). https://eur-lex.europa.eu/eli/dir/2008/56/oj

Directive (EU) 2016/802 (2016): Directive (EU) 2016/802 of the European Parliament and of the Council of 11 May 2016 relating to a reduction in the sulphur content of certain liquid fuels. https://eur-lex.europa.eu/eli/dir/2016/802/oj

Directive (EU) 2019/883 (2019): Directive (EU) 2019/883 of the European Parliament and of the Council of 17 April 2019 on port reception facilities for the delivery of waste from ships, amending Directive 2010/65/EU and repealing Directive 2000/59/EC. https://eur-lex.europa.eu/eli/dir/2019/883/oj

DNV GL (2019a): Global Sulphur Cap 2020 – 2019 Update, Focus on Scrubbers

DNV GL (2019b): Maritime Forecast to 2050 – Energy Transition Outlook 2019

DNV GL (2020): DNV GL's Alternative Fuels Insight platform. https://afi.dnvgl.com/ (07/05/2020)

Dulière, V.; Baetens, K.; Lacroix, G. (2020): Potential impact of wash water effluents from scrubbers on water acidification in the southern North Sea. Final project report. Royal Belgian Institute of Natural Sciences. Operational Directorate Natural Environment, Ecosystem Modelling. 31 pp.

European Union (2012): Toxicity and Assessment of Chemical Mixtures. European Commission & DG Health & Consumers.

ECETOC (2001): Aquatic Toxicity of Mixtures. European Centre for Ecotoxicology and Toxicology of Chemicals. Technical Report No. 80.

EGCSA (2012): EGCSA Handbook 2012 – A practical guide to exhaust gas cleaning systems for the maritime industry. https://www.egcsa.com/resources/reference-documents-and-studies

EGCSA (2019): Global Marine SOx Emissions Regulation. https://www.egcsa.com/map-regulations/ (30/04/2020)

EGCSA and Euroshore (2018): Report on analyses of water samples from Exhaust Gas Cleaning Systems. Submitted by CESA to MEPC 73 as document MEPC 73/INF.5

EMERGE (nd): Briefing Note – EMERGE

Endres, S.; Maes, F.; Hopkins, F.; Houghton, K.; Mårtensson, E.M.; Oeffner, J.; Quack, B.; Singh, P.; Turner D. (2018): A New Perspective at the Ship-Air-Sea-Interface: The Environmental Impacts of Exhaust Gas Scrubber Discharge. Front. Mar. Sci. 5:139

EnSys Energy and Navigistics Consulting (2016): Supplemental Marine Fuel Availability Study. Submitted by BIMCO and IPIECA to MEPC 70 as document MEPC 70/INF.9

European Union (2008): Summary Risk Assessment Report: Coal-Tar Pitch, High Temperature; 55 p.

Faber, J.; Nelissen, D.; Huigen, T.; Shanthi, H.; Hattum, B.; Van Hattum, B.; Kleissen, F. (2019): The impacts of EGCS washwater discharges on port water and sediment. CE Delft, Delft

Finland (2007): Proposal for amendments to the Guidelines for on-board exhaust gas-SOx cleaning systems. Submitted to BLG 12 as document BLG 12/6/11

Fridell, E.; Salo, K. (2014): Measurements of abatement of particles and exhaust gases in a marine gas scrubber. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 230(1): 154–162

GEOMAR (2020): Reduce ship emissions - but how? Press release on 4.05.2020. https://www.geomar.de/index.php?id=4&no_cache=1&tx_ttnews%5btt_news%5d=7002&tx_ttnews%5bbackPid%5d=185&L=1 (27/05/2020)

Georgefff, E.; Mao, X.; Comer, B. (2019): A whale of a problem? – Heavy fuel oil, exhaust gas cleaning systems, and British Columbia's resident killer whales. ICCT Consulting Report

GESAMP (2009): Annex – Advice by GESAMP on the interim criteria for discharge of washwater from Exhaust Gas Cleaning Systems for removal of sulphur-oxides. Submitted to MEPC 59 as document MEPC 59/4/19

Hakirevic, N. (2020): Prime Lake: Study of wastewater treatment from scrubbers paves way for sustainable usage. Offshore Energy on 10/07/2020. https://www.offshore-energy.biz/prime-lake-study-of-wastewater-treatment-from-scrubbers-paves-way-for-sustainable-usage/

Hansen, J.P. (2012): Exhaust Gas Scrubber Installed Onboard MV Ficaria Seaways – Public Test Report. Alfa Laval Aalborg A/S. Danish Environmental Protection Agency. Environmental Project No. 1429. Copenhagen

Hassellöv, I.-M.; Hermansson A. L.; 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 Chalmers University of Technology

