Høgskulen på Vestlandet

Master thesis

MMO5017

Predefinert informasjon

Startdato:	30-04-2020 14:39	**Termin:**	2020 VÅR
Sluttdato:	03-06-2020 14:00	**Vurderingsform:**	Norsk 6-trinns skala (A-F)
Eksamensform:	Master thesis		
SIS-kode:	203 MMO5017 1 MOPPG-1 2020 VÅR HAUGESUND		
Intern sensor:	(Anonymisert)		

Deltaker

Kandidatnr.:	301

Informasjon fra deltaker

Engelsk tittel *:	Impact on the Maritime Industry from an Introduction of a Hybrid Exhaust Gas Cleaning Technology
Navn på veileder *:	internal supervisor - Ove Tobias Gudmestad; external supervisor - Toms Torims

Sett hake dersom besvarelsen kan brukes som eksempel i undervisning?:	Ja	**Egenerklæring *:**	Ja
Jeg bekrefter at jeg har registrert oppgavetittelen på norsk og engelsk i StudentWeb og vet at denne vil stå på vitnemålet mitt *:	Ja	**Inneholder besvarelsen konfidensielt materiale?:**	Nei

Jeg godkjenner avtalen om publisering av masteroppgaven min *

Ja

Er masteroppgaven skrevet som del av et større forskningsprosjekt ved HVL? *

Nei

Er masteroppgaven skrevet ved bedrift/virksomhet i næringsliv eller offentlig sektor? *

Ja, Riga Technical University

Western Norway
University of
Applied Sciences

MASTER'S THESIS

Impact on the Maritime Industry from an Introduction of a Hybrid Exhaust Gas Cleaning Technology

Aivis Abele

Master of Maritime Operations
Faculty of Business Administration and Social Sciences
Western Norway University of Applied Sciences (HVL)

Supervisors: Ove Tobias Gudmestad, HVL
Toms Torims, Riga Technical University

Submission Date: 3 June 2020

I confirm that the work is self-prepared and that references/source references to all sources used in the work are provided, cf. Regulation relating to academic studies and examinations at the Western Norway University of Applied Sciences (HVL), § 12-1.

Acknowledgement

The Master's thesis "Impact on the Maritime Industry from an Introduction of a Hybrid Exhaust Gas Cleaning Technology" has been written in accordance to the requirements for the course MMO5017 and is the final assignment of the study programme "Master of Maritime Operations" at Western Norway University of Applied Sciences.

The Author’s contribution, by writing this thesis, is overall evaluation of the novel hybrid exhaust gas cleaning technology including safety aspects, explanation of barriers for implementation of the novel technology on board a vessel and, in the end, determination of possible impacts on the maritime industry from introducing the hybrid technology to the market.

The information used in this work refers to the latest publications from relevant fields and the most recently adopted and enforced applicable rules and regulations by respective legal authorities. The references mostly contain sources available on the internet, since libraries were closed during the time period when the author was writing the thesis, which limited the access to hard copy materials.

This thesis is written within the framework of a general agreement for academic cooperation between Western Norway university of Applied Sciences and Riga Technical University. The work has been supervised by professor Ove Tobias Gudmestad at Western Norway University of Applied Sciences (Haugesund, Norway), advising on the whole process from the very beginning, and professor Toms Torims at Riga Technical University (Riga, Latvia), providing information about topic-specific matters and introducing the author to the group of researchers studying and developing the subject of the thesis.

The progress of writing the thesis has been presented not only to the direct supervisors but also to the stakeholders who are involved in the projects doing research of the discussed technology. Those projects being "Accelerator Research and Innovation for European Science and Society" (ARIES) (Vretenar, 2019), hosted by the European Organization for Nuclear Research (CERN), and "Hybrid Exhaust-gas-cleaning Retrofit Technology for International Shipping" (HERTIS, 2019), organized by Riga Technical University.

The author would like to thank the acknowledged people and organizations who have been assisting in writing this material.

Abstract (ENG)

The Master's thesis "Impact on the Maritime Industry from an Introduction of a Hybrid Exhaust Gas Cleaning Technology" has been written because of the recent changes in the international regulations for air pollution prevention from ship engine exhaust gasses, limiting the maximum allowable sulphur content in fuels. The work is devoted to a novel exhaust gas cleaning technology which plans to integrate a particle accelerator into existing exhaust gas cleaning devices to form a hybrid system, which would be able to deal with SO_X, PM and NO_X emissions according to the international regulations.

This thesis contributes with overall evaluation of the novel hybrid system to be installed on board a vessel including safety aspects, an analysis of the technology development risks and determination of impacts on the maritime industry from its introduction to the market.

This work consists of 6 chapters, beginning with an introduction, which gives an overview of the latest international regulations, proposes a compliant solution, which is the research subject, and defines the tasks and scope of this work.

The second chapter gathers the most relevant international-scale regulations for exhaust gasses in the marine transport, as well as regional and national level restrictions. In the meantime, the chapter also includes respective compliance methods, mostly focussing on certification and exploitation of exhaust gas cleaning systems.

In the third chapter, evaluation of the most common exhaust gas cleaning technologies is carried out.

The fourth chapter describes the proposed hybrid technology. Here, results from laboratory tests are presented, as well as the outcome from the experiment at Riga Shipyard, cleaning exhaust gasses from a tugboat.

In the fifth chapter, a risk assessment with respective preventive and corrective actions is carried out for further technology development using PESTLE analytical template. The strengths and the weaknesses of the hybrid system are gathered and discussed in the SWOT matrix, closing with the impact on the maritime industry.

The thesis is concluded by summarizing the most important obstacles in development of the hybrid technology, as well as its expected impact on the maritime industry.

The thesis comprises 80 pages, counting in the introductory part, list of bibliography with 78 references and 4 appendices. The work also includes 30 figures and 6 tables.

Sammendrag (NOR)

Masteroppgaven "Effekter på den maritime næringen av en introduksjon av hybrid renseteknologi for avgasser" er skrevet på grunn av de nylige endringene i det internasjonale regelverket om forebygging av luftforurensning fra avgasser fra skipsmotorer, som begrenser det maksimalt tillatte svovelinnholdet i brensel. Arbeidet er dedikert til en nyskapende renseteknologi for avgasser som planlegger å integrere en partikkelakselerator i eksisterende renseanlegg til å lage et hybridsystem, som vil kunne rense utslippene av SOX, PM og NOX i henhold til alle internasjonale reguleringer.

Bidraget med denne masteroppgaven er en samlet evalueringen av dette innovative hybridsystemet, inkludert sikkerhetsaspekter, en analyse av risikoer for utvikling av hybridsystemet og en bestemmelse av potensielle effekter på den maritime næringen etter utviklingen.

Dette arbeidet består av 6 kapitler, og begynner med en introduksjon og gir en oversikt over de nyeste internasjonale forskriftene, tilbyr en kompatibel løsning, som er forskningsspørsmålet, og definerer oppgaven og omfanget av dette arbeidet.

Det andre kapittelet oppsummerer de mest relevante internasjonale forskriftene for avgasser i sjøtransporten, samt regionale og nasjonale nivåbegrensninger. Videre inkluderer kapittelet også de respektive metodene som gir aksept, hovedsakelig med fokus på sertifisering og utnyttelse av renseanlegg for avgasser.

I det tredje kapittelet evalueres de vanligste renseteknologiene for avgasser.

Det fjerde kapittelet beskriver den foreslåtte hybridteknologien. Resultatene fra tester av dette systemet i laboratorieforhold og fra forsøket på rensing av avgasser fra en slepebåt ved Riga verft er presentert her.

I det femte kapittelet analyseres potensielle risikoer og deres respektive forebyggende og korrigerende handlinger for videre teknologiutvikling ved bruk av PESTLE analyseskjema. Styrkene og svakhetene ved hybridsystemet er oppsummert og diskutert i en SWOT matrise, og kapitlet avsluttes med effekt på den maritime næringen.

Oppgaven konkluderes med å oppsummere de viktigste hindringene i løpet av utvikling av hybridteknologien, så vel som forventede effekter på den maritime næringen.

Masteroppgaven består av 80 sider, inkludert den innledende delen, bibliografi med 78 referanser og 4 vedlegg. Oppgaven inneholder også 30 bilder og 6 tabeller.

Anotācija (LAT)

Maģistra darba "Ietekme uz jūrniecības nozari, ieviešot izplūdes gāzu hibrīdattīrīšanas tehnoloģiju" aktualitāte ir saistīta ar nesenajām izmaiņām starptautiskajos noteikumos par gaisa piesārņojuma novēršanu no kuģu dzinēju izplūdes gāzēm, kuros samazināts maksimāli pieļaujamais degvielas sēra saturs. Darbs ir veltīts inovatīvai kuģu izplūdes gāzu attīrīšanas sistēmai, kas paredz daļiņu paātrinātāja integrēšanu jau esošās izplūdes gāzu attīrīšanas iekārtās, lai izveidotu hibrīdsistēmu, kas būtu spējīga attīrīt SO_X, *PM* un NO_X emisijas saskaņā ar starptautiskajām prasībām.

Diplomdarba devums ir šīs inovatīvās hibrīdsistēmas izvērtēšana, iekļaujot drošības aspektus, risku analīze tehnoloģijas attīstībai un iespējamās ietekmes noteikšana uz jūrniecības nozari pēc tehnoloģijas izstrādes.

Šis darbs sastāv no 6 nodaļām, sākot ar ievadu, kas sniedz ieskatu jaunākajos starptautiskajos noteikumos, attiecīgi piedāvājot risinājumu šo noteikumu izpildīšanai, kas ir šī raksta pētāmais priekšmets, un definējot darba uzdevumus un tā spektru.

Otrā nodaļa apkopo aktuālākos starptautiska mēroga noteikumus izplūdes gāzēm jūras transportā, kā arī reģionāla un valstiska mēroga ierobežojumus. Paralēli tam nodaļa ietver arī metodes attiecīgo noteikumu izpildīšanai, vairāk koncentrējoties uz izplūdes gāzu attīrīšanas sistēmu sertificēšanas un ekspluatācijas kārtību.

Trešajā nodaļā tiek izvērtētas līdz šim visvairāk pielietotās kuģu izplūdes gāzu attīrīšanas tehnoloģijas.

Ceturtā nodaļa apraksta piedāvāto hibrīdtehnoloģiju. Šeit tiek atspoguļoti rezultāti no šīs sistēmas izmēģinājumiem laboratorijas apstākļos un no eksperimenta, attīrot izplūdes gāzes no velkoņa Rīgas kuģu būvētavā.

Piektajā nodaļā tiek analizēti iespējami riski un to attiecīgas preventīvas un korektīvas darbības šādas hibrīdtehnoloģijas izstrādes procesā, izmantojot *PESTLE* analīzes formu. Tehnoloģijas stiprās un vājās puses ir apkopotas un iztirzātas *SWOT* matricā, noslēdzot nodaļu ar tās izrietošo ietekmi uz jūrniecības nozari.

Noslēgumā ir apkopoti nozīmīgākie šķēršļi hibrīdtehnoloģijas izstrādes procesā, kā arī paredzētā ietekme uz jūrniecības nozari.

Diplomdarba apjoms ir 80 lapas, ieskaitot ievaddaļu, izmantotās literatūras sarakstu ar 78 atsaucēm un 4 pielikumus. Darbs ietver 30 attēlus un 6 tabulas.

Contents

Abbreviations

A - ampere
ARIES - Accelerator Research and Innovation for European Science and Society
CERN - European Organization for Nuclear Research
CO_2 - carbon dioxide
EB - electron beam
ECA - emission control area
EEDI - Energy Efficiency Design Index
EEOI - Energy Efficiency Operational Index
EGC - exhaust gas cleaning
EGR - exhaust gas recirculation
EIAPP - Engine International Air Pollution Prevention
EMSA - European Maritime Safety Agency
EPA - Environmental Protection Agency
ETM - EGC System Technical Manual
EU - European Union
g - gramme
GT - gross tonne
Gy - Gray unit
HERTIS - Hybrid Exhaust-gas-cleaning Retrofit Technology for International Shipping
IAPP - International Air Pollution Prevention
IEEC - International Energy Efficiency Certificate
IMO - International Maritime Organization
k - kilo
l - liter
M - mega
m - milli
MARPOL - the International Convention for the Prevention of Pollution from Ships 73/78
MEPC - Marine Environment Protection Committee
m/m - mass fraction
NO - nitric oxide
NO_X - nitrogen oxides
NO_2 - nitrogen dioxide
PM - particulate matter
ppm - part per million
rpm - revolution per minute
SCR - selective catalytic reduction
SECC - SO_X Emissions Compliance Certificate
SEEMP - Ship Energy Efficiency Management Plan
SOLAS - the International Convention for the Safety of Life at Sea
SO_X - sulphur oxides
SO_2 - sulphur dioxide
t - tonne
USA - United States of America
V - volt
VOC - volatile organic compound
Wh - watt hour
°C - degree Celsius
% - percent

Figures and Tables

1. Introduction

1.1. Background

Shipping is relatively the most efficient way of transporting cargo, but, at the same time, this industry is a major air polluter in the transport industry (Walker, Adebambo, Feijoo, Elhaimer et al., 2019, p. 505). Although environmental protection in general has been actively promoted for around half a century already, the air pollution from ships became an important topic only couple of decades ago. During this short time spread, a noticeable progress from internationally cooperating organizations has taken place to eliminate ships from polluting air, which, consequently, affects the whole ecosystem and all its inhabitants.

The most obvious air polluters in the transport and energy industry are power plants running on heavy, raw fossil fuels containing a considerable amount of chemical elements, which, in the burning process, are thrown in the atmosphere in form of small solid particles or in gaseous form after reacting with other elements. The most concerned ones are heavy metals, sulphur, nitrogen, greenhouse forming gasses, ozone layer depleting substances and volatile organic compounds that disrupt air quality. The maritime industry has adapted by using lighter, more refine fuel oils, alternative fuels and retrofitting engines with exhaust gas cleaning systems, which retrieve and reform the harmful substances. Consequently, the existing technologies encounter challenges to fit under newer and stricter requirements. And even when using distillate fuel oils, there are still substances that have to be reduced.

The thesis is devoted to a novel hybrid exhaust gas cleaning system using electron beam (EB) technology in conjunction with a wet scrubber, that aims to satisfy the recently enforced international rules and rules soon to be in effect for the prevention of air pollution from ships. This assembly deals with the sulphur oxides (SO_X) and particulate matter (PM) content in the exhaust gasses, limited by The International Convention for the Prevention of Pollution from Ships 73/78 (MARPOL) Annex VI Regulation 14 outside the sulphur emission control areas (ECA) from 1 January 2020 (IMO, 2020b). It also aims to comply with the set limits for nitrogen oxides (NO_X), defined in MARPOL Annex VI Regulation 13, which have been in effect in the North American ECA and the United States Caribbean Sea ECA since 1 January 2016 and will come into force in the Baltic Sea ECA and the North Sea ECA as from 1 January 2021 (IMO, 2020a).

The technologies themselves, used in this exhaust gas cleaning system, are not recent discoveries, but they have not been used in such a combination in the marine environment on board a vessel. So, there are challenges from the technical side to incorporate all that in dynamic settings in a limited and specific-layout space. There is also a question about the possible long-term effects on the environment of this cleaning system, since there have not been extensive trials of this system, working with marine diesel engines in different dynamic modes. As for any novel solution, particularly in the maritime industry, safety is one of the matters that has to be discussed, especially because of the cleaning system's connection with critical components of the vessel and its dependency on other power-generating plants. This all encloses in legal issues that have to be addressed in most thorough and reasonable way, while following the guidelines for implementing new technologies in the maritime industry.

1.2. Objectives

Based on the background information, the objective of the thesis is to determine effect on the maritime industry from implementing a hybrid exhaust gas cleaning system on ships. Most focus is set on technical, maritime safety, environmental and financial matters.

This thesis aims to answer the following research questions:

- What is the efficiency of the hybrid technology and what factors may affect it?
- What maritime safety-related issues does this technology involve on board a ship?
- What existing rules do apply and what legal obstacles may impede the implementation process of this technology into the maritime industry?
- What impact would the hybrid technology leave on the maritime industry?

1.3. Methodology and Scope

To answer the research questions different analyzing techniques are used, among them PESTLE analysis and SWOT analysis (PESTLEAnalysis.com, n.d.). In order to conduct the analysis a description and evaluation of the proposed hybrid technology is presented. A review of academic publications in this field and respective rules by legal authorities is carried out. Patents, supporting this technology, and existing proofs of concept are discussed, taking alternative projects into account as well. What limits the scope of this work is the small number of attempts trying to introduce such a technology on ships in the marine environment, although similar approaches have been realized on land-based power plants.

2. Legislation for Air Pollution Prevention

2.1. Global

IMO in conjunction with the Marine Environment Protection Committee (MEPC) have set out international rules for air pollution prevention from ships in Annex VI of the MARPOL convention, that apply to all vessels. Additional certification and periodic surveys, according to Regulation 5 of MARPOL Annex VI, apply to vessels of 400 gross tonnes (GT) and above including all fixed and floating drilling rigs and other offshore platforms. An International Air Pollution Prevention (IAPP) certificate works as a proof that a vessel complies with the applicable regulations and is issued to the vessel after a survey conducted by a recognized organization, usually a classification society, for a period not exceeding five years (IMO, 2017, Annex VI, Reg. 5). Annex VI stipulates the maximum allowable air pollution levels globally and additionally in several concerned regions (ECAs), which are the Baltic Sea area, North Sea area, North American area and United States Caribbean Sea area. As for the air pollution from marine diesel engines, attention is paid to SO_X, PM, NO_X and CO_2 emissions. Table 2.1 lists all the ECAs of MARPOL Annex VI and Figure 2.1 shows them on a map.

Table 2.1 - MARPOL Annex VI Emission Control Areas
(IMO, 2020e)

ECA Region	Controlled Substances	In Effect From
Baltic Sea ECA	SO_X	19-May-2006
	NO_X	01-Jan-2021
North Sea ECA	SO_X	22-Nov-2007
	NO_X	01-Jan-2021
North American ECA	SO_X and PM	01-Aug-2012
	NO_X	01-Jan-2016
United States Caribbean Sea ECA	SO_X and PM	01-Jan-2014
	NO_X	01-Jan-2016

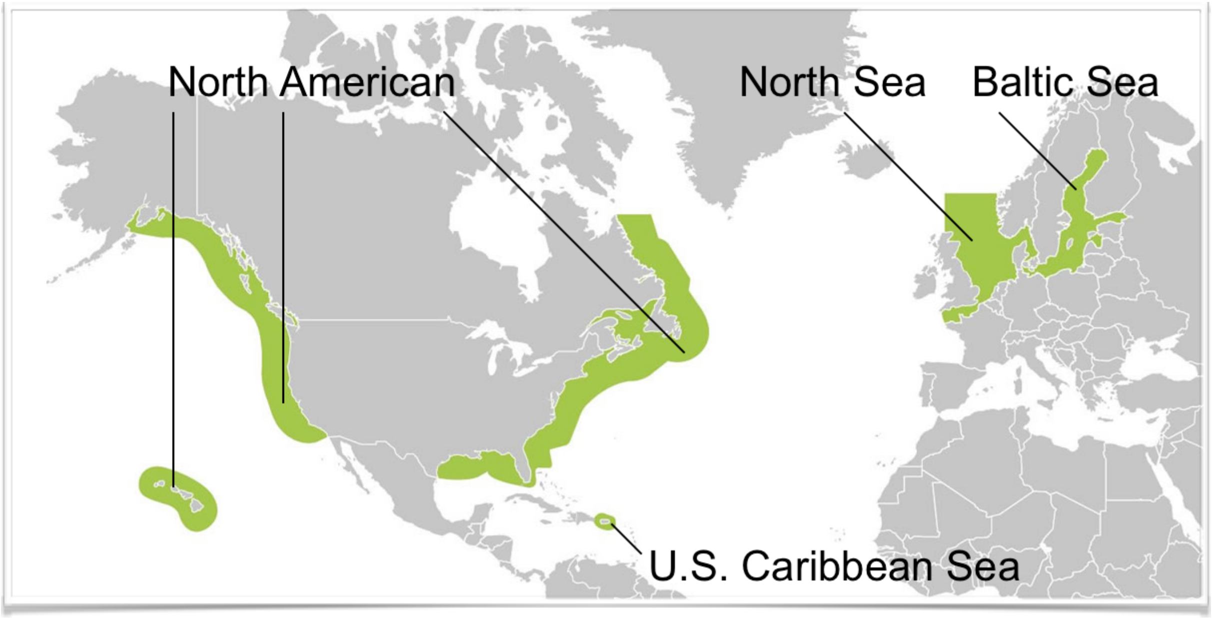

Figure 2.1 - MARPOL Annex VI Emission Control Areas
(Exhaust Gas Cleaning Systems Association, n.d.-b)

SO_X

SO_X, mainly referring to sulphur dioxide (SO_2) because of its relatively high content, is a gaseous compound, where sulphur particles in the fuel have oxidized during the fuel burning process. It causes respiratory health problems, takes part in the formation of acid rain and damages plants (Zis & Psaraftis, 2019, p. 250).

The SO_X emissions from ships are controlled by their content in fuels that are used on board, since sulphur has a relatively low oxidation temperature and, therefore, no engine-running parameters can change the emitted SO_X amount. From the moment MARPOL Annex VI was adopted in 1997, it took eight years for it to come into force in 2005 and another year for the first sulphur ECA in the Baltic Sea, setting maximum SO_X emissions at 1.50% m/m, while the initial global limit was 4.50% m/m (International Transport Forum, 2016, p. 11).

As from 1 January 2015, the SO_X content in the fuel cannot exceed 0.10% m/m while operating in the sulphur ECAs (IMO, 2017, Annex VI, Reg. 14.4). But from 1 January 2020, the sulphur content of any fuel used on board cannot exceed 0.50% m/m (IMO, 2017, Annex VI, Reg. 14.1). Figure 2.2 depicts the progress of SO_X emission limitations inside ECAs and globally on a timeline.

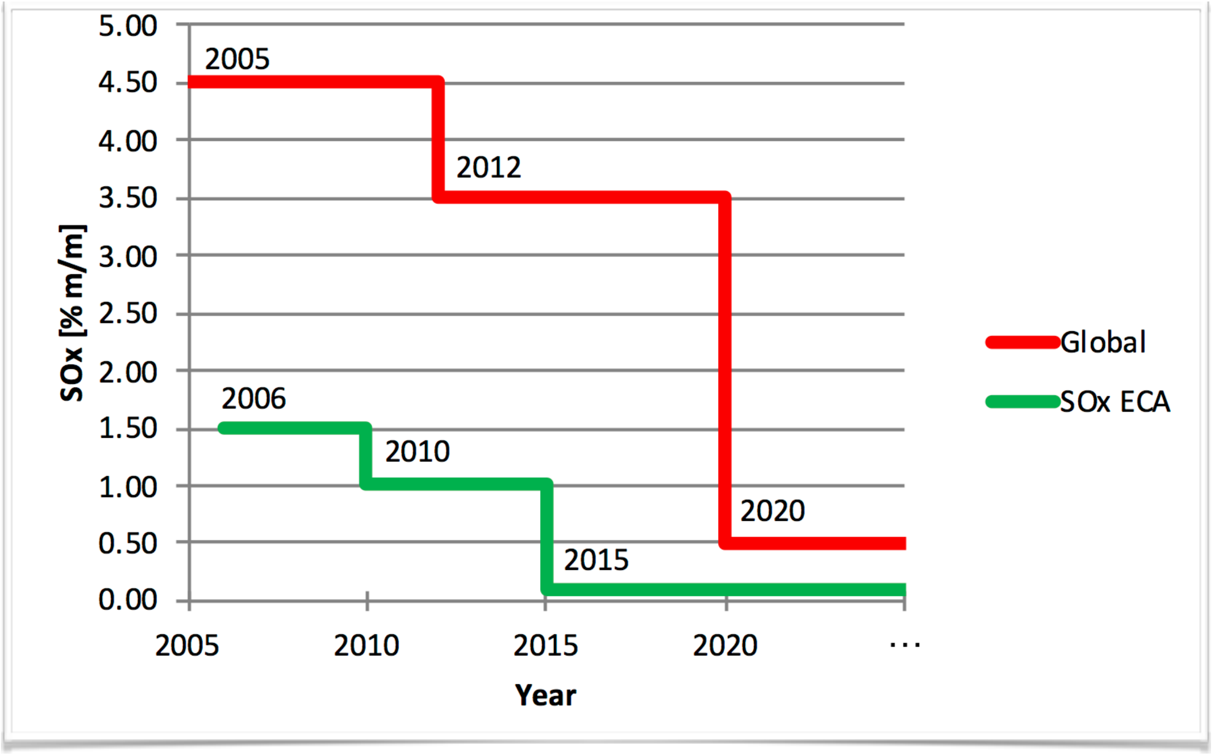

Figure 2.2 - Sulphur Limits Inside and Outside ECAs
(International Transport Forum, 2016, p. 12)

For the primary compliance method, i.e., using low-sulphur fuel oils, MEPC published guidelines in 2019 for consistent implementation of these requirements, addressing some common technical concerns as well as advising on legal matters. Although, similar recommendations were handed out before the SO_X limit changes in ECAs in 2015, which are stringent than the latest global limits. The guidelines also contain a blank of fuel oil non-availability report because of the raised concerns about the possibility that the low-sulphur fuel oils may not be available at all the world ports. This, though, does not work as an exemption or an excuse not to comply with the rules (MEPC, 2019, p. 12). As of 12 April 2020, there have been 256 fuel oil non-availability reports submitted, 75 of which are related to the low-sulphur fuel oils (IMO, 2020d). Similarly, MEPC has issued guidelines for port state control, addressing the inspection methods. Standard control measures that legal authorities may carry out in order to monitor the compliance of the said regulation are inspection of bunker delivery notes and oil record book (part 1), analysis of bunker samples and comparison of fuel change-over procedures with the vessel's navigation logbook (International Transport Forum, 2016, p. 11).

