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TEHNOLOOGILISED LAHENDUSED LAEVADE ÜMBEREHITUSES UUTE KESKKONNANÕUETE TÄITMISEKS

NEW TECHNOLOGIES AND REVERSE ENGINEERING AS A KEY FOR RETROFITTING COMPANIES TO PROVIDE TECHNICAL SOLUTIONS FOR NEW ENVIRONMENTAL REGULATIONS

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Lühikokkuvõte

Aastaks 2050 ennustatakse 60 protsendilist laevatranspordi mahu kasvu. Pidev transpordi mahtude kasv, pidev keskkonnanõuete rangenemine, kütusehindade tõus ning ühiskonna süvenev soov looduskeskkonna säilimiseks, tagab laevaehitusfirmadele kindla tehnoloogiliste ümberehituste tööpõli.

Suurimateks ajenditeks laevasüsteemide ümberehitusel on laienevad SO_x ning NO_x heitmekoguste kontrollalad (ECA) ning NO_x heitmekoguste nõuete rangemaks muutumine. Laienevad ECA'd on otseselt seatod kütusehindadega, kuna ilma vastava heitmepuhastussüsteemita nagu skraber ehk heitgaaside järelpuhastusseadme ning valikulise katalüütilise redutseerimiseta (SCR) peavad laevad opereerima madalama väävlisisaldusega diiselkütusega või kasutama alternatiivseid kütuseid. Teiseks suurimaks ajendiks on otseselt seadusega reguleeritud ballastvee puhastussüsteemide kasutamine, mis dikteerivad rahvusvaheliselt reisivaid laevu kasutama IMO ning riikide poolt kehtestatud standardeid ballastivee lossimiseks. Ballastvee konventsioon tagab ballastvee puhasussüsteemide ümberehituse ning installeerimise aastani 2024 ning edasi, alates millest peavad laevade ballastvee süsteemid vastama konventsiooni D-2 nõuetele.

Tehnoloogilised lahendused, mis aitavad laevadel olla vastavuses uute seadustega jagunevad kaheks – laevade efektiivsust tõstvad laevasüsteemid ning otseselt heitgaase ning ballastivett puhastavad süsteemid. Skraberid ja valikuline katalüütiline redutseerimine on kõige populaarsemad süsteemid, et olla vastavuses laienevate SO_x ja NO_x heitmekoguste kontrollaladega (ECA) ning NO_x heitmekoguste rangemate nõuetega. Alternatiivkütustest kõige potensiaalsem lahendus on veeldatud maagaas. Veeldatud maagaas ehk LNG on vastavuses nii SO_x kui ka NO_x heitmekoguste nõuetega ning omab ka stabiilset ning madalat kütsehinda. Laeva peamasinate ümberehitus LNG süsteemidele on kiirelt tasuv, kuid LNG ladustamiseks vajalik ümberehitus on keerukas ning infrastruktuur vähene. Diiselelektriliste peamasinatega laevadele akupankade lisamine on potensiaalikaim hübriidlahendus praamidele ning RoPax laevadele. Hübriidsüsteemide kasutatavus tõuseb, kui langeb akupankade hind ning tõuseb mahutavus.

Potensiaalseimateks turgudeks lähiaastatel leiti skraberite, akupankade (hübriidiks ümberehitus) ning ballastvee puhastussüsteemide paigaldus. Ballastvee puhastussüsteemide turg näitab kasvutrendi vähemalt kuni aastani 2030, mida reguleerib kehtestatud ballastivee konventsioon, mis teeb ballastvee puhastussüsteemide turu kõigutamatuks ning kohustuslikult laevadele, kes soovivad opereerida rahvusvahelistes vetes. Skraberite ning hübriidlahenduste turg on olenemata ülemaailmsest COVID-19 pandeemiast ning järsust kütusehindade langemisest näidanud kasvutrendi, mis tõestab ECA'de ning skraberi tehnoloogia tõhusust.

Töös väljatoodud süsteemide keerukuse tõttu muutuvad ümberehitused väljakutsete rohkemaks. Teine suur probleem on laevade dokumentatsiooni mittevastavus tegelikkusele. Selleks toodi töös välja 3D skanneerimise ning liitreaalsuse kasutamise võimalused. Leiti, et 3D skanneerimine ning liitreaalsus muutub vältimatuks osaks ning aluseks igale edukale ümberehitusprojektile. Liitreaalsuse kasutamise võimalikkus võib tulevikus anda firmadele

turueelise, kuna selle kasutamine järelteeninduses võib vähendada laevaomanikule aega ning vähendada kulusid.

Abstract

The shipping industry is predicted to grow by 60% up to the year 2050, which leads to stricter regulations for shipowners to maintain the sustainability of marine transport and lower the impact of shipping to global warming and the marine environment. The hardening regulations lead to difficult conversions of existing fleet's powerplants and ballast water systems. Aim of the thesis was to find the most potential conversion and retrofit solutions whilst adapting modern advancements of 3D scanning and augmented reality in the process.

The potential drivers found for the future conversions and retrofits are the hardening regulations from the IMO as well as port states like expanding emission control areas (ECA), more strict tiers for NOx emissions, energy efficiency design index (EEDI) and energy efficiency operational indicator (EEOI), continuously increasing fuel prices and ballast water regulations. For each driver, the possible technological solutions were brought out and assessed. The market share research for the most potential retrofits of the coming decade (Scrubbers, battery powered hybrid solutions and ballast water treatment systems) was carried out.

Based on the technical difficulty of the solutions, the modern engineering aids like 3D scanning and augmented reality possibilities were assessed, a guide to 3D scanning utilization was done and future development of the technologies was targeted.

It was concluded that the environmental regulations will show a trend of becoming stricter. The scrubber, battery powered hybrid solutions and ballast water treatment systems are a direction on which to put emphasis is the coming decade and the need for 3D scanning and augmented reality is becoming more imminent.

Keywords Shipping, IMO, carbon neutrality, scrubber, LNG, hybrid, 3D scanning, Augmented reality

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Acronyms and Abbreviations

AR	Augmented Reality
BWMS	Ballast Water Management System
BWT	Ballast Water Treatment
BWTS	Ballast Water Treatment System
CAGR	Compound Annual Growth Rate
DNV	Det Norske Veritas
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Index
EGCS	Exhaust Gas Cleaning System
EPA	Environmental Protection Agency
EU	European Union
GA	General Arrangement
GHG	Greenhouse Gas
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
HT-PEMFC	High Temperature Polymer Electrolyte Membrane Fuel Cell
IMO	International Maritime Organization
IOPPC	International Oil Pollution Prevention Certificate
LNG	Liquified Natural Gas
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
MMBtu	Million British Thermal Units
NO_x	Nitrogen Oxide
ODS	Ozone Depleting Substance
PEMFC	Polymer Electrolyte Membrane Fuel Cell

PM	Particulate matter
SEEMP	Ship Energy Efficiency Management Plan
SOFC	Solid Oxide Fuel Cell
SO_x	Sulphur Oxide
TEU	Twenty-foot Equivalent Unit
ULSFO	Ultra Low Sulphur Fuel Oil
USCG	United States Coast Guard
VLSFO	Very Low Sulphur Fuel Oil
VOC	Volatile Organic Compound

1 RESEARCH AREA

By 2050 the energy system of the world will go through a major transition, which will have a big influence on the shipping world. By the year 2050 the demand for shipping and seaborne transport will increase by 60% with having the biggest pace of growth by the year 2030 [1]. The pressure from governments, society and different international organizations pressure to reduce emissions to air and move towards decarbonization by the year 2050 [1], means that the fleet will change substantially by then and the existing fleet whether they are tankers, cruise ships, ferries etc., will need minor to major retrofits in order to meet new enforced regulation, which will be carried out by retrofitting companies with such competence.

Driven by the major transition in the world's energy system, the thesis will address the following research questions:

What are the drivers and emission and discharge regulations that must be met for the future?

In recent years significant improvement in environmental regulations has taken place. In order for shipowners to take action and move towards cleaner ship systems, new regulations must be enforced. It is necessary to assess which regulations will be the drivers of future ship conversions. It is important to address the new regulations that shipowners are going to face in the coming years. This is the decisive question, which will lay down the foundation for further development of this thesis.

What are the conversions and modifications of ship systems that will help meet the future regulations?

Existing fleet will need conversions to meet the new enforced regulations. The usual life span of a commercial ship is 20-25 years [2] and up to 30 years with a passenger ship [3]. This means that the ships built today and in the past, will need to have new more efficient systems retrofitted in order to meet new regulations. New cleaner energy and discharge systems must be assessed and addressed in order to foresee the retrofits of the years to come.

What is the market size for the potential solutions for retrofitting and conversion companies?

It is important to analyze the possible market size for the most potential solutions, which will give the retrofitting companies a direction in which to focus its know-how and manpower to as well as investments in terms of necessary tools and trained personnel.

What are the biggest hardships of conversions to existing fleet?

The issues with existing fleet comes from the lack of documentation of the ship in terms of the general arrangement, specifications and general documentation of the vessel which brings many difficulties to the conversion company. The crew must also be trained and become accustomed to the operations of the retrofitted systems and maintaining them. It is clear that the main concerns of vessel conversions should be analyzed and new technological solutions to overcome these hardships have to be addressed.

What modern technological advancements can be used to face these hardships?

If the vessels are lacking sufficient documentation, reverse engineering and other novel technologies must be used. The 3D scanning possibilities must be addressed as well as other possible future technological advancements like augmented reality, which can make the retrofitting process as accurate and efficient as possible.

1.1 Research scope

The thesis will focus on the environmental, economic as well as the technological aspects of retrofitting new efficient technologies of three main types of vessels over 100m of length – passenger ships (cruise, RoPax) and container ships.

The drivers will be defined by regulations, social drivers such as people becoming more environmentally conscious and by the economical drivers by comparing the cost of the conversion as well as the losses/gains in daily running costs.

The drivers that will be analyzed are based on regulations, social drivers and economical aspects to the shipowner.

1.2 Thesis structure

The thesis will begin with defining the current enforced regulations, which the shipowners must submit to. The possible and already stated future regulations will be analyzed. Once the regulatory part of the emission and ballast water control is thoroughly analyzed, possible technical solutions will be brought out to meet the environmental restrictions, their benefits and drawbacks will be analyzed in a numerical and holistic way. The modern novel technological advancements 3D scanning and augmented reality will be assessed, the possible ways to make retrofitting process as smooth as possible by utilizing those technologies will be brought out and possible future outlook to these technologies will be addressed.

2 THE DRIVERS OF CONVERSION

In order to fight climate change all parties must contribute, including governments, organizations, the private sector as well as society. Combined with rising fossil fuel prices they are the biggest drivers for technological advancements, which can make the future of shipping more sustainable.

A transition into a future fueled by green energy is in motion [1]. The wider use of renewable energy, omitting fossil fuels and a more sustainable energy management can be expected in the future. This will have a big impact on the existing worldwide maritime fleet as the shipping demand for seaborn transport grows.

In order to meet the global average temperature increase limit of 2.5°C and ensure the preservation of marine environment, stricter emission and discharge regulations must be introduced for existing ships and they must be complied.

The subchapters addressing fuel prices, conventions and regulations that control the different global pollution sources and quantities for different ships and their pollution types can be seen in Table 1.

Table 1 Drivers of conversion

Name of Convention/Regulation/Driver and the respective chapter	Reach	Pollution Type	
		Air Pollution	Ballast Water
MARPOL Annexe 6 (Subpoint 2.1.1; 2.1.4 - 2.1.6)	Global	x	
US Environmental Protection Agency (Subpoint 2.1.3; Subpoint 2.2.1)	Local/USA	x	x
European Emission Control (Subpoint 2.1.1)	Local/Europe	x	
BWM Convention (Subpoint 2.2.1)	Global		x
US Coast Guard Discharge Standard (Subpoint 2.2.1)	Local/USA		x
Fuel Prices (Subchapter 2.3)	Global	x	

2.1 Air pollution from ships

The air pollution cannot be linked with a direct and obvious effect like an oil spill, but it does have a negative effect on air quality especially in some areas, where people have suffered from acidic rain that the polluted air has caused [4].

MARPOL Annex VI, which was first adopted in 1997, has specific limits for different air pollution sources which can be found in the exhaust gas of ships with different fuel types, including Sulphur oxides (SO_x) and nitrous oxides (NO_x), and prohibits emissions of ozone depleting substances (ODS) as well as the emissions of volatile organic compounds (VOC) which is critical especially on tankers [4].

2.1.1 Emission Control Areas

The Emission control areas or ECAs are areas, which limit the SO_x, NO_x and particulate matter emissions [5]. The limits are mainly achieved by controlling fuels and the maximum Sulphur content of them [5], while they are loaded, bunkered and used onboard the ships. The content of Sulphur and particulate matter in these oils by 1st of January is 2020 are 0.5% [m/m] (mass by mass) outside the established ECAs and 0,10% [m/m] inside the established ECAs [5], this is also known as the Global Sulphur Cap.

At the moment, the established ECAs are [5]:

1. Baltic Sea area (SO_x)
2. North Sea area (SO_x)
3. North American area (SO_x, NO_x and PM)
4. United States Caribbean Sea area (SO_x, NO_x and PM)

The future possible ECAs are also brought out in Figure 1, which means that the market size for scrubber and SCR retrofits or new fuel types could increase in the near future.

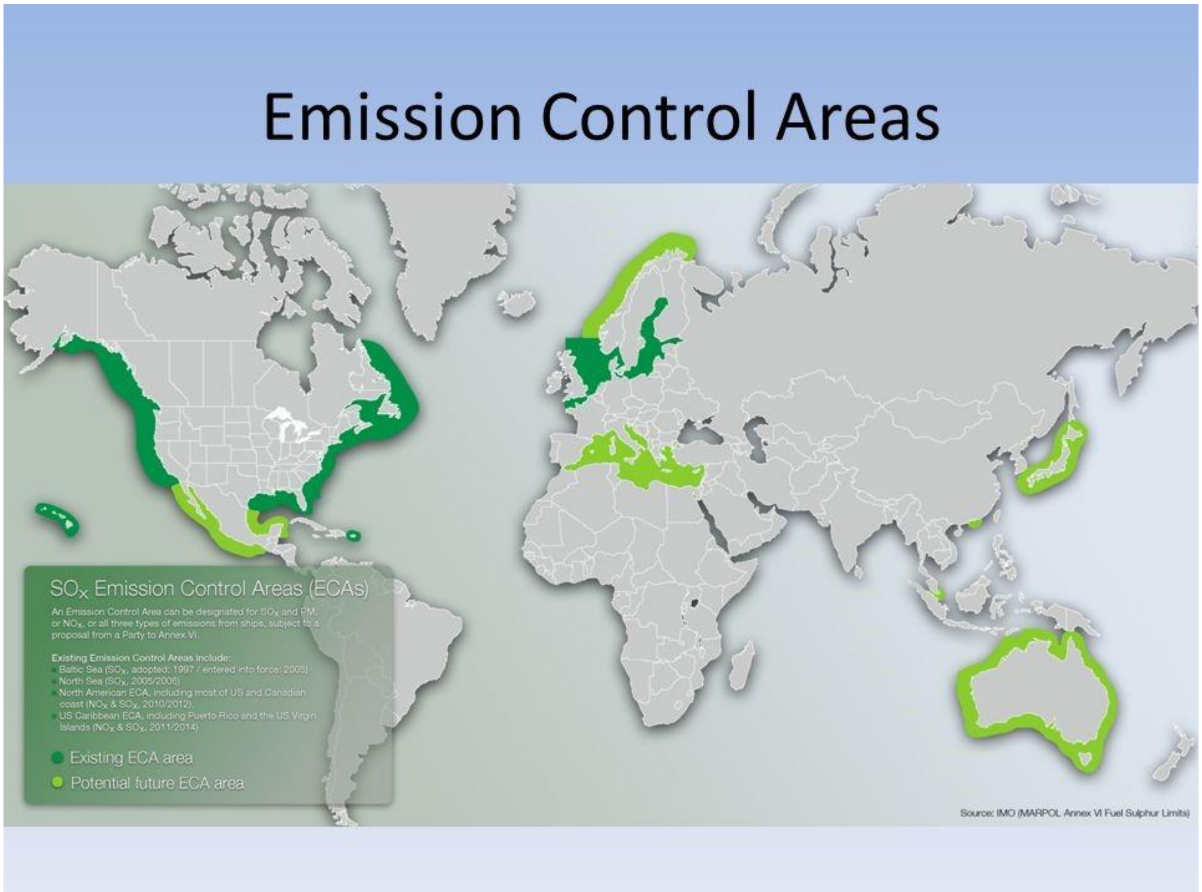

Figure 1 Emission Control Areas. Source: Seahawk Investments

Since most ships operate inside and outside of these ECAs in example on a route from Tallinn to New York, and therefore they cannot use HFO throughout the whole journey [5]. Once the ship enters the ECA, the ship is required to change over from one fuel to the ECA compliant fuel according to IMO’s regulation 14.6 and the switch-over must be documented [5].

There are two control methods for the ECAs. The first level being the documentation and control of bunkering fuels [5]. The ship’s crew must make sure that their vessels is being bunkered with the correct fuel type as well as ensure the mixing of different fuel types like MGO and HFO, which would rise the Sulphur content of the ECA desired fuel [5]. This raises problems in terms of separating fuel tanks for different fuels as well as brings extra labor to the ship’s crew in terms of cleaning and maintaining tanks as well as pumping fuels from one tank to another. The first level of control can be easily met by using new powerplants, which use alternative fuels like LNG or switching to a more expensive fuel, which is compliant with the Sulphur contents like changing from HFO to MGO.

The secondary control method is related to exhaust gas cleaning systems (EGCS) like scrubbers [5]. Through using scrubbers, the ship owner is cleared from using a more expensive and lower

Sulphur level fuel like MGO, since the exhaust gas is being washed or scrubbed of the SO_x emissions prior to releasing the exhaust gas into the atmosphere [5].

2.1.2 European Emission control

In addition to the ECAs, ships travelling in the European Union waters must also comply with European Commission regulations. The emissions from maritime transport have increasingly affected air quality in the EU, especially in terms of Sulphur dioxide [7]. For Europe the biggest problem of SO_x emissions is their ability to cause acid rain and their ability to combine with other pollutants and therefore generate fine particles [7].

Air pollutants like Sulphur dioxide can be emitted to long distances and in recent years, emissions from maritime transport have increasingly affected air quality in the EU [7]. Sulphur dioxide emissions cause acid rain and combine with other pollutants to generate fine particles.