Hassellöv, I.-M.; Turner, D.R. (2014): Seawater scrubbing – reduction of SOx emissions from ship exhausts. The Alliance for Global Sustainability office at Chalmers, Gothenburg

Havochvatten (2020): Uppdrag att ta fram underlag om utsläpp av tvättvatten från skrubbrar på fartyg (Assignment to develop documentation on the discharge of wash water from scrubbers on vessels). Website in Swedish https://www.havochvatten.se/hav/uppdrag--kontakt/vart-uppdrag/regeringsuppdrag/regeringsuppdrag/uppdrag-att-ta-fram-underlag-om-utslapp-av-tvattvatten-fran-skrubbrar-pa-fartyg-2020.html (05/02/2020)

Heywood, J.B.; Kasseris, E. (2019): Environmental Impact Evaluation of Marine Exhaust Gas Cleaning Systems (Scrubbers) – A Critical Literature Review. Submitted to MEPC 74 as document MEPC 74/INF.10

HS Flensburg (2020): Einzigartiger Versuchsstand: „Shipping“ wird noch umweltfreundlicher. https://hs-flensburg.de/hochschule/aktuelles/2020/6/16/einzigartiger-versuchsstand-shipping-wird-noch-umweltfreundlicher

Hufnagl, M.; Liebezeit, G.; Behrends, B. (2005): Effects of Sea Water Scrubbing – Final Report. BP Marine

IHS Marime (2020): https://maritime.ihs.com

IMO (2017): Global Integrated Shipping Information System (GISIS). https://gisis.imo.org (09/11/2020)

IMO (2020): Sulphur 2020 – cutting sulphur oxide emissions. http://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx (28/04/2020)

IOW (2020): SAARUS: Verbundprojekt: SAARUS - Optimization of scrubber exhaust gas scrubbing technology to reduce environmentally harmful ship emissions. https://www.io-warnemuende.de/project/235/saarus.html (05/05/2020)

Japan (2019): Proposal on the refinement of the title for a new output and the development of the guidelines for evaluation and harmonization of developing local rules on discharge of liquid effluents from EGCS into sensitive waters. Submitted to PPR 7 as document PPR 7/12/3

Kasseris, E.; Wang, D.; Zhang, Y.; Adams, E.; Heywood, J.B. (2020): Environmental Impact Assessment of EGCS effluent discharges. Submitted to MEPC 75 as document MEPC 75/INF.13

Kathmann, W.; Buchinger, S.; Reifferscheid, G. (2019): Adverse Biological Effects of Scrubber Wash Water from Seagoing Vessels – A Comparative Toxicity Assessment. *Manuscript submitted for publication*

Kjølholt, J.; Aakre, S.; Jürgensen, C.; Lauridsen, J. (2012): Assessment of possible impacts of scrubber water discharges on the marine environment – Public Test Report. COWI. Danish Environmental Protection Agency. Environmental Project No. 1431. Copenhagen

Koski, M.; Stedmon, C.; Trapp, S. (2017): Ecological effects of scrubber water discharge on coastal plankton: Potential synergistic effects of contaminants reduce survival and feeding of the copepod Acartia tonsa. Mar Environ Res. 129: 374-385

Kukkonen, J.; Jalkanen, J.-P.; Maragkidou, A.; Riikonen, K. (2019): Evaluation, control and Mitigation of the EnviRonmental impacts of shippinG Emissions – EMERGE [PowerPoint slides]. Finnish Meteorological Institute

Lahtinen, J.M. (2016): Closed-loop Exhaust Gas Scrubber Onboard a Merchant Ship – Technical, Economical, Environmental and Operational Viewpoints. Doctoral dissertation. Acta Wasaensia 342, University of Vaasa

Lange, B.; Markus, T.; Helfst, L.P. (2015): Impacts of Scrubbers on the environmental situation in ports and coastal waters. UBA Texte. Dessau-Roßlau

Linders, J.; Adams, E.; Behrends, B.; Dock, A.; Hanayama, S.; Luit, R.; Rouleu, C.; Tronczynski, J. (2019): Exhaust Gas Cleaning Systems – A roadmap to risk assessment. Report of the GESAMP Task Team on exhaust gas cleaning systems. Submitted to PPR 7 as document PPR 7/INF.23

Lindgren, F.T. (2020). Personal communication (12/02/2020)

Lloyd's Register (2012): Understanding exhaust gas treatment systems – Guidance for shipowners and operators. https://www.rtu.lv/writable/public_files/RTU_understanding_exhaust_gas_treatment_systems.pdf

Magnusson, K.; Thor, P., Granberg, M. (2018): Scrubbers: Closing the loop Activity 3 – Task 2 Risk Assessment of marine exhaust gas scrubber water

Manifold Times (2020): Argus Media: Parliament mulls IMO, maritime CO2, scrubbers. https://www.manifoldtimes.com/news/argus-media-parliament-mulls-imo-maritime-co2-scrubbers/