An exception to these rules applies if other equivalent, Administration approved, means are capable to ensure the effectiveness not less than required in the Regulation (IMO, 2017, Annex VI, Reg. 4.1). Mostly these equivalent means refer to exhaust gas cleaning (EGC) systems. For the secondary compliance method, i.e., cleaning exhaust gasses, MEPC issued guidelines in 2015 for EGC systems, which was at the time of a new SO_X limitation in ECAs and follows the structure similar to the NO_X Technical Code 2008. The guidelines work as a base for national maritime administrations to implement them in their local rules, which then may be passed to their recognized classification societies to survey, approve and certify on behalf of the flag state. Just like the majority of on-board machinery, EGC systems are subjects to initial, annual, intermediate and renewal surveys. The effectiveness of EGC systems has to be proven by one of two methods called schemes.

Scheme A requires the manufacturer of the EGC unit to provide the flag state with verifiable performance data of the effectiveness, which issues the unit with a SO_X Emissions Compliance Certificate (SECC) and does not require continuous exhaust gas monitoring as long as it is maintained as per manufacturer's instructions (MEPC, 2015, Reg 4.2.1).

While holding the SECC, the manufacturer also supplies an EGC System Technical Manual - Scheme A (ETM-A), which contains technical details of the unit, like the maximum mass flow rate, differential pressure and temperature range of the exhaust gasses, compatible power units for the EGC system, wash water flow characteristics, as well as maintenance procedures, necessary corrective actions, surveying procedures and any relevant unit-specific requirements and restrictions in terms of its safe operation and compliance with the rules (MEPC, 2015, Reg 4.2.2).

To install an EGC unit onto an engine, the information in ETM-A has to be compatible with an Engine International Air Pollution Prevention (EIAPP) certificate or an Exhaust Gas Declaration provided by the manufacturer, which also works as part of the proof for compliance (MEPC, 2015, Reg 4.4.1).

All periodic checks and repairs as per manufacturer's instructions are recorded in an Administration approved EGC Record Book (MEPC, 2015, Reg 4.4.10). An Administration approved Sulphur Emissions Compliance Plan (SECP) is a document that coordinates the whole compliance process for the EGC system and refers to other relevant documents and their instructions to be followed (MEPC, 2015, Reg 9.1.1).

Scheme B, on the other hand, does not require an initial documented proof of compliance for the EGC unit, which, respectively, is not issued with an SECC, but is so with ETM-B, EGC Record Book and SECP (MEPC, 2015, Reg 5.1; 5.5; 5.6).

A continuous exhaust gas monitoring system is required, which records SO_2/CO_2 emission ratio at least every 4 minutes and 45 seconds to prove its compliance with the rules (MEPC, 2015, Reg 5.4). It is allowed to have an Administration approved Electronic Logging System to substitute a physical EGC Record Book (MEPC, 2015, Reg 7). Also, Scheme B does not oblige to do repairs with the original manufacturer's spare parts as long as the performance of the whole EGC system keeps within the regulated limits.

To summarize, in case of an EGC system is used for compliance, the guidelines specify not the maximum allowable SO_2 content in the exhaust gasses but its ratio against CO_2 emissions, which, in turn, is also a dependent value of the engine performance (MEPC, 2015, p. 2). This means that the EGC unit has to be compatible not only with the fuel to be used but also the engine it is going to be fitted on. Marine engines themselves is a separate subject to MARPOL Annex VI regulations preventing the air pollution by other substances, which is described later in this chapter. Figure 2.3 shows the maximum allowed SO_2/CO_2 ratio values for distillate and residual fuel oils and, logically, MEPC tolerates less emissions from residual fuels compared to distillate fuels.

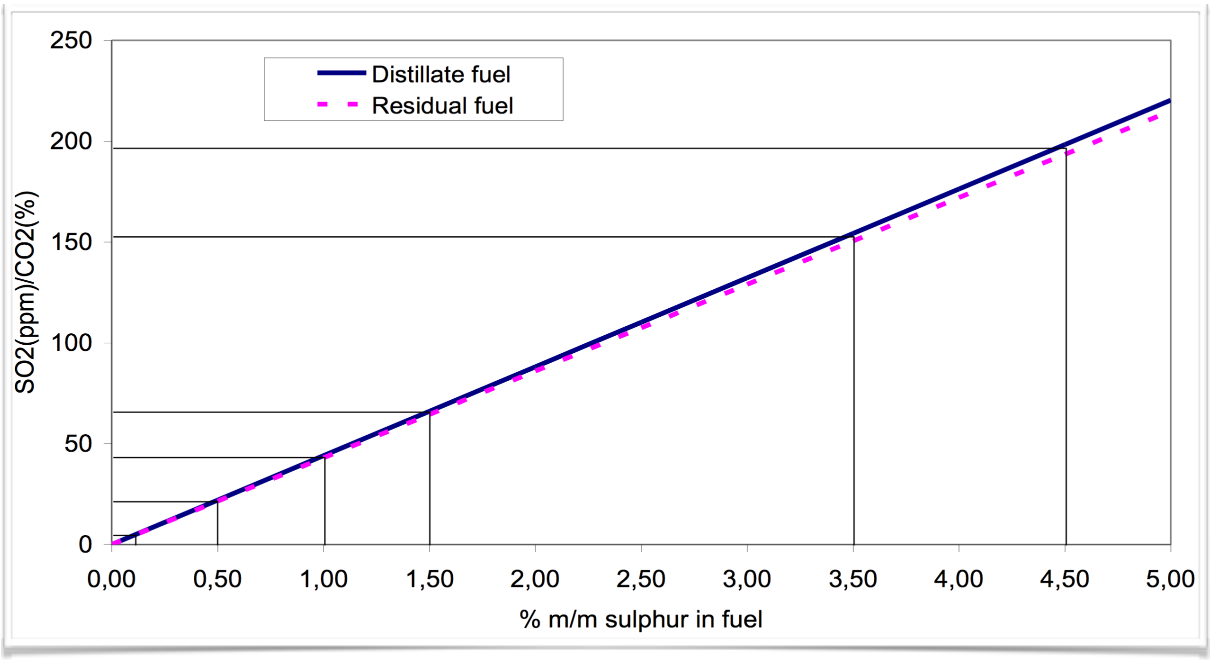

Figure 2.3 - Maximum Permitted SO_2/CO_2 Ratio Against Sulphur Contents in Fuel (MEPC, 2015, p. 20)

PM

Particulate matter is generally solidified carbon particles, in that count black carbon particles, polycyclic aromatic hydrocarbons, sulphates and heavy metals from incomplete combustion of residual fossil fuel oils, that visually look like soot or black smoke (Lloyd's Register, 2015, p. 45). As for the MARPOL Annex VI rules, the SO_X emissions have been accounted for the most of the concerned PM, so, they face the same limitations altogether. Sulphur-generated PM is responsible for many pulmonary diseases because of their tiny size of a few microns, that can be easily inhaled (International Transport Forum, 2016, p. 11).

PM in this context mean any solid particles that are exhausted out in the atmosphere during the combustion process. While IMO does not have a separate regulation targeted to this type of pollution, some national legislative establishments have distinguished it and put restrictions to these emissions locally.

NO_X

NO_X, focusing on nitric oxide (NO) and nitrogen dioxide (NO_2), are yellowish gaseous nitrogen compounds that form during fuel combustion and contribute to the formation of the ground-level ozone layer (smog) and acid rain, which may cause adverse health effects (MEPC, 2010, pp. 6-7). The emitted amount of NO_X depends on the fuel combustion temperature, cylinder compression ratio and inlet feed pressure, where the higher these parameters are, the more NO_X are emitted.

Rules for this type of pollution are written in MARPOL Annex VI Regulation 13. This concern has been addressed to all marine diesel engines of power output more than $130kW$ with an exception for diesel engines used solely for emergency purposes (IMO, 2017, Annex VI, Reg. 13.1). A guide for implementation of this Regulation with all the technical requirements, verification methods and certification procedures is written in MEPC issued document known as the NO_X Technical Code 2008. The latest amendment of this Code has been adopted on 7 July 2017 with an expected entry into force on 1 October 2020. This amendment pays special attention to marine diesel engines fitted with selective catalytic reduction (SCR) systems. All marine diesel engines that fall under these Regulations are subjects to annual, intermediate and renewal surveys by the Administration (MEPC, 2008, Reg. 2.1.1.3).

The NO_X restrictions, calculated as the total weighted emission of NO_2, are expressed as a decreasing function of engine's crankshaft revolutions (rated engine speed), where the higher they are, the less emissions are allowed for that particular engine to produce (IMO, 2017, Annex VI, Reg. 13.3; 13.4; 13.5). The permitted NO_X amount depends on date of the keel laid for a ship or the date of the engine undergoing a substantial conversion that could potentially exceed the respective emission limits (IMO, 2020a). A subsequent tier system has been created to group ships and their engines.

Tier I applies to ships constructed on or after 1 January 2000 but prior to 1 January 2011, regardless of their operating area (IMO, 2017, Annex VI, Reg. 13.3).

Tier II applies to ships constructed on or after 1 January 2011, regardless of their operating area (IMO, 2017, Annex VI, Reg. 13.4).

Tier III applies to ships constructed on or after 1 January 2016 while operating in the North American ECA and the United States Caribbean Sea ECA and to ships constructed on or after 1 January 2021 while operating in the Baltic Sea ECA and the North Sea ECA (IMO, 2017, Annex VI, Reg. 13.5.1.2).

Additionally, ships with large diesel engines (over 5000kW and each cylinder displacement at 90l or above) constructed on or after 1 January 1990 but prior to 1 January 2000 are subjects to the Tier I requirements with individual approval scheme and certification conducted by the flag Administration (IMO, 2017, Annex VI, Reg. 13.7.1). Table 2.2 compiles the above-mentioned Tier requirements and Figure 2.4 shows a visualization of the table.

Table 2.2 - MARPOL NOx Emission Limits
(IMO, 2020a)

Tier	Ship construction date on or after	Total weighted cycle emission limit [*g/kWh*] n = engine's rated speed [rpm]		
		n < 130	130 ≤ n < 1999	n ≥ 2000
I	1 January 2000	17.0	$45 \times n^{(-0.2)}$	9.8
II	1 January 2011	14.4	$44 \times n^{(-0.23)}$	7.7
III	1 January 2016 1 January 2021	3.4	$9 \times n^{(-0.2)}$	2.0

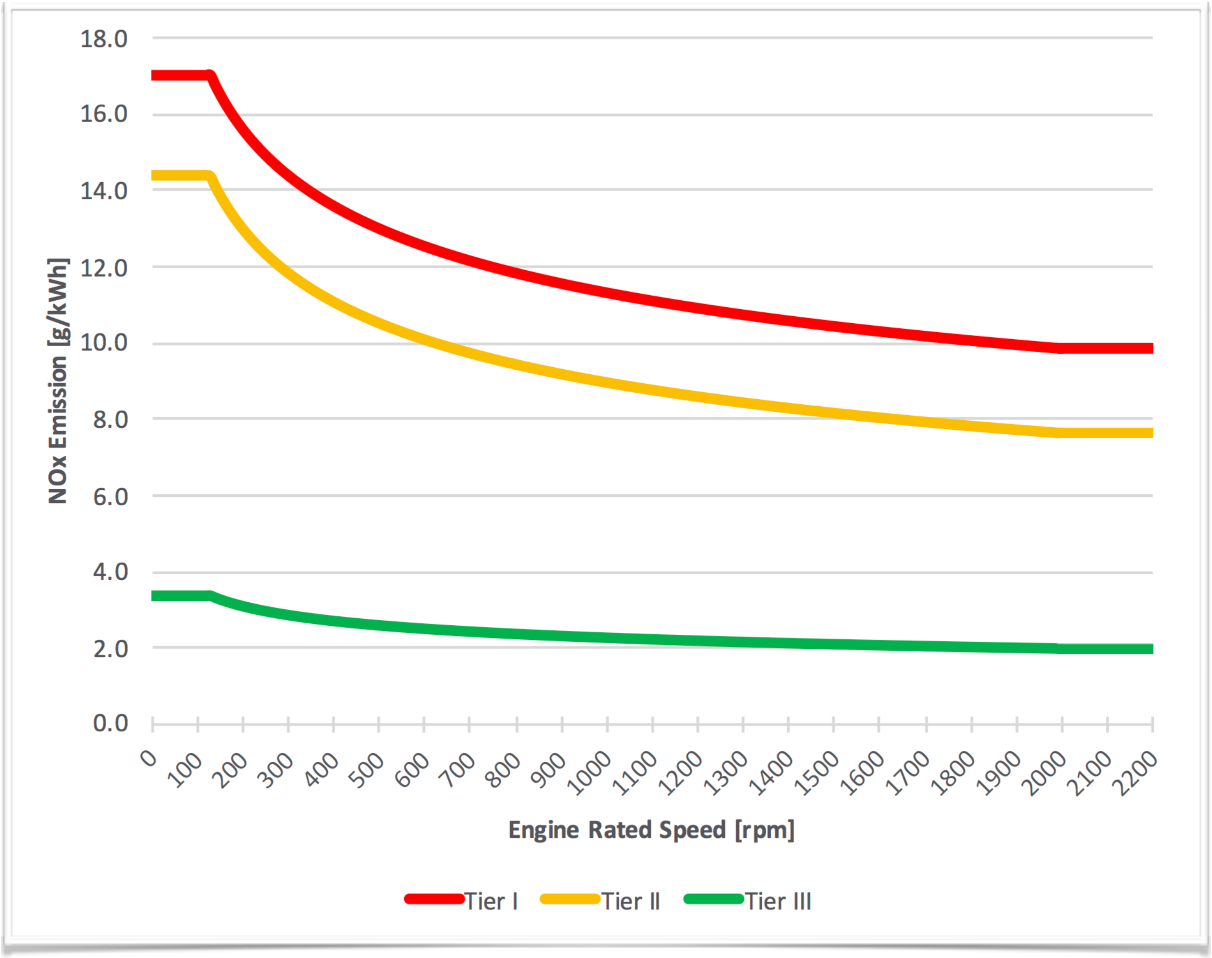

Figure 2.4 - MARPOL NOx Emission Limits
(IMO, 2020a)

Before an engine is installed onto a ship, the Administration carries out a pre-certification survey on a test bed to certify the engine itself by issuing an EIAPP certificate, which states the applicable Tier requirements, the measured NO_X value range for all operating modes, NO_X-critical components of the engine and the appropriate measurement and control methods (MEPC, 2008, Reg. 2.1.1.1). Normally, any new engine nowadays would be supported with this information in the engine's technical file, approved by a classification society at the manufacturing stage of the engine (MEPC, 2008, Reg. 2.2.2; 2.3.4).

After the engine has been installed with all its peripherals or after an engine has undergone a substantial conversion, the Administration performs an initial survey, where not only the engine but also other interconnected NO_X-critical machinery is inspected, which leads to issuance of a ship's IAPP certificate (MEPC, 2008, Reg. 2.1.1.2). Under normal circumstances, a main propulsion engine would be tested at 25%, 50% 75% and 100% of the nominal engine power (MEPC, 2008, Reg. 3.2.3; 3.2.4).

If an SCR system is fitted on the engine it has to be declared in the EIAPP certificate, since it is a NO_X-critical component. And engine's technical file has to be supplemented with detailed arrangements of the SCR and its verification procedures approved by the Administration (MEPC, 2017, Reg. 3.5.1). It describes the working principle with all the key parts of the system, type of the chemical reduction agent, position of the catalyst block, the range of normal exploitation parameters, as well as maintenance and control procedures with respective corrective actions (MEPC, 2017, Reg. 3.2).

SCR systems are also subjects to pre-certification survey that has two ways to perform it. Under Scheme A, the SCR system undergoes tests on a test bed together with the engine it is going to be fitted on (MEPC, 2017, Reg. 5). If for some technical or practical reasons the test for the SCR system cannot be performed nor on a test bed, nor on board the vessel, the EIAPP certificate may be issued based on computer-modeled calculations (MEPC, 2017, Reg. 6). Of course, the presence of an SCR system will amend the IAPP certificate as well.

CO_2

CO_2 falls into the category of greenhouse gasses and is regulated under MARPOL Annex VI Chapter 4 by introducing Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP), which were adopted during the 62nd session of MEPC in 2011. These regulations apply to all new ships of 400GT and above with the keel laid on or after 1 July 2013 and all existing ships undergoing a major conversion (MEPC, 2011, Reg. 19.1; 20.1; 21.1).

There have been contradictory opinions about the inclusion of greenhouse gasses in MARPOL Annex VI among other harmful gaseous substances. While some Member States like Japan, Denmark, Norway and United States of America (USA) fully support this approach, to implement regulations on greenhouse gasses within the MARPOL Annex VI regulatory framework, others - Brazil, Chile, China, Kuwait and Saudi Arabia - have different perspective on how this matter should be handled (Shi, 2016, p. 188).

The EEDI consists of measurement series of ship operating parameters that affect the energy consumption on board and is expressed in emitted grammes of CO_2 per tonne-mile. And since the energy is generated by burning fossil fuels, it has a direct impact on the emitted CO_2 amount. Before a vessel is commenced building or undergoing a major conversion, the Administration carries out a preliminary verification of the attained EEDI, which is calculated at the design stage and goes into the EEDI Technical File (MEPC, 2012b, Reg. 4.2; 4.4). The final verification of the attained EEDI is performed at sea trials, of course, after all other relevant surveys and certifications have been carried out like EIAPP and IAPP certificates with the NO_X Technical File and anything else that might affect the vessel's performance (MEPC, 2012b, Reg. 4.3).

A value of the required EEDI has to be calculated for bulk carriers, gas carriers, tankers, container ships, general cargo ships, refrigerated cargo ships and combination carriers (MEPC, 2011, Reg. 2.25-2.31; 21.1). As a rule of thumb, the attained EEDI has to be less or equal than the required EEDI, which follows a reference value for the specific ship type, and is expressed with the following formula:

$$Attained\ EEDI \leq Required\ EEDI = \left(\frac{1 - Reduction\ \ factor}{100}\right) \times Reference\ value \qquad (2.1)$$

(MEPC, 2011, Reg. 21.1)

A reference value is drawn depending on the ship type and its deadweight, that is diminished by a reduction factor depending on the ship type, its deadweight and also the date of construction or major conversion of the vessel (MEPC, 2011, Reg. 21.2; 21.3). The implementation process has been divided into phases, where the current (Phase 2) is applicable from 1 January 2020 till 31 December 2024 and the last (Phase 3) - from 1 January 2025 and onwards, having the steepest reduction factors (MEPC, 2011, Reg. 21, Table 1).

Comparatively the steepest reduction rate of required EEDI is dedicated to container vessels, which is mostly because of their relatively fast steaming and, thus, high energy consumption (Walker, Adebambo et al., 2019, p. 509), please see Figure 2.5 below. IMO collects the attained EEDI data from Member Governments and classification societies and publishes the information on its Global Integrated Shipping Information System (GISIS) to establish benchmark point for each ship type.

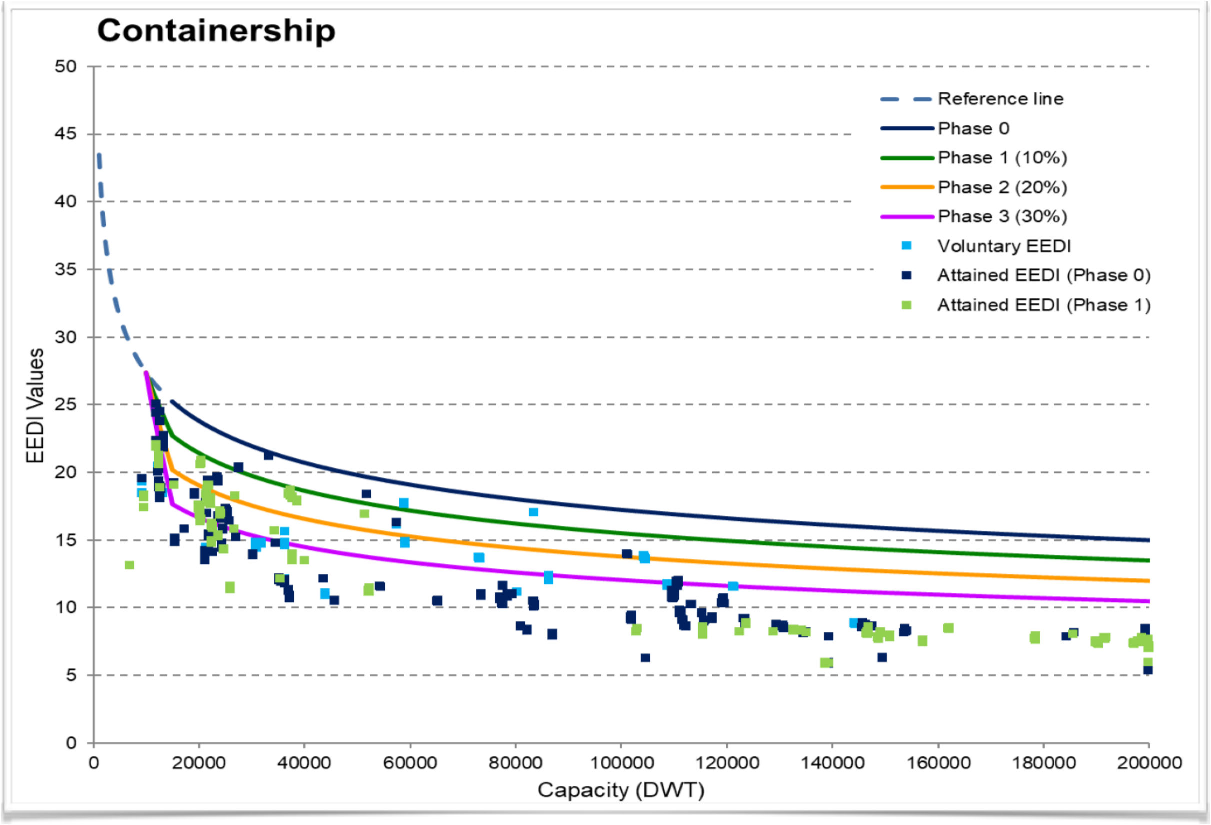

Figure 2.5 - Attained EEDI Data from Containerships on 10-Mar-2020
(IMO, 2020c)

SEEMP is mandatory to be implemented on all ships that are subjects to MARPOL Annex VI Chapter 4 (MEPC, 2011, Reg. 22). This plan is analogue to the ship's Safety Management Plan or company's environmental management system, but concerns the ship's operations regarding efficient energy usage (MEPC, 2011, Reg. 22.1). SEEMP does not have to follow a rigidly defined structure, but has to be approved by the Administration and shall include information about monitoring tools, self-evaluation and improvement tactics, fuel-efficient operations, optimized ship handling, hull maintenance, use of propulsion system and its maintenance, waste heat recovery and cargo handling (MEPC, 2012a, Reg. 4; 5). For this MEPC has created a monitoring tool called Energy Efficiency Operational Index (EEOI), which is not mandatory to use but is recommended by MEPC.

In addition, all vessels of 5000GT and above are obliged to continuously collect data of fuel consumption, traveled distance and hours underway and to send it to the Administration after each calendar year, which passes it to IMO, starting from the year 2019 (MEPC, 2016, Reg. 22A; Appendix IX).

All the above-mentioned information about energy efficiency is compiled in one document that is ship's International Energy Efficiency Certificate (IEEC) (MEPC, 2011,

Appendix VIII). It is issued for the lifetime of the ship, unless a major conversion or change of flag takes place (MEPC, 2011, Reg. 9).

There have been studies done on possible effects of various technical and organizational measures in order to achieve reduction in CO_2 emissions as per SEEMP on a cost-effectiveness scale. Figure 2.6 illustrates an optimistic prediction of effectiveness from the considered methods. Without much of an argument, reduction in speed is the most effective step to take towards reduction of CO_2 emissions. But it has a great drawback in terms of market competition where the lost time is a loss of a possible opportunity.

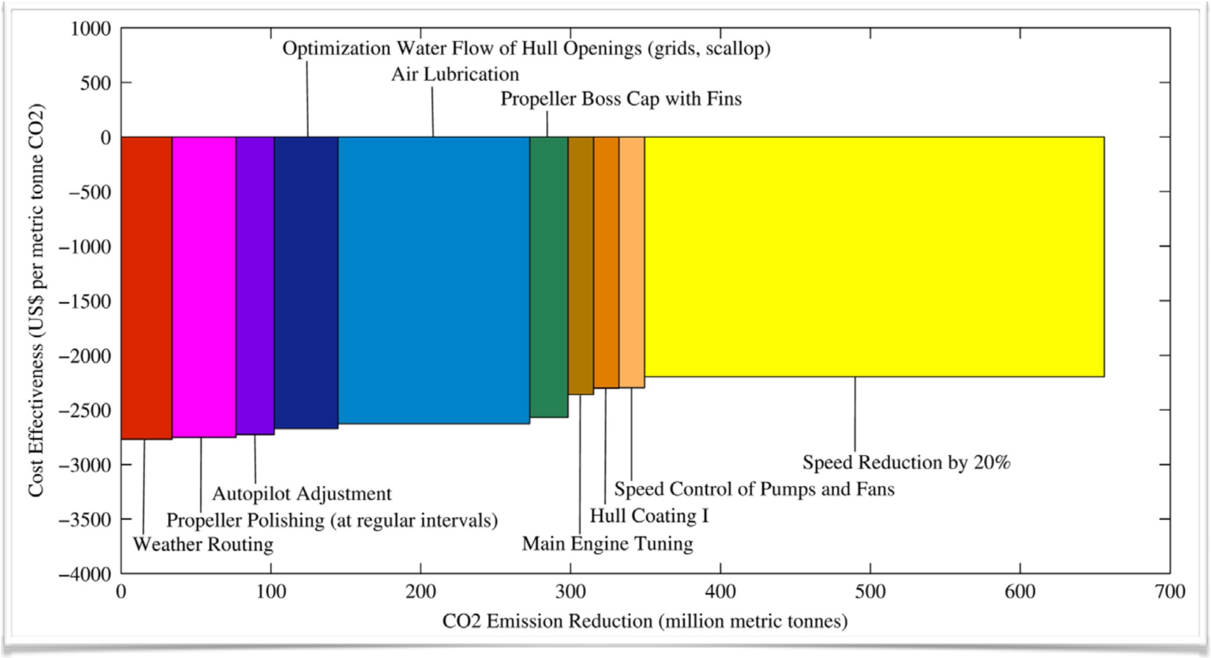

Figure 2.6 - CO_2 Emission Reduction Measures and Their Cost Effectiveness (Yuan, Ng, & Sou, 2016, p. 117)

To summarize, the air pollution from ships, regarding the use of fossil fuels, is prevented by restrictions on fuel chemical content, efficiency of the internal combustion engine and any other related equipment that may affect the emitted amount of concerned polluting substances. The primary solution is to use clean fuels, but secondary - exhaust gas treatment systems. Though, these solutions have to be used with energy-efficient engines in accordance to an appropriate Energy Efficiency Management Plan that is all under supervision of legal maritime authorities. A generalized cause-effect fish bone diagram in Figure 2.7 shows the relevant input factors for the total emission reduction in shipping.