As of January 1st 2015, the States of the EU must ensure that the ships that travel in the ECAs (North Sea, The Baltic Sea and the English Channel) use fuels with Sulphur content under 0.10% [m/m] [7]. This is not entirely a European Union regulation, but more the Regulation of the IMO, which also approves the use of higher Sulphur content level fuels, but does require the use of exhaust cleaning systems on board the ships travelling in the ECAs [7].

The ships that say at berth in EU ports, must use a fuel with a Sulphur content level of up to 0.1% [m/m]. In addition, the passenger ships operating regularly from or to an EU port, must use a fuel which has a Sulphur content of up to 1.5% [m/m] when operating outside the established ECAs [8].

2.1.3 Regulations in the United States according to the EPA

The United States Environmental Protection Agency or EPA has a similar regulation to the IMO’s Global Sulphur Cap. They have created an emission standard for U.S vessels, which have a category 3 marine diesels engines or marine diesel engines which have a per-cylinder displacement of at least 30 liters [9]. The regulation states that the ships using a category 3 marine diesel engine, must use a fuel, which has a Sulphur content of up to 1000 parts per million [9]. As well as the IMO, the EPA does allow using fuels with a higher that 1000 parts per million Sulphur level, if the ship is fitted with a emission gas cleaning system like a scrubber or has other compliance methods to achieve the stated level of Sulphur in fuels [9].

2.1.4 NO_x emission reductions

The MARPOL Annex VI controls the level of NOx levels and requirements in exhaust gases for marine diesel engines with a power output of more than 130 kW excluding ships that are solely used for emergency purposes [10]. The NO_x control tiers are brought out in Table 2 according to the construction years of the ships and their engine speed.

Table 2 NOx Tiers. Source: Adapted from [10]

Tier	Ship construction date on or after	Total weighted cycle emission limit (g/kWh) n = engine's rated speed (rpm)		
		n < 130	n = 130 - 1999	n ≥ 2000
I	1 January 2000	17.0	$45 \cdot n^{(-0.2)}$ e.g., 720 rpm – 12.1	9.8
II	1 January 2011	14.4	$44 \cdot n^{(-0.23)}$ e.g., 720 rpm – 9.7	7.7
III	1 January 2016	3.4	$9 \cdot n^{(-0.2)}$ e.g., 720 rpm – 2.4	2.0

Table 2 is divided into Tiers from I to III, which show a drastic change in allowed limit of NOx emissions per kWh. The Tier II and Tier III, which are for ships that are built from 2011 or from 2016 accordingly are for ships that operate in the North American and the U.S Caribbean Sea Emission Control area and as of 2021 the ships operating in the Baltic Sea and the North Sea ECA [10].

In addition, the Tier III requirements would apply to installed marine diesel engines when operating in other emission control areas which might be designated in the future for Tier III NO_x control. Tier III would apply to ships constructed on or after the date of adoption by the Marine Environment Protection Committee of such an emission control area, or a later date as may be specified in the amendment designating the NO_x Tier III emission control area [11].

The ANNEX VI regulation 13.7, has introduced the possibility of retrospective NOx certifications for engines of more than 5000 kW power output and over 90 liters of displacement per cylinder for ships built between 1990 and 1999 [10]. This does give conversion companies a prospect of adding new technologies in order for the medium speed engines to get a NOx certification.

2.1.5 Green House Gas (GHG) emissions

A study by the IMO in 2014 estimated that the international shipping in 2012 caused the up to 796 million tons of CO_2, which in 2012 was an estimated 2.2% of all the CO_2 produced that year. It also estimated that by the year 2050, the international shipping could grow between 50% to 250% [12], which means that the emitting of CO_2 volume that shipping produces could grow in the same tempo if certain measures aren't taken into action.

To keep the CO_2 volumes as low as possible as well as ensure new built ships with more efficient technologies to reduce GHG emissions in order to fight the growing shipping and maritime trade volumes, the IMO has brought out two main measures in their MARPOL Annex VI, which is directly linked to overall energy efficiency of the ships [12]:

1. the Energy Efficiency Design Index (EEDI), which requires new ships to comply with minimum mandatory energy efficiency performance levels, increasing over time through different phases [12] the Energy Efficiency Design Index is more thoroughly discussed in subpoint 2.1.6
2. the Ship Energy Efficiency Plan (SEEMP), which establishes a mechanism for shipowners to improve the energy efficiency of both new and existing ships using operational measures such as weather routing, trim and draught optimization, speed optimization, just-in-time arrival in ports, etc. [12] The SEEMP can be implemented to ship conversions in example of new ballast water systems and automation.

The IMO's strategy that could change the future regulations on greenhouse gases to be stricter can be seen through the strategy called the Vision [12]. The GHG emission reduction strategy is divided into three main categories:

1. The use of even stricter and further phases of the energy efficiency design index, which will be the main indicator of energy efficiency of new builds. The phases will be strengthened and revised according to the ship types [12].
2. Declining the carbon intensity of marine transportation by at least 40% by 2030 and up to 70% by the year 2050 [12].
3. Reducing the overall GHG emissions from shipping by having the peak of GHG emissions as soon as possible, therefore having a pathway to reduce the GHG emissions by at least 50% by 2050 and therefore keeping the reduction of emissions as par with the temperature goals of the Paris Agreement [12]

Having set the Goals for GHG emission reduction, the regulations for the emission levels can be hardened in order to meet the ambitious goals of the strategy called the Vision. The set goals could mean drastic changes in existing emission reduction technologies and lead the way to new conversions.

2.1.6 Energy Efficiency Design Index

For new ships the energy efficiency design index is the best way to understand the overall efficiency of the ship in terms of the powerplant and equipment installed on board [13]. EEDI itself shows the energy efficiency of the ship by showing the efficiency per capacity mile or ton mile for different ship type and size segments [13]. The EEDI itself is expressed in grams of carbon dioxide per ship's capacity mile or ton mile [13]. If the EEDI is smaller, then the ship is more energy efficient.

The EEDI was originally mainly developed for the most energy intensive parts of the world's fleet like tankers, bulk and gas carriers, general cargo and container ships as well as refrigerated cargo carriers and combination carriers [13]. In 2014 Marine Environment Protection

Committee extended the scope of the EEDI to LNG carriers, ro-ro cargo ships, ro-ro passenger ships and cruise ships with non-conventional propulsion [13]. The extension of the scope means that the EEDI affects 85% of the shipping induced CO_2 emissions around the globe [13].

In terms of future incrementations, the EEDI is expected to be tightened every five years [13], meaning that the EEDI will keep pace with technological innovations and development as well as be the driver for them. It also lets the shipbuilders be the setters of newer benchmarks in order to lower the EEDI ever further. The EEDI tightening step will be 10% in terms of CO_2 reduction levels and will be incrementally tightened every five years in example from 2025 the reduction rate will be 30% [13]. The reduction rate is calculated from the average efficiency of ships built between 2000 and 2010 [13].

The Marine Environment Protection Commission in 2020 will strengthen the existing EEDI requirements for some ship types like containerships, gas carriers, general cargo and LNG carriers. [12]. This leads to bringing the “phase 3” from taking effect in 2025 to 2022 [12]. This especially affects containerships over 200000 DWT, who will have their phase 3 reduction rate enhanced from 30% to 50% by 2022 [12]. The fact that reduction rate has already been enhanced, could mean that the future reduction rates could strengthen even more due to the growth of shipping capacities by 2050.

Given the extension of the scope, EEDI will be an important driver in ship conversions and the market segment will be wider in the following years, even though the EEDI is considered for new ships at the very moment. Considering conversions, EEDI is a good parameter for ships in use for finding disadvantages in their ship design. MARPOL Annex VI states that the EEDI and SEEMP or EEOI can help benefit both the ship owner and the environment by reducing emissions and having new more efficient technologies will help save money [14]. With the help of EEDI ja SEEMP and estimated 180 million tons of CO_2 is reduced by the new stricter EEDI for new ships and SEEMP for ships that are already operational [14]. In terms of the growing shipping rates as well as the newer stricter EEDI levels, the CO_2 reduction is estimated to be 390 million tons annually [14]. With reduced emissions, the positive outcome for shipowners are the significant fuel saving volumes with the help of newer more efficient technologies, which are estimated to be up to $85 – 150 billion by 2030 [14].

2.2 Discharges

Emissions from powerplants are not the only pollution sources from ships. The author feels that in recent years people have become more aware of the state of our oceans and the pollution levels of the oceans, which harm the flora and the fauna of the oceans and the bay areas from all over the world. The chapter will emphasize 2 main polluters of ships – ballast water, which can carry alien species to different parts of the world and effluents from ships.

2.2.1 Ballast Water Management

The ballast water came with the introduction of steel-hulled vessels, which provide the ships with a unison operating conditions and keep the vessel safe during its voyage [15]. With the help of ballast water, the ship can be trimmed or heeled in order to provide better stability, improve propulsion and overall maneuverability of the ship as well as compensate the uneven loading conditions of the different types of cargo to reduce the stress on the ship's hull [15]. The ballast water can be linked to the SEEMP or EEOI, which was brought out in a subchapter before, since the ballasting of a ship can have a major impact on ship's efficient operations by reducing/increasing the hydrodynamic resistance of a vessel as well as contribute to stability changes of a ship, which could cause a higher fuel consumption, damage of cargo on board as well as affect the well-being of crew and passengers.

The issue with ballast water comes from the invasive marine species that are carried in the ballast water, this poses many health, ecological as well as economic problems, by out-competing native species and multiplying [15], which can cause the native species to become extinct and therefore having economic problems to i.e. fishermen. The invasive marine species could be bacteria, eggs, microbes, invertebrates, cysts and larvae of various species [15].

The Ballast Water Management Convention, which took place in 2004 and entered into force on 8th of September 2017, required all ships to start using a ballast water management plan, which means that all ships must carry a record book and must act according to the regulated procedures [15].

The convention divides the standards into two main categories, D-1 and D-2, which covers ballast water exchange and the other covers the treatment of the ballast water [16]. D-1 means that the ballast water exchange takes place in open seas 200 nautical miles from the coast and requires the depth of the sea to be at least 200 meters deep, which reduces the possibility of the survival of the invasive species [17].

If a ship has gone under a renewal survey after the 8th of September 2019 by the IOPPC or International Oil Pollution Prevention Certificate, it must meet the D-2 standard [17]. If the shipowner opts to refuse the IOPPC survey, then the ship needs to meet the D-2 standard according to its flag state determined date or on the 8th of September 2024 the latest [17]. In order to meet the D-2 standard, the ship must retrofit a class approved ballast water management system [16]. The BWMS system conversion and retrofitting will likely see a growth up to 2024 if the flag States gradually determine the necessity for D-2 standard and peak in 2024 when it becomes mandatory to meet the D-2 standard regardless of the flag state.

In addition to the IMO's regulation, if the ship operates in the US waters, then it must also meet the regulations set by the US Coast Guard [16]. The latest regulation dates back to June 2012 and the ships sailing in US waters must comply to the regulations after their first scheduled dry-docking after 1st of January 2016 [16]. This means that if the ship has a BWT system, which is not approved by the USCG, they must change the system to the USCG compliant BWT system. The USCG has not removed the extension option for shipowners, but obtaining on an extension due to lack of type approved systems, will now be more difficult because shipowners must prove that none of the systems available are suitable for their vessel [16]. It has been possible for vessels to receive a 5-year extension if they've used an alternative IMO certified ballast water, which had received an alternative management system approval from USCG, but as of 2019 the alternative system certificates will not be renewed once the 5-year extension runs out [16].

2.3 Fuel prices

It is well known that the main reason for retrofits and conversions is economics. If the new technology is feasible, then it is desirable for the shipowner to have it in order to save on fuel and make more money. The main fuels expected to be used in ships from 2020 are [18]:

- Ultra-low Sulphur fuel oil (ULSFO), max 0.10% Sulphur
- Very-low Sulphur fuel oil (VLSFO), max 0.50% Sulphur
- Heavy fuel oil, max 3.50% Sulphur
- LNG (liquid natural gas)

2.3.1 ULSFO 0.10% S

A range of new fuels that entered the market to meet the 0.10% ECA requirements will continue to be used [18]. These types of fuels are mostly distillates. However, they could also be hybrids – gas oil blended with residual oil. In general, these fuels work well with standard engine configurations, though they may require operational changes [18]. The distillates have relatively low viscosity levels, that need careful management and some of the new hybrids use products not traditionally used in marine applications, introducing uncertainty about stability, compatibility, and contamination [18]. Because of the potentially high demand for these fuels, the marine sector may find itself in competition with other industries, and these fuels will be an expensive option [18], since the global Sulphur Cap entered into force January 1st 2020, the rise in the fuel price at the beginning of the year was considerable, for example in Singapore, which is the biggest bunkering port in the world, the ULSFO or MGO price was $745.5 per metric ton on January 6th and $594 a month prior to that, having started to grow in mid-September [19]. The MGO has seen a reduction of fuel price from January 6th to February 7th from the peaked $745.5 to $557.5, which is a similar price level compared to pre-January 2020 global Sulphur Cap prices.

2.3.2 VLSFO 0.50% S

The very low Sulphur fuel Oil is made of suitable residual products with low Sulphur distillates, where the blends can contain up to 40% residue and the Sulphur quantity is kept below 0.5% [18]. The issue with VLSFO at the moment is the insubstantial price gap between MGO and VLSFO, in Singapore the price of VLSFO was price was $742 per metric ton on 6th of January 2020. Up from $720 per metric ton a week prior to that and having been $581 per metric ton in December 2019 [19]. This means that the use of VLSFO is redundant until the price gap between VLSFO and MGO increases. The VLSFO has also seen a reduction in fuel price but the price gap between MGO and VLSFO is still insubstantial, being $544 and $535 per metric ton [20] accordingly.

2.3.3 Heavy Fuel oil (HFO)

HFO or Heavy Fuel Oil the cheapest option of the prior two, being $400 per metric ton on January 6th 2020 [20]. The fuel oil maximum Sulphur level is 3.5%, which means that the ship will need a scrubber in order to comply with the global ECAs that entered into force January

2020. Compared to ULSFO and VLSFO the price fluctuation has been substantially lower – in a month from the peaked fuel price of January 6th, the price of HFO has dropped to $322 per metric ton by the February 7th [20].

Considering the fact that the price difference between VLSFO and HFO is approximately $200 per metric ton, a quick calculation using Emma Maersk as an example shows that if the ship uses 380 tons of fuel per day [21], the daily cost difference using VLSFO or HFO is $80940. Given the quick calculation, it is clear that using a scrubber on board is a feasible choice when operating in the ECA, given the fact that the average price of scrubber retrofits is from $3 to $10 million [22], the feasibility of a scrubber installation using the Emma Maersk as an example is from approximately 38 to 123 days not taking into account the higher fuel consumption. Wärtsilä has brought out the payback time of a retrofit worth 3 million USD for a vessel with 10MW Main Engine, 3x0.5MW Auxiliary Engines (Figure 2) [23].

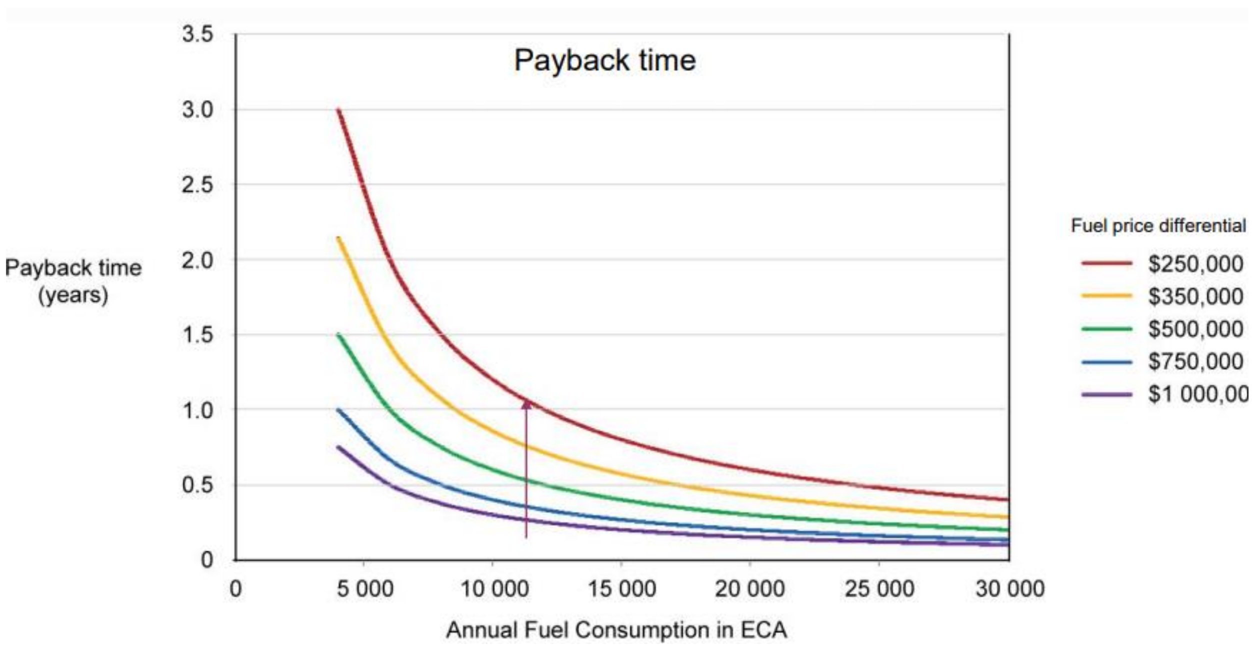

Figure 2 Scrubber Retrofit investment payback time. Source: Wärtsilä

2.3.4 LNG

LNG is considered an environmentally friendly alternative to more conventional MGO and fuel oil due to LNG having a Sulphur content well below the regulatory limit [18] as well as emitting zero Sulphur oxides, having very low particulate matter volumes and 90% less nitrogen oxides [24]. LNG does have an issue with methane slip, but it can be reduced and therefore achieving the reduction of GHG emissions by up to 10-20% [24].

The price of LNG cannot be directly compared as the fuels brought out prior – price per metric ton, but must be compared with using the unit dollars per million British thermal units [$/MMBtu]. As of 31st of January 2020, the using BP world energy review with average energy prices on gas and oil as well as Henry Hub's prices, the price of LNG was 6.64 [$/MMBtu] in the European Union and 2.24 [$/MMBtu] in the United States (Henry Hub, located in Louisiana), the average price for 0.1% Sulphur MGO was 15.57 [$/MMBtu] and the price for HFO or IFO380 (Sulphur content up to 3.5%) was 9.77 [$/MMBtu] [25].