Marandino, C. (2020). Personal communication (25/05/2020)

MEPC (2005): Resolution MEPC.130(53) – Guidelines for On-board Exhaust Gas-SOx Cleaning Systems. Adopted on 22 July 2005

MEPC (2008a): Resolution MEPC.170(57) – 2Guidelines for Exhaust Gas Cleaning Systems. Adopted on 4 April 2008

MEPC (2008b): Annex 16 – Response to GESAMP regarding EGCS interim washwater guidelines. MEPC 58/23 Report of the MEPC on its 58th session

MEPC (2008c): Resolution MEPC.176(58) – Revised MARPOL Annex VI. Adopted on 10 October 2008

MEPC (2009): Resolution MEPC.184(59) – 2009 Guidelines for Exhaust Gas Cleaning Systems. Adopted on 17 July 2009

MEPC (2015): Resolution MEPC.259(68) – 2015 Guidelines for Exhaust Gas Cleaning Systems. Adopted on 15 May 2015

MEPC (2017): Methodology for information gathering and conduct of work of the GESAMP-BWWG. BWM.2/Circ.13/Rev.4

MEPC (2019): MEPC 74/18 Report of the MEPC on its 74th session

MLIT (2018): Report by the expert board for the environmental impact assessment of discharge water from Scrubbers (Japan)

MPA (2018): Opening address by Mr. Andrew Tan, Chief Executive, Maritime and Port Authority of Singapore at the Singapore Registry of Ships (SRS) Forum 2018, Parkroyal on Beach Road on 30 November 2018.

https://www.mpa.gov.sg/web/portal/home/media-centre/news-releases/speeches/detail/d3ee505d-670a-4c38-a5c0-a0526bea1f1d (30/04/2020)

Niemi, S.; Mäkelä, K.; Hänninen, S.; Haahti, H.; Kankaanpää, H.; Mäkelä, K (2006): Environmental effects of caustic soda and sea water scrubbers. VTT Technical Research Centre of Finland. Report No. VTT-R-08868-06. Submitted to MEPC 56 as document MEPC 56/INF.5

North (2020): No Scrubs: More Ports Declare Ban on EGCS Discharges – Update. https://www.nepia.com/industry-news/no-scrubs-more-ports-declare-ban-on-egcs-discharges-update/ (30/04/2020)

Norway and Finland (2006): Washwater discharge criteria for EGCS-SOx units. Submitted to MEPC 55 as document MEPC 55/4/7

Petrini, C. (2020). Personal communication (31/01/2020)

Proelß, A., Schatz, V.J. (2019): Rechtliche Vorgaben zum Umgang mit Schiffsabwasser. UBA Texte, Dessau-Roßlau (in German)

Riviera and EGCSA (2020): Scrubbers: service experience, sulphur spreads, safety and science. Webinar in Maritime Air Pollution organized by Riviera and EGCSA on 29/05/2020. https://www.rivieramm.com/webinar-library/air-pollution/scrubbers-service-experience-sulphur-spreads-safety-and-science

SAACKE GmbH (2020): Scrubbers optimised for fine dust separation - the next level of exhaust gas cleaning. https://www2.saacke.com/uk/news-references/news/scrubbers-optimised-for-fine-dust-separation-the-next-level-of-exhaust-gas-cleaning/ (05/05/2020)

Schmolke, S.; Ewert, K.; Kaste, M.; Schöngaßner, T.; Kirchgeorg, T.; Marin-Enriquez, O. (2020): Environmental Protection in Maritime Traffic – Scrubber Wash Water Survey. UBA Texte. Dessau-Roßlau.

Ship&Bunker (2020): World Bunker Prices. https://shipandbunker.com/prices (15/05/2020)

Stips, A.; Bolding, K.; Macias, D.; Bruggeman, J.; Coughlan, C. (2016): Scoping report on the potential impact of on-board desulphurisation on water quality in SOX Emission Control Areas. European Union. Report EUR 27886 EN

Teuchies, J.; Cox, T.J.S.; Van Itterbeeck, K.; Meysman, F.J.R.; Blust, R. (2020): The impact of scrubber discharge on the water quality in estuaries and ports. Environmental Sciences Europe 32(1): 103

TriOS Mess- und Datentechnik (n.d.): enviroFlu – Operating Instructions. D01-032en201904 Manual enviroFlu

Turner, D.R.; Hassellöv, I.-M., Ytreberg, E.; Rutgersson A. (2017): Shipping and the environment – Smokestack emissions, scrubbers and unregulated oceanic consequences. Elem Sci Anth, 5: 45. https://doi.org/10.1525/elementa.167

UNCTAD (2020): Merchant fleet by flag of registration and by type of ship, annual. http://stats.unctad.org/fleet (08/05/2020)