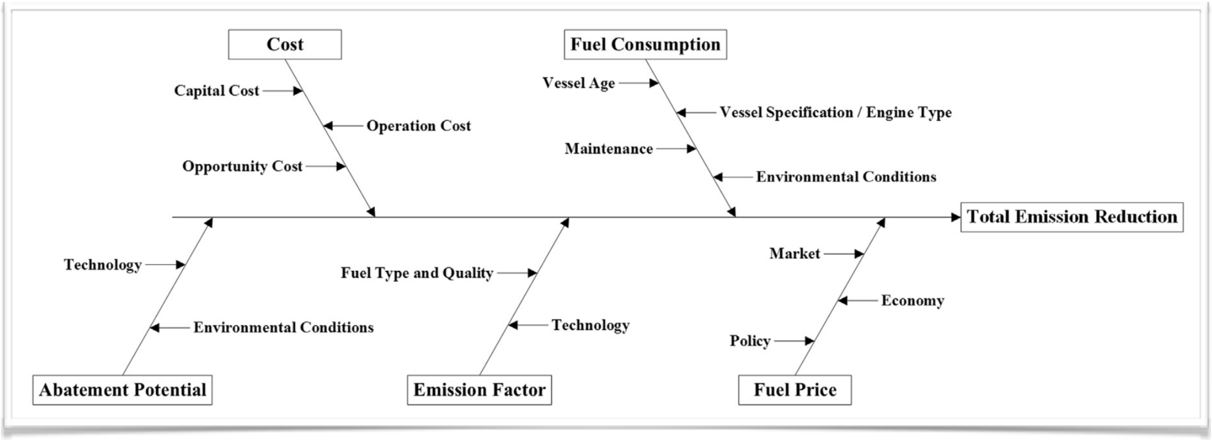

Figure 2.7 - Cause-Effect Diagram for the Total Emission Reduction
(Yuan, Ng et al., 2016, p. 116)

Each compliance method faces its challenges, such as technical compatibility, long-term cost effectiveness and dependent outer factors like changes in global economy and the law. There is a number of different sources and data processing methods to apply for decision making, but none of them are completely objective and they meet ambiguity to some degree.

2.2. Regional

Although IMO has also declared rules for specific regions, there are other organizations as well that are fighting for cleaner environment and are pushing the shipping industry to reduce the harm by emitted exhaust gasses. For example, goal 14 in the United Nations 2030 Agenda for Sustainable Development sets forward an initiative for sustainable use of oceans and marine resources, which also tensions up discussions about pollution from the maritime transport.

European Union

For maritime-related matters, the European Union (EU) is represented by the European Maritime Safety Agency (EMSA), which also actively participates at IMO gatherings and promotes EU's interests at a global scale. The European Parliament and Council have the authority to enforce the law within the jurisprudence of the EU by issuing regulations and directives applicable to all Member States.

Directive (EU) 2016/802 sets out the latest restrictions related to reduction of the sulphur content in fuels oils. Currently, if a vessel enters territorial waters or exclusive economic zone of EU, fuel of not more than 0.50% m/m sulphur content shall be used

(European Parliament and Council, 2016, Article 6.1b). In addition to the latter, if these waters fall within the MARPOL Annex VI sulphur ECAs, the vessel shall use fuel with the sulphur content of not more than 0.10% m/m (European Parliament and Council, 2016, Article 6.2b). These two limitations clearly show the enforcement of the MARPOL regulations in EU. Since 1 January 2010, the maximum sulphur content of fuel used on board while at berth in any port of the EU is set to 0.10% m/m (European Parliament and Council, 2016, Article 7.1).

Just like IMO and MEPC, also the EU legislative body in collaboration with the European Sustainable Shipping Forum have permitted the use of existing alternative compliance methods, written in Directive 2014/90/EU, generally referring to IMO approved. Article 31 of this Directive allows trials of new compliance methods within the jurisdiction of each flag state.

Any merchant or passenger vessel of 5000GT and above has been required to report the emitted CO_2 emissions under the EU "Monitoring, Reporting and Verification of CO_2 Emissions Programme" while operating within the waters of European Economic Area (European Parliament and Council, 2015, Article 2). The programme took effect in the beginning of 2018, which is a year earlier than the same rules were adopted by IMO globally.

Besides the rules addressed merely to the maritime transport, EU also exercises an Emission Cap and Trading System to limit and control amounts of emissions from relevant industries, mainly focusing on reduction in CO_2, which was adopted by the Directive 2003/87/EC in 2003 with the latest amendments in 2018.

Mediterranean Sea

A group of environmentally concerned organizations, led by the Nature and Biodiversity Conservation Union, have expressed necessity to step up on limiting exhaust gas emissions in the Mediterranean Sea by including it in the European Sulphur Directive and in the list of MARPOL Annex VI ECAs. The mentioned reason is that the Mediterranean Sea is an intensive transit area with relatively restricted water exchange, which is why they propose to lower the maximum allowable sulphur content in fuel oils down to 0.10% m/m and, eventually, ban the use of EGC systems (Nature And Biodiversity Conservation Union, 2018).

2.3. National

Even though the majority of all maritime-related countries are also members of IMO, some of them have implemented their own rules at national level, which are more stringent or with different approach than the globally adopted ones. The Member States can also submit proposals to amend the existing IMO regulations or establish new ones according to their viewpoint.

A note to mention beforehand is that many countries worldwide have prohibited the use of EGC systems in open-loop mode while the ship is in port areas or even within the territorial waters. The concern here is that, instead of letting the SO_X emissions in the air, where they would form into sulphuric acid, an EGC system in the open-loop mode directs the sulphuric acid into the water. Some countries like Australia, a few ports in USA, India, United Arab Emirates, Estonia and Finland still allow discharge of the scrubbing water from open-loop scrubbers, but only if the ship complies with the nationally approved compliance and monitoring procedures and can provide continuous reporting (Gard, 2019). On the other hand, some recent studies claim that there is no adverse effect on the marine environment, its fauna and flora, so, the major scrubber manufacturers defend their technology and its benefits to the maritime industry at international forums (Strømmen, 2019).

United States of America

Environmental matters in USA are controlled by the Environmental Protection Agency (EPA), who issue rules for prevention of air pollution under the United States Code of Federal Regulations Title 40. Part 94 of the Title regulates the operational requirements of in-use marine engines manufactured until 29 June 2010 and divides engines into three categories according to their cylinder displacement, which are then subjects to maximum allowable exhaust gas emission requirements of hydrocarbons, NO_X, carbon monoxide and PM, depending on the engine manufacturing year, a finer division of cylinder displacement and the rated engine power (Environmental Protection Agency, 2020, § 6; 8). With a similar approach, new marine engines are discussed in Part 1042 of the Title 40.

USA has implemented MARPOL Annex VI regulations under Part 1043 of the same Title and, in a long run, keeps the same methodology but with a more detail-oriented approach. Nevertheless, each State can introduce their own regulations too, as long as they are not less stringent than the Federal ones, like it has been done in the State of California, where only distillate fuel oils with the maximum sulphur content of 0.10% m/m are allowed to be used on ocean-going vessels while in the contiguous waters (24 nautical miles zone) since 1 January 2014 without the option to comply with the rules by using exhaust gas cleaning devices except for research purposes (California Air Resources Board, 2020).

The People's Republic of China

Since 2015, China has declared a domestic ECA along their coastline, where relatively more stringent rules apply for vessels that enter the territorial waters of China including Hong Kong and Hainan Island. Since 1 January 2019, all ocean-going vessels have been obliged to use fuel oil with sulphur content not exceeding 0.50% m/m when entering coastal ECA and starting from 1 January 2022 - 0.10% m/m when entering coastal ECA of Hainan Island (Huatai Insurance Agency & Consultant Service, 2018). Additionally, a 0.10% m/m sulphur limit has been set for vessels entering inland ECA, which includes Yangtze River and Xi Jiang River, since 1 January 2020 (Urdahl, 2020). It is worth mentioning that the same restrictions have been also enforced in Taiwan (Urdahl, 2020). Figure 2.8 shows the China's domestic ECA on a map.

Figure 2.8 - China's Domestic Sulphur ECA
(Skuld, 2019)

As for the NO_X emission control, China stick with the MARPOL Annex VI regulations. But every inland river vessel built on or after 1 January 2019 and most of the domestic coastal vessels, except tankers, built on or after 1 January 2020 shall be equipped with a ship-shore power system to use shore-generated electricity (Huatai Insurance Agency & Consultant Service, 2018).

South Korea

The Ministry of Oceans and Fisheries and the Ministry of Environment in South Korea enforced the IMO global sulphur limit by creating their own ECA, which covers the main five ports in the country: Busan, Ulsan, Yeosu-Gwangyang, Incheon and Pyeongtaek-Dangjin (Finamore, 2019). The regulation stipulates that starting from 1 September 2020 ships are requested to switch to 0.10% m/m sulphur fuel when berthing at the mentioned ports, but from 1 January 2022 - also when navigating within the Korean ECA (Finamore, 2019). There are also set speed limits for different ship types, which go down to 10-12 knots (DNV GL, 2020). This is done to also reduce CO_2 emissions, and mostly affects the transit of container vessels. Figure 2.9 maps all these areas.

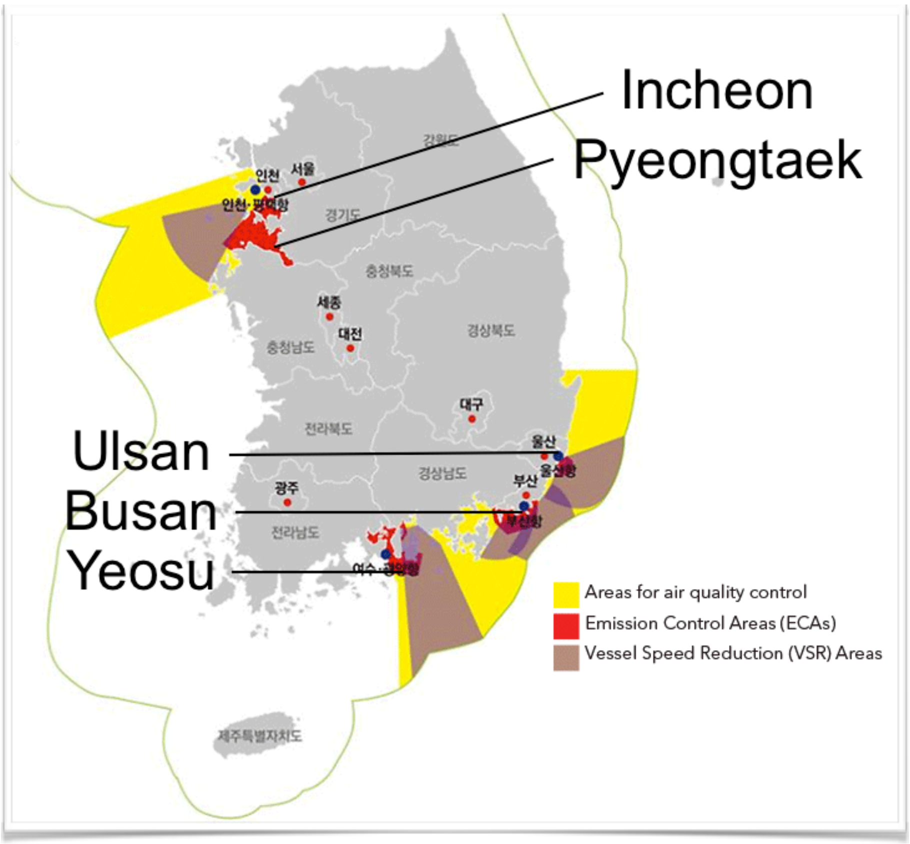

Figure 2.9 - Restricted Zones of Korean Waters
(DNV GL, 2020)

Australia

In June 2018, Australian Maritime Safety Authority issued new directions, making every cruise vessel with the capacity of more than 100 passengers to use fuel with sulphur content that does not exceed 0.10% m/m or comply alternatively by using an IMO approved EGC system while at berth in the Sydney Harbour (Prosser, 2018).

Western Norwegian World Heritage Fjords

Since 1 March 2019, the existing North Sea ECA sulphur restriction (maximum 0.10% m/m) has been applied to ships that enter the Norwegian World Heritage Fjords in Western Norway, but it still allows to comply by using an EGC system in closed-loop mode (Norwegian Maritime Authority, 2019, Section 14b). Also, starting from 1 January 2025, all vessels above 1000GT, irrespective of their construction date, will have to obey IMO NO_X Tier III requirements of MARPOL Annex VI, Regulation 13 (Norwegian Maritime Authority, 2019, Section 14c).

Regardless of the above, the Norwegian Parliament has adopted rules for all passenger vessels entering the fjords to sail emission-free from the year 2026, which, although for a relatively small territory, are the first rules of such magnitude so far in the world (Latarche, 2020).

Iceland

At the time when IMO introduced the global sulphur cap on 1 January 2020, the Minister for the Environment and Natural Resources issued restriction on sulphur content in marine fuels used in the territorial and inland waters of Iceland, which was a fall from 3.50% m/m to 0.10% m/m (Ministry for the Environment and Natural Resources of Iceland, 2019). Heavier fuel oils may be used with IMO approved EGC systems.

Turkey

Although Turkey is not part of EU or European economic Area, it adopted relatively strict limitations on sulphur emissions in 2012. It states that ships are not allowed to use fuel which sulphur content exceeds 0.10% m/m while at berth or passing through inland waterways of Turkey, except for passenger ships that provide regular services in Turkish waters, giving a slack of up to 1.50% m/m (General Directorate of Marine Transport of Turkey, 2011).

3. Conventional Exhaust Gas Treatment

There are several widely available exhaust gas treatment systems available, which clean the gasses physically or reduce the concerned substances down to harmless elements chemically. The technologies themselves are not the latest innovations, but at the same time, when incorporated into marine power plants, they face some technical challenges that are created by legal restrictions from many sides, as seen in the previous chapter. Figure 3.1 shows the number of confirmed scrubber system installations, taking a noticeable leap in 2019 because of the IMO 2020 global sulphur cap.

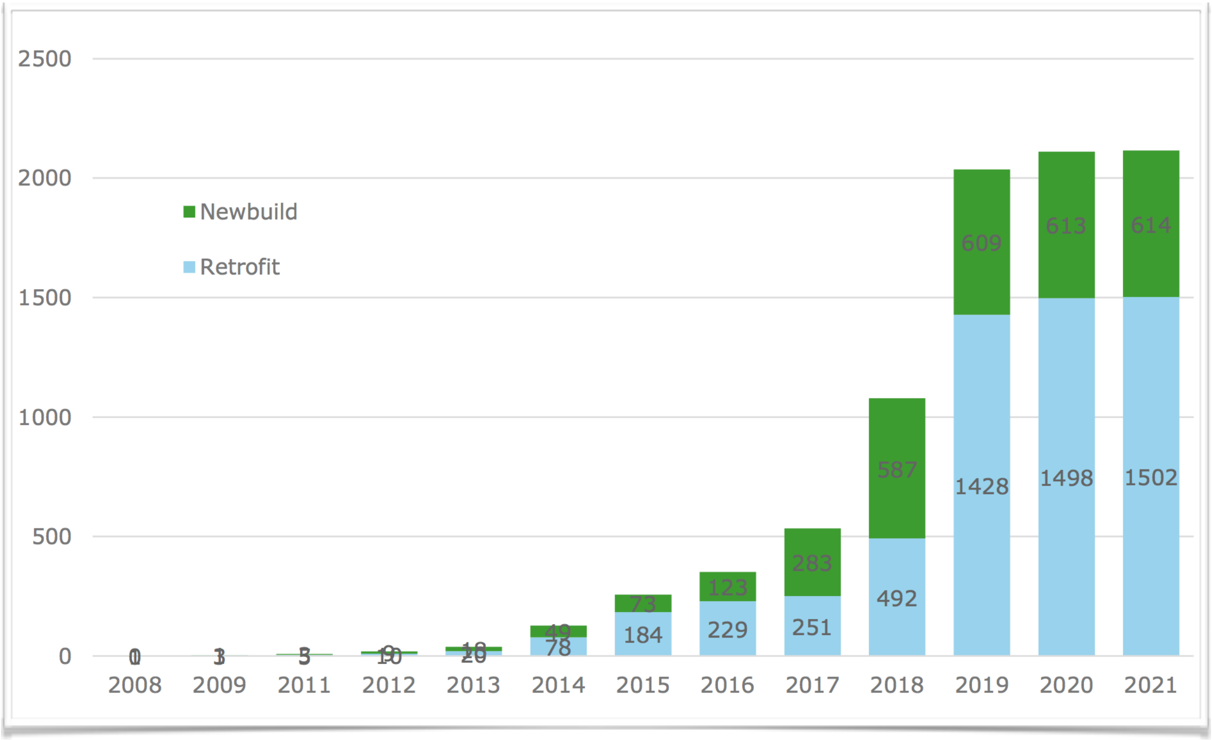

Figure 3.1 - Number of Ships with Installed or Confirmed Scrubber System Installations (Kock, 2018)

Whatever exhaust gas treatment method is applied, it has to deal not only with legal operational requirements but also with organizational and, simply, physical restrictions. Some of the technologies need a significant space for the whole installation to be set up, especially if that is a retrofit, which has not been optimized particularly for the given machinery set-up and the lay-out of the vessel. The following introduces to the most common exhaust gas abatement systems for each regulated emission.

3.1. SOx

Lately, a lot of effort is spent on scrubber systems to deal particularly with the SO_X emission standards, because of the stringent limitations in MARPOL Annex VI ECAs since 2015 and the global sulphur cap as from 2020. By using scrubbers, ships can run on cheaper high-sulphur fuel oils if the flag state and port state allow it. The recent IMO global sulphur cap requires at least 85% reduction in the SO_X content (IMO, 2020b).

Newer vessels (up to 10 years old) with regular voyages trough ECAs are most suited to be equipped with scrubbers because of the relatively high installation costs, which would normally pay off within five years, compared to using low-sulphur fuel oil at reasonable and stable fuel prices (Solakivi, Laari, Kiiski, Töyli et al., 2019, pp. 340, 344). Table 3.1 approximates the payback period for a vessel, which consumes 12500*t* heavy fuel oil annually with a scrubber system worth 2'500'000$.

Table 3.1 - Scrubber Payback Period by Time Spent in ECAS and Fuel Price Differential (Hamworthy Krystallon, 2010, p. 9)

Fuel Price Differential		20$/*t*	50$/*t*	100$/*t*	200$/*t*	500$/*t*
Proportion of time spent in ECAs	5%	200 years	80 years	40 years	20 years	8 years
	25%	40 years	16 years	8 years	4 years	2 years
	50%	20 years	8 years	4 years	2 years	10 months
	100%	10 years	4 years	2 years	1 year	5 months

Recent study results, collected from ports of Finland in 2015-2017, confirm that vessels with fixed itineraries through ECAs compose the majority of the vessels equipped with EGC systems, to be more precise, Roll-on—Roll-off vessels ~ 48%, pure car carriers ~ 22% and cruise ships ~ 11% (Solakivi, Laari et al., 2019, p. 342). Of course, these approximations are devoted to the IMO sulphur ECA restrictions of 0.10% m/m maximum content after 2015, but still, the point that has been made here coincides by far with the IMO global sulphur cap 2020 limits.

At the time of writing this work, the most recent global sulphur cap had been in force for just a few months, the world's leading oil suppliers had been in dispute about the global oil production volume, taking it to the stage of international politics, which reflects in the oil prices, and, on top of that, a globally spread virus had seriously affected just about any industry world-wide (Wang, 2020). An objective and clear evaluation is difficult to achieve in such conditions, since the scrubber technologies compete on the cost of the price differential between high and low-sulphur fuel oils.

Wet scrubbing

One of the most common and efficient method of cleaning the exhaust gasses is scrubbing them with water, which is capable of removing SO_2 at over 90% and PM ~ 80% and is suitable for the use of high-sulphur fuels with SO_X up to 3.50% m/m (Poullikkas, 2015, p. 96). SO_2, composing most of the SO_X group and being one of the most concerned pollutant, is soluble in the water, resulting in sulphureous acid, which can be neutralized by the surrounding seawater in large amounts (open-loop mode) or by alkali solution in smaller amounts (closed-loop mode), which stabilizes the pH level (Poullikkas, 2015, p. 96). The alkalinity has a correlation with the salinity of the water to some extent, and the seawater in open oceans is generally alkaline enough to ensure the efficiency of an open-loop scrubber, but in some closed-in coastal areas and rivers the efficiency might be reduced (Exhaust Gas Cleaning Systems Association, n.d.-a).

As discussed earlier, many countries have banned the discharge of open-loop scrubbing water, so, most shipowners would like to go for a hybrid wet scrubber system, which is designed to circulate the wash water in a closed loop, while constantly adding pH neutralizing solution, collect solid residues in a sludge tank to dispose them later at port reception facilities and store liquid waste in a holding tank to discharge it in open waters in a manner according to applicable rules. Such system requires more automation of monitoring and control equipment, paying special attention to critical points like the pH level sensor and exhaust gas sensors, that give input signal to the water pumps, chemical dosing pump and exhaust fan.

The whole system brings extra weight with its casing, piping and liquid storage tanks, with the free surface effect, that might be challenging for ships with low initial stability (Panasiuk, Lebedevas, & Čerka, 2018, p. 200).

To increase the absorbing contact area, thus, the SO_2 absorption efficiency, the scrubbing liquid may be ejected in a form of mist or the exhaust gasses may be directed through a liquid sorbent packing bed.

There are multiple widely available alkali liquid solutions on the market, but cautiousness must be taken if the substance is under the International Maritime Dangerous Goods Code with its consequent carriage and handling requirements. Figure 3.2 demonstrates a schematic principle of a hybrid-loop wet scrubber system. The difference from a closed-loop system is that the wash water (pure seawater), when leaving the treatment unit (separator), goes directly overboard without settling in the holding tank.

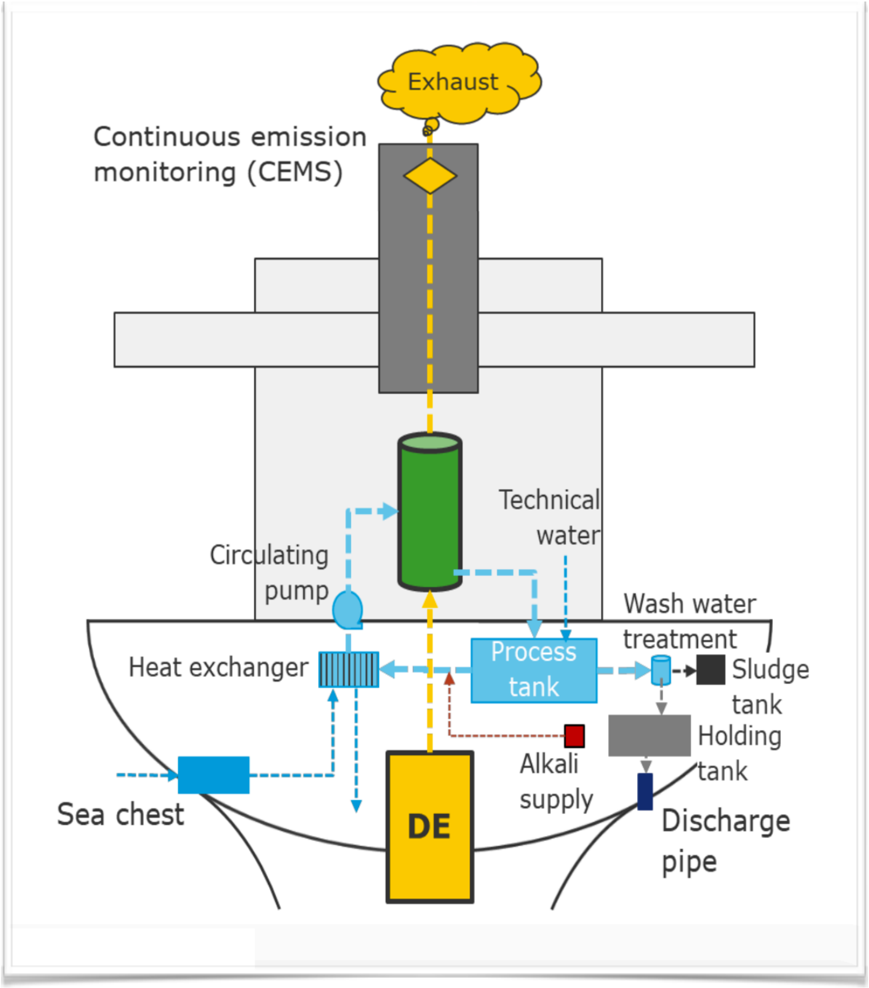

Figure 3.2 - Hybrid-Loop Wet Scrubber System Scheme
(Mundal, Sandal, & Springer, 2018)

Advantages and disadvantages of wet scrubbing systems:

(+) The most important reason for this system's popularity is its high SO_2 reduction efficiency, going above 90%.

(+) Outside territorial seas and sensitive areas, the surrounding seawater can be used as a scrubbing agent without any need for chemical additives.

(-) Because the system, when used in closed loop, envisages the use of alkali solution to neutralize the acidic wash water, a risk of corrosion exists, that has to be avoided by corrosion-resistant materials and periodic inspections of pumps, valves and connections.