The cost of LNG can be divided roughly into two – only 25% of the cost of LNG is the natural gas and the rest of it is the transportation and cooling of the gas [24]. The big benefit of LNG is the stability of the price of LNG, which does not fluctuate as much as other fuel oils [24] due to the low percentage of the cost being natural gas. The cost will also stay the same or rather go downward in the future due to the infrastructure of LNG transportation continuingly developing and LNG becoming more widely used [24].

The price fluctuation over the past 6 years can be seen in the below Figure 3 [25]. Over the past 6 years, the LNG price for Henry Hub has stayed relatively similar and has not fluctuated as much as the prices in EU and Japan. The prices in EU and Japan can be seen to follow a similar pattern as other oils, but the scale is much smaller in terms of fluctuations. Looking at the price difference between MGO and EU gas, the maximum fluctuation has been approximately 7 dollars over the past 6 years when MGO has seen the biggest price difference of over 14 dollars. Henry Hub's gas prices have stayed relatively same by having a maximum price difference of 4 dollars over the 6 years [25]. This leads to shipowners having a steadier assessment in fuel costs and helping with budget planning as well as saving money at the same time.

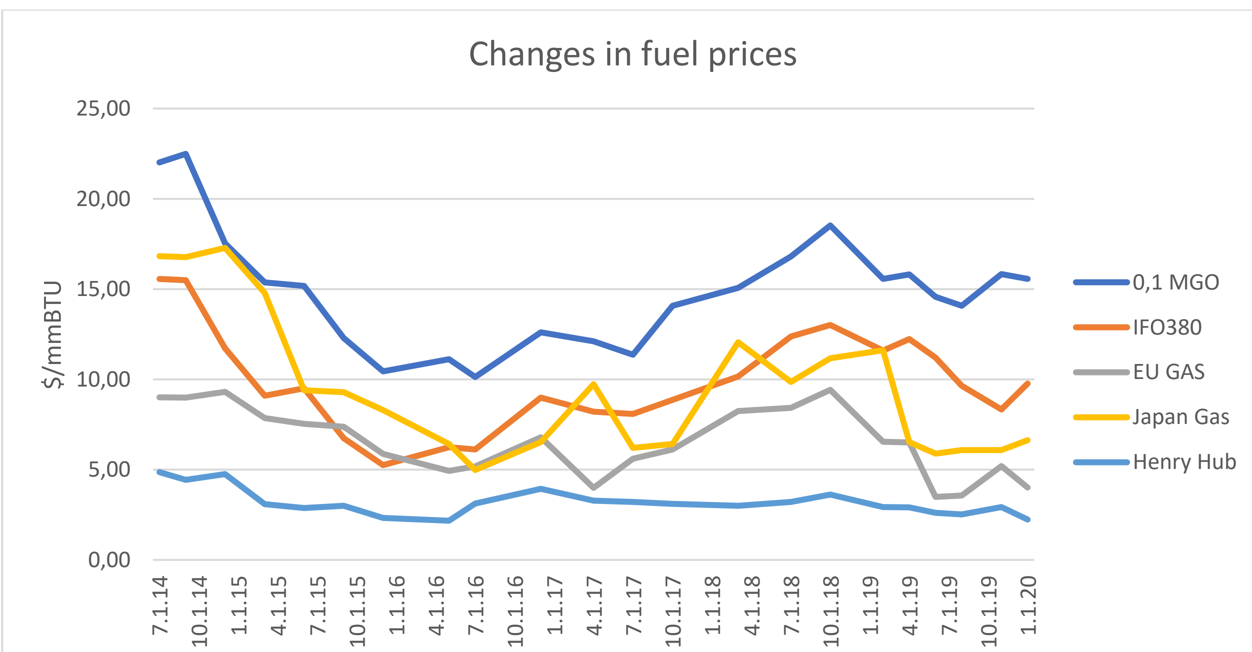

Figure 3 Changes in Fuel Prices. Source: DNV GL

2.3.5 Fuel energy density and specific emission of CO_2 comparison

Table 3 shows the gross heating value of the previously addressed fuels as well as the specific emission of CO_2 [26], the values of energy density are shown in MJ/m^3 for a more adequate read due to the fact, that the LNG storage requires much space even though its energy density per kg is very high (55.2 [MJ/kg]) [27]. Due to the high density of MGO, LFO and HFO, the energy density does not change much when comparing the energy density of the fuel according to its volume versus mass. This does not affect the price of fuel but does raise an issue with storage volumes and the location of LNG tanks.

Table 3 Fuel comparison. Source: Adapted from [29,30]

Fuel Type	Specific Emission of CO_2 [t-CO2/t-Fuel]	Calorific value [MJ/m^3]	Calorific value [MJ/kg]
MGO	3.206000	41.08	43.08
LFO	3.141040	41.08	43.08
HFO	3.114400	41.83	41.83
LNG	2.750000	23.6	55.2

2.4 Conclusion

The shipping industry is going through a transition to greener energy sources. In a capital world, the transition can only be accelerated by economical accelerators, which are brought by hardening laws and the higher fuel prices, which are also directed to environmental policies through fuel excise enforced by countries and councils.

The main drivers that lead to ship retrofits and powerplant conversions are strongly linked to each other and to the pricing (market demand, excise) and use of different fuels. The most potential drivers of the coming years are listed below:

- MARPOL Annex VI has specific limits for different air pollution sources which can be found in the exhaust gas of ships with different fuel types, including Sulphur oxides (SO_x) and nitrous oxides (NO_x). This mandates the ECAs, which is directly linked to the use of suitable fuels and respective technologies like scrubbers. The ECAs are forecasted to expand substantially, which will lead to powerplant conversions and scrubber and selective catalytic reduction (SCR) system retrofits.
- EEDI and SEEMP/EEOI – The IMO's strategy to reduce GHG emissions by at least 50% by 2050 and decline the carbon intensity of marine transportation by at least 2030 and up to 70% by the year 2050 [12]. This could lead to stricter EEDI and SEEMP regulations as well as the whole alteration of the fleet's energy system. EEDI is still mandatory only for newbuilds, but EEDI is expected to be tightened every 5 years, which could eventually lead to the adaptation to existing vessels. SEEMP on the other hand is

for existing vessels, which is a strong measure in utilizing new technologies in order to optimize the overall efficiency of a vessel.

- Fuel prices – the price for different fuels has seen a relatively linear growth in the past with a few extreme temporary fluctuations. As seen on Figure 3, the Henry Hub LNG price has remained steady. As the regulations for emissions become stricter, the use of low Sulphur diesel fuels could become even more expensive with the example of the Global Sulphur Cap. This could lead to a large number of powerplant conversions in terms of LNG, hybrid solutions, fuel cells as well as scrubber installs.
- The BWM Convention – The BWTS system conversion and retrofitting will likely see a growth up to 2024 as the flag States gradually determine the necessity for D-2 standard and peak in 2024 when it becomes mandatory to meet the D-2 standard regardless of the flag state.

The laws are enforced in a way that all parties could benefit from them. From an environmental side of the transition, by having laws enforced, the climate change can be slowed down and the environment can be kept as untouched as possible. In terms of the shipowner, the laws are not going to prohibit or limit business volumes, but rather force the shipowners to find more sustainable ways for operations through newer and cleaner technologies. The biggest benefiter from the energy transition and new enforced laws are the retrofitting and conversion companies, who will have growing volumes in the field of new powerplants and sustainable ship systems.

3 TECHNICAL SOLUTIONS

The following chapter will analyze the possible current as well as future technologies to meet the regulations that are in effect right now as well as the possible future forecasted regulations. The principles of technical solutions/ship systems to achieve the regulation-enforced emission and discharge requirements will be divided into 2 main categories – Emission reducing systems and discharge cleaning systems, which will then be divided into 4 subcategories:

a. Exhaust gas cleaning systems (i.e. Scrubber/SCR systems)
b. New fuels and engine/powerplant types
c. Miscellaneous emission reducing/EEOI increasing systems (i.e. rotor sail systems)
d. BWT systems and solutions

Each of these subcategories will be assessed by bringing out different types of systems and their characteristics for each solution.

3.1 Exhaust Gas Cleaning Systems

The environmental regulations which are already in effect as well as future possible ECAs and other emission regulations brought out in chapter 2, play a big role in exhaust gas cleaning system retrofittings as well as the overall development of the ship systems. Since the ECAs are constantly broadening and the fuel prices are constantly linearly rising, means that more ships are going to install exhaust gas cleaning systems on board their ships. The specter ranges from cargo ships to cruise ships. The cruise industry can benefit from greenwashing in terms of advertising their service as environmentally conscious and providers of cleaner air to their cruise passengers.

The main emissions that the cleaning systems must face are Sulphur oxides, Nitrous oxides, particulate matter and Ozone depleting substances. There are two main systems that fight the emissions listed – scrubbers and SCR. Both systems have certain emissions that they clean and a ship could need either of them or both systems depending on their operational area and fuel used.

3.1.1 Scrubber

A scrubber is used in order to lower the SO_x volumes in a ship's exhaust gas. They can be mainly divided into four different solutions:

1. Closed-loop Scrubber – scrubbing water is dosed with alkaline and recirculated, once the water is dirty, the sludge is put to a tank. Can be used anywhere but comes with a high operating cost [28].
2. Open-loop Scrubber – Exhaust gas is cleaned with seawater and the water is discharged into the body of water. Cheapest to build and operate but has its limitations in terms of operational area and sea alkalinity [28].

3. Hybrid Scrubber – can run on open- and closed-loop operational mode according to the area the ship operates. Most expensive system of the previous 2 but flexible [28].
4. Dry Scrubber – pellets of hydrated lime are being used to remove Sulphur. The system works at a higher temperature than wet scrubbers and therefore soot and oily residues are also burned off. Costly, heavy and storage consuming [29].

Open-loop Scrubber

An open-loop scrubber is a type of wet scrubber, where the exhaust gas is washed with the sea water in which the ship is sailing in. The exhaust gas enters the scrubber through a venturi and inside the scrubber unit the exhaust gases are sprayed with the caustic sea water, the liquid in the exhaust gas must be eliminated in order to make sure it sets in the bottom of the scrubber unit to move on to the scrubbing water processing. During the processing period, the PM, metals and other residual burning side products are separated from the wash water and placed in a sludge tank, while the processed wash water is discharged overboard.

The main issue with an open-loop scrubber is the insufficient quality of the sea water, which means that if the water isn't alkaline enough, the CO_2 in the water will not dissolve into carbonic acid or bicarbonate/carbonate ions [30]. This makes the scrubbing process inefficient, meaning that the decision to opt for an open-loop scrubber, needs a thorough analysis and understanding if the operational area meets the required alkalinity as well as defining the future outlook in terms of operational areas, as the use of additives to meet the required alkalinity might not be feasible in long term. The alkalinity levels of the Baltic sea can be seen in Figure 4 [31]. The figure shows that most of the Baltic sea has the appropriate pH levels (1000 µmol/L being a safe margin) [31] excluding the northern part of the Gulf of Bothnia and the eastern part of the Baltic sea, in example the port of St. Petersburg. Other areas, where low alkalinity levels impede the open-loop scrubbing process include mostly lakes and rivers in example the Mississippi river and the Great Lakes [31].

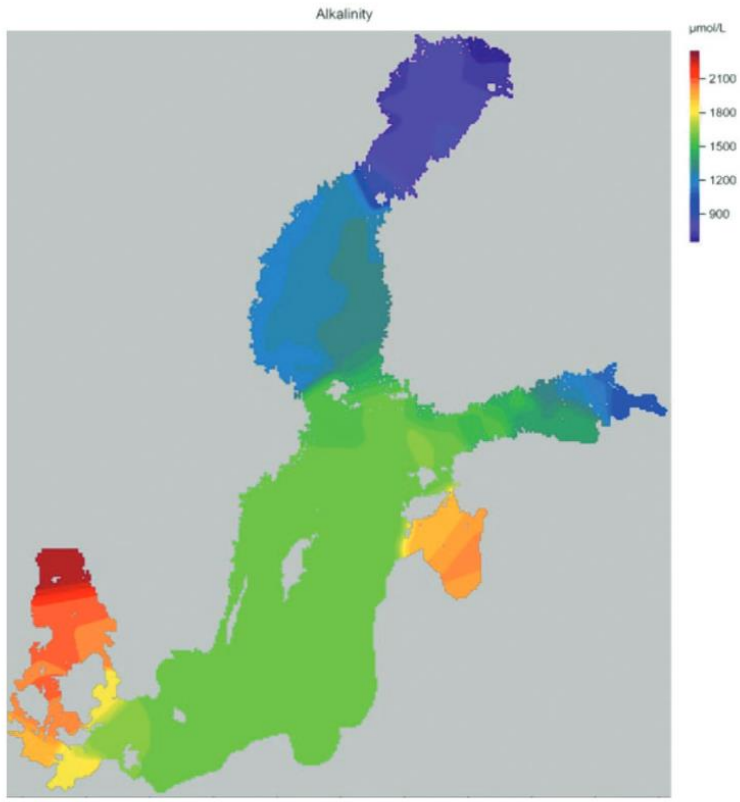

Figure 4 The Baltic sea alkalinity levels. Source: Wärtsilä

Another issue comes with sulphates being discharged into bodies of water, which could change the local acidity of the water and this could have a negative impact on the flora and the fauna of the body of water, which means that there are areas, where discharging the effluents of scrubbing is prohibited, therefore an open-loop scrubber cannot be used in given areas.

Closed-loop Scrubber

A closed-loop scrubber is a type of wet scrubber, where the exhaust gas is scrubbed with a circulating wash liquid and thereby the SO_x compounds and PM are removed. In a closed loop system, a ship does not have to account for the pH level of the water that they are sailing in as well as not having the need to discharge the scrubbing water, this removes the need to process the wash water prior to discharging as well as not having to account with the discharge regulations. Usually Sodium hydroxide is used to make the alkalinity of the water higher, the same substance is used when the wash water is recirculated [30]. This raises a need for a process tank, in which the wash water is processed to allow it to scrub again as well as the need for a bigger holding tank and a freshwater generator or a freshwater tank, which raises the issue of needing more space onboard, which could not be possible for certain types of ships.

Hybrid scrubber

The hybrid scrubbers combine the benefits of both systems listed prior. In a hybrid scrubber system, the scrubber can be operated in both closed- and open-loop modes, which means that the cheaper HFO fuel can be used in all areas as well as in ports. This means that the most expensive type can become the cheapest over-all if the ship operates in areas, where both operational modes are necessary, meaning that it can run on the cheaper HFO constantly as well as discharge the sludge where allowed.

The downsides of the system is the higher price of the equipment and the difficulty of retrofitting. The system also requires more space than the prior two.

Dry Scrubber

The dry scrubber types use pellets of hydrated lime or calcium hydroxide as the cleaning agent instead of alkaline water [30]. In dry scrubbers the agent reacts with the SO_x and $CaSO_4$ is the product of the reaction. The scrubber works by having exhaust gases pass a layer of hydrated lime pellets, the pellets absorb the SO_x components and form pellets of $CaSO_4$ as a byproduct. The byproduct pellets are stored and must be disposed ashore, which fortunately is not considered as waste, since $CaSO_4$ can be used as fertilizer or a construction material [29], making the disposal much cheaper.

The disadvantage of a dry scrubber is the necessity for pellet storage as well as the systems weighing more than its wet counterpart. The advantage of using a dry scrubber comes from the low amount of temperature drop of exhaust gases due to the usage of dry cleaning-agents (Exhaust gas temperature over 350°C) [30] ergo the system can be used with a selective catalytic reduction system, which will be assessed in the next chapter.

The shipowners must choose a most suitable type of scrubber for their ship by taking account the operational area of the ship whether the ship can use an open-loop at all times or has to opt for a hybrid, closed-loop or even a dry system. The size of the system is also a key aspect in choosing a suitable option, for instance a cargo ship will have less of an issue with retrofitting a hybrid system due to the available space of the system as well as storage of sludge. Another issue is the power output of the engine and the power the system needs and the weight of the system, which can reduce the feasibility of the system all together by using more fuel.

3.1.2 Selective Catalytic Reduction

IMO's Tier III of reducing NO_x emissions has been addressed in subchapter 2.2. The Selective Catalytic Reduction (SCR) is not a new concept since it has been patented since 1957 [32] and has had many different applications from cars to locomotives and power plants. The Tier III has raised the use of them in ships in the last couple of years, since it is the only available technology that achieves the Tier III NO_x standards with the use of conventional fuels by being able to reduce up to 90% of emissions under certain conditions, as well as having a low or non-existent rise in fuel consumption. [32]

The SCR uses NH_3 with a ceramic monolith to reduce NO_x emissions by forming nitrogen and water. In order for the process to work, the exhaust gas temperatures must be a minimum of 260°C-340°C [32]. If the load conditions do not provide the system with the needed temperature, the exhaust gas temperatures must be boosted, which can be the case with wet scrubbers as described in the previous subchapter.

3.2 New Fuels and Powerplants

As the conventional fuel prices show a steadily growing trend, the research and development of alternative fuels and their powerplants grows as well as the infrastructure. The use of alternative fuels should cut the dependence on oil and thereby reduce the dependency of other countries outside the EU [33].

The alternative fuels are going to be the game-changers of the shipping industry in the coming years, with the shipping industry's goal to become carbon neutral by the year 2050. This will lead to a technological leap towards new technologies and their installations on new and existing fleet. In the last 10 years, the European Union has seen many new ships that use alternative fuels and have been successful in utilizing them. For example, Tallink Megastar and Viking Grace both use LNG regardless of not having LNG bunkering stations available at the ports and Stena Germanica being the first methanol fueled ship conversion [33].

In order to comply with the new enforced Sulphur limits as well as the goal to reach carbon neutrality, the future fuels are considered to be LNG, Biodiesel, Methanol, DME, LPG and most importantly electricity and hybrid solutions. The author suggests that nuclear energy will not be considered for commercial use in the following 50 years due to its reputation as being dangerous, even though nuclear energy being one of the most potential alternatives to fossil fuels.

3.2.1 LNG

LNG is soon to be considered a conventional fuel due to its common use. The main engine concepts utilizing LNG are brought out in Figure 5 [34]. Each of the engine types have specific characteristics from which a suitable application must be selected by the shipowner considering the ship type, operational area and initial investment.