United Kingdom (2006): Washwater Criteria Guidelines for Exhaust Gas Cleaning Systems-SOx (EGCS-SOx) Units. Submitted to MEPC 55 as document MEPC 55/4/5

United States (2007): Annex to the report of the correspondence group – washwater discharge criteria. Submitted to MEPC 56 as document MEPC 56/4/1

US EPA (2011): Exhaust Gas Scrubber Washwater Effluent. EPA-800-R-11-006

US EPA (2002): EPA Air Pollution Control Cost Manual (Sixth Edition). EPA/452/B-02-001

Ushakov, S.; Stenersen, D.; Einang, P.M.; Ask, T.Ø. (2019): Meeting future emission regulation at sea by combining low-pressure EGR and seawater scrubbing. J Mar Sci Technol. https://doi.org/10.1007/s00773-019-00655-y

Ülpre, H.; Eames, I. (2014): Environmental policy constraints for acidic exhaust gas scrubber discharges from ships. Mar Pollut Bull. 88: 292-301

Vallhagen, C. (2020). Personal communication (13/02/2020)

Wärtisilä (2010): Exhaust gas scrubber installed onboard MT "SUULA". Public test report. Wärtsilä Finland Ecotech Scrubber Project Team

Winnes, H.; Fridell, E.; Moldanova, J.; Peterson, K.; Salberg, H. (2018): Scrubbers: Closing the loop Activity 3 – Task 1 Air emission measurements

Woodfall, P. (2020): Scrubbers: service experience, sulphur spreads, safety and science. Webinar in Maritime Air Pollution organized by Riviera and EGCSA on 29/05/2020

Ytreberg, E.; Hassellöv, I.-M.; Nylund, A.T.; Hedblom, M.; Al-Handal, A.Y.; Wulff, A. (2019): Effects of scrubber washwater discharge on microplankton in the Baltic Sea. Mar Pollut Bull. 145: 316-324

A Appendix

A.1 Market analysis of EGCS

Table A-1: Notifications in GISIS about ships EGCS-fitted

Flag State	Notifications [i.]		Total fleet [ii.]		Portion of fleet EGCS-fitted
	Amount	%	Amount	%	
Antigua and Barbuda	7	0.3%	780	0.8%	0.9%
Bahamas	76	2.7%	1 401	1.5%	5.4%
Belgium	4	0.1%	201	0.2%	2.0%
Bermuda (UK)	23	0.8%	148	0.2%	15.5%
Canada	9	0.3%	669	0.7%	1.3%
Cayman Islands (UK)	18	0.6%	170	0.2%	10.6%
Cyprus	62	2.2%	1 039	1.1%	6.0%
Denmark	87	3.1%	566	0.6%	15.4%
Finland	27	1.0%	269	0.3%	10.0%
France	12	0.4%	94	0.1%	12.8%
Germany	17	0.6%	609	0.6%	2.8%
Gibraltar (UK)	1	0.0%	232	0.2%	0.4%
Greece	102	3.7%	1 308	1.4%	7.8%
Hong Kong (China)	192	6.9%	2 701	2.8%	7.1%
India	5	0.2%	1 731	1.8%	0.3%
Isle of Man (UK)	36	1.3%	392	0.4%	9.2%
Italy	34	1.2%	1 353	1.4%	2.5%
Japan	49	1.8%	5 017	5.2%	1.0%
Liberia	402	14.4%	3 496	3.6%	11.5%
Lithuania	5	0.2%	58	0.1%	8.6%
Malaysia	3	0.1%	1 748	1.8%	0.2%
Malta	195	7.0%	2 172	2.3%	9.0%
Marshall Islands	580	20.8%	3 537	3.7%	16.4%
Netherlands	55	2.0%	1 217	1.3%	4.5%
Norway	41	1.5%	611	0.6%	6.7%
Panama	405	14.5%	7 860	8.2%	5.2%
Portugal	60	2.2%	624	0.6%	9.6%