(-) The system consists of several power consumers like water pumps, residue separators and exhaust fan that increase the total fuel consumption by 1.0%-2.5%, depending on whether it is operating in closed or open-loop (Kock, 2018).

(-) Sludge, the by-product of scrubbing, has to be properly stored and disposed of at port reception facilities. Though, on some shore power plants, the sludge is treated with limestone, which results in gypsum and can be used as fertilizer or a raw substance in construction materials (Poullikkas, 2015, p. 95).

Dry scrubbing

Not as popular choice in marine installations as the wet scrubbing method, but it is much simpler in its design. The absorbing agent, as the name "dry scrubbing" implies, is in a dry form, usually calcium hydroxide granules that are packed in standardized interchangeable modules (Lloyd's Register, 2015, p. 26). The simplest design of such system comprises of an absorbent module, closed in a casing, and a continuous exhaust gas monitoring system. Of course, in reality, a transfer equipment and separate storage rooms for fresh and used absorbents would have to be counted in.

The reason why it is a rarity on ships is its efficiency that does not exceed 50% with an equivalent size wet scrubber system, making it efficient for fuels with up to 1.00% m/m sulphur content only (Poullikkas, 2015, p. 93). The absorbent modules are bulkier and weigh more than an equivalent complete wet scrubber system, and the absorbents have to be periodically changed with fresh ones, that increases downtime for the engine (Lloyd's Register, 2015, p. 28).

To increase the scrubbing efficiency, the size of the absorbent granules may be reduced, though, the smaller they are, the more back pressure there will be in the exhaust duct, requiring an exhaust fan (Siwek & Chmielewski, 2018, p. 39). Speculations with the exhaust gas may be done as well, by placing angled flaps in the exhaust duct, which makes the gas to swirl in a centripetal motion, thus, increasing its residence time in the scrubbing section.

There is a compromise called packed gas absorption, taking the simplicity of the dry scrubber and the effectiveness of the closed-loop wet scrubbing method, which prolongs the lifetime of the dry absorbent and reduces the necessary absorbent volume, see Figure 3.3 (Siwek & Chmielewski, 2018, p. 38). This approach requires less, but still, frequent absorbent replacement and brings in some precautionary measures and control equipment from the wet scrubbing technology.

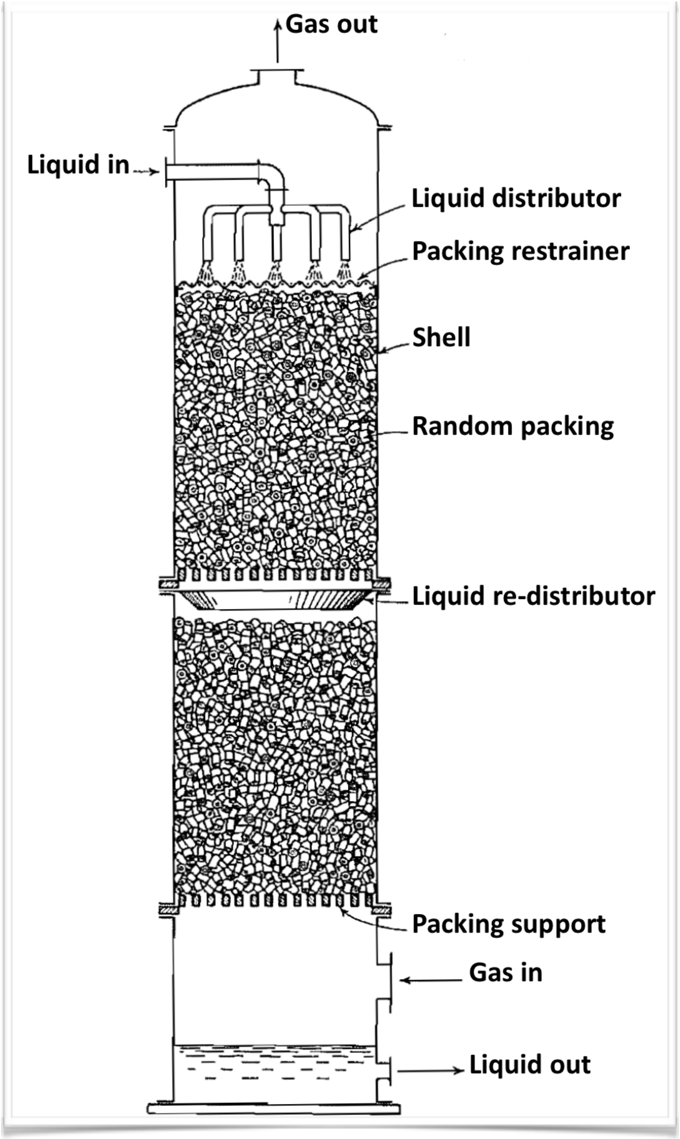

Figure 3.3 - Packed Gas Absorption Scrubbing Method
(Siwek & Chmielewski, 2018, p. 37)

Pros and cons of dry scrubbing systems:

(+) The system does not require any fluids, pumps and separators in the scrubbing process, making it a more robust assembly.

(+) There is just a negligible increase in the total fuel consumption of approximately 0.2% (Siwek & Chmielewski, 2018, p. 29).

(+) It is especially compatible with the SCR systems, because the exhaust gasses are not cooled down in the absorption chamber, which increases the efficiency of an SCR system to reduce NO_X emissions and allows to install the scrubber before a heat recovery system (Siwek & Chmielewski, 2018, p. 30).

(-) The maximum sulphur content in the fuel oil, that the dry scrubbing method can cope with on an average sea-going vessel, is 1.00% m/m.

(-) It takes considerable space and brings extra mass, not only from the absorbent in use but also what is in reserve and already used.

(-) Introduces frequent down time for the engine during replacement of the absorbent.

Technically the most important key factor for these scrubber systems on ships is the maximum permissible SO_2/CO_2 ratio, which, in turn, associates with EEDI. Each scrubbing method has some strengths and drawbacks in the technological process or performance indicators, which have to be evaluated for each ship individually.

While the primary and most promoted method for complying with the international regulations is agreed to be switching to low-sulphur distillate fuel oils or alternative fuels, studies have shown that it appears to be less harmful for the environment to use high-sulphur residual fuel oils with efficient scrubbers rather than distillate fuels in terms of the total CO_2 emissions released (Krantz, 2016, pp. 13-16). It takes approximately 3 times more energy to produce the same amount of electricity from diesel oil compared with heavy fuel oil, taking into account the consumed energy from production processes of each fuel type (Simonsen, 2014, p. 23).

3.2. PM

Incomplete combustion of residual fuel oils is what creates particulate matter, and the wet scrubbing method, as discussed earlier, does a decent job in removing PM as well. Studies have shown at least 75% removal efficiency on seawater (open-loop) scrubbers (IMO, 2015, p. 12). Since these are physical, solid particles that have to be dealt with, a physical filter is another option that has been used for decades in on-road transport sector, but its working capacity is very limited, making it inefficient for the residual marine fuel oils (IMO, 2015, pp. 11-12). Selective catalytic reduction (SCR) and EGR systems that reduce NO_X emissions, discussed in the next subchapter, have not shown any added value in fighting PM (IMO, 2015, pp. 12-13).

3.3. NOx

Because NO_X emissions are unavoidable for ships that run on fuel oils, there is a need for additional applications for the engines. The primary control methods manipulate with the fuel injection (pressure, timing, rate, nozzle configuration), air intake (temperature, pressure, humidity) and cylinder compression ratio (Siwek & Chmielewski, 2018, p. 44).

Secondary methods treat the emissions after the combustion process. The two most predominant ways of doing that are selective catalytic reduction and exhaust gas recirculation. To meet the latest IMO NO_X Tier III standards, a reduction in NO_X levels should be about 90% and for Tier II - approximately 80% (Siwek & Chmielewski, 2018, p. 63).

Selective catalytic reduction

The oldest and most advanced technology, that has been also used in numerous applications for land-based power plants, is the SCR system. It is capable of reducing NO_X emissions down by 80%-90%, going below 2*g/kWh* (Lloyd's Register, 2015, p. 32).

This technology reduces nitrogen oxides by injecting urea solution into the exhaust duct, which, mixed with the exhaust gasses, go through a catalyst filter, usually made from porous titanium dioxide (TiO_2), vanadium pentoxide (V_2O_5) or tungsten trioxide (WO_3), and, after the reaction, leave as nitrogen and water (Siwek & Chmielewski, 2018, p. 47). These catalytic metals are known to be poisonous and, although, they do not compose any noxious compounds with the exhaust gasses, they have to be properly recycled after their lifetime. The catalyst block will eventually become foul because of the oxidation processes and will increase back pressure, which requires periodic cleaning (Siwek & Chmielewski, 2018, p. 51).

The system introduces a refrigerated reductant holding tank, a transfer pump, an evaporator with a buffer tank, a high-pressure reductant dosing unit, a reactor housing with the catalyst blocks and all the piping, valves, monitoring and control units that come along with a series of equipment like such. Figure 3.4 describes the working principle of the SCR system.

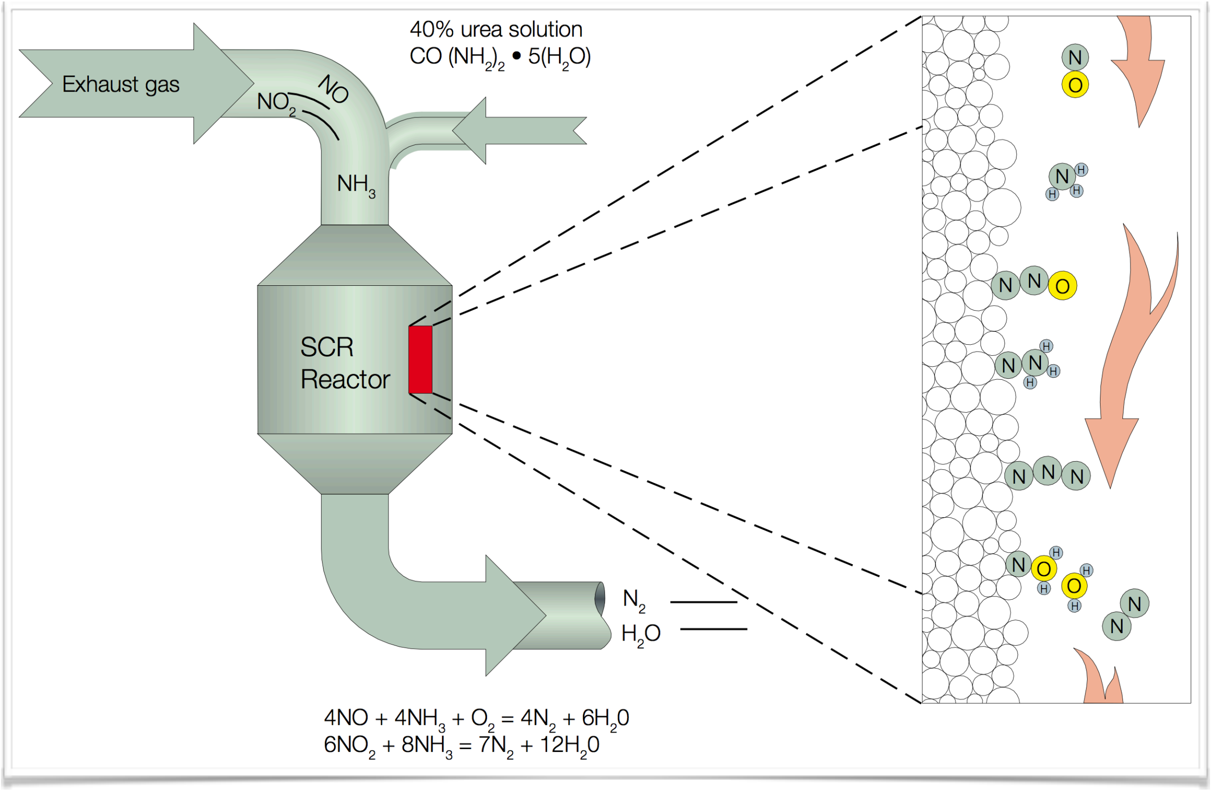

Figure 3.4 - The Working Principle of an SCR System
(MAN Diesel & Turbo, 2012, p. 6)

The reductant consumption is approximated to 15*l/MWh* for typical 40% urea solution, which would compose up to 8.5% of the total fuel consumption, requiring a significant storage space and increased operational costs as a function of fuel consumption (Guo, Fu, Ma, Ji et al., 2015, p. 942).

Similar to wet scrubbers, this system also brings a considerable amount of weight on board, but, because NO_X emissions are faced by all internal combustion engines burning fuel oils, most of the SCR systems have been integrated onto the engine by the manufacturer at the designing phase, allowing to optimize the available space and operational parameters of the engine.

The technology requires high exhaust gas temperature of 350°C-450°C, to remove emissions according to the regulations, which is why this technology has some grey zones on two-stroke engines that have cooler exhaust gasses than four-stroke equivalents (Siwek & Chmielewski, 2018, pp. 46-47). The minimum required exhaust temperature, for an effective NO_X removal, is also dependent on the sulphur content in the fuel, where the higher it is the higher is the required minimum exhaust gas temperature, see Figure 3.5.

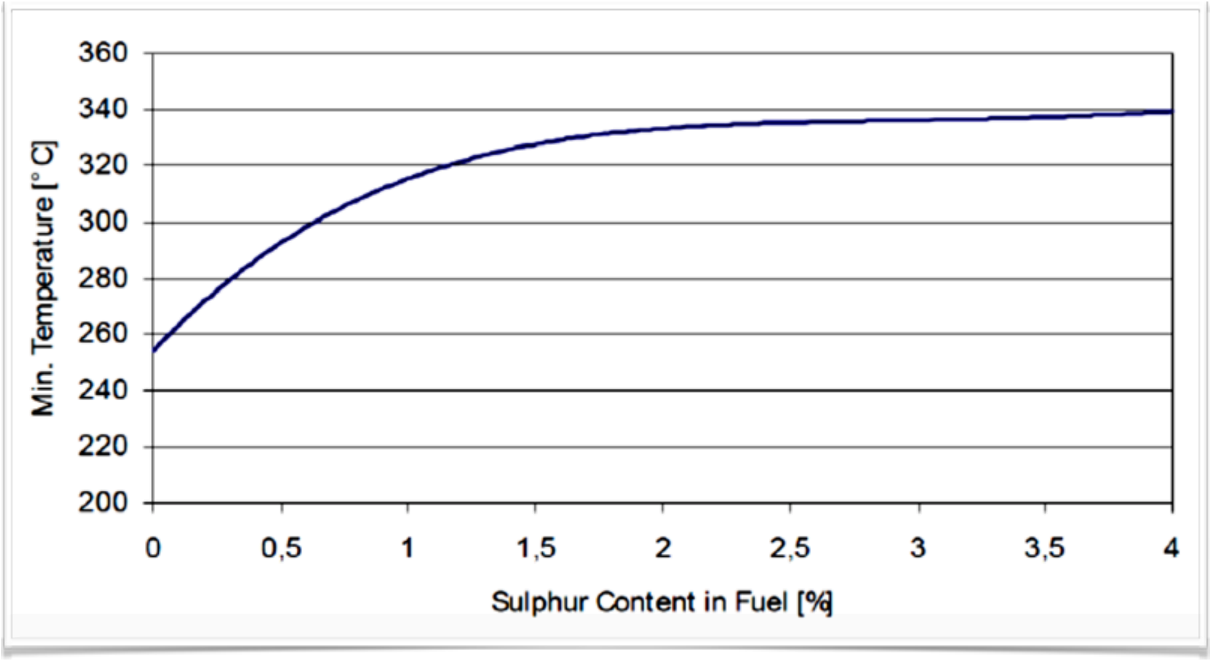

Figure 3.5 - Sulphur Content in Fuel and Required Minimum Exhaust Gas Temperature
(Siwek & Chmielewski, 2018, p. 46)

Advantages and disadvantages of SCR systems:

(+) The main advantage is the operational effectiveness, allowing to clean exhaust gasses even beyond the international maritime regulations.

(-) The effectiveness depends strongly on the exhaust gas temperature, which has to be in a specific range and is dependent on the sulphur content in the fuel.

(-) The widely used two-stroke marine engines have comparatively low exhaust gas temperatures, especially at lower loads, which is the case while maneuvering in port areas.

(-) It requires periodic cleaning of the catalyst blocks.

(-) Urea, which is used as a reduction agent and decomposes to ammonia, is classified as volatile organic compound in many countries and faces important safety measures to be followed.

Exhaust gas recirculation

The basic principle of this NO_X reduction mechanism is to send part of the exhaust gasses back to the engine inlet, mixed with fresh air, for the next combustion cycle. The reason to do so is because CO_2 and water molecules, being byproducts of fuel oil combustion, have a greater heat capacity than O_2, reducing peak temperatures in the cylinders, which is one of the factors for increased NO_X emissions in the first place (Latarche, 2017). Please see Figure 3.6 for a schematic diagram of an EGR system.

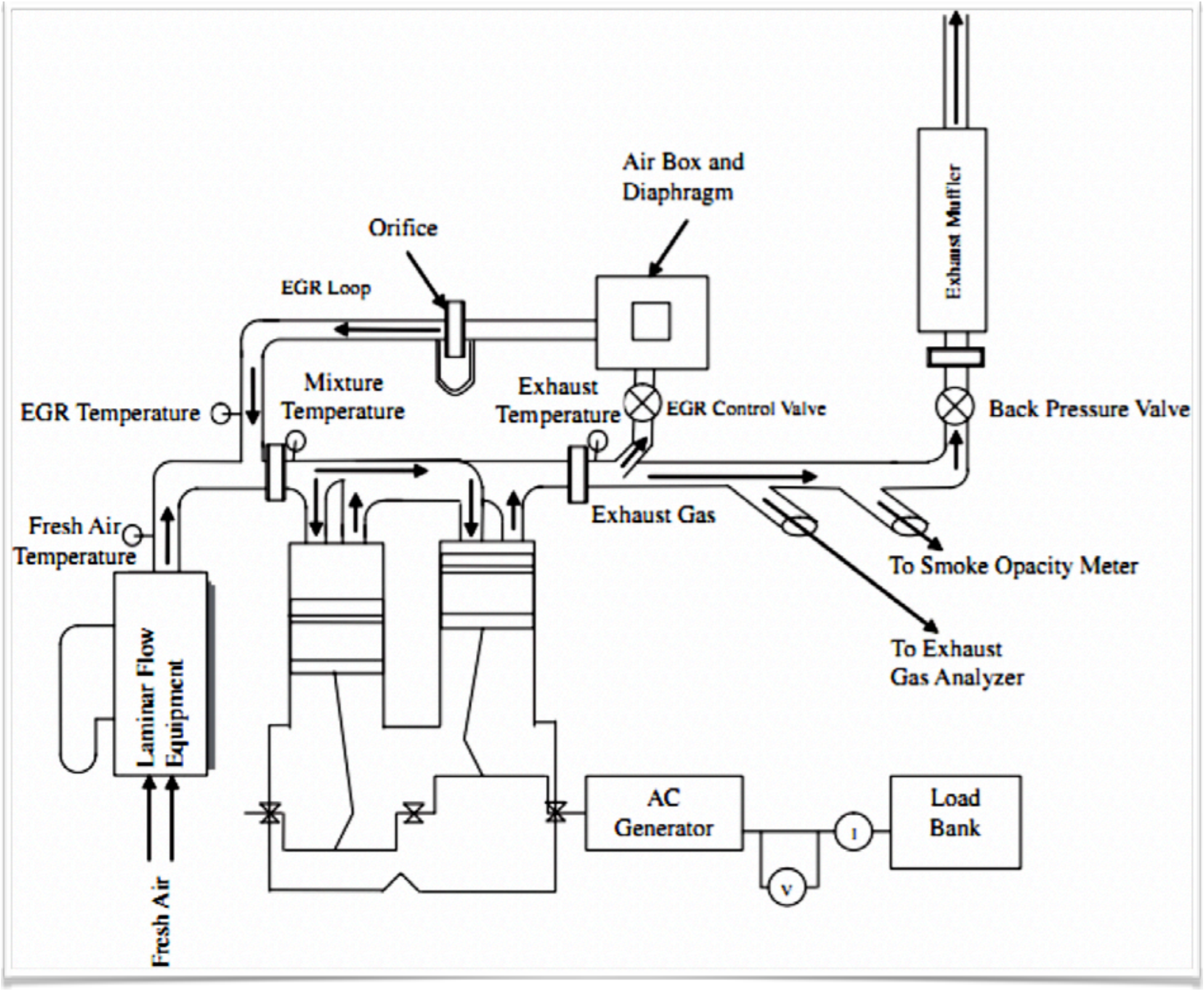

Figure 3.6 - Schematic Diagram of an EGR System
(Guo, Fu et al., 2015, p. 941)

This method alone is able to reduce NO_X emission by 50%, which is not enough to meet the IMO NO_X Tier III standards (Guo, Fu et al., 2015, p. 940). Returning exhaust gasses back to the engine increases the frequency for internal maintenance jobs and brings up risks to damage engine parts if high-sulphur fuel is used. If so, the EGR system should be coupled with wet scrubber system to wash off PM. But that introduces a risk of water carry-over, leading to corrosion and build-up of sulphate deposits in the EGR system (MAN Diesel & Turbo, 2012, p. 22). Selection of stainless materials can diminish the corrosion effect.

Pros and cons of EGR systems:

(+) It is compact and does not require sophisticated machinery to operate.

(-) Because the exhaust temperature decreases, an increase in PM comes in (IMO, 2015, p. 13).

(-) This solution alone cannot deal with the NO_X emission standards.

(-) Increased wear of the engine.

3.4. Compatibility and Competition

All of the discussed technologies have some side-effects in the cleaning process directly on the concerned emissions or on the performance of the engine. None of the solutions can deal with all the regulated emissions alone, so, in case high-sulphur fuel oil is used, it requires a separate system for SO_X and PM and another one for NO_X emissions, but these systems must complement each other or, at least, not impede.

So far, the only developed and proven combination to meet all the relevant IMO regulations, while burning high-sulphur fuel oil, is to use an SCR with a wet scrubber system (Siwek & Chmielewski, 2018, p. 57). Figure 3.7 compares the ability to reduce emissions of three different compliance methods, those being SCR with wet scrubber, SCR while using marine gas oil (MGO) and the use of a dual fuel engine. The latter burns liquified natural gas, mostly methane, which emits less CO_2 after combustion, but, at the same time, it does contribute to CO_2 emissions because of the practically unavoidable methane slip, and methane having a considerable global warming potential value over a 20-year period (Vaidyanathan, 2015). It can be seen that using high sulphur fuel oils with an SCR and wet scrubber system is comparatively effective in the NO_X and SO_X reduction.

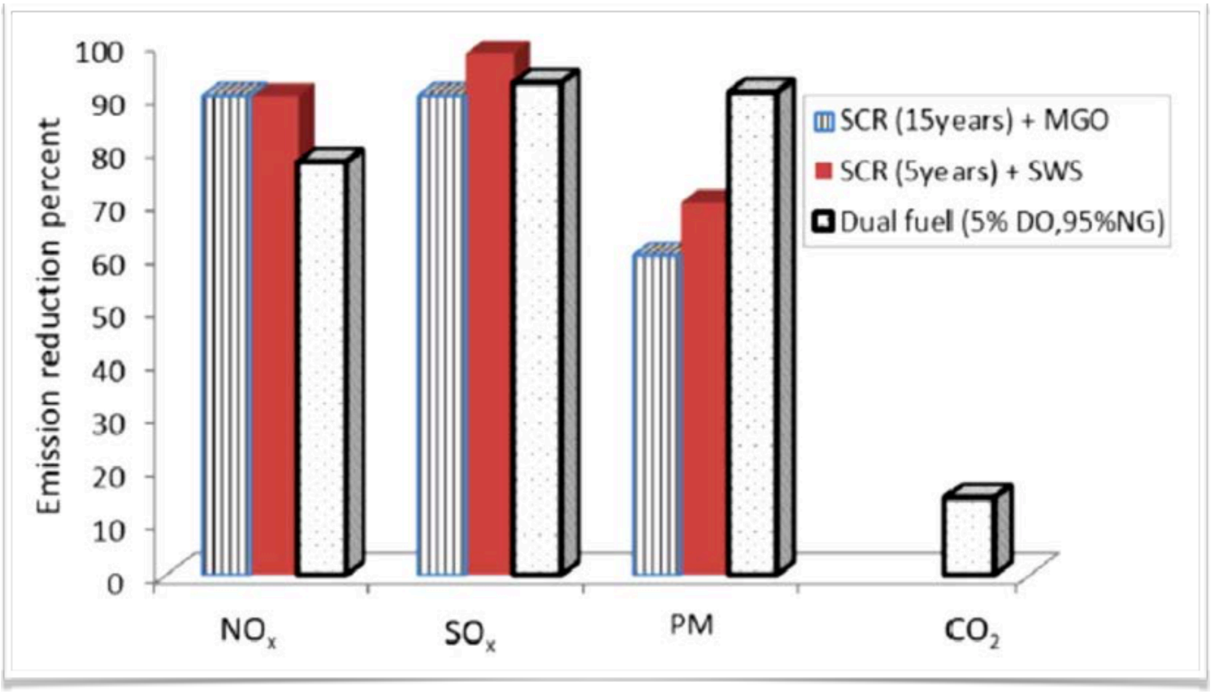

Figure 3.7 - Emission Reduction Ability of Different Solutions
(Ammar & Seddiek, 2017, p. 171)

As discussed earlier, production of distillate fuel oils requires significantly more energy than residual fuel oil. But for methane, the energy used for storage, or refrigeration in this case, has to be counted in as well, because its evaporation temperature in normal conditions is approximately -161°C. This introduces constant operation of refrigeration compressors and insulated storage tanks.

The slip of methane arises from incomplete combustion, venting and during bunkering operations. Different studies have approximated the methane slip from about 2%-8% (Sanchez & Mays, 2015, p. 170). Figure 3.8 compares study results of green-house gas footprint on a time scale from generating electricity using solar energy, coal and methane. The graph shows that increased methane slip propagates green-house gas footprint exponentially, which has the greatest impact in the first 20 to 30 years after release into the atmosphere.