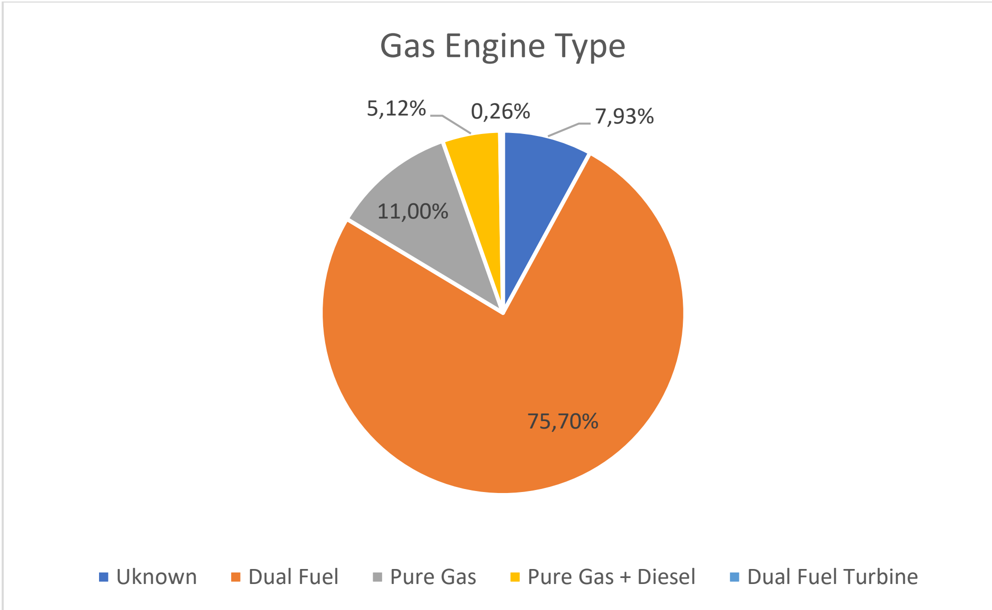

Figure 5 LNG engine types. Source: Adapted from DNV AFI

The reason for the prior statement that LNG can soon be considered a conventional fuel is due to the fact that as of 2020 182 LNG powered vessels are already in operation, 55 are on order and 123 are LNG ready [34]. The order of LNG powered vessels will grow rapidly in the following two years from 138 to 200 [34]. There are already 44 LNG power RoPax ferries with 12 on order, 9 containerships in operation with 38 on order, 2 cruise ships in operation and 33 in order [34]. The numbers does not only consist of newbuilds. There are 22 vessels with retrofitted LNG powerplants, and this number could grow in the following years, when fuel prices continue to grow and the infrastructure for LNG bunkering develops.

Dual Fuel 4 stroke engine

Dual Fuel engines are popular due to their flexibility to run on natural gas, light fuel oil or HFO, which means that the engine can work on both Otto and Diesel cycle. It must be stated that a dual fuel engine cannot operate with LNG entirely – a regular Otto engine uses a spark plug to ignite the air/fuel mixture, wherein diesel engines a small amount of diesel is used as pilot fuel to ignite the LNG.

The dual fuel market has taken a big leap in the last years, many big engine manufacturers like Wärtsilä, Man Energy Solutions and MaK have come out with newer more efficient models. A dual fuel gas engine meets the new Tier III as well as ECA requirements but has a 1-2% methane slip.

Dual Fuel 2 stroke engine

The 2-stroke dual fuel engine works similarly to the 4-stroke dual fuel engine with the difference of engine speed. Pilot fuel is 1% of the whole fuel consumption and with the help of low pilot fuel consumption, Tier III and SECA requirements are met.

The 2 stroke engines also require a fairly simple gas supply system, with the necessary gas pressure being below 16 bars [35].

Pure Gas 4 stroke engine

A pure gas 4-stroke engine runs entirely on gaseous fuels. The engine works similar to the dual fuel's Otto mode, but rather than using pilot fuel as ignition, the engine has a spark plug. A pure gas engine meets the new Tier III as well as ECA requirements, but has a 1-2% methane slip.

For pure gas 4 stroke engines, Wärtsilä's 31SG pure gas 4 stroke engine is a suitable option for i.e. hybrid solutions due to its high thermal efficiency and low investment cost, which help offset the price of batteries [36].

3.2.2 Methanol

Methanol is a widely used alcohol, it has the lowest carbon content and the highest hydrogen content of any liquid fuel [34]. It is produced mostly from natural gas or coal. In order for it to be considered a green fuel, it must be produced from hydrogen and CO_2, which can be received from agricultural or forest waste or from the CO_2 captured from industries and power plants.

The fuel can be used in a two-stroke diesel engine and a four-stroke Otto engine, but the latter is not commercially used in shipping. Methanol can also be used in fuel cells, which will be addressed in the next subpart.

3.2.3 Fuel Cell

The fuel cell technology converts chemical energy stored in fuel into electrical and thermal energy. This process is called electrochemical oxidation [34]. The technology can offer up to 60% efficiency [34], which is higher than conventional engines. As a plus it has lower noise and vibration levels than a conventional counterpart.

Even though there are more than 7 different well-known fuel cell technologies solid oxide fuel cell (SOFC), proton exchange membrane fuel cells (PEMFC) and high temperature proton exchange membrane fuel cells (HT-PEMFC) are the most promising technologies for marine use [34].

In terms of usable fuels, with the help of fuel reformers different low flashpoint fuels from pure hydrogen can be used like LNG, methanol low-flashpoint diesel.

Solid Oxide Fuel Cell

The SOFC is a very high temperature technology. It operates in temperatures between 500-1000°C. As seen on Figure 6 the electrolyte is a porous ceramic i.e. yttrium stabilized zirconia [37]. The anode is a nickel alloy and the cathode is a lanthanum strontium manganite.

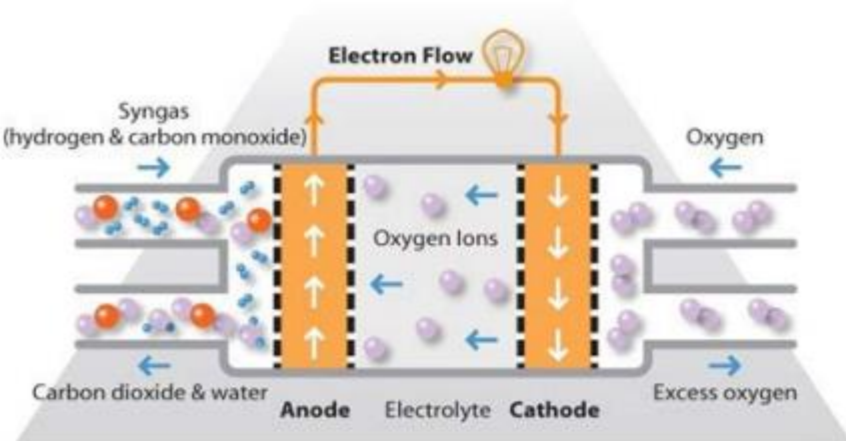

Figure 6 SOFC principle. Source: DNV GL

The main benefit of SOFC is its fuel flexibility. Hydrogen, LNG, methanol and low flashpoint diesels can be used in SOFC, but this does raise the issue of CO_2 as an emission if other fuels than hydrogen are used.

Proton Exchange Membrane Fuel Cells

The PEMFC technology is quite widely used from cars to ships. For instance, the Alsterwasser passenger ship has a 96kW PEMFC unit as seen on the Figure 7 [37]. In the Alsterwasser the fuel cell is coupled with battery powered propulsion, which makes it a hybrid solution.

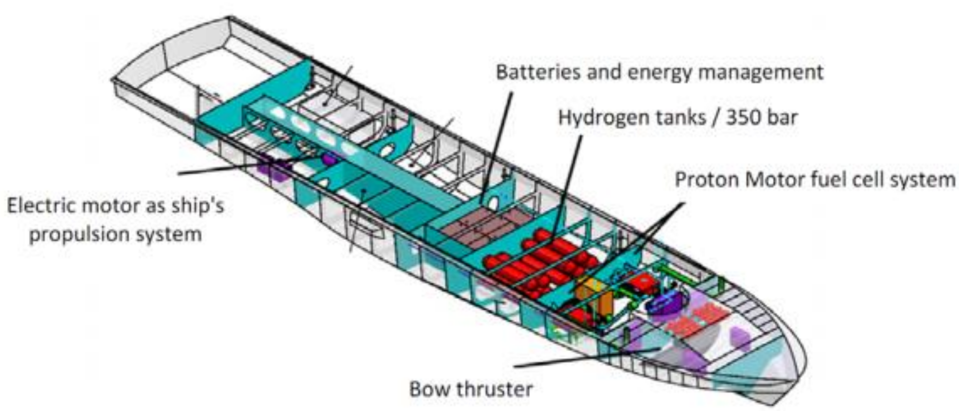

Figure 7 FCS AlsterWasser. Source: DNV GL

In PEMFC, hydrogen and oxygen is used in the process and water is a byproduct in addition to electric power and heat. The system itself uses platinum electrodes and humidified polymer membrane as an electrolyte (See Figure 8) [37].

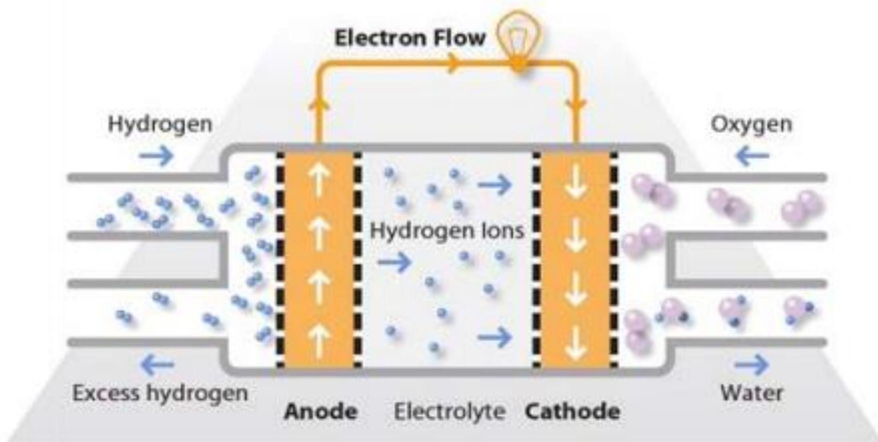

Figure 8 PEMFC principle. Source: DNV GL

As the PEMFC technology has a high power to weight ratio 100-1000W/kg and a low operation temperature, makes it a suitable option for different categories of transportation. As a negative, the excess heat cannot be recovered and the platinum electrodes cost much and can be ruined by carbon monoxide and Sulphur contamination.

High Temperature Proton Exchange Membrane Fuel Cells

The difference between HT-PEMFC and PEMFC is the operating temperature. The temperature difference comes from the use of different electrolytes as the HT-PEMFC uses mineral acid and PEMFC uses water-based electrolyte, which raises the temperature up to 200°C.

Utilizing high temperature reduces the risk of contaminating the platinum electrodes with carbon monoxide and Sulphur. The technology also allows the utilization of heat recovery, but has a lower power density and a relatively same efficiency, which can be further raised by using heat recovery.

3.2.4 Hybrid Solutions and Batteries

Hybrid systems and batteries are considered the key technology in achieving the zero emission vessels by the year 2050. Fully electric vessels are limited by the battery technology, which needs to have a major leap in the capacities and prices. With the current battery technologies, the most feasible hybrid and fully electric solutions are for ferries on short voyages, which have already been implemented in Norway, Estonia and will find much use in Scandinavian archipelagos and Europe.

The zero-emission vessel slogan is controversial due to the production process of batteries as well as the production of electricity comes from different sources. Wind power is a 100% renewable energy, but if electricity is made from coal or shale, then the production of electricity itself does not overweigh the production of power from i.e. diesel or LNG.

As far as battery production goes, the environmental impact from utilizing electric power outweighs conventional fuels in major way. The environmental payback period for both a hybrid powerplant as well as fully electric engine were studied. The environmental payback from an energy intensive battery production is 1.5 months for global warming potential (GWP) and 0.3 months for NO_x [34]. In terms of the electricity utilized for recharging, for the fully electric vessel the GWP is decreased by 0.1 months when using Norwegian electricity, which is known for its renewable energy usage. With EU electricity, the GWP rises to 2.5 months and when taking account the global average, then the GWP will be increased to 1 year [34].

3.3 Miscellaneous Green Technologies

There are other yet smaller ways to increase the efficiency of an existing ship and help meet the hardening regulations as well as reduce daily operational cost for shipowners. The subchapter addresses technologies that are not yet widely used in the present, but could show a growth in the coming years as the regulations are revisited, hardened and the shipowners look for cheaper options on older existing vessels, which could improve the EEDI and SEEMP/EEOI.

A rotor sail system, air lubrication system and solar energy are assessed in the following subchapter.

3.3.1 Rotor Sail System

The rotor sail system has been around since the 1920, but has not been utilized in a numerous way. The Flettner rotors utilize the Magnus effect, where a vertical rotor placed in the upmost deck of the ship, is being rotated by the wind and the rotation causes propulsion (See Figure 9) [38].

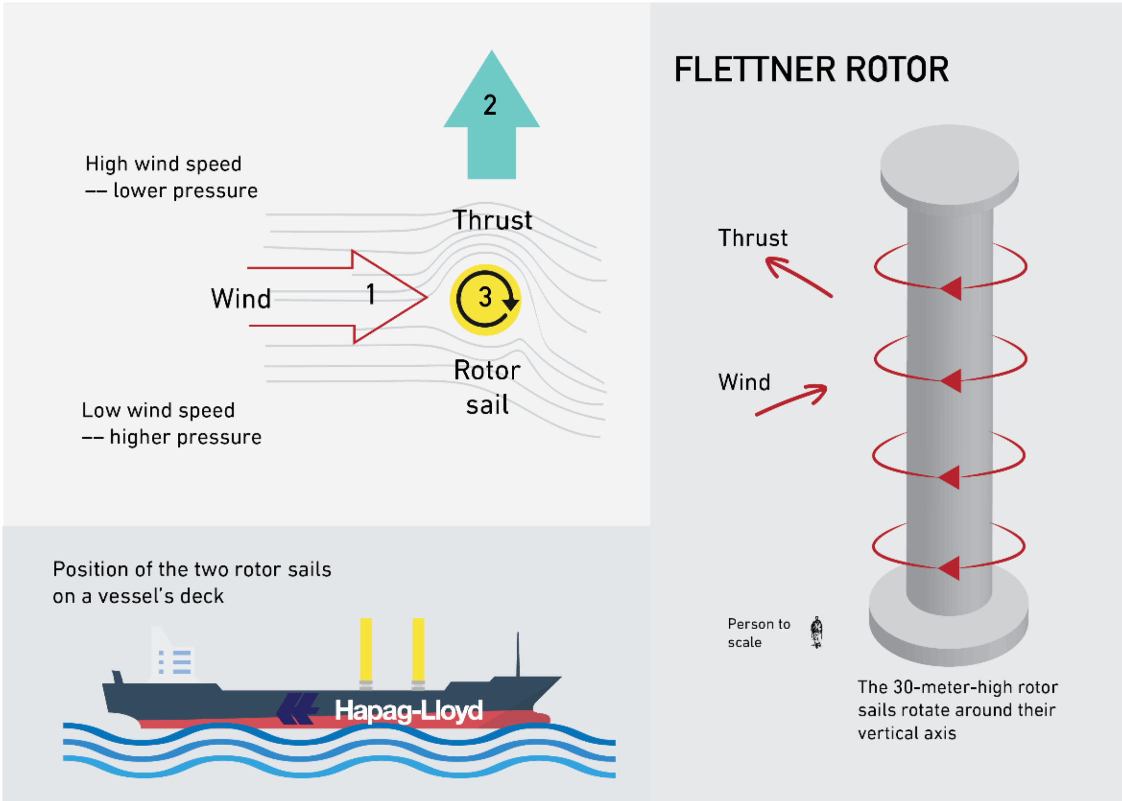

Figure 9 Flettner Rotor. Source: Ivey Business Review

The Flettner rotor is said to reduce the fuel consumption from 3% to 15% on average and has shown a peak reduction at 35% depending on the ship and the operational area [39]. Another perk of the rotor sail is the ability to achieve higher speeds than with only the engines, for example a coaster Fehn Pollux was able to achieve extra 2 knots of high speed at Beufort force 7 [40]. The rotor sails have also been accepted by the IMO in calculating the EEDI, which was discussed in the chapter 2.

The economy of the rotor sail can be calculated with a simple formula by the Emden/Leer University, where in average or medium wind conditions the rotor sail produces about 2kW of propulsion power per m^2. If the rotor sail has a projected area of $60m^2$ then the sail can provide the ship with up to 120kW of propulsion power. With the concrete example of Viking Grace, the 24m high rotor sail saves up to 300 tons of LNG per year [41] and the CO_2 emissions can be reduced by 900 tons a year [41].

3.3.2 Air Lubrication Systems

Fuel consumption is directly linked to the water and air resistance of a ship. Water resistance is divided into two components – frictional resistance and residual resistance/wave resistance. The frictional resistance depends on the ship's wetted area, which means that if the ship is slenderer, it will have more wetted area and therefore the frictional resistance will be bigger. Slender ships are usually faster ships like ferries and cruise ships. The frictional resistance is also linked to speed, it is a more substantial factor on slower ships, as for faster ships, the goal is to reduce wave resistance, which is a bigger part of overall resistance of a faster vessel. A way to reduce frictional resistance is by using an air lubrication system.

The air lubrication systems can be divided into 3 main different methods air film/layer, air cavity and microbubbles [42]. Even though air cavity does not require much airflow in calm water and is a very effective way of reducing the resistance by reducing the wetted surface [43], it will not be addressed in this subchapter due to the fact that it is technically not feasible to retrofit this kind of a system on an existing hull and the system does not work well in waves.

Air Film/Layer and Microbubbling

The air film works similarly to microbubbling, where air is blown through holes under the hull of the ship to create a layer of air between the water and the ship's hull. This reduces the viscous/frictional resistance of the ship but loses its efficiency at higher speeds.

With microbubbling, the holes underneath the hull produce a layer of turbulent air or bubbles, which work in the same way as the air film (See Figure 10) [44] by reducing the viscous frictional resistance, but are not very effective at low speeds due to buoyancy. The microbubbling phenomenon is not clearly established on why the system reduces friction. It has been acknowledged that the bubbles reduce liquid density and therefore the Reynolds stress [45]. Two other theories have been listed as the turbulence suppression effect and flow viscosity reduction by bigger void fraction [45].