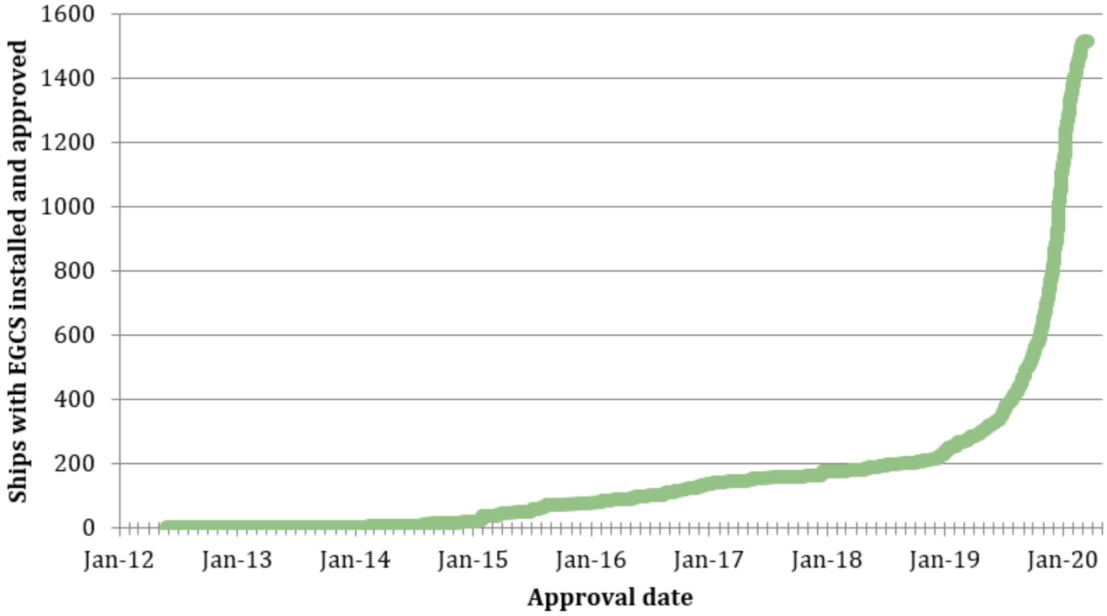
Flag State	Notifications [i.]		Total fleet [ii.]		Portion of fleet EGCS-fitted
	Amount	%	Amount	%	
Republic of Korea	20	0.7%	1 880	2.0%	1.1%
Saudi Arabia	2	0.1%	374	0.4%	0.5%
Singapore	206	7.4%	3 433	3.6%	6.0%
Sweden	4	0.1%	360	0.4%	1.1%
Turkey	17	0.6%	1 234	1.3%	1.4%
United Kingdom	26	0.9%	1 031	1.1%	2.5%
United States	6	0.2%	3 671	3.8%	0.2%
Total amount	**2 788**	**100%**	**51 986**	**54.0%**	**2.9%**

Source: Raw information obtained from GISIS (IMO, 2017) as of 9 November 2020: 2,788 ships (notifications).

i. Every notification represents a ship EGCS-fitted already approved.

ii. UNCTAD (2020) reports 96,295 propelled seagoing merchant vessels of 100 GT and above in 2019.

Figure A-1: Notifications about ships EGCS-fitted by approval date



Source: Raw information obtained from GISIS (IMO, 2017) as of 3 March 2020: 1,513 ships. The detailed information of notifications made in the period 3 March – 9 November 2020 (1,275 notifications) has not been processed.

Table A-2: EGCS manufacturers and amount of ships equipped

Company	Amount of ships	Market fraction
Alfa Laval	234	15,5%
Wärtsilä	194	12,8%
EcoSpray	138	9,1%
Panasia	101	6,7%
FMS Opco Inc. [i.]	79	5,2%

Company	Amount of ships	Market fraction
Yara	78	5,2%
CR Ocean	77	5,1%
Clean Marine [i.]	73	4,8%
AEC Maritime	71	4,7%
ME Production	47	3,1%
ContiOcean	45	3,0%
Pacific Green [ii.]	43	2,8%
Hyundai Power Systems [iii.]	35	2,3%
Langh Tech	32	2,1%
Weihai Puyi	26	1,7%
Valmet	23	1,5%
PureteQ	22	1,5%
Unknown	21	1,4%
Fuji Electric	20	1,3%
ZE Marine	20	1,3%
Kangrim	16	1,1%
SMDERI	16	1,1%
Others	102	6,7%
Total amount	**1,513**	**100%**

Source: Raw information obtained from GISIS (IMO, 2017) as of 3 March 2020: 1,513 ships.

i. The companies FMS Opco Inc. and Clean Marine announced last year the intention to merge under the name Clean Marine (https://cleanmarine.no/clean-marine-and-fmsi-announce-intention-to-merge/).

ii. It includes PowerChina SPEM, having a joint venture with Pacific Green Marine (https://www.egcsa.com/portfolio-item/pacific-green-marine/).

iii. It includes units registered under HHI Power Systems.