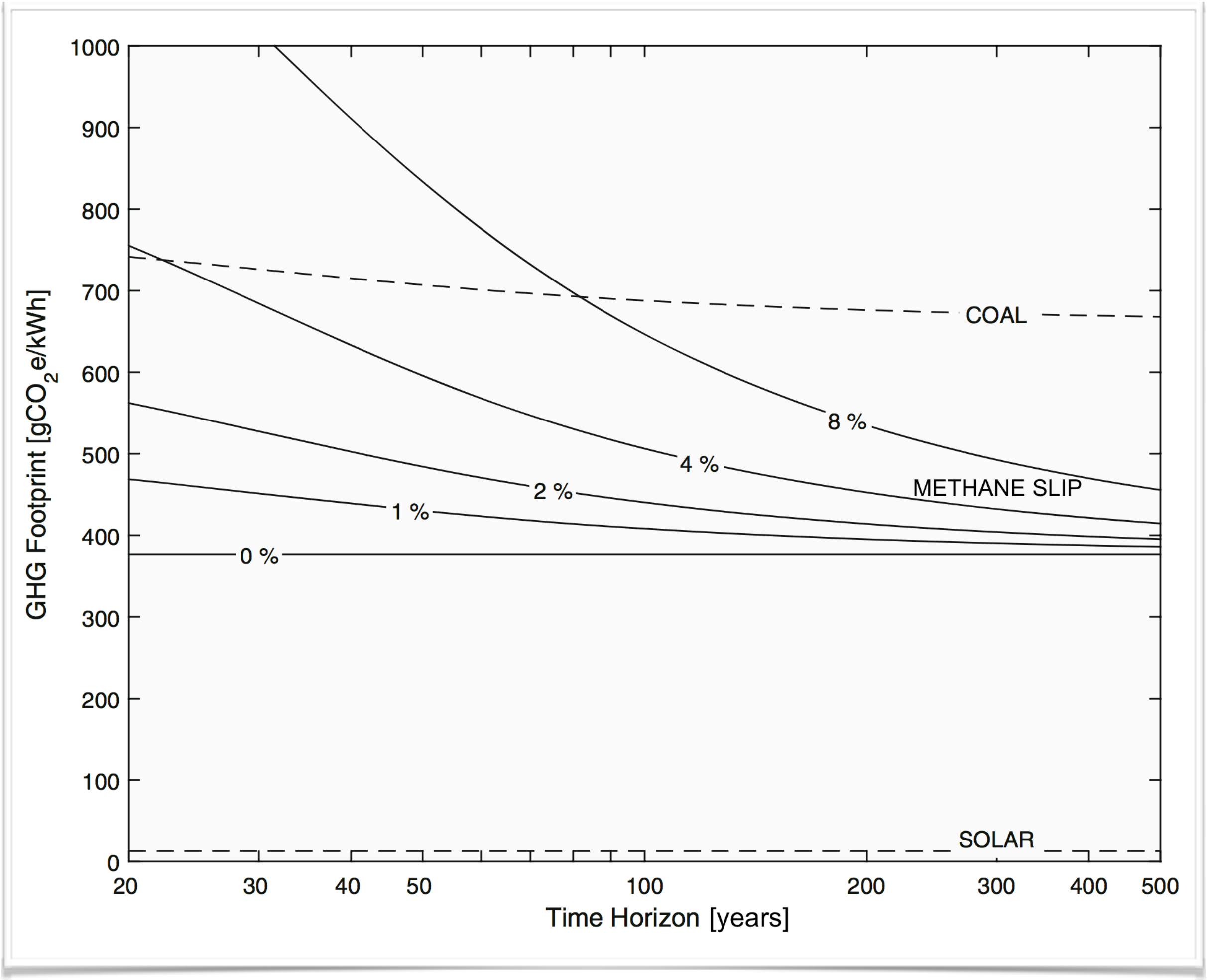

Figure 3.8 - Comparison of Green-House Gas Footprint from Different Energy Sources (Sanchez & Mays, 2015, p. 175)

Scientists have also tried to develop single-technique solutions to clean exhaust gasses, though, none of them have been able to properly deal with the whole spectrum in one take.

4. The Proposed Hybrid Technology

The latest global restrictions on air pollution from ships focus on SO_X, PM and NO_X emissions and that is the reason why research is being done to find a universal solution to deal with all these limitations with new effective technological solutions. One of the approaches is to incorporate an EB technology into the well-known wet scrubber system.

This EGC method has been developed by an international group of maritime-related companies and research institutions under a project called Accelerator Research and Innovation for European Science and Society (ARIES), hosted by the European Organization for Nuclear Research (CERN) (Vretenar, 2019). The potential of this EGC arrangement was proven, and now continues its development under the Hybrid Exhaust-gas-cleaning Retrofit Technology for International Shipping (HERTIS) project, organized by Riga Technical University (HERTIS, 2019).

Exhaust gasses have been cleaned with the help of EB irradiation at coal-fired power plants for several decades now, which was first presented in Japan in the 1970s (Chmielewski, Zwolińska, Licki, Sun et al., 2018, p. 1). Today, Poland generates 90% of its electricity by burning coal, and the exhaust gasses are cleaned by using EB irradiation and ammonia, which turn them into fertilizer (Jawerth, 2015, p. 12). Industrial-scale electron beam EGC systems have also been widely applied in China and Japan for fossil fuel power plants (Park, Ahn, Kim, & Son, 2019, pp. 360-361). The technology has been also used at sewage treatment facilities to neutralize harmful organic impurities (Han, Kim, Kim, Kim et al., 2006).

A project named DEECON, in 2014, incorporated EB irradiation in a wet scrubber system for ships. The series of experiments in this project revealed the potential of this kind of solution for exhaust gas treatment exceeding 90% reduction in all the regulated emissions, but only for a short time period because of issues in plasma stability (Balachandran, 2014).

4.1. Technological Process

The concept of the proposed technology here has been designed by learning from previous tries of applying EB technology in EGC systems on sea-going vessels. Most of the focus is put particularly on the performance of the particle accelerator and its effect on the processes in the wet scrubber.

The exhaust gasses are first irradiated by the EB from the particle accelerator to oxidize SO_X and NO_X to higher oxides, then the gasses are passed through a wet scrubber tower, where the soluble formations are dissolved, and, lastly, the wash water is separated from solid particles and discharged overboard, while monitoring the pH level, or is collected in a holding tank, please see Figure 4.1 for a schematic description (Licki, Pawelec, Zimek, & Witman-Zając, 2015, pp. 692-693).

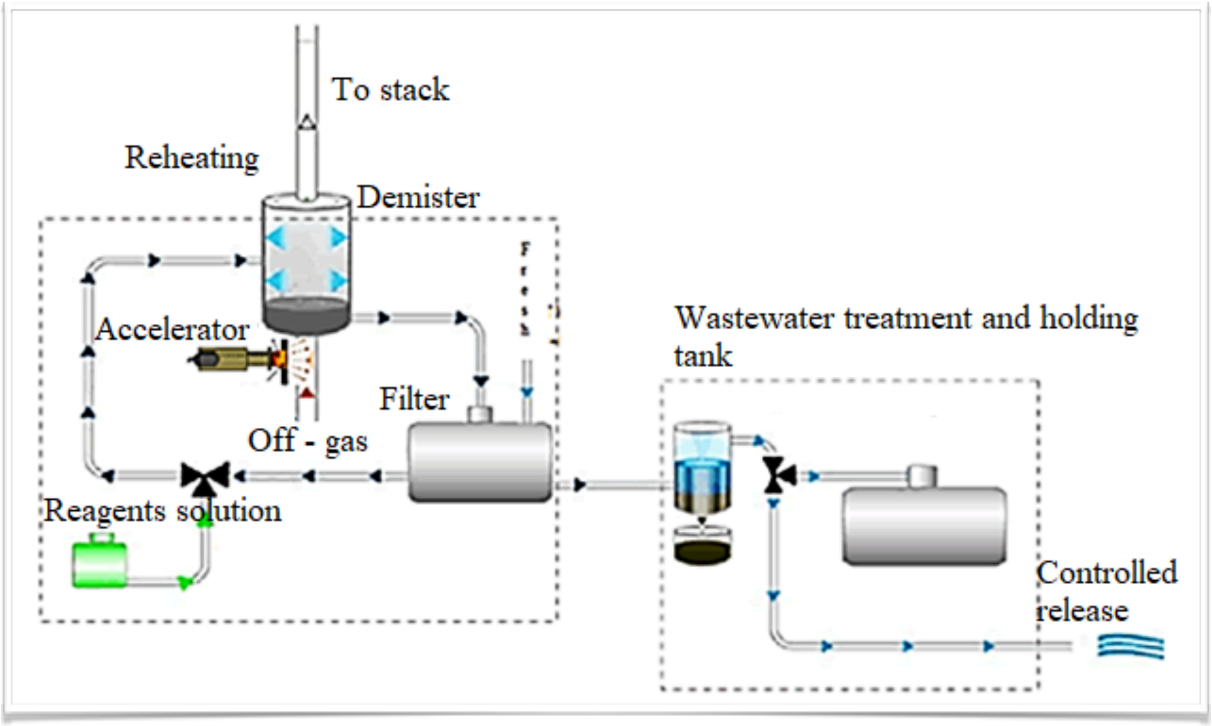

Figure 4.1 - Conceptual Work Scheme of the Proposed Hybrid Technology
(Siwek & Chmielewski, 2018, p. 69)

Particle accelerator

Experiments so far have shown difficulties to maintain a stable plasma distribution, which brings challenges for the whole system to operate sufficiently on continuous basis in a dynamic and spatially limited environment. A low-energy toroidally shaped particle accelerator has been developed and patented by Fraunhofer-Gesellschaft, a participant of the HERTIS project (Mattausch, Feinäugle, Kirchhoff, Rögner et al., 2015). This particle accelerator uses annular cold cathode, which requires a less sophisticated high-voltage power supply and can operate in soft vacuum (Sokovnin & Balezin, 2017, p. 82). The radially accelerated flux of electrons ensures their homogeneous distribution and higher overall radiation absorption for the exhaust gasses over the whole cross section of the exhaust duct, please see Figure 4.2.

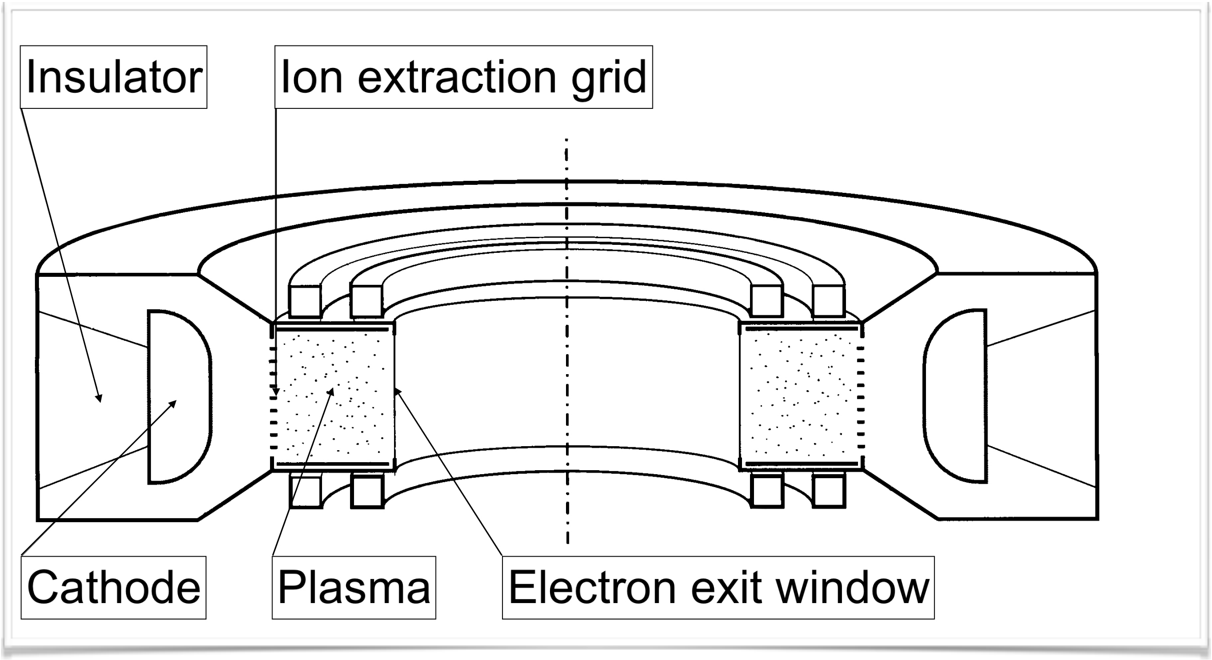

Figure 4.2 - Design of the Toroidal Particle Accelerator
(Mattausch, Feinäugle et al., 2015)

Upon interaction with the exhaust gasses, the EB generates cold plasma and its energy is deposited in the main components of the gas - nitrogen, oxygen, water vapour and CO_2. Then, the formed ions and free radicals lead to oxidation of SO_2 and NO, which compose 95% of the exhaust gasses, and form water-soluble substances - sulphur trioxide SO_3, sulfuric acid H_2SO_4 and nitrogen dioxide NO_2, nitric acid HNO_3 (Chmielewski, Zwolińska et al., 2018, pp. 3-4). The irradiation process also converts volatile organic compounds (VOC) and charge particulate matter to increase their collection rate in the scrubbing zone.

Wet scrubber

The application and options of wet scrubber systems have been discussed in the previous chapter and, naturally, a hybrid wet scrubber (open/closed loop) system is used here to be able to legally operate in territorial waters and ports and to control the physical and chemical parameters of the wash water. If necessary, the content of the scrubbing liquid can be adjusted to increase removal efficiency of other targeted emissions. Figure 4.3 summarizes the chemical processes during the hybrid exhaust gas treatment. The absorbed particles in the water are separated and stored as sludge for disposal. The dissolved sulphates and nitrates may be used as fertilizers in horticulture and farming.

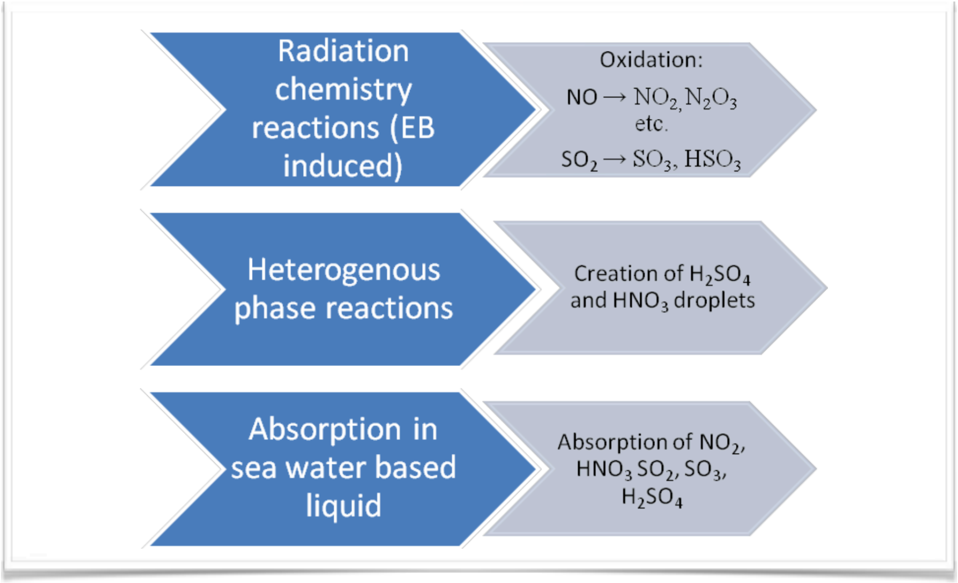

Figure 4.3 - Reaction Processes in the Proposed Hybrid Technology
(Pawelec, Burliński, Dobrowolski, & Chmielewski, 2019, p. 8)

Efficiency variables

The wet scrubber itself is a great sulphur abatement technology already, but the EB gives it also decent NOx removal capabilities, as well as treatment of VOCs. The Institute of Nuclear Chemistry and Technology in Warsaw has been extensively researching this hybrid system to optimize its operation in marine environment.

Studies have shown that increased SO_2 concentrations in the exhaust gas actually raises the removal efficiency of NO_X in the EB process. This can be seen in Figure 4.4.

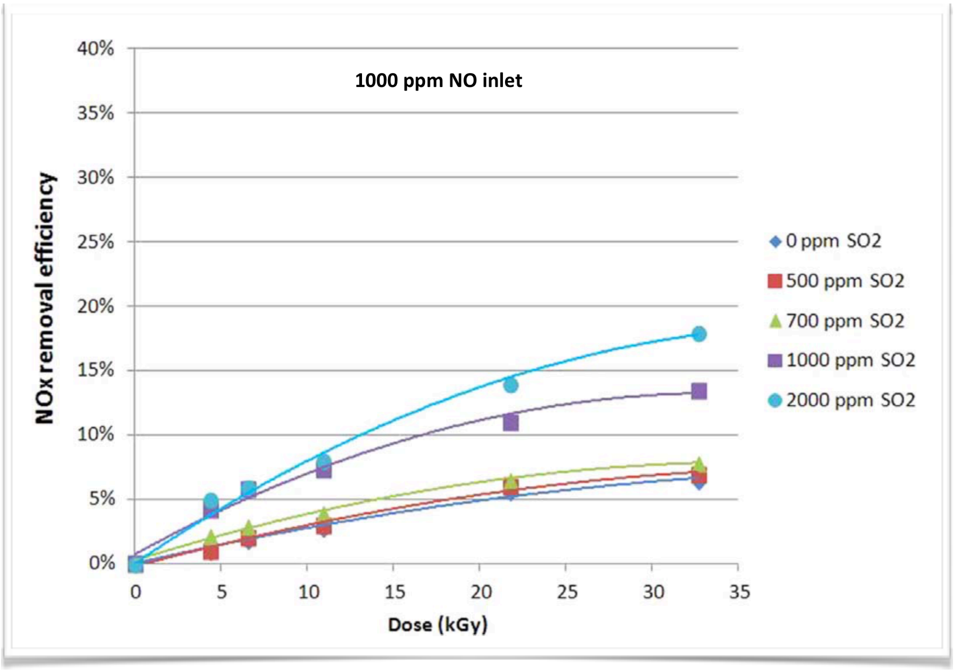

Figure 4.4 - SO_2 Influence on NOx Removal Efficiency in EB Process
(Chmielewski, Zwolińska et al., 2018, p. 3)

This phenomenon is explained by the presence of hydroperoxyl radicals, which form during the EB reaction with SO_2, and oxidize NO to NO_2 (Chmielewski, Zwolińska et al., 2018, p. 3). This shows that high-sulphur fuels are particularly compatible with the EB technology to remove NO_X emissions.

On the other hand, an increase of NO inlet concentration has adverse effects on removal of SO_2, seen in Figure 4.5. A theory that stands behind this is the competition of NO_2 and SO_2, while attracting OH radicals during the oxidation, where NO_2 has a higher reaction rate constant, thus, dominating over SO_2 (Chmielewski, Zwolińska et al., 2018, p. 4).

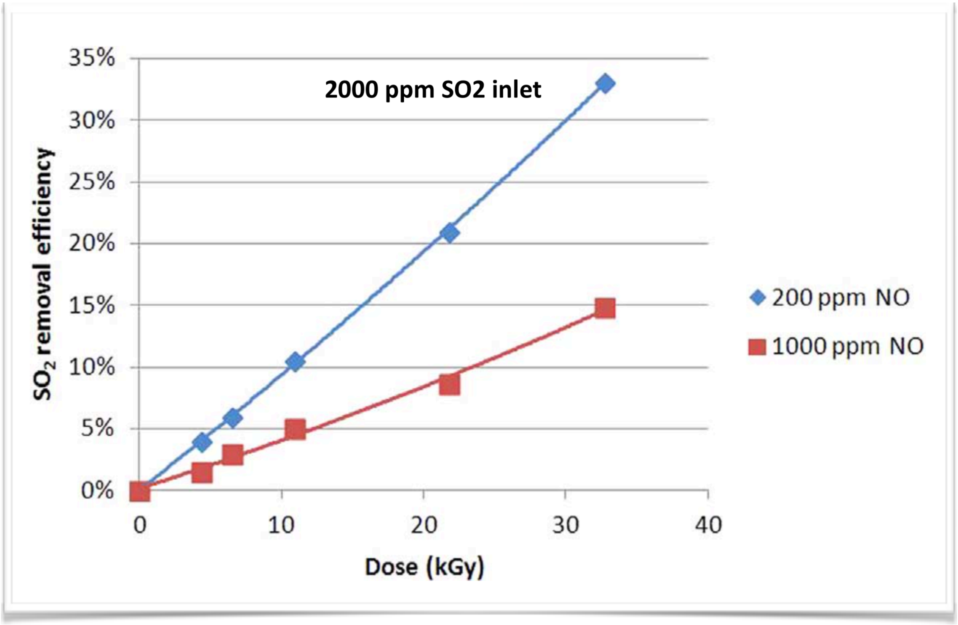

Figure 4.5 - NO Influence on SO_2 Removal Efficiency in EB Process (Chmielewski, Zwolińska et al., 2018, p. 4)

Pretty self-explanatory is the fact that increased NO inlet concentrations reduce NO removal efficiency, just like high SO_2 concentrations result in its own low removal efficiency, which can be compensated with higher irradiation doses, though, until a certain point (Chmielewski, Zwolińska et al., 2018, p. 4).

A slight increase in NO_X and SO_2 removal efficiency was also achieved by adjusting the exhaust gas temperature, which was tested in the amplitude of 70°C-90°C, if the EB would be working in conjunction with the wet scrubber (Chmielewski, Zwolińska et al., 2018, p. 4).

As expected, the overall efficiency of emission removal enhances, when the exhaust gasses, after irradiation, were passed through the wet scrubber using simulated seawater. Figure 4.6 shows a significant increase in NO_X removal, when the NO inlet concentration is

1500 ppm, which is a realistic number for a typical slow-speed two-stroke marine engine (Woodyard, 2009, p. 62). Although NO_X removal does not exceed 50%, it has been reached at relatively low irradiation dose of less than 10*kGy* and using seawater as the scrubbing agent.

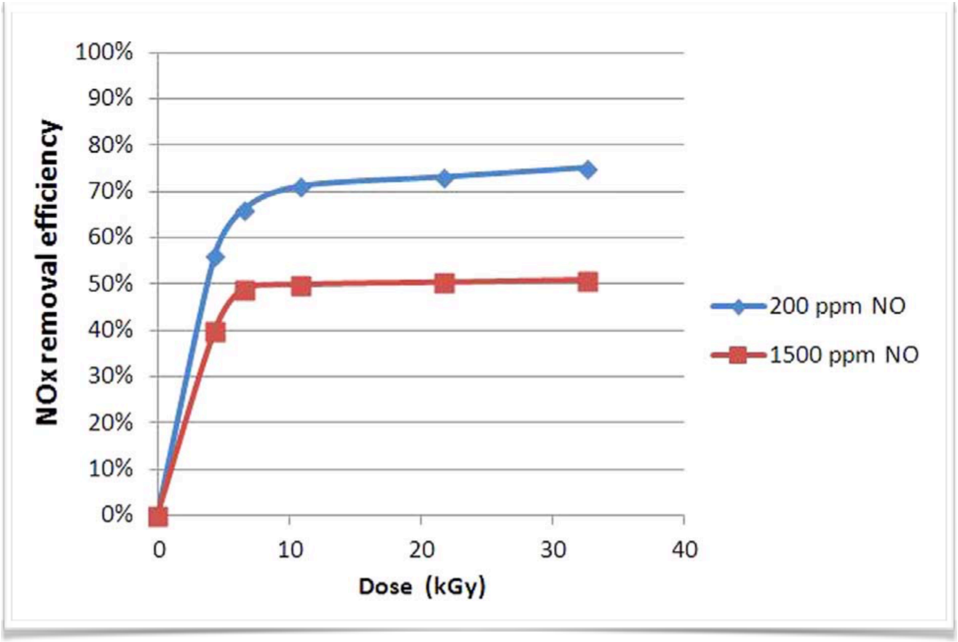

Figure 4.6 - NO Influence on NOx Removal Efficiency in Hybrid Process
(Chmielewski, Zwolińska et al., 2018, p. 5)

A similar trend was observed for SO_2 removal, in Figure 4.7, where the optimal efficiency was achieved at little bit over 10*kGy*.

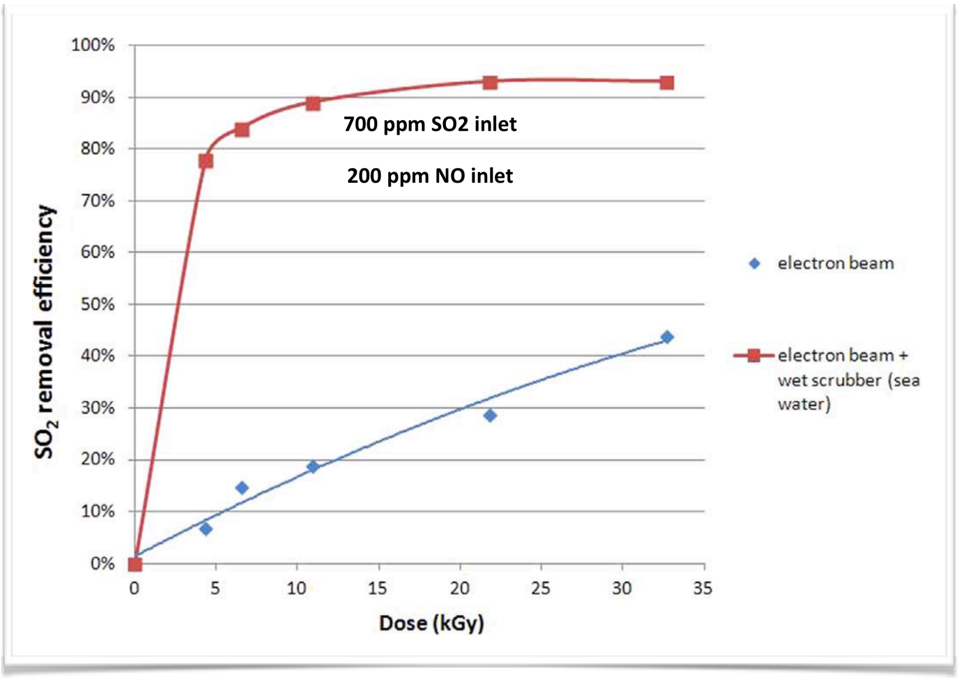

Figure 4.7 - SO_2 Removal Efficiency in Hybrid Process
(Chmielewski, Zwolińska et al., 2018, p. 5)

These laboratory tests have indicated the variables in exhaust gasses that tend to work for and against optimal removal efficiency of the whole EGC set-up. While increased sulphur concentration in the exhaust gas supports the work of electron beam fighting NO_X compounds, an increase in NO sets back the abatement efficiency. Similar observations were noticed for the exhaust gas temperature, where higher temperatures increase NO_X reduction, but decrease SO_2 removal efficiency. This requires individual approach for each engine and fuel type to be used, to achieve the optimal results.