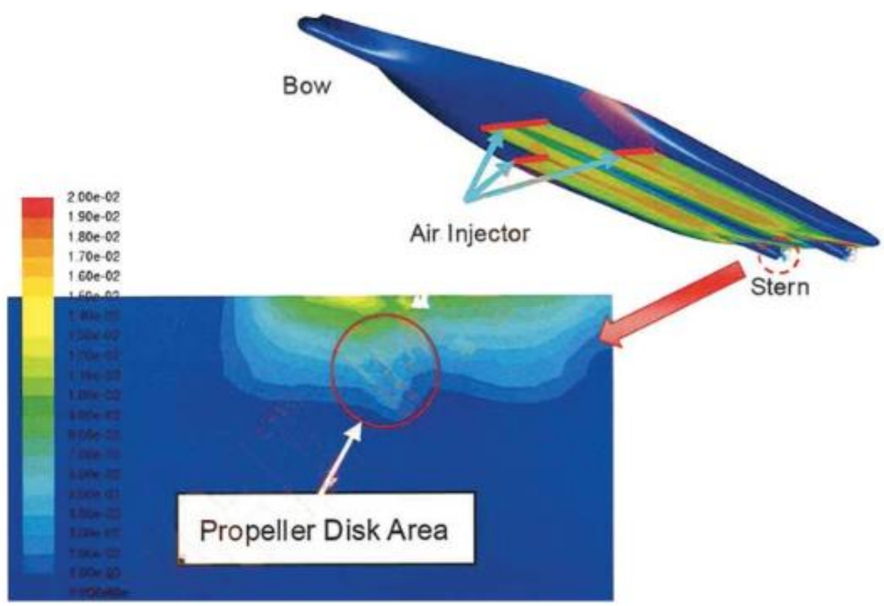

Figure 10 Air Bubbling system. Source: Class NK

3.3.3 Solar Energy Utilization possibilities

Solar panels are not very common on commercial ships as of 2020, but are expected to be used more commonly due to the price of watt per installed capacity as well as the integration possibilities like photovoltaic glass, which could be used very effectively cruise ship balcony railings, which would cover a far more bigger area than using the upmost deck of a vessel.

The price of the solar panels and elements is forecasted to reduce, but they are not expected to become more efficient. The panels give up to 1000W/m^2 at 25C° during a sunny day. This however is the perfect condition as they are rated at a 10%-30% efficiency throughout their lifetime [46]. The potential of the fuel consumption reduction depends on the capacity of panels installed.

3.4 Ballast Water Treatment

Ballast Water treatment systems are reaching peak installation growth rates due to the legislations described in chapter 2.2. As the legislations are ever-hardening, some older systems will be switched to newer models, especially due to the USCG, which has more stringent ballasting laws.

There are seven main types of ballast water treatment systems [47]:

- UV
- Electrolytic
- Advanced Oxidation
- Ozone
- Deoxygenation
- Heat / Deoxygenation
- Filtration

The first two listed are the main systems that are used, often the other five are added to the UV or electrolytic system. The UV reactor-based system will be addressed in this chapter due to the technology having the biggest percentage of G8 approved systems. 55.6% of all G8 approved systems are UV reactor based, 51.2% are electrolytic systems [47]. The UV based systems are also the most popular with the thesis' destination ship types 76% and 82% [48] for container ships and passenger ships respectively.

The UV system can be seen on the Figure 11 below. The system pictured is an Alfa Laval 3.2 UV + filtration system, which already complies with G8 BWT legislation, meaning that the ballast water system is approved by every port state.

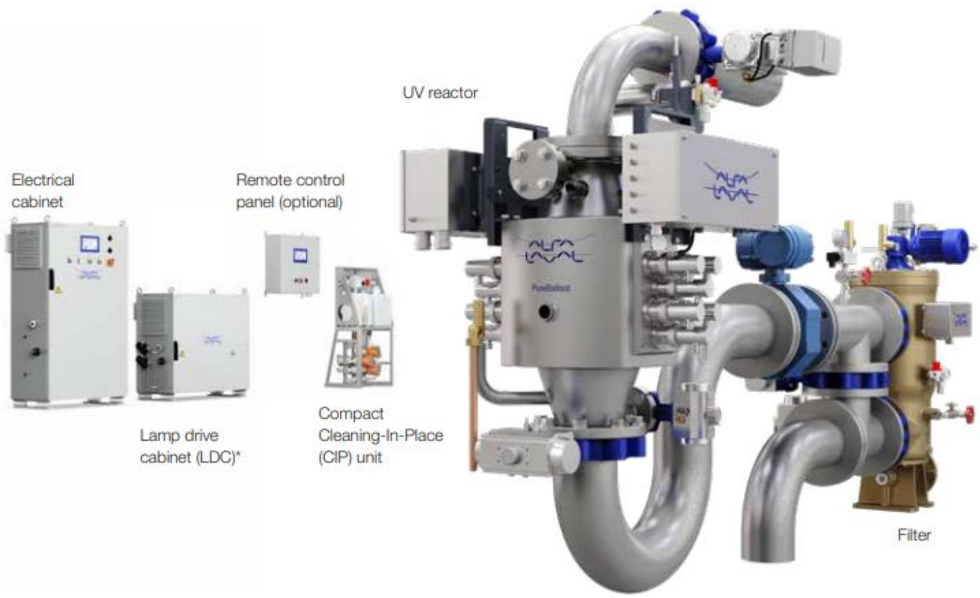

Figure 11 Alfa Laval Pureballast 3.1. Source: Alfa Laval

If additional piping and foundations for components excluded, the system consists of [49]:

- A filter - used for reducing the number of larger organisms and sediments in the system and tanks (bypassed during de-ballasting, cleaned via backflush)
- The UV reactor -the heart of the treatment system. Uses UV lamps to disinfect the water by generating free radicals, which destruct the invasive species membrane, by this the cell's DNA molecule is destroyed and it cannot reproduce
- CIP unit - cleans the UV lamps to reduce the buildup on UV lamps to ensure their effective work
- The electrical cabinet – included cabinet powers a system with up to 300m^3/h flow as well as other components, if the flow is over 300m^3/h, additional lamp drive cabinets must be used

3.5 Biggest Markets for Conversions

The technical solutions for meeting new regulations can be divided into 4 main categories, first three being directly connected to reducing emissions to air by either cleaning the exhaust gases of making the ships more efficient by reducing fuel consumption or by using newer cleaner alternative fuels and technologies. The last category is ballast water treatment, which is directly connected to the marine environment and with the new regulations as well as the society's increased awareness of ships polluting the marine environment.

Retrofitting companies are expected to have three main markets in which they have to prove their capability in engineering and fast outfitting of turnkey projects. The three main technologies to put emphasis on are scrubber installs, hybrid conversions and ballast water treatment systems. The scrubber retrofits being the easiest way to meet ECAs as well as maintain the use of cheaper fuel HFO, hybrid solutions being a feasible way to evade port and fairway fees as well as reduce fuel cos, and ballast water treatment systems being directly required by the IMO and port states.

3.5.1 Scrubbers

On 20th of April 2020 the DNV database showed that the scrubber market started booming in 2019 by growing from 737 in operation and on order scrubbers to 3137 [34]. In 2020 the number set to be 4047 (See Figure 12) [34], which was driven by the Sulphur Cap. The number of in operation and on order scrubbers does not show a remarkable growth until the year 2023 (4131) which is linked to a high waiting list.

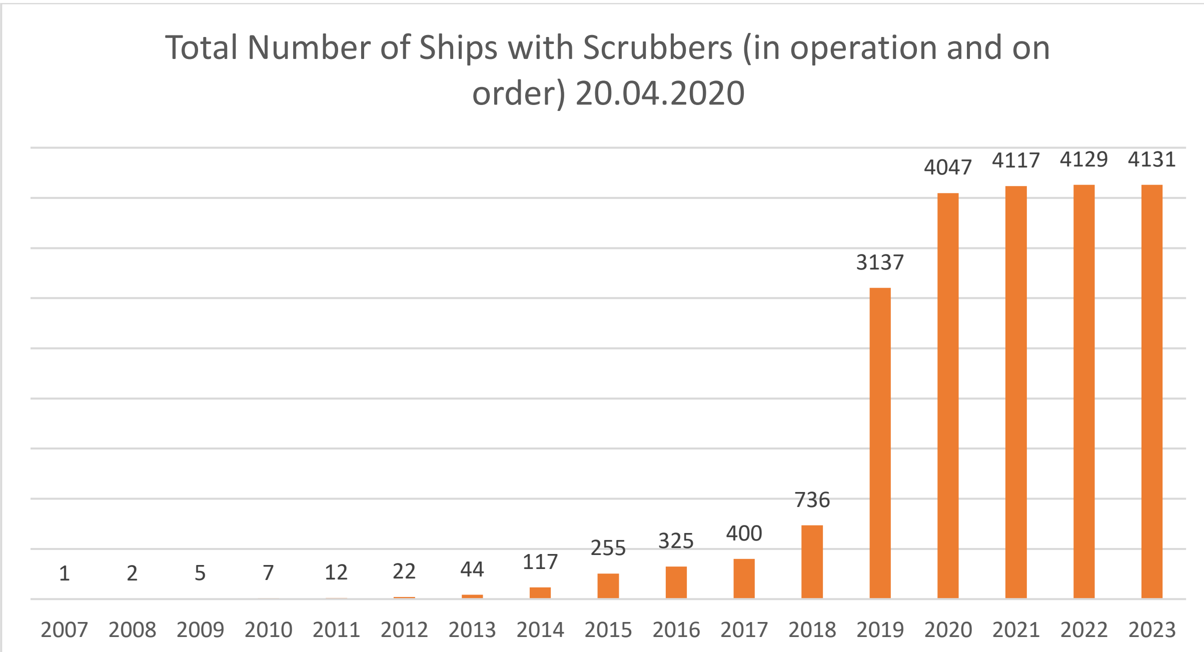

Figure 12 Number of scrubbers (in operation and on order). Source: DNV AFI

As of sixth of May 2020, the number of on order scrubbers has risen despite the worldwide COVID-19 pandemic, which has been drastically reducing cashflow for cruise and ferry companies as well as lowered crude oil price to a historical low of -40.32 USD per barrel on the 20th of April 2020 [50]. The increased number of ships with scrubbers both in operation and on order can be seen in Figure 13. The number of orders has increased by 959 despite the COVID-19 pandemic and low crude oil prices, showing the growing market size of scrubber installations contrary to beginning of March 2020, when the shipping companies started calling back the scrubber installations. This shows that the scrubber installation market, especially for cargo ships, is predicted to grow even with lower fuel prices and world economic changes.

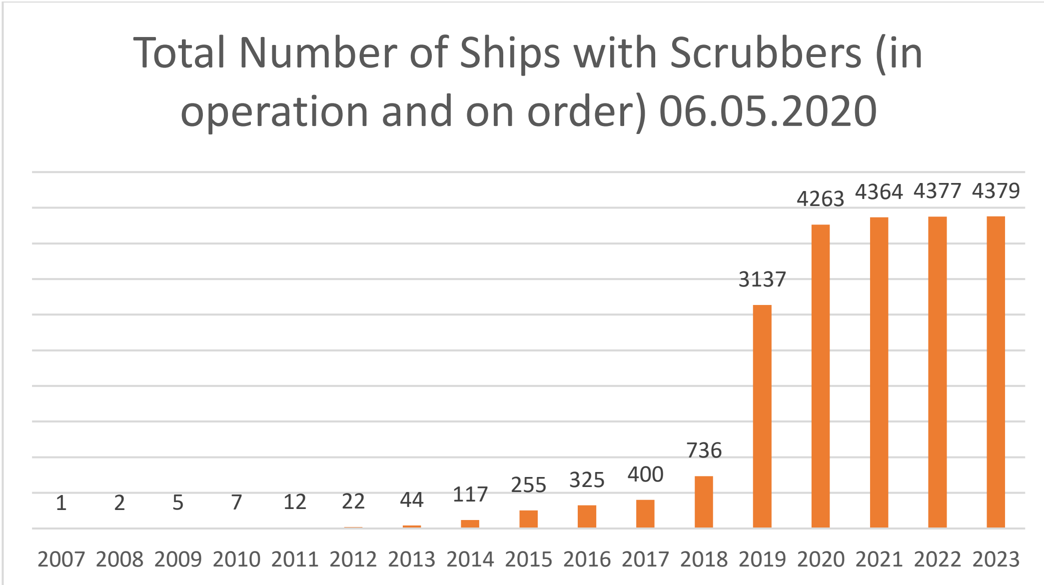

Figure 13 Number of ships with scrubbers as of 06.05.2020. Source: DNV AFI

As of sixth of May 2020, the scrubber market consists mostly of cargo ships (See Figure 14) with the highest number of scrubbers installed per ship type is bulk carriers with 1495 installed and on order and cargo ships in total having 4047 scrubber installations or orders, while cruise ships and other passenger ships have a total of 324 installed or on order [34]. This leads to a belief that the scrubber market is dominated by cargo ships and will be in the future, while passenger ships rather opt for alternative solutions due to the frequent port calls and operational areas being too close to the shorelines, which reduces the possibility to release sludge and other scrubbing effluents overboard.

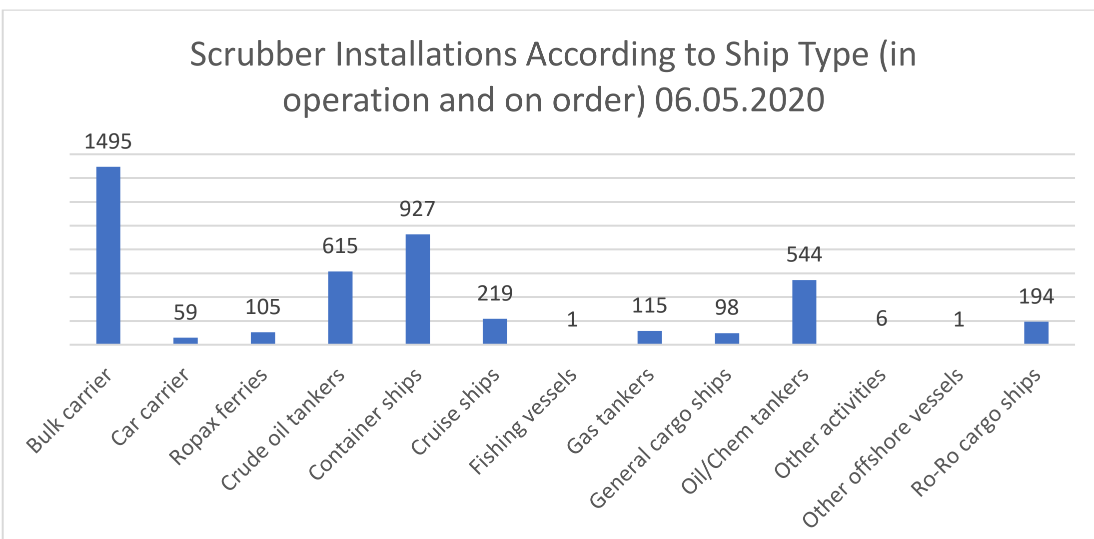

Figure 14 Scrubber Installations According to Ship Type as of 06.05.2020. Source: DNV AFI

The percentage of scrubber retrofits in that statistic is 28% with 1230 conversions in 4379 overall installs as of sixth of May 2020, which does not directly mean that the work field for conversion companies is just 28%, having dedicated to scrubber installs gives the conversion companies an advantage in designing and installing scrubbers to newbuilds as well.

The most popular scrubber types installed and on order are open (3536pcs, 80.75%) and hybrid scrubbers (753pcs, 17.2%) being the simplest and most complicated systems respectfully. The hybrid scrubbers being more flexible in operational terms offer a huge advantage to ships with various operational routes like cruise ships with changing itineraries and many port calls. Hybrid systems are more design capacious and especially on passenger ships, having competence in 3D scanning and contemporary engineering methods, will play a substantial advantage to retrofitting companies.

The price of a scrubber conversion ranges from $1 to $5 million [51] depending on the system type and the output of the vessel's engines. The market share from 2020 to 2026 is estimated to grow up to $10 billion with a compound annual growth rate of 36.1% [52] and could grow even more if the regulations are hardened or price of crude oil rises to its end of 2019 state.

3.5.2 Hybrid conversions

Due to the growing capacity and constantly lowering price of batteries, the hybrid ferry business is estimated to grow by $10 billion from $5.2 billion to $15.6 billion [53]. The compound annual growth is estimated to be 13.2% between 2025 to 2030. The stagnation of the number of installs in use and on order seen on Figure 15 [34] from 2020 to 2024 can suggest a high waiting list. This implies that retrofitting companies could have a major possibility to retrofit hybrid systems on board existing vessels in the following years.

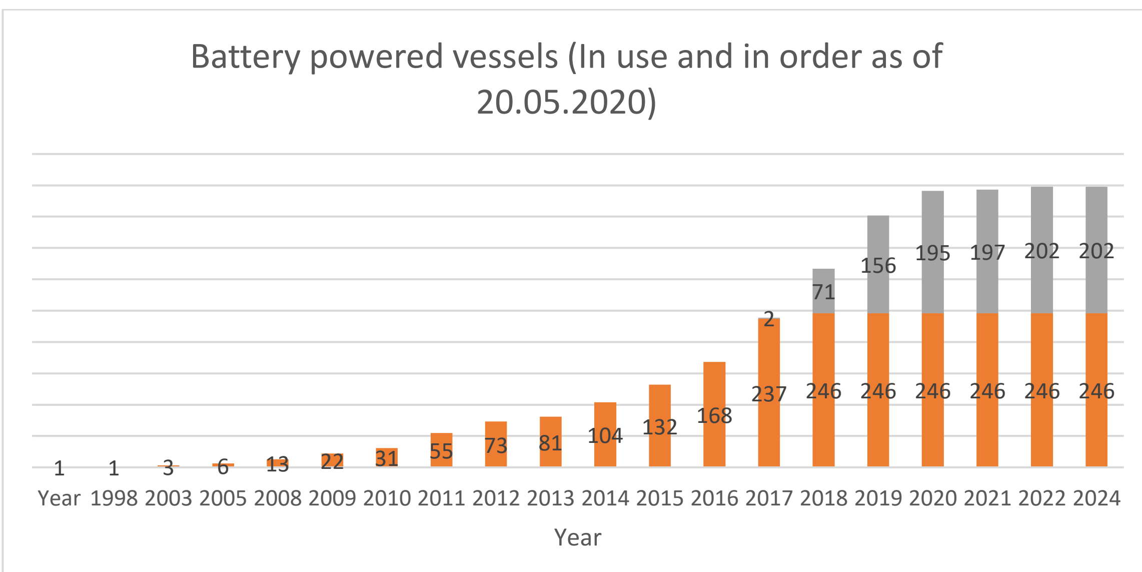

Figure 15 Battery Powered Vessels. Source: Adapted from DNV AFI

The market is dominated by short distance ferries and inland cargo ships, which operate in short distances. The Figure 16 [34] shows a clear dominance of RoPax ferries.