A.2 Research studies on EGCS discharge water, its chemical composition and ecotoxicological effects

Table A-3: Research works related to EGCS discharge water and covered aspects

Research work	Sampling campaign	Chemical composition	Ecotox assays	Dispersion modelling	Risk assessment (PEC/PNEC)	Literature review	Acidification	Legal aspects	Discharge criteria evaluation	Other aspects (additional information)
Behrends and Liebezeit (2003)										Theoretical approach
Hufnagl et al. (2005)	X	X	X							Harbour samples
Buhaug et al. (2006)	X	X							X	
Niemi et al. (2006)									X	
United Kingdom (2006)									X	
Hassellöv and Turner (2007)										Required dilution
Wärtisilä (2010)	X	X						X		Sludge analysis
US EPA (2011)	X	X				X			X	
Hansen (2012)	X	X								
Kjølholt et al. (2012)	X	X		X						ERA and sludge analysis
Ülpre and Eames (2014)				X			X			

Research work	Sampling campaign	Chemical composition	Ecotox assays	Dispersion modelling	Risk assessment (PEC/PNEC)	Literature review	Acidification	Legal aspects	Discharge criteria evaluation	Other aspects (additional information)
Den Boer and Hoen (2015)						X				
Lange et al. (2015)						X		X		ERA
Lahtinen (2016)	X	X								ERA
Stips et al. (2016)				X		X	X			
Koski et al. (2017)		X	X							
Turner et al. (2017)	X	X				X				
EGCSA and Euroshore (2018)	X	X								
Endres et al. (2018)						X		X		
Magnusson et al. (2018)	X	X	X		X					
MLIT (2018)		X	X		X					
Carnival and DNV GL (2019)	X	X								
Faber et al. (2019)				X	X					
Georgeff et al. (2019)										Theoretical approach
Heywood and Kasseris (2019)						X				
Linders et al. (2019)						X				

Research work	Sampling campaign	Chemical composition	Ecotox assays	Dispersion modelling	Risk assessment (PEC/PNEC)	Literature review	Acidification	Legal aspects	Discharge criteria evaluation	Other aspects (additional information)
Ushakov et al. (2019)	X	X			X					
Ytreberg et al. (2019)			X							
Dulière et al. (2020)				X			X			
Kasseris et al. (2020)				X	X	X				
Teuchies et al. (2020)	X	X		X	X		X			
Schmolke et al. (2020)	X	X		X						
Kathmann et al. (not published)			X							

X indicates that the research work covers that aspect by conducting practical studies; ERA means Environmental Risk Assessment; PEC/PNEC refers to the ratio of Predicted Environmental Concentration over Predicted No-Effect Concentration.

Table A-4: Results of research studies on chemical composition of EGCS discharge water

Parameter	Open loop							Closed loop			
	BSH [5]	IVL [1]	CCL [53]i)	CESA [20]ix)	NORW [1]xi)	DTU [1]	COWI [1]	BSH [3]	IVL [2]	CESA [4]	COWI [1]
General parameters											
Turbidity (NTU)	4.5 – 17.2	2.5	NA	NA	1.7	NA	NA	4.6 – 39.4	9.3 – 12.9	NA	NA
SS (mg/L)	0.8 – 3.2	NA	NA	NA	NA	NA	10 – 15	3.5 – 125	NA	NA	25 – 39
pH	2.8 – 5.5	NA	NA	NA	3.2	~3	3.7 – 5.8	4.9 – 7.1	6.9 – 7.6	NA	6.5 – 7.0
Alkalinity (mmol/L)	0.0 – 1.4	NA	NA	NA	NA	NA	NA	0.0 – 0.0	6.0	NA	NA
Nitrogen and sulphur											
Nitrate (mg/L)	0.1 – 1.7	0.80iv)	NA	<0.5 – 22.3	<0.033	NA	NAv)	44 – 290	<4.4 – 80iv)	90.4 – 194	NAv)
Nitrite (mg/L)	<0.2 – 1.3	<LODiv)	NA	<0.02 – 0.1	<10	NA	NA	6.3 – 351	161iv)	<0.02	NA
Sulphur (g/L)	0.16 – 0.8iii)	1.2	NA	NA	NA	NA	0.87 – 0.90	8.2 – 21.7iii)	19.0 – 22.0	NA	4.8 – 9.0
Organic pollutants											
Oil content (mg/L)	0.1 – 0.3vi)	0.39vii)	NA	NA	0.30x)	NA	0.11 – 0.33viii)	5.3 – 11.4vi)	2.0 – 7.1vii)	NA	11 – 21
$\text{PAH}_{\text{EPA16}}$ (µg/L)	1.6 – 14	13.5	6.7ii)	0.5 – 24	3.4	NA	0.96 – 1.8	11.8 – 54.4	16 – 21.9	0.8 – 12.6	3.8 – 24
NAP (µg/L)	0.6 – 9.5	7.5	2.4	0.02 – 14	1.85	NA	0.48 – 0.57	0.1 – 3.9	4.4 – 4.8	0.06 – 5.7	0.32 – 0.49
PHE (µg/L)	0.7 – 2.9	NA	1.9	0.08 – 6.1	1.00	NA	NA	2.4 – 20.1	10.0	0.5 – 4.5	NA
B[a]P (µg/L)	<0.012 – 0.1	0.017	0.066	<0.01 – 0.55	<0.01	NA	<0.01	0.06 – 0.4	0.014 – <0.1	<0.01	<0.01
Heavy metals											