4.2. Proof of Concept

The technical efficiency and financial feasibility of the proposed method has been addressed through the ARIES project, where a test was carried out on tugboat "Orkans" at Riga Shipyard in June 2019 (Vretenar, 2019).

A note to make before discussing the results is that the tested particle accelerator was not specifically made for dealing with exhaust gasses from burning heavy fuel oils but for seed sterilization, which does not have the toroidal design, described in the previous subchapter. The EB was generated using a particle accelerator with linear cathode along the exhaust duct, which was applied from one side only due to technical issues (Pawelec, Burliński et al., 2019, p. 14). Also, the wet scrubbing took place in a packed absorption column in the exhaust duct without oxidant spray applied, unlike it is intended in the conceptual design (Pawelec, Burliński et al., 2019, p. 16). Port of Riga is located in the Baltic Sea sulphur ECA, which does not allow the use of fuel with the sulphur content higher than 0.10% m/m, so, marine gas oil was used. Because of that, the focus was put on reduction of NO_X emissions, which will be relevant from 1 January 2021, when the Baltic Sea and North Sea ECAs will take on the IMO NO_X Tier III standards.

The exhaust gas was generated from two two-stroke diesel engines on the tugboat. Water spray coolant was applied to decrease the exhaust gas temperature for protection of the EB window (Pawelec, Burliński et al., 2019, p. 15). The Baltic Sea water was used as the scrubbing medium in a closed loop while adding sodium hydroxide, to keep the pH level above 7.5, and sodium chlorite oxidant, to increase NO_X removal efficiency (Pawelec, Burliński et al., 2019, p. 22). Figure 4.8 lays out the arrangement of the test site.

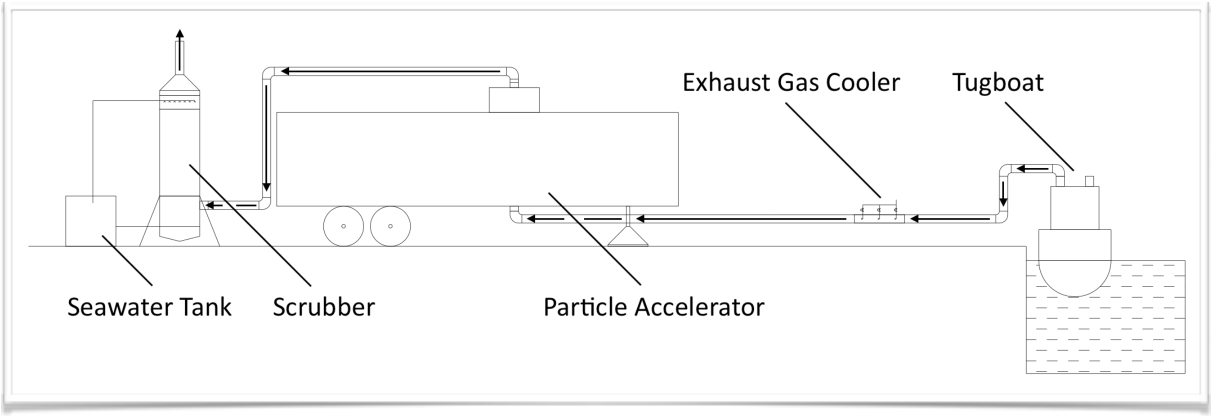

Figure 4.8 - Test Site Arrangement
(Pawelec, Burliński et al., 2019, p. 15)

During the tests, velocity, temperature and content of the exhaust gas were measured for three different engine loads - 0% (idle), 50% (half load) and 100% (full load) - while oxidant was added proportionally to the corresponding engine loads - 0.0*mg/l*, 1.0*mg/l* and 3.3*mg/l* (Pawelec, Burliński et al., 2019, p. 22; 27).

Since the fuel contained basically no sulphur at all, which would have helped in NO oxidation and NO_2 absorption respectively, theoretical calculations were added taking the factual NO_X removal efficiency trend and other measurement data into account to model possible removal efficiency, if the toroidal particle accelerator and a high efficiency wet scrubber were used.

High oxygen concentrations in the exhaust gas were observed, especially when the engines were idling. This was explained by the fact that these old-design engines work in high air excess regardless of the engine load (Pawelec, Burliński et al., 2019, p. 28). The measured parameters of the hybrid EGC system in details are shown in Appendix A and Appendix B.

Figure 4.9 shows some dependence of NO_X removal rate on the engine load and irradiation dose, which did not exceed 5.7*kGy* and was applied from one side of the exhaust duct only (Pawelec, Burliński et al., 2019, p. 28).

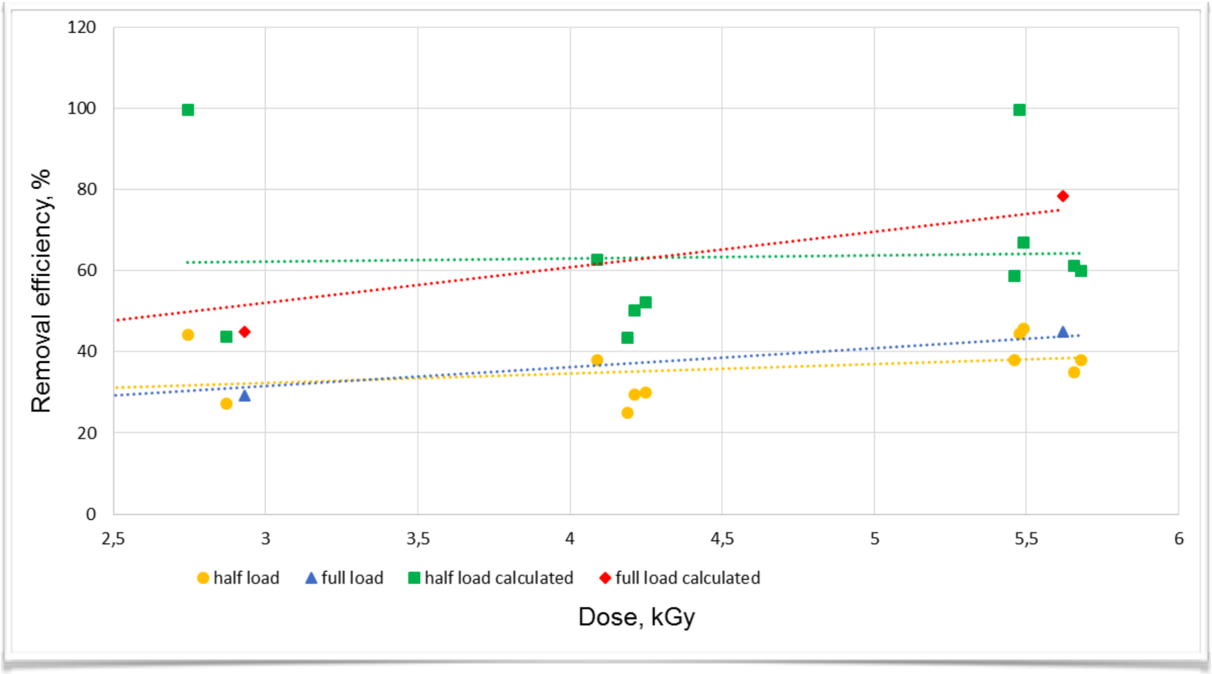

Figure 4.9 - Irradiation Dose and Engine Load Influence on NOx Removal
(Pawelec, Burliński et al., 2019, p. 31)

The strongest influence on NO_X removal was observed with the increase of the oxidant concentration, which was increased together with the increase of the engine load, seen in Figure 4.10.

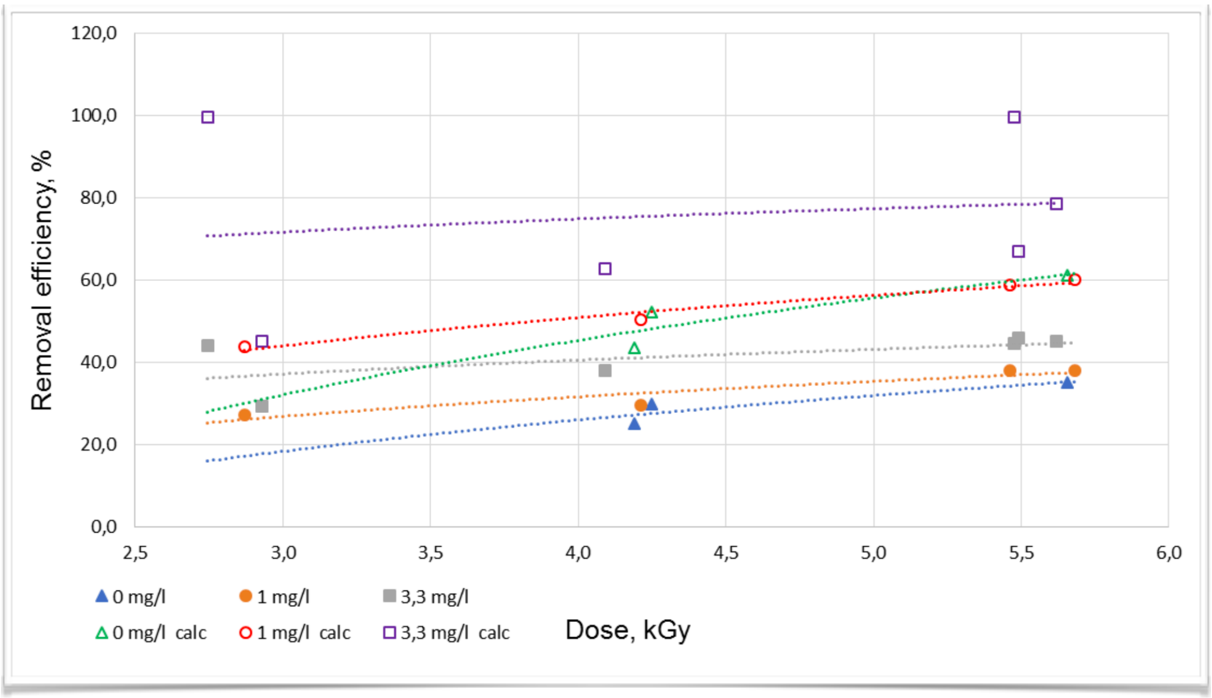

Figure 4.10 - Irradiation Dose and Oxidant Concentration Influence on NOx Removal
(Pawelec, Burliński et al., 2019, p. 31)

Although the factual results at full engine load and high oxidant concentration show NO_X removal efficiency of little bit over 40%, the efficiency of the EB shall be evaluated by the NO removal efficiency, which forms around 95% of NO_X anyway. Figure 4.11 shows that the EB does a decent job in removing NO. There was noticed some inconsistency in the NO removal efficiency, that is explained by the arrangement of the single linear-cathode particle accelerator, which would mostly excite those exhaust gas particles being closer to the EB window and not reach the ones on the other side of the exhaust duct (Pawelec, Burliński et al., 2019, p. 23).

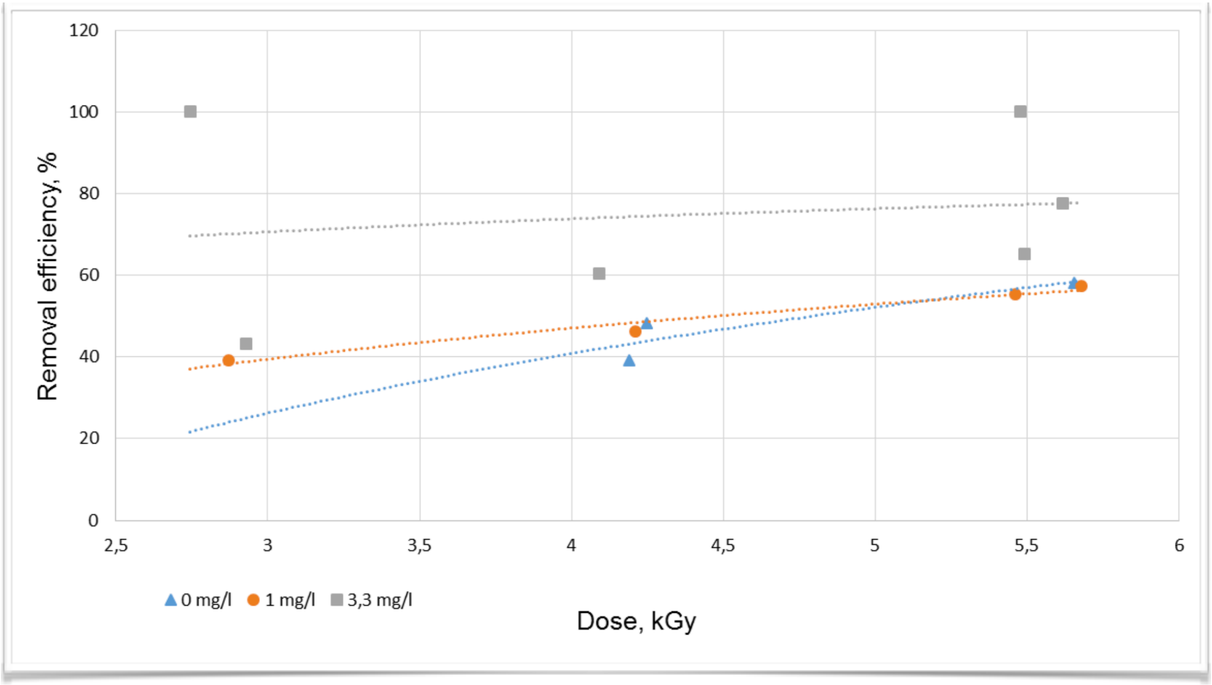

Figure 4.11 - Irradiation Dose and Oxidant Concentration Influence on NO Removal (Pawelec, Burliński et al., 2019, p. 32)

Exhaust gas temperature is another variable that, although negligibly, still decreases the NO_X removal efficiency with its increase, which coincides the laboratory results from the Institute of Nuclear Chemistry and Technology in Warsaw, discussed in the previous subchapter. Such comparison was also made for the overall performance of the tested EGC system. Figure 4.12 shows that the experiment carried out at Riga Shipyard corresponds closely to the laboratory experiment at the given irradiation dose, assuming that the oxidized NO molecules would have been absorbed properly by the wet scrubber. Though, the optimal irradiation dose, according to the laboratory tests, is approximately $10kGy$. The measured and calculated removal efficiencies in details are shown in Appendix C.

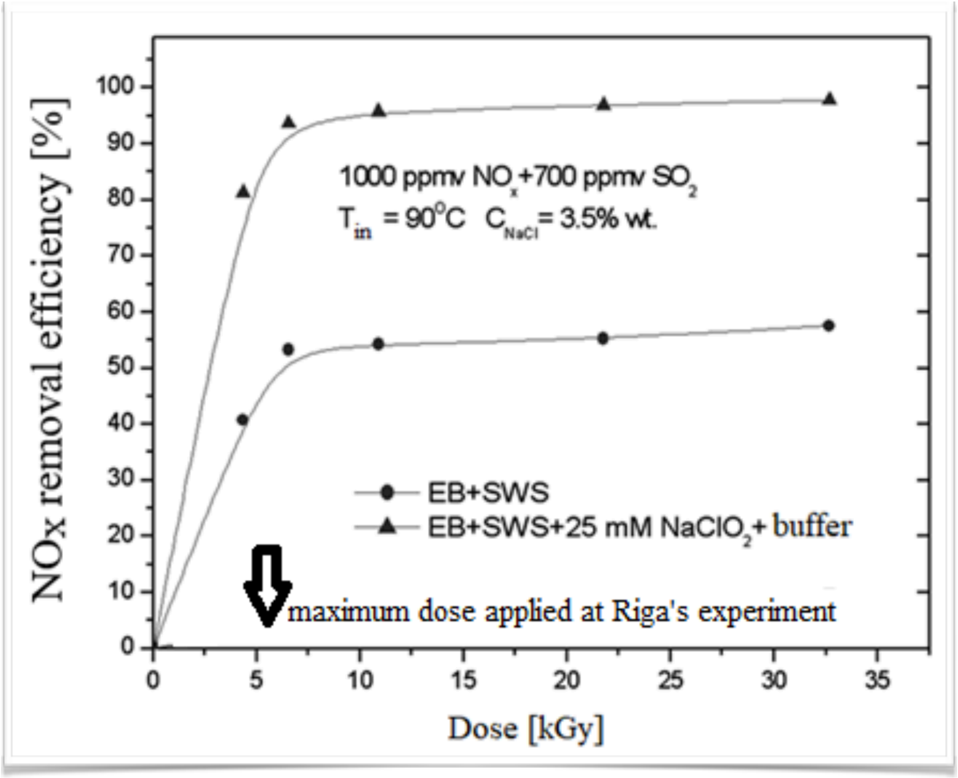

Figure 4.12 - Laboratory Results and its Take from the Experiment at Riga Shipyard (Pawelec, Burliński et al., 2019, p. 40)

The effectiveness of the hybrid technology is dependent on the performance of the engine, fuel content and physical exhaust gas parameters. Further tests are required to prove the capability of removing VOCs as well, which are believed to become as restricted pollutants in the near future. Besides that, the whole system has to be installed and tested on an actual ocean-going vessel while en route, which is the objective of HERTIS project.

The proof of concept was also supported by doing accounting on investment profitability of this hybrid EGC system. The strongest argument for the choice of EGC systems in a long run is the price difference between residual and distillate fuel oils and operational costs for a given time period. But competition between the different EGC systems mainly considers initial and operational costs and some conveniences regarding the technical and commercial nature of the vessel. The investment analysis was carried out for three scenarios - optimistic, pessimistic and optimal. For the optimal scenario the investment value was approximated to 7'000'000€, a price difference of 200€/*t* between high and low-sulphur fuel oils was taken and a 3% increase in the total energy consumption was assumed (Pryzowicz, 2019, p. 27). This resulted in two years to get to the break-even point (Pryzowicz, 2019, p. 29). Detailed input parameters of the calculations are shown in Appendix D.

4.3. Integration on Board

To install such a solution on a ship as a retrofit option, there are also other obstacles besides the technical performance. Safety is definitely the number one priority for integration of a particle accelerator on board.

Stability of the vessel

First of all, the system has to be fitted in the funnel room, which might be physically challenging for smaller vessels, knowing that the supporting machinery of the wet scrubber like pumps, fans and valves have to be backed up by duplicates, which ensure at least 100% of the required work capacity (American Bureau of Shipping, 2020, §4.9.1-iii). In addition, vessels with low initial stability may not be legally able to install such a system onboard. This is connected with the introduced mass of the whole system, which may impede the vessel's stability and exceed the maximum allowable figures in stability reduction. The International Association of Classification Societies has agreed on the following limits, noted in Table 4.1.

Table 4.1 - Main Acceptable Tolerances to Ship's Stability
(Panasiuk, Lebedevas et al., 2018, p. 202)

Limiting Parameters		Maximum Allowable Figures
Lightship weight	$m_{lightship}$	2.0%
Centre of gravity	δX_{CG} δY_{CG} δZ_{CG}	1.0% or maximum 50 cm 0.5% or maximum 5 cm 1.0% or maximum 5 cm
Draught midships	T_{MD}	1.0% or maximum 5 cm
Metacentric heights	GM_L GM	1.0% or maximum 50 cm 1.0% or maximum 5 cm
Trimming angle	θ	1.0%
Heeling angle	φ	Not allowed

Electricity

The particle accelerator operates on high voltage electricity, which requires an appropriate electricity generator, transformer, converter and other installation parts of the supply system, facing higher safety requirements for operation, maintenance and materials used in the electrical units. Part 4, Chapter 8, Section 1 of the International Convention for the Safety of Life at Sea (SOLAS) defines high voltage as between $1kV$ and $15kV$, but the voltage, that the toroidal particle accelerator requires, exceeds $100kV$ (Mattausch, Feinäugle et al., 2015). It means that accepted practices from other regulatory bodies have to be implemented before such a system can be used in the international shipping. Some classification societies have established rules for such high-voltage installations in the offshore and power industry, but, still, referring to standards from other globally recognized organizations like the International Organization for Standardization, the International Electrotechnical Commission and the International Council on Large Electric Systems.

Materials of electrical machines have to be resistant to humid, salty and dusty environment and fire retardant (DNV GL, 2015, §3.2.3). Humidity is a great danger for high voltage systems because of the possible unwanted arcing between connectors. Most attention has to be paid to switchgear, which require vacuum or dielectric gas connectors with additional monitoring (DNV GL, 2015, Section 6). The arcing also leads to increased clearance distances, advanced insulation materials and more sophisticated cooling systems (DNV GL, 2015, §5.2.1). An increased distance is also necessary to keep from other machinery nearby because of the electromagnetism, which may cause malfunction (DNV GL, 2015, §12.2). Not only the ambient atmosphere content may damage the machinery but also physical forces like vibration and inclination. High voltage systems are prone to changes in the power supply, this require specific surge arresters and fire extinguishing agents (DNV GL, 2015, §10.3.11; §4.4). Like for the majority of critical equipment on ships, redundancy of power supply has to be ensured, which could lead to duplication of some machinery. As for the occupational safety, higher safety class personal protective equipment shall be used by the personnel working on such machinery.

Radiation

Protection against the ionizing radiation in the maritime context is not addressed as detailed as the electricity because of the small number of applications. It has been relevant just for nuclear powered vessels and vessels carrying irradiated substances. These subjects are briefly regulated in SOLAS and in the Code of Safety for Nuclear Merchant Ships, passing specific matters to flag states. Clearly, it requires rules to be implemented in the maritime industry for the use of particle accelerators on board merchant vessels for societal applications. Today, particle accelerators are used in science, medicine, industrial processing, sterilization, public security and other practical applications, like non-destructive testing which has been used in the offshore industry for the inspection of subsea installations.

In Europe, an international treaty has been adopted by the countries of EU, Switzerland and United Kingdom, establishing the European Atomic Energy Community where basic standards are given for safe procedures involving radiation (The Council of the European Union, 2013). A more global organization called International Atomic Energy Agency has gone deeper into the topic with series of safety standards concerning radiation risks.

First, the choice of shielding for the particle accelerator is an important factor in protection against radiation. Popular shielding material is lead due to its high density and availability, but it has a drawback for this particular application because of its low melting point at 327.4°C (Cossairt, 2016, p. 158). Alloys containing metals with high melting point and high density shall be used for this purpose.

The radiation levels have to be continuously monitored in the compartment where the particle accelerator is installed. The compartment has to be sealed and classified as enclosed space to avoid any leakage of radiation that could contaminate the air in the accommodation areas and workplaces. The space has to be equipped with adequate capacity exhaust fans and high efficiency particulate air filters to ensure fresh air in the compartment during maintenance (International Atomic Energy Agency, 2018, p. 232).

Some of the accessible spots on the particle accelerator itself have to ensure their tightness and endurance against vibrations, changes in the ambient air characteristics and the possible physical and chemical parameters of the exhaust gasses to prevent leakage of radiation and ingress of other environment into the electrically exposed compartments. An independent fixed fire extinguishing system, dedicated to the particle accelerator, shall be at the place of its operation. To avoid any unwanted excess of radiation, in case of an emergency, the particle accelerator shall have an automatic circuit breaker. During maintenance jobs, the involved personnel must be wearing appropriate personal protective clothing and equipment.

Energy consumption

Other than the safety concerns, additional energy consumption of this appliance is another key factor when deciding, whether to choose the hybrid EGC system as the compliance method or not. The required energy consumption from this system has to be worth it for the job it does, comparing with other EGC systems. When planning to retrofit a vessel, an answer has to be sought, whether an additional diesel generator will have to run to support the whole EGC system, which would introduce a financial step cost to operate the vessel.

4.4. Development Process

So far, the new technology has proven its conceptual abilities and work is being done on designing a prototype of the whole hybrid EGC system, which is to be tested on board a vessel. Since the hybrid technology has to be certified by a recognized classification society, before it can be legally installed and operated, guidelines for development of new technologies (American Bureau of Shipping, 2017) are followed. The guidelines from American Bureau of Shipping are referred here because the project refers to these guidelines. Other classification societies, for example, DNV GL, also have such guidelines for development of new technologies.

According to the scheme of new technology qualification process, in Figure 4.13, the initialization stages and the first verification stage have been done.