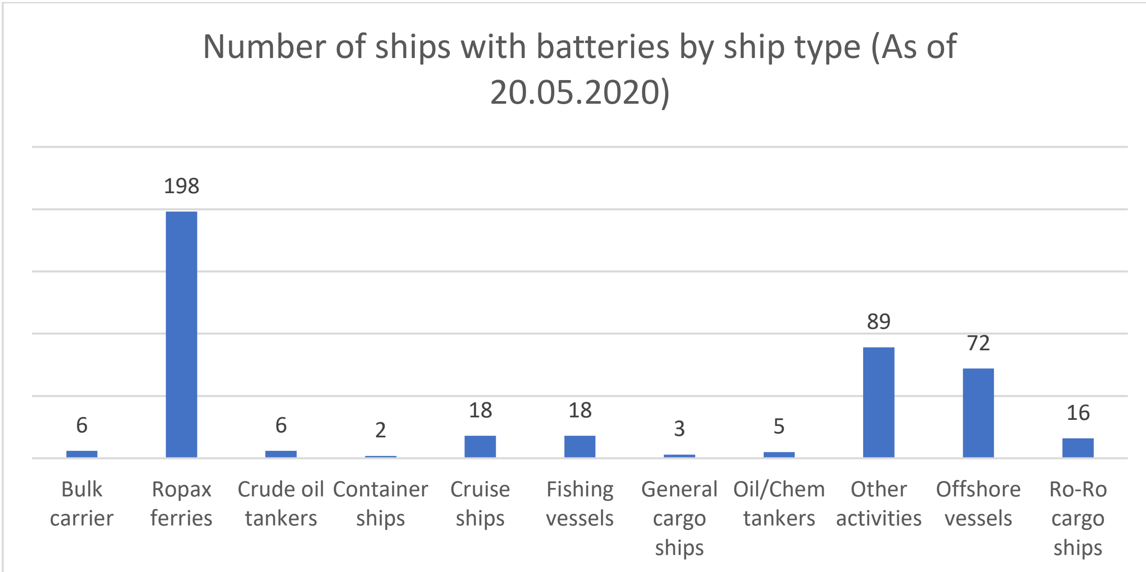

Figure 16 Battery powered ship types. Source: Adapted from DNV AFI

The Figure 17 [34] shows the that both hybrid and plug-in hybrid systems hold the biggest market share. As the hybrid systems are the most potential powerplant conversion types, retrofitting companies must focus on converting diesel-electric short distance ferries to hybrids and plug-in hybrids using battery packs.

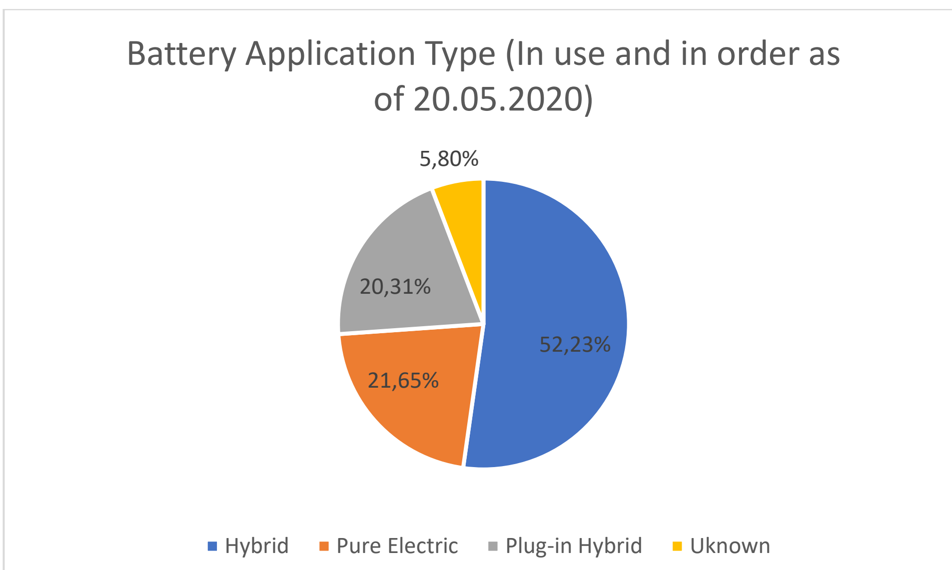

Figure 17 Battery Application Type. Source: Adapted from DNV AFI

The main markets to focus on are Norway with 42% and Europe with 24% (See Figure 18) [34]. The high percentage of those areas is linked to the high amounts of short range shipping volumes, especially RoPax ferries operating in Nordic archipelagos as well as the Global Sulphur Cap limiting the Sulphur limit in diesel fuel to 0.10% in all EU and SECA ports.

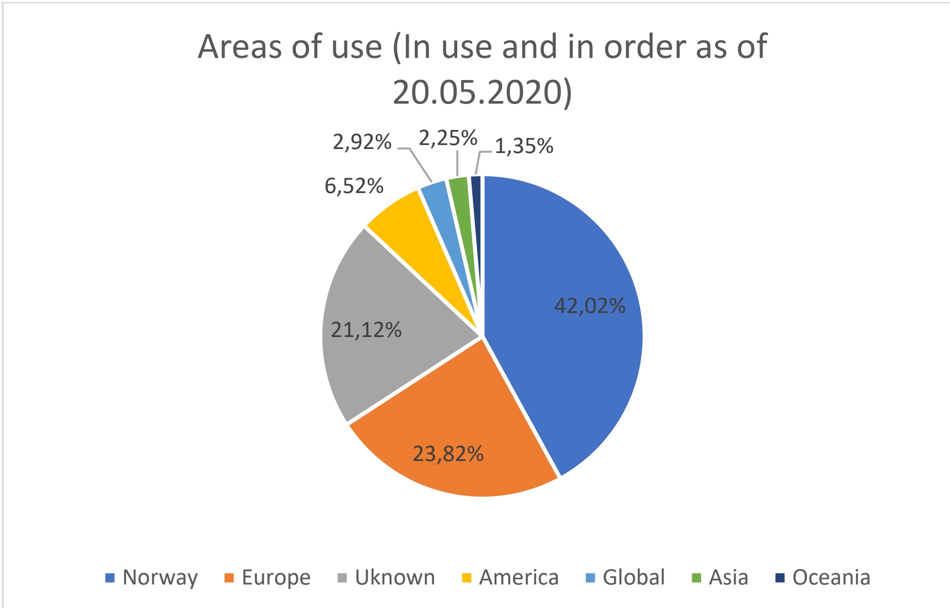

Figure 18 Areas of battery powered powerplant use. Source: Adapted from DNV AFI

The retrofitting companies must become accustomed to retrofitting hybrid systems onboard existing vessels as the regulations become stricter and as the battery technology advances. The European market is forecasted to stay the biggest until the year 2030, but the Asian and North American market will also grow considerably as the ECAs broaden and as the shipping volumes in those areas are substantially higher. The Nordic companies could hold an advantage in being the first to become accustomed to hybrid conversions as the market grows.

3.5.3 Ballast water treatment systems

Ballast water treatment systems are a firm market for retrofitting companies, as the ballasting of a ship is often an inevitable process, the systems must be compatible to ensure the wide operational area and itineraries of different vessels. When compared to exhaust gas cleaning systems like scrubbers, the ship owner has an option to opt for a more expensive fuel like MGO/MDO to comply with local or ECA regulations as they enter it, but with ballast waters, it is not as simple. The requirement to comply with new regulations will bring substantial revenue to both retrofitting companies as well as companies producing the BWT systems like Wärtsilä, Alfa Laval etc.

The predicted market for BWTS is seen on Figure 19 [54]. As of 2020, the BWTS market is already $4.57 billion, which shows the extent of BWTS systems being used in a substantial amount in shipping. The CAGR of the BWTS market is expected to be at a steady 10% and by 2027 the market share for BWTS systems is already $8.9 billion, almost double of 2020, which shows the estimated growth of shipping as well as the environmental regulations becoming even more strict, especially in the growing public pressure to maintain marine environment.

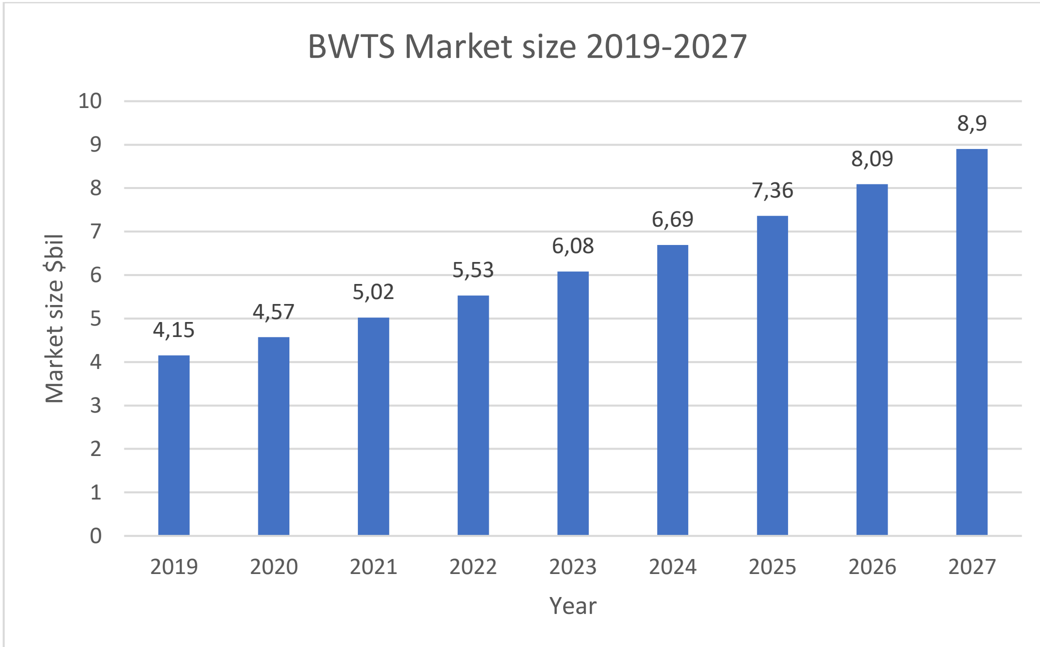

Figure 19 BWTS Market size. Source: Statista

As the main market regions (in a decreasing order) are North America, Europe, Asia Pacific, Latin America and Middle East and Africa [54], the USCG dictates the requirements for BWT systems with its most demanding requirements, which the IMO has yet to implement to its regulations. As the ships sailing in US coastal waters have the most freedom in operational areas due to the highest standard BWT systems, leaves the USCG determined regulations to be the key for retrofitting new systems, if the shipowner plans to utilize its ship in global extents.

The market for BWTS retrofits is going to grow even more after 2027 as the shipping volumes grow, ships are sold to new owners who operate in stricter areas and as the regulations become more stringent, which could mean that the systems installed in 2020, will not be compliant in 2030.

3.6 Conclusion

Throughout history the biggest accelerator of technological growth has been market demand. As the regulations become more strict, marine engineering will come up with solutions to meet the new demands as there is a market for it. There will be a big leap in new technologies and solutions to the year 2050 with a couple of technologies already being widely installed onboard existing vessels.

The two main categories that shipowners must put emphasis on, are overall efficiency and fewer emissions of the vessel and the other being ballast water treatment systems, which help reduce the spread of invasive species and maintain the local marine environment. The first category expands to three subcategories - the first being directly linked to lowering emissions of a vessel (scrubbers, SCR), the second being new fuels and powerplant types (LNG, methanol, fuel cells, batteries) and the final being miscellaneous emission reducing and efficiency increasing systems (Flettner Rotors, air lubrication systems, solar panels). The final category cannot be discarded as even a 5% drop in fuel cost could lead to substantial environmental and economic benefits considering the yearly expenditures of shipping companies.

The drivers addressed in chapter 2 and the possible technical solutions lead to a market research of three most potential markets that retrofitting companies must focus on:

- Scrubber installations – As the global shipping volumes grow, the SECAs expand and the fuel cost of MGO rises, scrubber install market is predicted to grow albeit the momentary setback of cashflow and fuel price drop due to the worldwide COVID-19 pandemic. The market share from 2020 to 2026 is estimated to grow up to $10 billion with a compound annual growth rate of 36.1% [52]. The scrubber market seems unflappable for the following 5 years, but the rise of new technologies could lead to shipowners opting for new fuels and powerplants due to the accelerating growth of stricter regulations.
- Hybrid solutions – Battery powered hybrid solutions are becoming more popular in short sea shipping especially in the EU and Nordic countries with the help of vast battery technology growth and price decrease, the market can triple in value in the following decade by $10 billion from $5.2 billion to $15.6 billion [53]. The compound annual growth rate is estimated to be 13.2% between 2025 to 2030. The European retrofitting companies could hold an advantage of having firsthand experience in hybrid conversions as the global market broadens from EU and Norway.
- BWTS retrofits – The BWTS market will show a definite growth in market size as the inevitable need for BWT systems is dictated by the BWT Convention. As of 2020, the BWTS market is already $4.57 billion, which shows the extent of BWTS systems being used in a substantial amount in shipping. The CAGR of the BWTS market is expected to be at a steady 10% and by 2027 the market share for BWTS systems is already $8.9 billion [54], almost double of 2020 and will continue to grow as shipping volumes do accordingly.

The market research for the most imminently growing technologies showed the immense influence of conventions and regulations have to the retrofitting market with the example of the inevitable retrofit of a BWTS. The research also shows the temporality of the retrofitting market as the scrubber could become obsolete with hardening regulations. The more sustainable solutions like LNG still show a low number of 22 retrofits [34] due to scrubbers being cheaper and more easily retrofittable.

4 RETROFITTING OF LISTED SOLUTIONS

The extent, difficulty and the price of retrofitting the technical solutions brought out in chapter 3 can range greatly. Having hindsight, expertise, the amount of highly trained manpower and previous experience in the following retrofitting has a strong influence in determining the outcome of a project. The following subchapter addresses the main characteristics and nuances of each technical solution, which must be taken account in a retrofitting project.

The main stages of a retrofitting can be seen on Figure 20. The flowchart describes the process and of a high volume retrofit project like scrubber or BWTS retrofits, where new components and systems are added to existing vessel equipment, which leads to numerous stages of design and class approvals.

Every project starts with a thorough inspection of the vessel, where the client’s wishes and suggestions are considered, the documentation is reviewed with the crew and the preliminary visual routing of the system is done. The previously listed actions define the extent of 3D scanning, which can be considered a foundation for the following retrofit stages.

The design process of a major retrofit divides into two – basic and detail design. During the basic design period general arrangements for equipment and construction are reviewed, preliminary pipe and equipment routing is done. Safety plans must be updated and class approvals must be gotten for the new systems as the stability conditions, fire safety, evacuation plans and environmental aspects could change with the retrofitted systems. During detail design, the same aspects are revised, collision checks are done with the help of point clouds and production drawings are made.

The design process lays a foundation for prefabrication, where the quality of engineering during the design period could influence the outcome and quality of the assembly. During prefabrication period, constant quality checks must be carried out and drawings must be revised to the as-built conditions.

During the outfitting period, the prefabricated components and assemblies are installed to the vessel. Quality control must be done constantly and in case of errors, on site design alterations must be done as quickly as possible to reduce the possible additional downtime. The collisions addressed in the design process can be handled prior to arrival to the outfitting location (i.e. removal of railings, ventilation ducts).

During the commissioning phase, the new systems are put to a trial to ensure their correct efficiency, safety and reliability. The as-built documentation package must be compiled and final class approvals must be obtained.

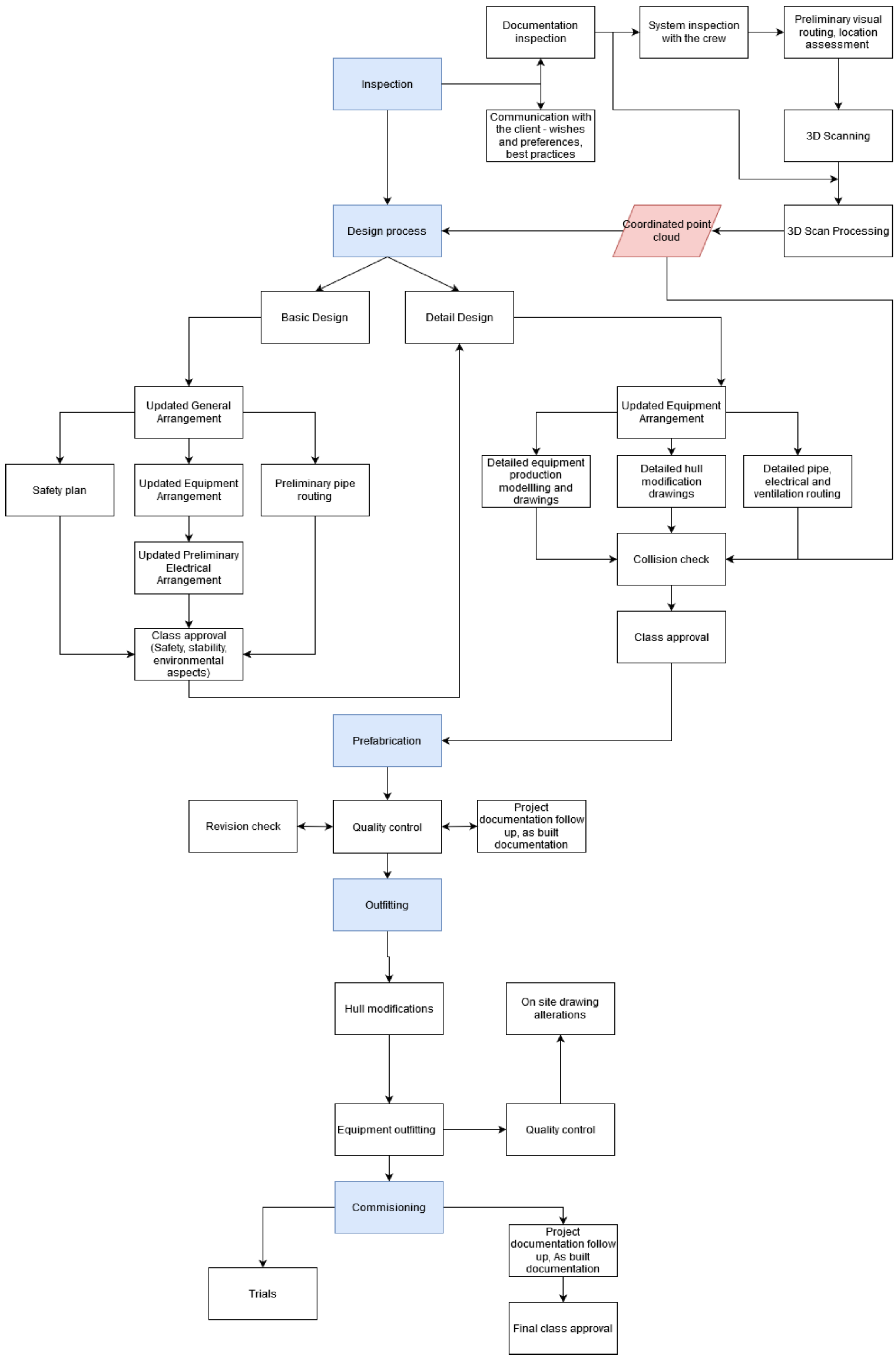

Figure 20 Retrofit process flowchart

4.1 Scrubber retrofitting

A scrubber retrofit demands a high level of conversions to the ship's hull and various ship systems. As seen from the Figure 21 [55], many new components must be added to the ships exhaust gas cleaning system apart from the scrubber itself, which include a process tank, which could reach through many decks of a ship, a various number of bleed off treatment units, numerous amounts of pumps for scrubbing water, alkali feed, wash water, cooling; fans to maintain the pressure and speed of exhaust gases as well as other components and tanks, which must all be connected with pipes of various diameters.