Parameter	**Open loop**							**Closed loop**			
	BSH [5]	**IVL [1]**	**CCL [53]i)**	**CESA [20]ix)**	**NORW [1]xi)**	**DTU [1]**	**COWI [1]**	**BSH [3]**	**IVL [2]**	**CESA [4]**	**COWI [1]**
Aluminium (µg/L)	NA	180	NA	NA	NA	NA	NA	NA	8,300	NA	NA
Arsenic (µg/L)	1 – 7	2.4	19.6 *18.7 (df)*	<5 – <10	1.6	1.4	<1 – 1.8	9 – 25	10 – 20	<10 – 30	8.8 – 9.8
Cadmium (µg/L)	0.01 – 0.07	<0.5	5.1 *5.6 (df)*	<0.2 – <2.0	<0.05	<0.3	<0.2	0.05 – 0.4	<0.2 – <0.5	0.96 – <20	<0.05 – 0.094
Chromium (µg/L)	NA	31	16 *16 (df)*	<1.5 – 60	<0.9	1.9	NA	NA	9 – 22	<10 – 14,000	NA
Copper (µg/L)	2 – 16 *2 – 16 (df)*	14	49 *84 (df)*	6 – 140	1	21	110 – 260	10 – 58 *8 – 57 (df)*	32 – 150	<10 – 200	390 – 860
Iron (µg/L)	24 – 221	NA	NA	NA	NA	NA	NA	314 – 709	NA	NA	NA
Lead (µg/L)	0.09 – 2.2	0.63	12.0 *12.3 (df)*	<1 – 120	<0.5	0.61	3.6 – 21	1 – 3	0.16 – <6	<5 – <10	1.6 – 3.8
Manganese (µg/L)	2 – 6	NA	NA	NA	NA	NA	NA	23 – 51	NA	NA	NA
Mercury (ng/L)	NA	6.5	140 *140 (df)*	<200	NA	NA	64 – 99	NA	1.4 – 5.2	<200	<50
Nickel (µg/L)	6 – 73 *4 – 67 (df)*	32	70 *61 (df)*	<10 – 440	42	41	9.1 – 43	478 – 6,289 *295 – 5,646 (df)*	830 – 4,400	220 – 6,600	1,300 – 3,100
Vanadium (µg/L)	12 – 313 *11 – 290 (df)*	84	126 *106 (df)*	20 – 860	164	162	25 – 180	3,542 – 10,637 *3,222 – 9,014 (df)*	9,800 – 13,000	2,800 – 25,000	6,100 – 14,000

Parameter	**Open loop**							**Closed loop**			
	BSH [5]	**IVL [1]**	**CCL [53]i)**	**CESA [20]ix)**	**NORW [1]xi)**	**DTU [1]**	**COWI [1]**	**BSH [3]**	**IVL [2]**	**CESA [4]**	**COWI [1]**
Zinc (µg/L)	2 –133 *2 – 133 (df)*	82	55 *51 (df)*	<10 – 2,000	11	6.7	98 – 450	76 – 240 *23 – 208 (df)*	<70	40 – 2,400	160 – 420

Sources: BSH, Schmolke et al. (2020); IVL, Magnusson et al. (2018); CCL, Carnival Copr. & plc and DNV GL (2019); CESA, EGCSA and Euroshore (2018); NORW, Ushakov et al. (2019); DTU, Koski et al. (2017); COWI, Kjølholt et al. (2012).

Legends: [n], number of sampled ships; *df*, dissolved fraction; SS, suspended solids; <LOD, below limit of detection; NA, not analysed/reported; NAP, naphthalene; PHE, Phenanthrene; B[a]P, benzo[a]pyrene .

i) Average-3σ values Post-DeSOx. Samples taken before any dilution for pH adjustment.
ii) Sum of average-3σ values of single PAHs.
iii) Values shown in this table were calculated, for better comparability, from the originally sulphate measurements (SO_4^{2-} mg/L) reported in Table A-4 of that study.
iv) Values shown in this table were calculated, for better comparability, from the originally reported values in NO_3-N and NO_2-N, respectively, from that study.
v) Instead, total nitrogen was measured. Results range between 0.22 – 0.56 mg N/L in OL and 86 – 120 mg N/L in CL.
vi) Measured parameter was Hydrocarbon Oil Index (HOI) according to standard ISO 9377-2.
vii) Reported value corresponds to the sum of all aliphatic (C_5-C_{40}) and aromatic (C_{10}-C_{36}) fractions measured, in the report called Total Hydrocarbons.
viii) Reported value corresponds to the sum of benzene – C_{35}, in the report called Total Hydrocarbons.
ix) Samples taken before any dilution for pH adjustment.
x) Reported value corresponds to the sum of hydrocarbon fractions (C_{10}-C_{40}).
xi) Values taken from the Table 6 column “Washwater before discharge” – “IMO (no dilution)” of the referenced article. Samples were taken after water treatment (particle removal) and prior any dilution.