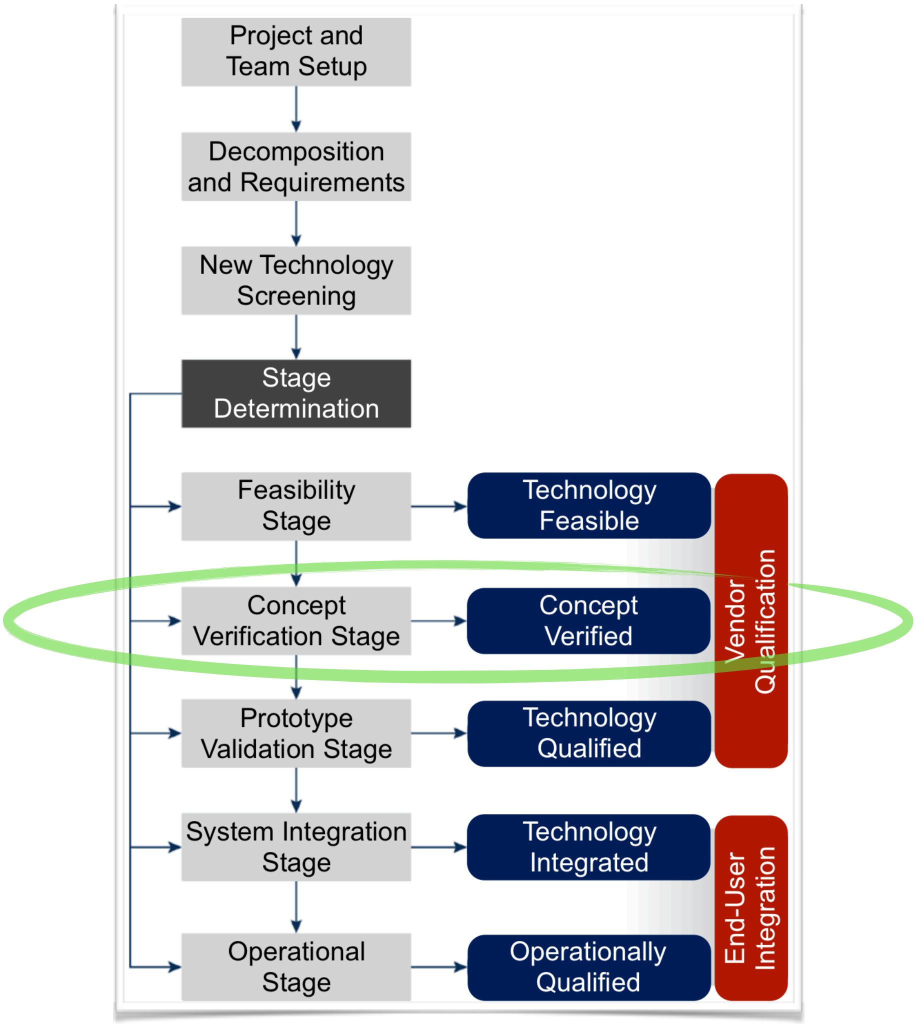

Figure 4.13 - New Technology Qualification Process
(American Bureau of Shipping, 2017, p. 3)

The initialization stage involves setup of team, covering technological, academic, safety, quality, financial, organizational and legal support. It follows by creation of a research and development proposal, addressing the novelty of the technology and its objectives. The first verification stages consist of feasibility approval by theoretical simulations of the technology, a preliminary design plan and risk assessment (American Bureau of Shipping, 2017, p. 19). Next, the concept verification stage takes place, where the theoretically described technology is tested for its performance in controlled conditions (American Bureau of Shipping, 2017, p. 21). This stage has been done in laboratory tests and the practical demonstration at Riga Shipyard, though, not exactly with the proposed equipment, which has to be tested before moving to the next stage - validation of the prototype.

The development of this technology is supported by a multi-disciplinary group of academic and research institutions, maritime-related companies and classification societies from different European countries. Riga Technical University organizes and administers the processes of the project. Fraunhofer-Gesellschaft and CERN work on the particle accelerator technology. Institute of Nuclear Chemistry and Technology in Warsaw has done extensive research on the electron beam applications in exhaust gas treatment and supports the partners with the technical evaluation. Ecospray Technologies manufactures exhaust gas treatment systems and provides a high-efficiency wet scrubber to work in conjunction with the particle accelerator. Grimaldi Group provides a motor vessel for the prototype to be tested on. Remontowa Shiprepair Yard has expertise in ship retrofits and advises on technical solutions for integration of the hybrid EGC system on board a vessel. American Bureau of Shipping (Europe) and Registro Italioano Navale are the legal advisors of this project, dealing with maritime-juridical matters for successful integration of the system. University of Tartu manages the intellectual property and dissemination of public information within the project frame. KPMG Baltics and Biopolinex perform economic and financial analysis and maintain effective dissemination activities and communication with stakeholders. Western Norway Research Institute has been researching air pollution and has developed a model to track emissions from ships using information from Automatic Identification Systems (AIS) and linking that with relevant databases (Simonsen, Walnum, & Gössling, 2018). Within development of this project, a life-cycle assessment is performed for the environmental impact of the hybrid EGC technology.

5. Analysis of the Technology Development

The proposed hybrid technology is still at development. The results from proof of concept within the ARIES project have shown an actual potential in real conditions, although it was not done under the best circumstances. HERTIS goal is to develop a compliant EGC system prototype and prove the concept of the technology on board a vessel while en route (HERTIS, 2019). The proof is supported by three key accomplishments - first, that it works; second, that it is safe; third, that it is feasible.

Regardless of the development stage, an analysis of different factors has to be carried out to avoid obstacles in the proceeding design phases or at least to have a plan of corrective actions to conquer them. The analysis is done for the current and the following technological development stages, considering internal and external factors and the probable impact on the technology. The analysis also includes possible impact on the maritime industry from a fully developed and commercially ready technology.

To do the analysis of the hybrid technology, widely used analytical templates are used. To cover as many different risk factors as possible, the PESTLE analysis technique is applied, which concerns Political, Economic, Social, Technological, Legal and Environmental factors (PESTLEAnalysis.com, n.d.). The SWOT template is used to group Strengths of the technology and its introduction into the maritime industry after complete development, which would lead to Opportunities, but on the other hand, Weaknesses are counted in to picture the possible Threats to the technology (PESTLEAnalysis.com, n.d.).

5.1. Technology Development Risks

Since the development of the proposed technology has reached the stage of concept verification, a preliminary risk assessment has been carried out already, also noting experience from some of the previous projects, where EB technology has been involved. Table 5.1 sums up probable risks for further development and introduction of this technology to the maritime industry. The risks are evaluated and addressed with respective mitigating actions. Some of the risks here are interconnected, where one risk may be the cause for another risk factor to occur. The Likelihood and Impact columns have two positions - before the mitigating action, at the top, and after the action has been applied, at the bottom.

Table 5.1 - PESTLE Analysis for the Hybrid Technology Development and Introduction

Risk	Action	Likelihood *before* *after*	Impact *before* *after*
Political Factors			
Unexpected changes in the maritime regulations.	Consistent tracking of global, regional and national legal requirements is maintained, so that respective decisions can be considered as soon as possible.	low ↓ low	high ↓ medium
Flag states put ban on the discharge of scrubbing water in their territorial waters.	A high-efficiency wet scrubber is developed, which is capable of working in closed-loop mode.	medium ↓ medium	medium ↓ low
Flag states do not ratify new rules for the use of particle accelerators on board vessels.	The technology development is carried out according to guidelines from internationally recognized organizations. The involved risks are identified and appropriately addressed. The technology is presented at national and international maritime conferences.	medium ↓ low	high ↓ high
Economic Factors			
The dedicated funding for the project is not sufficient to address all the technological challenges and to cover all equipment costs during development.	Project partners thoroughly consider costs and consult experts, possible vendors and suppliers to confirm assumptions. The involved parties ensure financial support to provide additional funds if necessary.	medium ↓ low	high ↓ medium
Due to technological and legal factors, the initial costs of the hybrid EGC system increase.	Monitoring of all the changes in the development process and estimation of costs in financial analyses is carried out for further decision making. Close contact is maintained with the policymakers to ensure high integration level of the hybrid technology.	medium ↓ medium	medium ↓ low
Due to political and legal factors, the operational costs of the hybrid EGC system increase.	Sensitivity analysis is used to determine, whether it is feasible for the particular motor vessel to use the hybrid technology before a retrofit project.	medium ↓ medium	medium ↓ low
Low price difference between residual and distillate fuel oils. The hybrid EGC system is not competitive.	Due to the fact that many fuel price oscillations are imposed by political disputes, the project team has no force to act against that. Sensitivity analysis is used to determine whether it is feasible for the particular motor vessel to integrate the hybrid EGC system before a retrofit project.	medium ↓ medium	high ↓ high

Table 5.1 continues - PESTLE Analysis for the Hybrid Technology Development and Introduction

Risk	Action	Likelihood *before* *after*	Impact *before* *after*
Social Factors			
Safety concerns about the operation of the particle accelerator from public organizations or trade unions may cause contradictory comments.	A series of testing to ensure the safety and efficient operation capacity in maritime environment is monitored. Classification-approved risk assessments for failure and hazard identification are applied.	medium ↓ low	medium ↓ low
Crew unfamiliarity with the operation and maintenance procedures of the hybrid EGC system.	Flag State approved procedures for safe installation, operation and maintenance of the hybrid EGC system are prepared. An approved safety training programme for seafarers is developed.	high ↓ medium	medium ↓ low
Low acceptance of the technology by the maritime industry.	Close communication with stakeholders is maintained. The system is presented at maritime conferences, exhibitions and relevant publications.	medium ↓ low	medium ↓ medium
Technological Factors			
The layout of a vessel may not allow appropriate installation of the system.	Detailed layout and arrangement plan of the vessel is shared in the beginning of the design stage. This is followed by 3-dimensional scanning of the installation space and respective computer modelling.	medium ↓ low	high ↓ medium
Smaller size vessels may not be able to install the hybrid EGC system as a retrofit solution due to space requirements and additional mass.	The hybrid technology is promoted to marine engine and ship-building companies to integrate this technology into design of the engine and its auxiliary machinery to optimize space and weight.	high ↓ medium	medium ↓ medium
Vessels carrying dangerous cargo are subjects to higher safety standards, which may bring obstacles for the integration of the particle accelerator.	The risk assessments and hazard identification tools shall also refer to requirements for safe storage and handling of dangerous substances that may trigger chain reactions.	high ↓ low	medium ↓ low
Increased downtime of a vessel due to planned maintenance tasks of the hybrid technology.	The system is developed to ensure ergonomic and safe access to change modular components of the system according to the established risk assessments.	medium ↓ low	medium ↓ medium

Table 5.1 continues - PESTLE Analysis for the Hybrid Technology Development and Introduction

Risk	Action	Likelihood *before* *after*	Impact *before* *after*
Increased risk of fire due to high voltage equipment on board.	The high voltage equipment is protected with the class approved technological solutions in materials, design, layout and monitoring and control measures. An appropriate class independent fixed fire extinguishing system is installed at the location of the concerned machinery.	medium ↓ low	high ↓ medium
Risk of radiation due to lack of seaworthiness of the particle accelerator	Best practices from other industries are implemented into maritime safety regulations concerning the choice of materials, design, physical arrangements and monitoring and control measures that are supported by class approved risk assessments. The compartment is sealed with appropriate shielding and not accessible to unauthorized persons.	medium ↓ low	high ↓ medium
Legal Factors			
Permits to use a particle accelerator on board a vessel may delay the testing and development process.	Close communication with the policymakers is maintained. The test vessel flies the flag of an interested party, which has legal authority within the flag state.	medium ↓ low	high ↓ high
Legal requirements have not been written yet for such a technological solution for the use on board a vessel. Cannot be certified.	Preliminary design assessment is carried out for statutory and classification purposes. Risk assessments with hazard identification and safety evaluation follow the development stages and are submitted to policymakers.	medium ↓ low	high ↓ high
An increase in CO_2 emissions may exceed the required EEDI for the vessel to be retrofitted, especially after year 2025 when phase 3 becomes effective.	The vessel's SEEMP is reviewed to see, whether adjustments in the hybrid technology or optimization of other power consumers is necessary to carry out.	medium ↓ low	medium ↓ medium
The technology may lose its uniqueness on the market by other particle accelerator manufacturers.	The novel toroidal accelerator is patented and protected against commercial manufacturing by others.	medium ↓ low	high ↓ medium
Environmental Factors			
Confrontational studies are published about the impact on the marine environment from the scrubber wash-water.	A high-efficiency wet scrubber is developed, which is capable of working in closed-loop mode.	medium ↓ medium	medium ↓ low

Table 5.1 continues - PESTLE Analysis for the Hybrid Technology Development and Introduction

Risk	Action	**Likelihood** *before* *after*	**Impact** *before* *after*
Concerns about the effectiveness of the hybrid EGC system and the air pollution levels from environmental protection organizations.	A life-cycle assessment for the environmental impact is carried out using credible methodology and published in academic articles.	high ↓ medium	medium ↓ low

Legal factors are the ones that will have to be faced inevitably, because of the technology's novelty in the maritime industry. Even if the technology fully complies with established international regulations for its exploitation, some flag states may not ratify these regulations and not recognize such technology use on their vessels. Reasons for that could be social pressure from organizations of various motivation or the country's energy and environmental policy. A lot of technological risks are expected because of the specific power requirements, the operating nature of the technology and the characteristics of the marine environment. Environmental factors have the lowest impact, since the system faces the same requirements as any other EGC system for its operating efficiency. Some of the risks also cause economic risk factors because some of them require more expensive manufacturing processes or introduce higher operational costs. Of course, the price difference between residual and distillate fuel oils plays an important role for decision making and payback time.

5.2. Developed Hybrid Technology Analysis

At the point where this technology has been developed and ready for commercial use as a hybrid EGC system on board vessels, most of the risks should have been resolved and their likelihood eliminated. Table 5.2 points out the bright side of this system and its drawbacks on the market in the maritime industry. It is followed by discussing the strengths of the hybrid technology and their effects, as well as the weaknesses and their extent on the hybrid system.

Table 5.2 - SWOT Analysis for a Developed Hybrid EGC System

POSITIVE		NEGATIVE	
Strengths	**Opportunities**	**Weaknesses**	**Threats**
Interdisciplinary technology.	Connects scientific and industrial particle accelerator communities with the maritime community.	Space requirements and extra weight, which decreases ship stability.	May not be feasible for small motor vessels with low initial stability.
Possible value of the by-product.	Sludge may be disposed at lower prices than other types of sludge.	High power supply requirements for EB generation.	May not be feasible for vessels with older design power machinery.
Requires no dangerous chemical additives	The technology has higher chances to be promoted as a green solution	Introduces a list of equipment to support the operation of the particle accelerator.	May increase the initial costs against other EGC systems
Potential of removing VOCs.	May be relevant for future rules for air pollution prevention.	Slightly increased fuel consumption leads to some slight increase in CO_2 emissions.	Some possible customers may retrofit their ships for the use of alternative fuels.

Strengths - Opportunities

This technology connects the particle accelerator community and the maritime industry closer, and initiates work on other applications of the proposed technology like treating ballast water on ships, which is controlled similarly to exhaust gasses. Also, sewage water may be treated with this technology, which would be more relevant to passenger liners and livestock carriers.

The sludge could become more valuable as raw fertilizer if the global SO_X emissions decreased, which would increase the alkalinity of the soil respectively and increase demand for acid fertilizers in horticulture and farming.

Unlike most of the SCR systems, which use ammonia-based reagents, the proposed technology does not require such chemicals, that are classified as dangerous substances in many countries. The solution has the lead in terms of sustainability, compared with the existing EGC techniques, and facilitates deployment of innovative and green waterborne transport technology.

Some national and regional environmental initiatives may attract attention from the global policy makers to adopt rules against volatile organic compounds, including polycyclic aromatic hydrocarbons, that the hybrid EGC system has potential of removing by default.

Weaknesses - Threats

The space requirements and additional mass are the obstacles that most of the EGC systems face for retrofit solutions, especially on smaller vessels. The best that can be done in this regard is to cooperate with engine manufacturers, so that the EGC system can be implemented at the designing phase of the engine and its auxiliary machinery.

The specific input requirements for the particle accelerator may deter some of the possible clients to go for the hybrid EGC system. To reach as many customers as possible, this solution has to be presented at maritime conferences, exhibitions and in relevant publications through promotional campaigns. The partners of the project team, representing the maritime community, have an established contact list and up-to-date information about the maritime industry, which helps to distinguish the relevant clientele for the hybrid EGC system.

As for the CO_2 emissions, this concerns all ships running on fuel oils. As studies have shown, the life-cycle CO_2 emissions from producing, transporting and burning distillate fuel oils are higher than from residual fuel oils. The alternative fuels, like methane, have considerably lower calorific value, requiring more fuel for the vessel to be transported the same distance when compared with fuel oils. Methane, being a gaseous substance in normal conditions, has stricter rules for storage and bunkering operations. Plus, methane, when released into the atmosphere, reacts with the air molecules forming green-house gasses, which is reflected in its large global warming potential value over a 20-year period.

5.3. Impact from the Hybrid Technology

From the risk analysis and evaluation of the hybrid EGC system, the following impact on the maritime industry from an introduction of this technology is expected.

The hybrid EGC system introduces a new technological application in the maritime industry, to be precise, on motor vessels, and connects the particle accelerator community with the maritime industry. After successful implementation, the development process of this system could be taken as a model for similar developing technologies.

Such a system, if successfully developed and economically available, will significantly increase the number of retrofit EGC projects on existing vessels. This would support the demand for heavy fuel oils at the level as it was before the IMO global sulphur cap.

Additionally, the developed EGC system would enhance competitiveness in the global maritime ship-building, ship-repair and supply sectors, supporting relevant businesses and their economic growth.

This example may facilitate deployment of innovative and green waterborne transport technologies to support the sustainable future of the maritime and other related industries.

6. Conclusion

New technologies, when introduced to the maritime industry, have to be either more efficient in their operation or cheaper than other existing technologies. The economic side is even more important for the merchant fleet, because the vessels have expected payback time.

As an EGC system on a vessel, the hybrid technology has to comply with the same rules as any other EGC system today, but the particle accelerator is what has to prove its necessity, by showing successful test results in operational efficiency and satisfying safety requirements in the marine environment, to be eligible for certification by recognized organizations.

The efficiency of the hybrid technology in cleaning marine exhaust gasses has been demonstrated with pilot-scale tests, which support the potential of it in full-scale applications. The most important obstacles are safety issues and technical compatibility, which emerge from the danger of radiation and specific power supply requirements. The particle accelerator is what introduces these obstacles, and the international maritime rules do not cover these aspects for such application yet, but an example could be taken from other practices of this technology. Other than that, the hybrid EGC system would have to be tested and certified according to the international rules already in place.

As for the impact to the maritime industry from an introduction of the hybrid EGC system, first, it connects the particle accelerator community with the maritime industry, which opens doors to other practical application as well. Secondly, it increases competitiveness between EGC system manufacturers. Thirdly, it supports demand for heavy fuel oils, at the same time strengthening innovative and sustainable technological approach. Burning heavy fuel oil might be comparatively more sustainable if the exhaust gasses are effectively treated. Treating by-products in an efficient way, which contributes to other industries, is one of the key provisions for moving towards the sustainable future.

Nowadays, sustainable development goals have to be implemented into new developing technologies to get acceptance not only from legal maritime authorities but also from other related communities and the general public. Many novel technologies, in the beginning, face common obstacles like lack of trustworthiness and low cost effectiveness, because of low demand. But once the industry and related communities accept the idea, it helps to boost these qualities when successful examples of the technology are presented in full-scale applications.

Bibliography

American Bureau of Shipping. (2017). *Guidance Notes on Qualifying New Technologies.* Retrieved on 11-May-2020 from https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/other/272_qualifyingnewtechnologies/NTQ_GN_e-Apr17.pdf

American Bureau of Shipping. (2020). *Guide for Exhaust Emission Abatement.* Retrieved on 19-May-2020 from https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/other/204-exhaust-emission-abatement/exhaust-emission-ebatement-guide-may20.pdf

Ammar, N.R., & Seddiek, I.S. (2017). Eco-Environmental Analysis of Ship Emission Control Methods: Case Study RO-RO Cargo Vessel. *Ocean Engineering, Vol. 137.* (pp. 166-173). Alexandria: Elsevier. Retrieved on 22-Apr-2020 from https://www.sciencedirect.com/science/article/abs/pii/S0029801817301671

Balachandran, W. (2014). *Innovative After-Treatment System for Marine Diesel Engine Emission Control (DEECON). Project Final Report.* Retrieved on 29-Apr-2020 from https://cordis.europa.eu/docs/results/284/284745/final1-deecon-final-report-v20.pdf

California Air Resources Board. (2020). Reminder of Requirements for Complying with the California Ocean-Going Vessel Fuel Regulation. *Marine Notice 2020-1.* Retrieved on 04-Apr-2020 from https://ww2.arb.ca.gov/sites/default/files/2020-01/Marine%20Notice%202020-1_final_rev_ADA.pdf

Chmielewski, A.G., Zwolińska, E., Licki, J., Sun, Y., Zimek, Z., & Bułka, S. (2018). A Hybrid Plasma-Chemical System for High-NOx Flue Gas Treatment. *Radiation Physics and Chemistry, Vol. 144.* (pp. 1-7). Sciencedirect.com: Elsevier. Retrieved on 27-Apr-2020 from https://www.sciencedirect.com/science/article/pii/S0969806X17311301

Cossairt, J.D. (2016). *Radiation Physics for Personnel and Environmental Protection. Fermilab Report TM-1834*. Retrieved on 20-May-2020 from https://esh-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=1007&filename=Fermilab_TM_1834_Rev_15.pdf&version=9

DNV GL. (2015). *Design of Electrical Installations for Wind Turbines. Standard DNVGL-ST-0076*. Retrieved on 20-May-2020 from https://rules.dnvgl.com/docs/pdf/DNVGL/ST/2015-05/DNVGL-ST-0076.pdf

DNV GL. (2020). A New ECA and Speed Reduction Limits in South Korean Ports. *Statutory News*. Retrieved on 10-May-2020 from https://www.dnvgl.com/news/a-new-eca-and-speed-reduction-limits-in-south-korean-ports-173622

Environmental Protection Agency. (2020). *CFR Title 40 - Protection of Environment. Part 94 - Control of Emissions from Marine Compression-Ignition Engines*. Electronic Code of Federal Regulations Database: U.S. Office of the Federal Register. Retrieved on 04-Apr-2020 from https://ecfr.io/Title-40/pt40.22.94#sp40.22.94.a

European Parliament and Council. (2015). *Regulation (EU) 2015/757 of the European Parliament and of the Council of 29 April 2015 on the Monitoring, Reporting and Verification of Carbon Dioxide Emissions from Maritime Transport, and Amending Directive 2009/16/EC.* Official Journal of the European Union: EUR-Lex. Retrieved on 03-Apr-2020 from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32015R0757&from=EN

European Parliament and Council. (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.* Official Journal of the European Union: EUR-Lex. Retrieved on 31-Mar-2020 from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2016.132.01.0058.01.ENG

Exhaust Gas Cleaning Systems Association. (n.d.-a). *What Qualities Must the Water Supplied to an Exhaust Gas Cleaning System Have?* Retrieved on 15-Apr-2020 from https://www.egcsa.com/technical-reference/what-qualities-must-the-water-supplied-to-an-exhaust-gas-cleaning-system-have/

Exhaust Gas Cleaning Systems Association. (n.d.-b). *MARPOL Annex VI Emission Control Areas.* Retrieved on 10-May-2020 from https://www.egcsa.com/wp-content/uploads/Figure-08-MARPOL-Annex-VI-Emission-Control-Areas.jpg

Finamore, B. (2019). Natural Resources Defense Council - Expert Blog. *South Korea Establishes an Emission Control Area for Ships.* Retrieved on 06-Apr-2020 from https://www.nrdc.org/experts/barbara-finamore/south-korea-establishes-emission-control-area-ships

Gard. (2019, updated on 16-Mar-2020). *Beware of Local Restrictions Before Discharging Washwater from Exhaust Gas Scrubbing.* Retrieved on 04-Apr-2020 from http://www.gard.no/web/updates/content/26939066/beware-of-local-restrictions-before-discharging-washwater-from-exhaust-gas-scrubbing

General Directorate of Marine Transport of Turkey. (2011). *Circular No: 517 / 2011. About Quality of Fuel.* Retrieved on 05-Apr-2020 from http://www.gard.no/webdocs/TurkishChamberofShipping.pdf

Guo, M., Fu, Z., Ma, D., Ji, N., Song, C., & Liua, Q. (2015). A Short Review of Treatment Methods of Marine Diesel Engine Exhaust Gases: 9th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC) and the 3rd International Conference on Building Energy and Environment (COBEE). *Procedia Engineering, Vol. 121.* (pp. 938-943). Retrieved on 20-Apr-2020 from https://www.sciencedirect.com/science/article/pii/S1877705815028878

Hamworthy Krystallon. (2010). *SMM International Maritime Trade Fair. Scrubbing Technology - Update.* Hamburg: Exhaust Gas Cleaning Systems Association. Retrieved on 15-Apr-2020 from https://www.egcsa.com/wp-content/uploads/Hamworthy-Krystallon-EGCS-SMM-Workshop-2010.pdf

Han, B., Kim, S.M., Kim, J.K., Kim, Y.R., Choi, J.S., Ahn, S.J., Salimov, R.A., & Kuksanov, N.K. (2006). *Application of High Power Electron Accelerator in Wastewater Treatment.* Retrieved on 21-May-2020 from https://accelconf.web.cern.ch/r06/PAPERS/THLO02.PDF

HERTIS. (2019). *HERTIS Flyer. Hybrid Exhaust Gas Cleaning Retrofit Technology for International Shipping.* Retrieved on 28-Apr-2020 from https://indico.cern.ch/event/811370/contributions/3380993/attachments/1922740/3181531/HERTIS_flyer_A4.pdf

Huatai Insurance Agency & Consultant Service. (2018). *Circular Ref No.: PNI1816. Chinese Ministry of Transport (MOT) Issued New Requirement Regarding Emission Control Areas in Chinese Territorial Waters to be Effective from 01.01.2019.* Retrieved on 05-Apr-2020 from http://www.huataimarine.com/index.php?m=newscon&id=361&twoid=543

International Atomic Energy Agency. (2018). *Occupational Radiation Protection. IAEA Safety Standards Series No. GSG-7*. Retrieved on 20-May-2020 from https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1785_web.pdf

International Maritime Organization. (2015). *Investigation of Appropriate Control Measures (Abatement Technologies) to Reduce Black Carbon Emissions from International Shipping.* London: International Maritime Organization. Retrieved on 28-Mar-2020 from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Air%20pollution/Black%20Carbon.pdf

International Maritime Organization. (2017). *MARPOL articles, protocols, annexes and unified interpretations of the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the 1978 and 1997 protocols ; incorporating all amendments in force on 1 January 2017* (6th ed.; Consolidated ed.). London: International Maritime Organization.