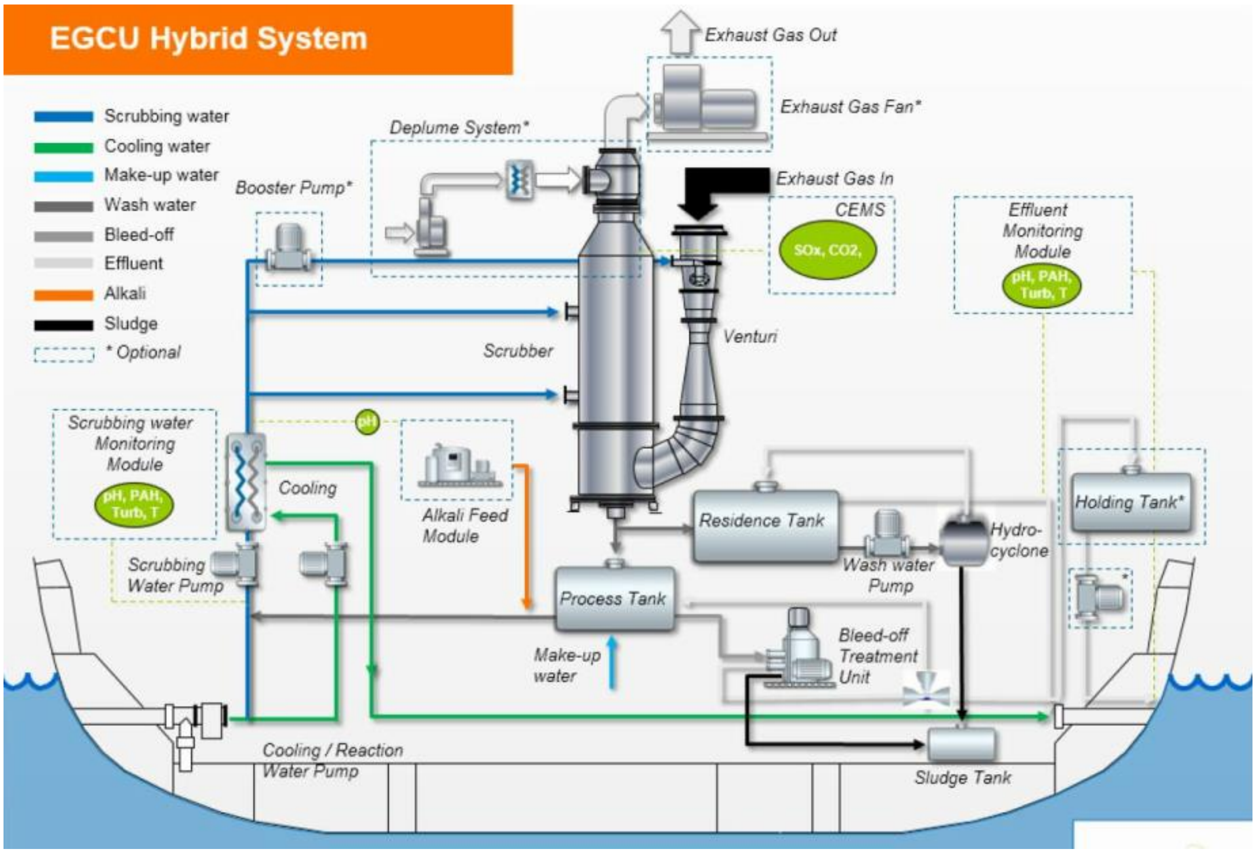

Figure 21 Wärtsilä Hybrid Scrubber. Source: Wärtsilä

This could change the overall appearance of a ship, changes in stability conditions, fuel consumption and in the case of space-critical vessels like passenger ships - the loss of usable space, which could directly be considered as loss of profit. The retrofit hardships and characteristics in accordance with the ship type are brought out below.

Retrofitting a scrubber to a container ship

Depending on the size and general arrangement (GA) of the container ship, the funnel is usually at the aft of the ship in order to minimize the distance between the main engines and propulsion. The accommodation superstructure could however be located throughout the length of the ship especially in today's bigger container ships. If the accommodation is connected to the funnel of the ship, the scrubber installation could be more space critical. In the Figure 22 the 3D model [56] shows that the scrubber module has been installed towards the aft of the ship, which in that ship's case is possible, but in bigger ships, where containers are stored beyond the accommodation superstructure, this would lead to a decrease of the number of TEU.

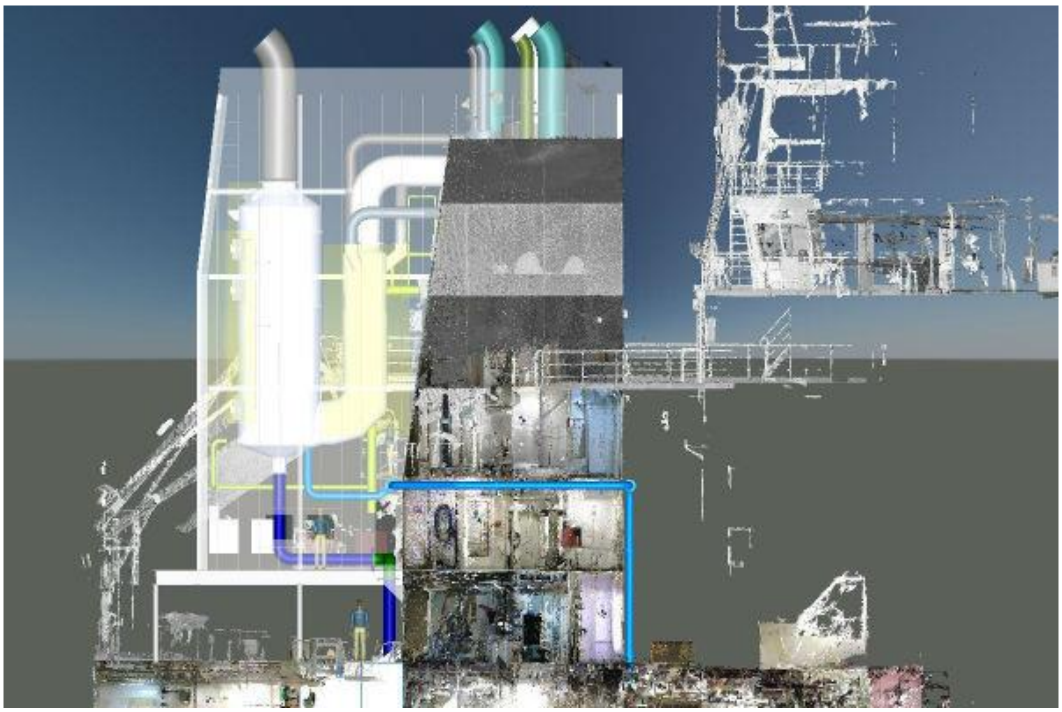

Figure 22 Scrubber 3D model. Source: MFAME

A more compact solution can be used on the side of the funnel as seen on Figure 23 [57], where the cargo area is not affected, but does restrict the navigational visibility as well as accommodational well-being in terms of light. This solution does not affect the TEU capacity of a container vessel, but it cannot be adapted to every vessel as the size of the scrubber system depends on the type (hybrid, open-, closed-loop) and the space available on the vessel.

Figure 23 Containerships VII scrubber. Source: Wärtsilä

Retrofitting a scrubber to a passenger ship

As passenger ships especially cruise ships are space-critical, means that the conventional scrubber system as shown on Figure 21 cannot be easily fitted onboard without sacrificing a secondary funnel worth of space, which would lead to loss of accommodation or recreational spaces as with the case of Superspeed II, where the process tank is fitted on a car deck Figure 24 [57], which unfortunately leads to a loss of lane meters ergo loss of cars taken onboard and less profit per travel. In case of passenger ships, a inline scrubber is often used, which doesn't require a by-pass and the scrubbers are placed to replace the silencers in the funnel seen on Figure 25 [58], meaning that the space taken up by the system is much smaller than with a conventional system, but the down side is the limitation that the fuel can't have a higher Sulphur percentage than 2.5% [55].

Figure 24 Superspeed 2 process tank. Source: Wärtsilä

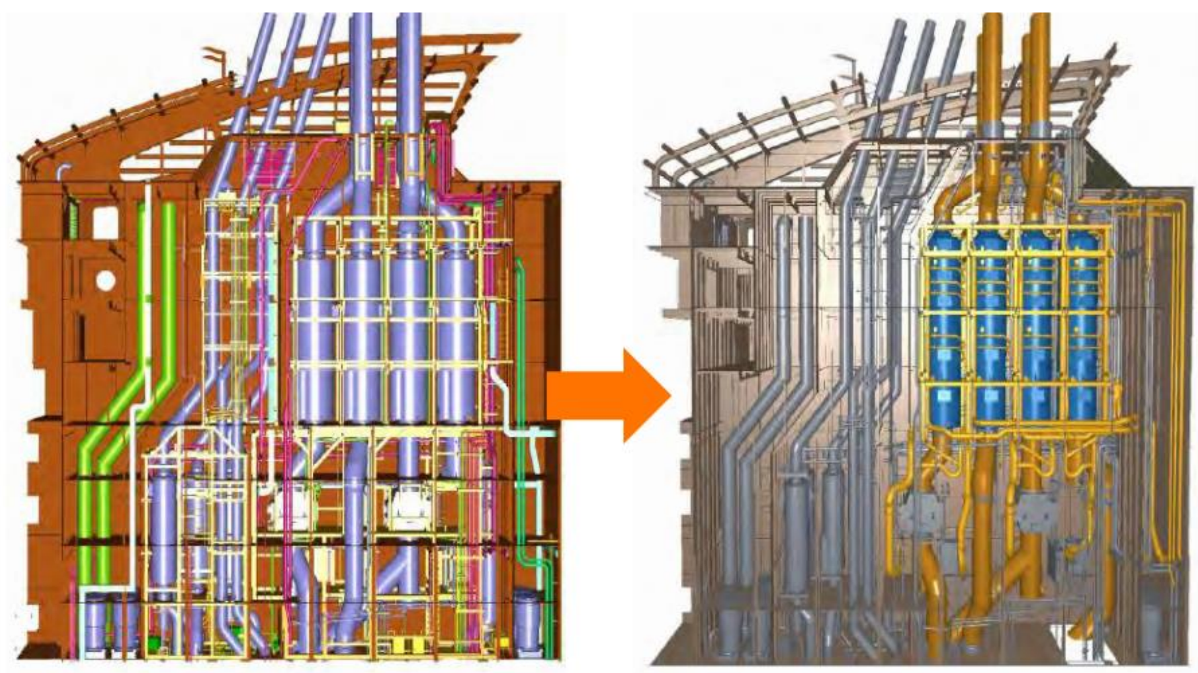

Figure 25 Superspeed II Scrubber. Source: Wärtsilä

In terms of installation process, the hardship comes from the enclosed nature of the vessel, wherein transportation of a scrubber system component to its assigned location is more difficult than with a container ship. A passenger ship has a superstructure on top of the engine room and the funnel is mounted through-out the superstructure and hull. This will lead to cutting openings into the ship's hull and superstructure.

The high number of components in a space critical environment makes the design and outfitting process difficult. Even with proper documentation, the use of 3D scanning is essential in a high-quality turnkey project as the pipe routing and the number of new components listed prior will lead to an immense number of design hours, collisions and down-time without the use of novel technologies.

4.2 Installing an SCR

Compared to a scrubber, an SCR takes less space and has less components as seen on Figure 26 [59]. The biggest difference comes from the SCR's working principle, where urea is sprayed to the exhaust gas wherein scrubbers use seawater. This means that the modifications for sea chest are not needed as well as water pumps and piping. The two biggest components are the converter and injection pipe, which could need openings in order to transport the components to its given position. The fitting of the new converter/silencer is especially complicated in passenger ships where the funnel runs throughout the superstructure, meaning that the converter must be fitted from the top of the funnel and its path must be disassembled, which could be a sizable job especially if the ship has been previously been fitted a scrubber.

What must be taken into account is that the exhaust gas temperatures must be a minimum of 260°C-340°C [32] as described in the previous chapter. The load conditions must provide the system with the needed temperature. If the exhaust gas temperature is not achieved, they must be boosted, which is case sensitive with wet scrubbers.

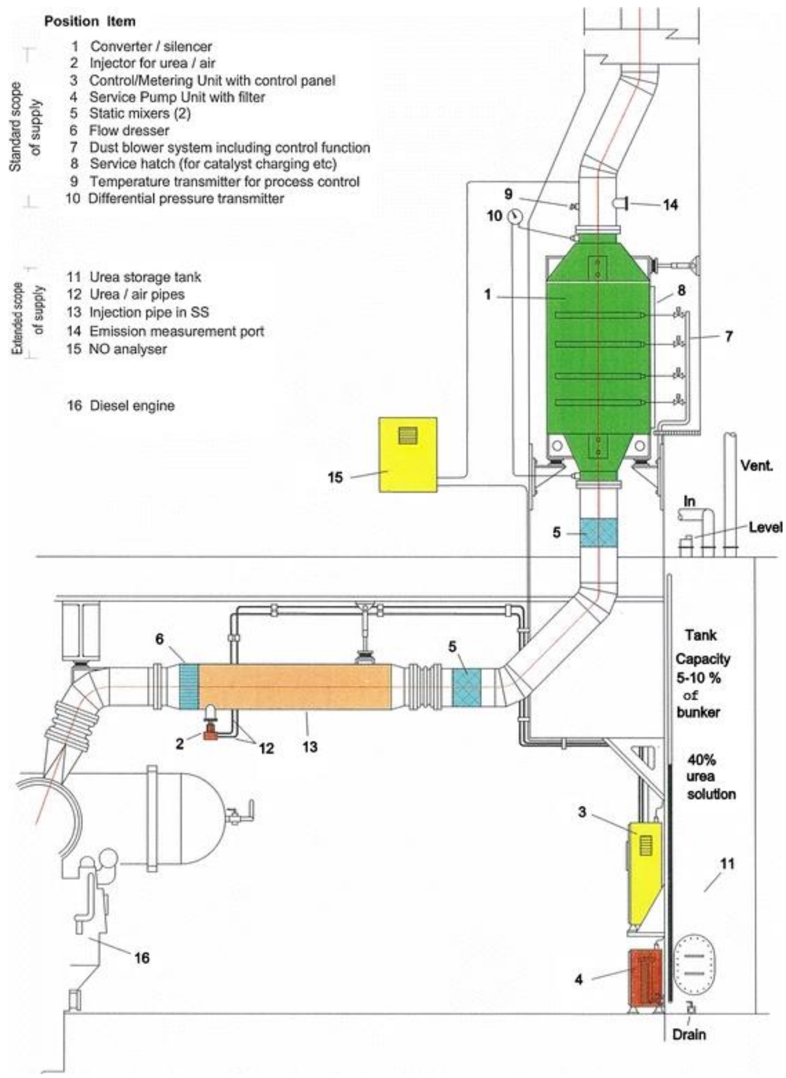

Figure 26 Installation of an SCR. Source: Springer

If a ship is not originally built to operate with an SCR then the exhaust piping needs modifications and thorough calculations. The biggest issue comes from exhaust pipe characteristics, if the exhaust gas velocity is too high, the process will not be sufficient enough in terms of mixture of urea and exhaust gas, which will lead to efficiency losses [59], which puts an emphasis on early engineering phases rather than installation itself.

The payback time for SCR systems depends highly on the operational area. The payback time for a RoPax ship, which mostly travels in fairways and ports, has a payback time of just over 2 years [59] by avoiding fairway and port fees.

4.3 Retrofitting an LNG engine

The shipping industry has already seen a couple LNG retrofits in both cargo and passenger ships. In 2011 Bit Viking was the first ship to retrofit an LNG powerplant to its oil/chemical tanker and Abel Matutes being the first Car/Passenger ferry in 2017 [34]. The cruise company Hurtigruten is planning to retrofit LNG powerplants to most of its fleet by the year 2021.

Retrofitting an LNG engine can be done mainly in two ways, one is changing the whole powerplant to a new LNG based powerplant and the other is converting the existing diesel engine to a dual fuel powerplant.

If the existing engine would be converted into a dual fuel engine, many steps must be taken in order to achieve it. Both MAN diesel and Caterpillar’s MaK engines have the possibility to be converted to a dual fuel engine, while maintaining the same crankcase [60].

In order to convert the existing diesel engine into a dual fuel version, a separate pilot ignition system must be fitted, which would provide the ship with gas-independence in terms of still having the common rail system on the ship. In terms of engine components cylinder jackets, liner pistons and piston rings must be changed in order to provide the engine with a bigger bore. Due to additional fuel feed, cylinder heads and combustion chambers must be changed as well as new camshafts and a modified turbocharger assembly [60].