Table A-5: Results of research studies on ecotoxicological effects of EGCS discharge water

Research study	Tested water	Analysis and results
Koski et al. (2017)	Samples taken on board from an OL system and HFO with 2.5% sulphur content.	▪ Algal growth inhibition (*Rhodomons* sp., no standard reported) ○ At 100% exposure – 100% inhibition ○ At 10% exposure – increase growth compared to control ▪ Zooplanktonic copepod (*Acartia tonsa*, no standard reported) ○ Lethal effects analysed – adult (LC_{50} between 20-30%) and egg mortality (LC_{50} >50%) as a function of EGCS discharge water exposure ○ Sublethal effects analysed – feeding and reproduction as a function of EGCS discharge water and dietary exposure
MLIT (2018)	Produced in laboratory from exhaust from a four-cylinder 257 kW engine, HFO with 2.2% sulphur content and hybrid system operated in OL mode (~47 m^3/MWh). Dissolved oxygen and pH were not adjusted during sample preparation	▪ Algal growth inhibition – acute toxicity (*Skeletonema costatum*, ISO 10253) using growth rate after 72 hours as the endpoint ○ LC_{50} of 49% (48~50%) ○ NOEC of 32% and LOEC of 100% ▪ Crustacean – acute toxicity (*Hyale barbicornis*, US EPA OPPTS 850.1020) using mortality rate after 96 hours as the endpoint ○ LC_{50} of 20% (12.5~25%), the acute effects were expressed immediately ○ NOEC of 12.5% and LOEC of 25% ▪ Fish – acute toxicity (*Oryzias javanicus*, OCDE TG203) using mortality rate after 96 hours as the endpoint ○ LC_{50} of 35% (25~50%), the acute effects were expressed immediately ○ NOEC of 25% and LOEC of 50%
Magnusson et al. (2018)	Samples taken on board from OL and CL systems	▪ Luminescent bacteria – acute toxicity (*Vibrio fischeri*, ISO 11348-3) ○ IC_{50} of 15.5% with CL discharge water ▪ Zooplanktonic copepod medium term – chronic toxicity (*Calanus helgolandicus*, non-standard species), 7-14 days exposure time ○ Toxic effects (mortality) at 0.04-0.1% with CL discharge water ○ Toxic effects (mortality) at 1.0% with OL discharge water ▪ Blue mussel – chronic toxicity (*Mytilus edulis,* non-standard species), 15-35 days exposure time ○ Toxic effects (byssus strength) at 1.25% with CL discharge water ○ No observed effects with OL discharge water
Ytreberg et al. (2019)	Produced in laboratory from exhaust from a four-cylinder 100 kW engine,	▪ Mesocosm experiment (microplankton community, non-standard species)

	MGO with 1% sulphur content and OL system	○ Biological parameters (photosynthetic activity, phytoplankton biovolume, chlorophyll a, bacterial abundance and productivity, POC, POP and PON) ○ Stimulating effects were reported for algae and bacteria ▪ Cyanobacteria – Laboratory experiment (*Nodularia spumigena*, non-standard species) ○ Biological parameters (photosynthetic activity, phytoplankton biovolume, primary productivity) ○ EC_{10} of 8.6% (decreased on photosynthetic activity) ▪ Diatom algae – Laboratory experiment (*Melosira* cf. *arctica*, non-standard species) ○ Biological parameters (photosynthetic activity, phytoplankton biovolume, primary productivity) ○ EC_{10} of 5.5% (increased on primary productivity)
Kathmann et al. (2019)	Samples taken on board from OL and CL systems (Schmolke et al., 2020). Prior to testing, all water samples were filtered (0.4 µm) and pH was adjusted to 7 for samples with a pH lower than 6	▪ Luminescent bacteria – acute toxicity (*Vibrio fischeri*, ISO 11348-2) ○ IC_{50} of 31-57% with CL discharge water ○ No observed effects with OL discharge water ▪ Algal growth inhibition – acute toxicity (*Phaeodactylum tricornutum*, ISO 10253) ○ IC_{50} of 2-9% with CL discharge water ○ No observed effects with OL discharge water ▪ Dioxin-like activity – Yeast dioxin screen (ISO 19040-1) ○ OL discharge water and CL discharge water tested positive ▪ Mutagenic activity - Ames Assay ○ OL discharge water and CL discharge water tested positive

Legends: OL, open loop EGCS; CL, closed loop EGCS; SPE, solid-phase extraction; HFO, heavy fuel oil; MGO, marine gas oil.