International Maritime Organization. (2020a). *Air Pollution. Nitrogen Oxides (NOx) – Regulation 13.* Retrieved on 28-Jan-2020 from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Nitrogen-oxides-(NOx)-–-Regulation-13.aspx

International Maritime Organization. (2020b). *Air Pollution. Sulphur oxides (SOx) and Particulate Matter (PM) – Regulation 14.* Retrieved on 28-Jan-2020 from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Sulphur-oxides-(SOx)-–-Regulation-14.aspx

International Maritime Organization. (2020c). *EEDI Database Report on 10-Mar-2020.* Global Integrated Shipping Information System (GISIS). Retrieved on 28-Mar-2020 from https://gisis.imo.org/Public/MARPOL6/EEDIData.aspx

International Maritime Organization. (2020d). *Fuel Oil Non-Availability Reports on 12-Apr-2020.* Global Integrated Shipping Information System (GISIS). Retrieved on 12-Apr-2020 from https://gisis.imo.org/Public/MARPOL6/Notifications.aspx?Reg=18.2.5

International Maritime Organization. (2020e). S*pecial Areas under MARPOL. Annex VI: Prevention of air pollution by ships (Emission Control Areas).* Retrieved on 17-Mar-2020 from http://www.imo.org/en/OurWork/Environment/SpecialAreasUnderMARPOL/Pages/Default.aspx

International Transport Forum. (2016). *Reducing Sulphur Emissions from Ships. The Impact of International Regulation.* OECD iLibrary: Organisation for Economic Co-operation and Development. Retrieved on 17-Mar-2020 from https://www.itf-oecd.org/sites/default/files/docs/sulphur-emissions-shipping.pdf

Jawerth, N. (2015). Electron Beams Help Poland's Coal-Driven Power Industry Clean up its Air. *IAEA Bulletin - Solutions to Pollution.* Retrieved on 28-Apr-2020 from https://www.iaea.org/sites/default/files/5631213_0.pdf

Kock, D.F. (2018). *SOx Scrubber Retrofit: Best Practices.* DNV GL On-Demand Webinars. Retrieved on 13-Apr-2020 from https://www.dnvgl.com/maritime/webinars-and-videos/on-demand-webinars/Scrubbers-meeting-the-Global-Sulphur-Cap-2020.html

Krantz, G. (2016). *CO_2 and Sulphur Emissions from the Shipping Industry. CO_2 Emissions Related to the Fuel Switch in the Shipping Industry in Northern Europe.* Stockholm: Trans Oleum. Retrieved on 16-Apr-2020 from http://www.transoleum.se/wp-content/uploads/2016/11/CO2-and-sulphur-emissions-from-the-shipping-industry.pdf

Latarche, M. (2017). *Methods for Meeting the NOx Tier III Targets.* ShipInsight News. Retrieved on 22-Apr-2020 from https://shipinsight.com/articles/methods-meeting-nox-tier-iii-targets

Latarche, M. (2020). *Norway Adopts Zero-Emission Regulations in World Heritage Fjords.* ShipInsight News. Retrieved on 10-May-2020 from https://shipinsight.com/articles/norway-adopts-zero-emission-regulations-in-world-heritage-fjords

Licki, J., Pawelec, A., Zimek, Z., & Witman-Zając, S. (2015). Electron Beam Treatment of Simulated Marine Diesel Exhaust Gases. *De Gruyter Open, 60*(3). (pp. 689-695). Retrieved on 30-Apr-2020 from http://www.nukleonika.pl/www/back/full/vol60_2015/v60n3p689f.pdf

Lloyd's Register. (2015). *Your Options for Emissions Compliance. Guidance for Shipowners and Operators on the Annex VI SOx and NOx Regulations.* Retrieved on 16-Apr-2020 from http://info.lr.org/l/12702/2017-07-12/45zqcl/12702/164659/Your_options_for_emissions_compliance.pdf

MAN Diesel & Turbo. (2012). *Tier III Two-Stroke Technology.* Copenhagen: MAN Group. Retrieved on 20-Apr-2020 from https://marine.mandieselturbo.com/docs/librariesprovider6/technical-papers/tier-iii-two-stroke-technology.pdf?sfvrsn=12

Marine Environment Protection Committee. (2008). *NOx Technical Code 2008. Resolution MEPC.177(58).* London: International Maritime Organization. Retrieved on 23-Mar-2020 from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Air%20pollution/Resolution%20MEPC.177(58)%20NOx%20Technical%20Code%202008.pdf

Marine Environment Protection Committee. (2010). *Interpretations of, and Amendments to, MARPOL and Related Instruments: Designation of an Emission Control Area for Nitrogen Oxides, Sulphur Oxides and Particulate Matter (Submitted by the United States).* London: International Maritime Organization. Retrieved on 28-Mar-2020 from https://www.epa.gov/sites/production/files/2016-09/documents/mepc61-inf-9.pdf

Marine environment Protection Committee. (2011). *Resolution MEPC.203(62): Ammendments to the Annex of the Protocol of 1997 to Amend the International*

Convention for the Prevention of Pollution from Ships, 1973, as Modified by the Protocol of 1978 Relating Thereto (Inclusion of Regulations on Energy Efficiency for Ships in MARPOL Annex VI). London: International Maritime Organization. Retrieved on 28-Mar-2020 from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Technical%20and%20Operational%20Measures/Resolution%20MEPC.203(62).pdf

Marine environment Protection Committee. (2012a). *Resolution MEPC.213(63): 2012 Guidelines for the Development of a Ship Energy Efficiency Management Plan (SEEMP).* London: International Maritime Organization. Retrieved on 29-Mar-2020 from http://www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Marine-Environment-Protection-Committee-%28MEPC%29/Documents/MEPC.213%2863%29.pdf

Marine environment Protection Committee. (2012b). *Resolution MEPC.214(63): 2012 Guidelines on Survey and Certification of the Energy Efficiency Design Index (EEDI).* London: International Maritime Organization. Retrieved on 28-Mar-2020 from http://www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Marine-Environment-Protection-Committee-%28MEPC%29/Documents/MEPC.214%2863%29.pdf

Marine Environment Protection Committee. (2015). *Resolution MEPC.259(68): 2015 Guidelines for Exhaust Gas Cleaning Systems.* London: International Maritime Organization. Retrieved on 11-Mar-2020 from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/MEPC.259(68).pdf

Marine Environment Protection Committee. (2016). *Resolution MEPC.278(70): Ammendments to the Annex of the Protocol of 1997 to Amend the International Convention for the Prevention of Pollution from Ships, 1973, as Modified by the Protocol of 1978 Relating Thereto (Data Collection System for Fuel Oil Consumption of Ships).* London: International Maritime Organization. Retrieved on 29-Mar-2020 from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/278(70).pdf

Marine Environment Protection Committee. (2017). *Resolution MEPC.291(71): 2017 Guidelines Addressing Additional Aspects of the NOx Technical Code 2008 with Regards to Particular Requirements Related to Marine Diesel Engines Fitted with Selective Catalytic Reduction (SCR) Systems.* London: International Maritime Organization. Retrieved on 24-Mar-2020 from http://www.imo.org/en/

KnowledgeCentre/IndexofIMOResolutions/Marine-Environment-Protection-Committee-%28MEPC%29/Documents/MEPC.291%2871%29.pdf

Marine Environment Protection Committee. (2019). *Resolution MEPC.320(74): 2019 Guidelines for Consistent Implementation of the 0.50% Sulphur Under MARPOL Annex VI.* London: International Maritime Organization. Retrieved on 09-Mar-2020 from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/Documents/Resolution%20MEPC.320%2874%29.pdf

Mattausch, G., Feinäugle, P., Kirchhoff, V., Rögner, F.H., Kubusch, J., Weiss, S., Schmidt, S., Ender, F., & Kaufmann, S. (2015). *Vorrichtung zum Erzeugen beschleunigter Elektronen (Apparatus for generating accelerated electrons).* German Patent No. DE102013111650B3. Munich: Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V. Retrieved on 20-Apr-2020 from https://patents.google.com/patent/DE102013111650B3/en

Ministry for the Environment and Natural Resources of Iceland. (2019). News. *Regulation banning the use of heavy fuel oil in the territorial sea of Iceland.* Retrieved on 05-Apr-2020 from https://www.government.is/news/article/?newsid=05452daa-183d-11ea-944f-005056bc530c

Mundal, S., Sandal, D., & Springer, D. (2018). *DNV GL On-Demand Webinars. Scrubbers – Meeting the Global Sulphur Cap 2020 Limits.* Retrieved on 13-Apr-2020 from https://www.dnvgl.com/maritime/webinars-and-videos/on-demand-webinars/Scrubbers-meeting-the-Global-Sulphur-Cap-2020.html

Nature And Biodiversity Conservation Union. (2018). *Emission Control Area (ECA) for the Mediterranean Sea: Effective Measure to Tackle Air Pollution from Ships.* Retrieved on 06-Apr-2020 from https://en.nabu.de/imperia/md/content/nabude/verkehr/hg_mediterranean_eca_final.pdf

Norwegian Maritime Authority. (2019). *Regulations of 30 May 2012 No. 488. Environmental Safety for Ships and Mobile Offshore Units (Amended by Regulations No. 842 of 1 March 2019).* Retrieved on 05-Apr-2020 from https://www.sdir.no/contentassets/046ced2d174b490a9d371c411f45c3fe/30-may-2012-no.-488-environmental-safety-for-ships-and-mobile-offshore-units.pdf?t=1586104777714

Panasiuk, I., Lebedevas, S., & Čerka, J. (2018). The Assessment Algorithm of Technological Feasibility of SOx Scrubber Installation. *Vilnius Gediminas Technical University -*

Transport, 33(1). (pp. 197-207). Retrieved on 14-Apr-2020 from https://journals.vgtu.lt/index.php/Transport/article/view/154

Park, J.H., Ahn, J.W., Kim, K.H., & Son, Y.S. (2019). Historic and Futuristic Review of Electron Beam Technology for the Treatment of SO_2 and NOx in Flue Gas. *Chemical Engineering Journal, Vol. 355.* (pp. 351-366). Sciencedirect.com: Elsevier. Retrieved on 29-Apr-2020 from https://www.sciencedirect.com/science/article/abs/pii/S1385894718315742

Pawelec, A., Burliński, H., Dobrowolski, A., & Chmielewski, A.G. (2019). *Report on Operation of Demonstrational Pilot Plant for Hybrid Treatment of Flue Gas from Marine Diesel Engine Operated on Ship Berthed in Riga Shipyard: Within the framework of the project ARIES Proof of Concept Fund „Development of Hybrid Electron Accelerator System for the Treatment of Marine Diesel Exhaust Gases”.* Warsaw: Institute of Nuclear Chemistry and Technology.

PESTLEAnalysis.com. (n.d.). *What is PESTLE Analysis? A Tool for Business Analysis.* Retrieved on 10-May-2020 from https://pestleanalysis.com/what-is-pestle-analysis/

Poullikkas, A. (2015). Review of Design, Operating, and Financial Considerations in Flue Gas Desulfurization Systems. *Energy Technology & Policy 2*(1). (pp. 92-103). Tandfonline.com: Taylor & Francis Group. Retrieved on 12-Apr-2020 from https://www.tandfonline.com/doi/full/10.1080/23317000.2015.1064794

Prosser, G. (2018). Regulations and Standards. *AMSA Marine Notice 6/2018—Limitation of Sulphur Emissions from Cruise Vessels while at Berth in Sydney Harbour.* Retrieved on 05-Apr-2020 from https://www.amsa.gov.au/about/regulations-and-standards/62018-limitation-sulphur-emissions-cruise-vessels-while-berth-sydney

Pryzowicz, A. (2019). *Report on Implementation of WP5 Tasks. Development of hybrid electron accelerator system for the treatment of marine diesel exhaust gases.* Lublin: Biopolinex.

Sanchez, N., & Mays, D.C. (2015). Effect of Methane Leakage on the Greenhouse Gas Footprint of Electricity Generation. *Climatic Change, 133*(2). (pp. 169-178). Retrieved on 18-May-2020 from https://link.springer.com/article/10.1007/s10584-015-1471-6

Shi, Y. (2016). Are Greenhouse Gas Emissions from International Shipping a Type of Marine Pollution? *Marine Pollution Bulletin 113*(1-2). (pp. 187-192). Sciencedirect.com: Elsevier. Retrieved on 29-Mar-2020 from https://www.sciencedirect.com/science/article/abs/pii/S0025326X16307305

Simonsen, M. (2014). *Cruise Ship Tourism - A LCA Analysis.* Sogndal: Western Norway Research Institute. Retrieved on 12-May-2020 from http://transport.vestforsk.no/Dokumentasjon/pdf/Skip/Cruise.pdf

Simonsen, M., Walnum, H.J., & Gössling, S. (2018). Model for Estimation of Fuel Consumption of Cruise Ships. *Energies, 11*(5). Retrieved on 12-May-2020 from https://www.mdpi.com/1996-1073/11/5/1059/htm

Siwek, M., & Chmielewski, A.G. (2018). *Process Engineering Aspects of Diesel Engine Off Gases Treatment.* Warsaw: Institute of Nuclear Chemistry and Technology. Retrieved on 16-Apr-2020 from http://www.ichtj.waw.pl/ichtj/publ/b_report/PDF-B-raport/siwek2018B_02.pdf

Skuld. (2019). *Ban on Discharging Wash Water from Open Loop Scrubbers in Part of China ECAs as of 1 January 2019.* Retrieved on 10-May-2020 from https://www.skuld.com/topics/ship/bunkers/ban-on-discharging-wash-water-from-open-loop-scrubbers-in-part-of-china-ecas-as-of-1-january-2019/

Sokovnin, S.Y., & Balezin, M.E. (2017). *I*nvestigation of Cold Cathode for Nanosecond Electron Accelerators. *Vacuum, Vol. 146*. Sciencedirect.com: Elsevier. Retrieved on 30-Apr-2020 from https://www.sciencedirect.com/science/article/abs/pii/S0042207X17312241

Solakivi, T., Laari, S., Kiiski, T., Töyli, J., & Ojala, L. (2019). How Shipowners Have Adapted to Sulphur Regulations – Evidence from Finnish Seaborne Trade. *Case Studies on Transport Policy, 7*(2). (pp. 338-345). Retrieved on 10-Apr-2020 from https://www.sciencedirect.com/science/article/abs/pii/S2213624X1830292X?via%3Dihub

Strømmen, S.O. (2019). *Washwater Discharge from Scrubbers is SAFE.* Retrieved on 04-Apr-2020 from https://cleanmarine.no/criticism-that-washwater-from-marine-scrubbers-transfer-harmful-emissions-from-air-to-sea-is-unfounded-shows-numerous-independent-scientific-studies/

The Council of the European Union. (2013). *Council Directive 2013/59/EURATOM: laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom.* EUR-Lex: Official Journal of the European Union. Retrieved on 20-May-2020 from https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2014:013:0001:0073:EN:PDF

Urdahl, K. (2020). Gard Insight. *Regional Sulphur Emission Limits at a Glance.* Retrieved on 04-Apr-2020 from http://www.gard.no/web/updates/content/29212584/regional-sulphur-emission-limits-at-a-glance

Vaidyanathan, G. (2015). *S*ustainability. *How Bad of a Greenhouse Gas Is Methane?* Scientificamerican.com: Springer Nature America. Retrieved on 25-Apr-2020 from https://www.scientificamerican.com/article/how-bad-of-a-greenhouse-gas-is-methane/

Vretenar, M. (2019). Bringing Particle Accelerators on Ships. *CERN Accelerating News, 2019*(29). Retrieved on 28-Apr-2020 from https://acceleratingnews.web.cern.ch/article/bringing-particle-accelerators-ships

Walker, T.R., Adebambo, O., Feijoo, M.C.D.A., Elhaimer, E., Hossain, T., Edwards, S.J., Morrison, C.E., Romo, J., Sharma, N., Taylor, S., & Zomorodi, S. (2019). Chapter 27 - Environmental Effects of Marine Transportation. In C. Sheppard (Ed.), *World Seas: an Environmental Evaluation* (Second ed., Vol. III). (pp. 505-530). Cambridge, Massachusetts: Academic Press.

Wang, H. (2020). Natural Gas & Oil. *OPEC+ Awaits Green Light from Other Key Producers as Oil Cut Math Gets Complicated*, Jonathan Dart (Ed.). London: S&P Global Platts. Retrieved on 17-Apr-2020 from https://www.spglobal.com/platts/en/market-insights/latest-news/natural-gas/040720-opec-awaits-green-light-from-other-key-producers-as-oil-cut-math-gets-complicated

Woodyard, D. (2009). Chapter Three - Exhaust Emissions and Control. *Pounder's Marine Diesel Engines and Gas Turbines.* (pp. 61-86). Sciencedirect.com: Elsevier. Retrieved on 04-May-2020 from https://www.sciencedirect.com/science/article/pii/B9780750689847000035

Yuan, J., Ng, S.H., & Sou, W.S. (2016). Uncertainty Quantification of CO_2 Emission Reduction for Maritime Shipping. *Energy Policy Vol. 88.* (pp. 113-130). Sciencedirect.com: Elsevier. Retrieved on 29-Mar-2020 from https://www.sciencedirect.com/science/article/abs/pii/S0301421515301488

Zis, T.P.V., & Psaraftis, H.N. (2019). Chapter 7 - Reducing Sulfur Emissions: Logistical and Environmental Considerations. In H. N. Psaraftis (Ed.), *Sustainable Shipping: A Cross-Disciplinary View.* (pp. 249-284). Cham: Springer.

Appendices

Appendix A

Scrubber Parameters During the Tests at Riga Shipyard

Experiment code			1	2	3	4	5	6	7	8	11	12	13	14	15	16	17
Engine load		%	0	50											100		
Oxidant added		kg	0				3				10						
Gas flow rate		Nm^3/h	-	4763,9	4831,2	4771,8	4703,0	4807,1	4942,7	4751,7	4915,2	4950,0	4917,8	4927,6	4605,5	4494,6	4804,1
Gas temperature	Engine outlet	°C	-	140	146	147	147	156	151	159	152	155	156	157	229	237	226
	Scrubber inlet	°C	-	76	97	98	81	96	90	108	80	90	95	90	97	100	96
Accelerator	Beam voltage	kV	-	125	125	125	125	125	125	125	125	125	125	125	125	125	125
	Beam current	mA	-	75	75	100	50	75	100	100	100	75	50	100	50	0	100
Scrubber	Water flow rate	m^3/h	-	10	10	10	10	10	10	20	10	10	10	20	10	10	10
	Water pH	-	-	8,6	8,3	8,3	8,3	8,3	7,4	7,4	9,1	8,7	8,3	7,9	7,9	7,9	7,8
Inlet gas composition	CO_2	%	-	2,4	2,4	2,4	2,5	2,5	2,5	2,5	2,0	2,6	2,6	2,5	4,2	4,3	4,1
	O_2	%	-	18,1	18,2	18,1	17,0	17,9	17,9	17,9	17,4	17,9	17,9	17,8	15,6	15,6	15,8
	NO	ppm	-	209	211	212	216	228	233	252	298	237	244	239	667	673	615
	NO_2	ppm	-	20	18	18	19	20	22	19	19	17	18	21	25	27	28
	NO_x	ppm	-	229	229	230	235	248	255	271	317	254	262	260	692	700	643
	HC	ppm	-	13	22	25	13	0	0	1	0	0	1	0	0	0	5
Scrubber parameters	HTU	m	-	0,834	0,879	0,878	0,838	0,874	0,871	0,902	0,842	0,868	0,878	0,869	0,869	0,874	0,874
	NTU	-	-	3,117	2,958	2,961	3,103	2,975	2,985	2,882	3,088	2,995	2,961	2,992	2,992	2,975	2,975
	H	m	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6

(Pawelec, Burliński et al., 2019, p. 25)

Appendix B

Measured Parameters of the Hybrid EGC System and Exhaust Gasses During the Tests at Riga Shipyard

Experiment code			1	2	3	4	5	6	7	8	11	12	13	14	15	16	17
Engine load		%	0	50											100		
Oxidant added		kg	0				3				10						
Gas velocity		m/s	13,6	24,0	24,4	24,1	22,8	24,4	24,4	24,6	24,7	25,0	24,9	24,7	26,0	26,0	27,0
Gas temperature	Engine outlet	°C	70	140	146	147	147	156	151	159	152	155	156	157	229	237	226
	Accelerator inlet	°C	51	125	126	126	110	128	117	136	124	126	127	123	173	184	171
Accelerator	Beam voltage	kV	125	125	125	125	125	125	125	125	125	125	125	125	125	125	125
	Beam current	mA	50	75	75	100	50	75	100	100	100	75	50	100	50	0	100
Scrubber	Water flow rate	m^3/h	10	10	10	10	10	10	10	20	10	10	10	20	10	10	10
	Water pH	-	10,1	8,6	8,3	8,3	8,3	8,3	7,4	7,4	9,1	8,7	8,3	7,9	7,9	7,9	7,8
Inlet gas composition	CO_2	%	1,4	2,4	2,4	2,4	2,5	2,5	2,5	2,5	2,0	2,6	2,6	2,5	4,2	4,3	4,1
	O_2	%	19,1	18,1	18,2	18,1	17,0	17,9	17,9	17,9	17,4	17,9	17,9	17,8	15,6	15,6	15,8
	NO	ppm	95	209	211	212	216	228	233	252	298	237	244	239	667	673	615
	NO_2	ppm	15	20	18	18	19	20	22	19	19	17	18	21	25	27	28
	NO_x	ppm	110	229	229	230	235	248	255	271	317	254	262	260	692	700	643
	HC	ppm	0	13	22	25	13	0	0	1	0	0	1	0	0	0	5
Outlet gas composition	CO_2	%	1	1,9	2	1,9	2	2,1	2,1	2,2	2,2	2,1	2,2	2,1	2,7	2,8	2,7
	O_2	%	19,9	18,7	18,8	18,7	18,7	18,6	18,5	18,4	18,2	18,4	18,5	18,5	17,7	17,6	17,8
	NO	ppm	10	85	101	70	103	96	85	90	79	77	0	0	230	312	84
	NO_2	ppm	29	41	34	48	31	41	44	51	52	52	119	113	67	47	132
	NO_x	ppm	39	126	135	118	134	137	129	141	131	129	119	113	297	359	216
	HC	ppm	0	16	0	11	13	3	0	12	13	0	7	0	0	0	2

(Pawelec, Burliński et al., 2019, p. 26)

Appendix C

Removal Efficiencies of the Measured Emissions During the Tests at Riga Shipyard

Experiment code			1	2	3	4	5	6	7	8	11	12	13	14	15	16	17
Engine load		%	0	50											100		
Oxidant concentration		mg/l	0				1				3,3						
Gas flow rate		Nm^3/h	3316,1	4763,9	4831,2	4771,8	4703,0	4807,1	4942,7	4751,7	4915,2	4950,0	4917,8	4927,6	4605,5	4494,6	4804,1
Gas temp. at accelerator inlet		°C	51	125	126	126	110	128	117	136	124	126	127	123	173	184	171
Dose		kGy	4,1	4,2	4,2	5,7	2,9	4,2	5,5	5,7	5,5	4,1	2,7	5,5	2,9	0,0	5,6
Inlet concentration	NO	ppm	95	209	211	212	216	228	233	252	298	237	244	239	667	673	615
	NO_x	ppm	110	229	229	230	235	248	255	271	317	254	262	260	692	700	643
Removal rate	NO	%	81,8	48,2	39,1	58,2	39,2	46,3	55,3	57,4	65,2	60,4	100,0	100,0	43,2	26,5	77,6
	NO_x	%	38,8	30,0	25,0	35,1	27,3	29,6	38,1	38,0	45,8	38,1	44,2	44,4	29,2	18,7	45,0
Calculated removal rate if high efficiency scrubber applied *	NO_x	%	83,6	52,3	43,5	61,1	43,7	50,2	58,8	60,1	67,0	62,7	99,7	99,6	45,0	29,1	78,4

(Pawelec, Burliński et al., 2019, p. 27)

Appendix D

Assumed Parameters for the Analysis of Investment Profitability

Description	IU	Parameter value for the specified option		
		Optimal	Optymistic	Pesimistic
Discount rate	%	6,20	6,00	8,00
Investment value	EUR	7 000 000	5 000 000	8 000 000
Working hours of the vessel	h	7 000	7 500	5 000
Unit fuel consumption	t/h	4,00	8,00	2,96
Engine power	kW	40 000	40 000	40 000
Power from the fuel unit	kg/kWh	0,100	0,200	0,074
Difference in fuel price	EUR/t	200,00	220,00	180,00
LSMGO	EUR/t	555,00	570,00	530,00
IFO380	EUR/t	355,00	350,00	350,00
Power costs of accelerator and scrubber				
Fuel unit price	EUR/t	555,00	570,00	530,00
Fuel consumption of the generator	t/year	1 176	720	1 280
Unit fuel consumption of the generator	kg/kWh	0,14	0,12	0,16
Accelerator and scrubber total power	kW	1 200	800	1 600
Energy demand indicator	%	3,00%	2,00%	4,00%
Costs of other consumables	EUR	310 800,00	342 000,00	235 320,00
Calculation base - fuel value	EUR	15 540 000,00	34 200 000,00	7 844 000,00
Consumables costs indicator	%	2%	1%	3%
Service costs	EUR	350 000	200 000	480 000
Investment value	EUR	7 000 000	5 000 000	8 000 000
Service costs indicator	%	5%	4%	6%
Other variable costs	EUR	621 600,00	1 026 000,00	392 200,00
Other variable costs	EUR	15 540 000,00	34 200 000,00	7 844 000,00
Other variable costs indicator	%	4%	3%	5%
FIXED COSTS				
Personnel costs	EUR	216 000,00	120 000,00	336 000,00
Number of employees	employees	3	2	4
Monthly rate	EUR/month	6000	5000	7000
Number of months	months	12	12	12
Other fixed costs	EUR	350 000,00	250 000,00	400 000,00
Interest on loan				
Interest rate	%	7%	6%	8%

(Pryzowicz, 2019, p. 27)