Another issue comes from the engine management systems, where the newer engine type is much more complex and therefore requires new sensors and instrumentation in order to provide the engine with smooth operation and autonomy.

The biggest issue with an LNG conversion is the retrofitting of a gas tank, which requires a lot of space as well as cooling. The LNG tanks can be roughly separated into two types – independent of hull and integrated. The independent type divides into three types A, B, C, with the C type being the most common, simplest and safest version of the three, but does impose an issue of space efficiency compared to other types. The location of the tank for retrofit projects depends on the ship type, for retrofit projects the most feasible way is to install the tank above or under the main deck due to its lack of structural changes, but the tank location is not just a question of ease of conversion.

According to the IGF code the tanks must be [61]:

- Minimum distance from ship side B/5 or 11.5m whichever is less
- Passenger ships: B/10 but greater than 0.8m
- Minimum distance from bottom line: B/15 or 2m whichever is less

The possible locations for tanks have been brought out in the Figure 27 below [61].

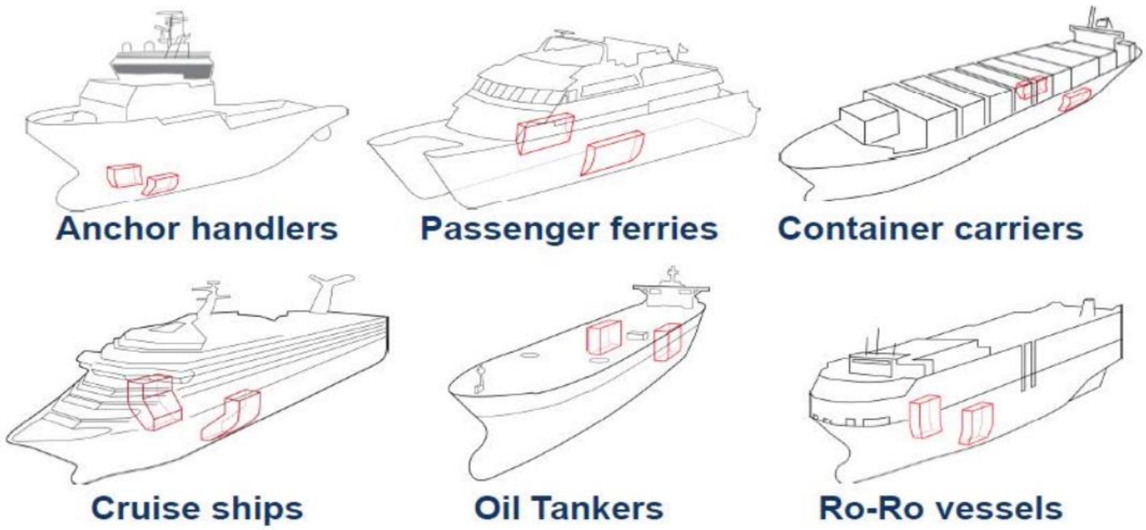

Figure 27 LNG tank locations for various ship types. Source: Bureau Veritas

For cruise ships the retrofit can be done in two ways. One being the previously described way of drydocking the ship, adding the LNG tanks to the recommended locations and converting the powerplant. This unfortunately is not the most feasible way due to the loss of cabin and public spaces.

DNV GL has proposed a more feasible way, in which a prefabricated block consisting of the LNG tank and LNG systems is installed to the midbody section of the existing ship. A similar project has been done with Royal Caribbean Enchantment of the Seas in 2005, where a 22m long midbody section was added in a month of dry docking.

The operation is very complex and many aspects must be considered. In terms of length of the new section, the gap ranges from half of the main vertical fire zone to the length of the main vertical fire zone, 22m to 43m respectively. The fire zone length is not the only restriction as the longitudinal strength becomes limited by the hull girder and in order to maintain the required section modulus, additional steel work must be done, which is deemed too expensive.

Design wise new damage stability study must be done, fire safety must be considered, machinery spaces must be arranged in order to fit the new components, bunker station location must be assessed to ensure maximum safety for passengers. If the new midbody section adds new cabins to the ship, ventilation as well as sewage systems must be modified accordingly to provide the accommodation with the needed commodities, but in terms of cooling the LNG cold recovery can be utilized [62].

As the length of the ship grows, the wetted surface grows ergo the resistance of the ship will be bigger, which could mean that propulsion must be changed, which could lead to a very costly investment if the ship has azimuthing thrusters. Due to the bigger resistance, conversion of the existing diesel engines could be problematic due to LNG’s lower efficiency and the necessity of more power post conversion.

The existing LNG engine conversions provided by the engine manufacturers are becoming more widespread, the LNG storage issues remain the same. The retrofitting of a gas tank requires a vast amount of hull modifications, which require dry-docking, numerous amounts of class approved solutions (stability, fire safety) and changes in piping, ventilation and electrical looming. 3D scanning addressed in chapter 4 will make the process faster and increase overall quality of the new system.

4.4 Methanol conversion

A regular marine two stroke diesel engine cannot be directly used, but the conversion of existing diesel engines is possible and has been carried out. In example the Stena Germanica had a dual fuel engine, where the LNG gas compressor was replaced with a high-pressure methanol pump to increase the fuel pressure [63]. MAN has been converting its existing engines with newer cylinder covers that are equipped with methanol booster injectors [63].

Putting the engine conversion aside, the fuel could need cooling instead of heating as with HFO, a part of the piping must be double-walled due to the fuel's low viscosity. In terms of safety, methanol shares many safety requirements as LNG due to its low flashpoint, which means that the fuel cannot be stored in the engine room as seen on Figure 28 [63]

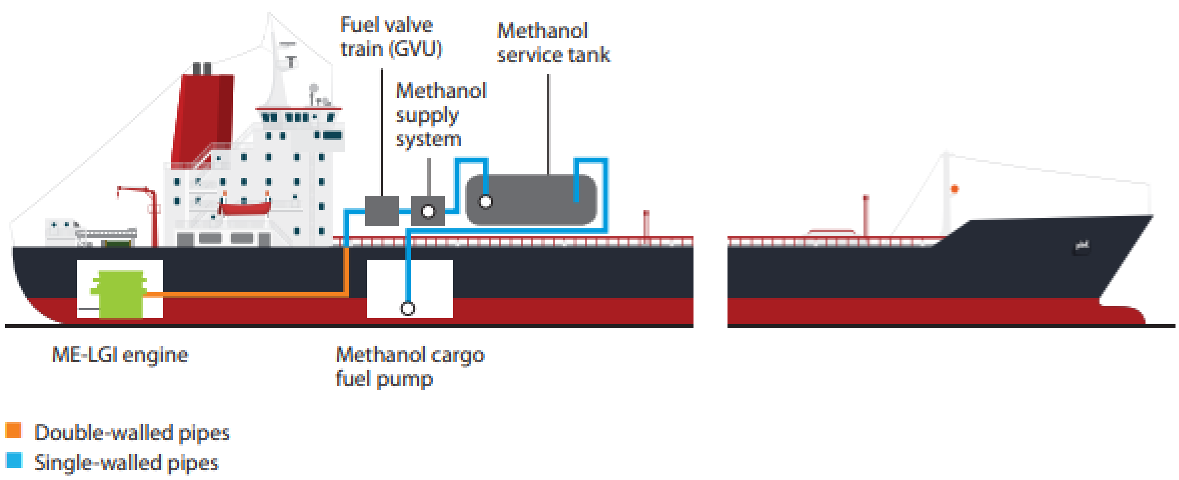

Figure 28 Methanol Conversion. Source: MAN

This does oppose the same issues as with LNG, where the fuel storage is an issue. Methanol opposes the equivalent energy density as LNG, which means that the methanol tank must be approximately twice as big as a diesel tank, but compared to LNG, methanol can be stored in tanks meant for liquid fuels with a few modifications. This does make methanol an easier conversion if the fuel tanks are already situated away from the engine room. With Stena Germanica, the ballast water tank was converted into a methanol tank.

Parallels can be drawn with the conversion process of diesel to LNG as the engine producers already have a number of methanol conversion carried out to existing diesel engines and the issue comes from fuel storage. As the fuel can be stored in tanks meant for liquid fuels, dry docking is not required and hull modifications are kept to a minimum. The 3D scanning will be a major aid for pipe routing, system integration and commissioning especially in the case of lacking documentation.

4.5 Retrofitting a fuel cell system

The fuel cell shows a promising alternative to conventional powerplants with the combination of batteries and electric propulsion. This does propose the issue of space onboard ships, where the main hardships are the size of the fuel cell and their quantity due to the fact that the single fuel cell does not provide as much power as a conventional diesel, the size of batteries and their weight and the fuel storage, which becomes an issue discussed in prior subpoints with hydrogen, LNG and methanol.

The example of MS Alsterwasser (See Figure 7) also proposes an issue with the containment of the system, where the fuel cell module and the hydrogen storage had to be separated from themselves as well as other systems with gas-tight bulkheads, which leads to hull modifications and ventilation system conversions.

As for using fuel cells as an auxiliary power source, the MS Mariella fitted the fuel cell module to an outer deck in the superstructure. This is a very simple plug-n-play type of conversion, where the module is lifted onboard the ship and main work goes into connecting the fuel cell into the ships grid. This omits the necessity for integrated fuel storage, hull modifications and can be used as a tool of “green-washing”, where the customer sees a green technology with their own eyes and feel more environmentally conscious.

4.6 Retrofitting hybrid solutions and batteries

As far as the current technology goes, the hybrid and fully electrical conversions will mostly be performed on currently already utilizing diesel-electric powerplants, which makes the retrofitting quite straightforward and simple in terms of hull modifications but does need strong electrical engineering and automation.

In 2018, Wärtsilä converted the offshore supply ship Viking Lady into an LNG and battery powered ship, where one of four dual fuel engines were replaced with a battery pack [64]. This shows the simplicity of the conversion, if the engine is already diesel-electric, where the propulsion is powered by electricity powered by gensets.

In 2020, an Estonian ferry Tõll was converted into a hybrid, which according to the owner was a straightforward job and required minimum conversion of the ship’s hull and powerplant as stated prior, where only the battery pack, charging systems and control units were needed to add and connect in order to make the system work [65].

Due to the low volume of hull modifications, the systems can be supplied as a plug-n-play solution, where the battery pack is lifted on board the ship. What needs to be considered is the weight of the battery packs, as placing it to a higher deck, will lead to the reduction of metacentric height, which could lead to stability issues. Another issue can come from fire safety as the extinguishing of lithium ion batteries is complex, which can lead to class approval issues.

4.7 Retrofitting a Flettner rotor sail

The biggest issue with retrofitting a rotor sail on an existing ship or a newbuild is finding the adequate location for the sail. The sail requires space around it in order for the wind to be uninterrupted and effective.

With passenger ships, the maximum height of the rotor sail must be accounted for. For a passenger ship, the upmost deck is the most reasonable location for a rotor as seen on Viking Grace. The rotor sail adds an additional 24m to the height of the ship, which in the case of Viking Grace is not an issue, but on cruise ships on various global routes, this could lead to restrictions of voyages where bridges must be passed under.

Another point that must be accounted for is the foundation of the sail, since the sail transmits forces to the structure of the ship, hull modifications in terms of added stiffeners must be accounted for. The wind induced forces also play a major role in the heeling and yaw of the ship, which can be omitted with the help of stabilizers or active tanks.

4.8 Retrofitting an air lubrication system

Both of the technologies are fairly similar and can be concluded with the same necessities for retrofitting. The air lubrication systems can be retrofitted to existing vessels and retrofits have been done in the past. In 2014, the Silverstream system was retrofitted to 40 000DWT Tanker MT Amalienborg and has been retrofitted to the cruise ship Diamond Princess in 2017. The retrofits have shown a 5% gain in efficiency [66] for both ships and could be even more with flat bottomed ships like ferries and bulkers.

The systems consist of piping, compressors and air dispensers, which must be located under the hull. Since the structural modification is done under the hull, dry docking is necessary for retrofitting this technology. The dispensers could provide an issue of local stress concentrations, which must be accounted for due to cutting openings to the ship's bottom, which undergoes tensile and compressive stresses in waves at hogging and sagging conditions. Space for new equipment and piping could be an issue, but 3D scanning can help with the piping routing and system integration as well as commissioning and as built documentation.

A game changing technology in air lubrication systems could be utilizing exhaust gasses. With new clean fuels, the engine exhaust gasses could be bypassed and used as the air used for bubbling or film, this would reduce the energy required for pressurized air production as well as reduce the amount of particulate matter emitted to the air.

4.9 Retrofitting solar panels

Retrofitting solar panels requires open deck space and are not suitable for every ship. In the case of cruise ships and RoPax ferries, the best location would be the glasses of balcony railings, but technology and has the efficiency of up to 10% [67]. The containerships would also be inefficient in retrofitting solar panels due to the only applicable area of installation would be the monkey island or the roof of the accommodation. A very suitable ship type would be car carriers, tankers and bulkers as they have a bigger amount of clear upper deck space.

The retrofitting of panels and systems is not difficult. The photovoltaic panels are fixed on a metal frame, the photovoltaic panels are connected to a battery charging system, which powers a battery pack. It also needs automation systems. Overall the retrofitting does not require hull modifications, which means that the retrofitting can be done while the ship is operating, which leads the ship owner to minimal loss of profit.

4.10 Retrofitting a ballast water treatment system

The UV reactor-based systems are relatively compact, but still require space near the existing ballast water systems in order to reduce the amount of piping. On existing ship's this could be an issue especially due to the necessary service spaces. The systems also come as modules as seen on Figure 29 [49], but pipe routing and piping prefabrication is still a substantial job.

Figure 29 Pure Ballast module. Source: Alfa Laval

The stages of BWTS installation is similar to scrubber installation, but the extent of design and conversions are much smaller. Even with existing documentation, a 3D scan still plays an important role in modelling and pipe routing (See Figure 30) [68]. The piping can be pre-fabricated, whether they are GRE pipes or galvanized steel as well as the foundations for the equipment.

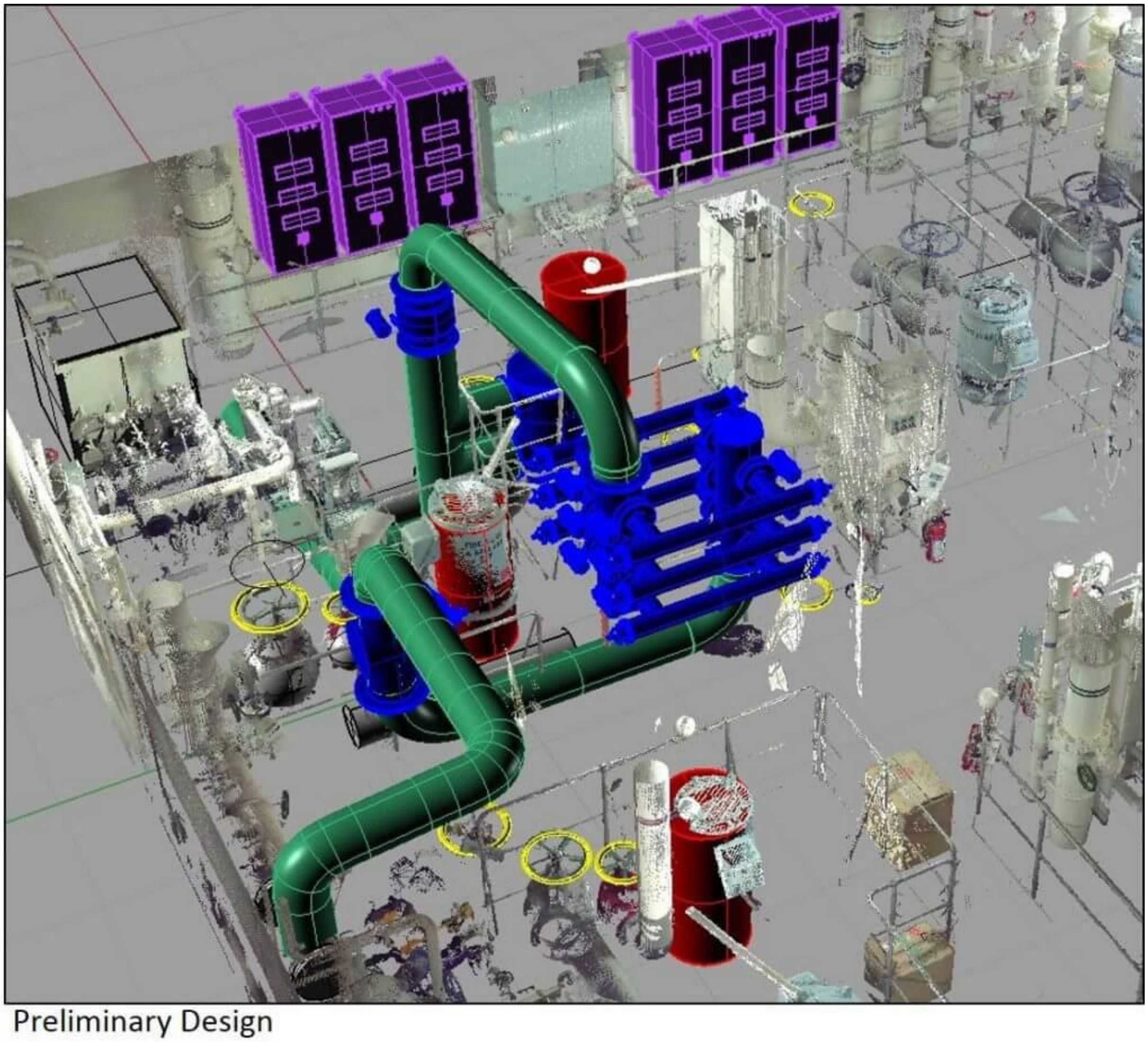

Figure 30 3D Scan + Cad model. Source: Goltens

The conversion process can mostly be done mid-operation, which leads to minimal downtime. The piping must be connected to the existing ballast water systems, electrical cabinets must be connected and installed and the automation system must be integrated.

4.11 Conclusion

The complexity the retrofit projects of the possible technological solutions ranges greatly. The amount of engineering work, prefabrication, outfitting and commissioning of an LNG project cannot be compared with i.e. retrofitting solar panels.

Table 4 concludes the technical difficulty of each listed technological solutions on a scale from 1 to 5. The table suggest the complexity of each stage of a technical retrofit with the hardships brought out in prior subchapters according to every technology:

- Necessity of novel technologies – The documentation and visualization for a project can vary from 1-5. 1 being a project like solar panels, where simple measurements taken from i.e. the upper deck can be utilized throughout the project and 5 being the highest for projects like scrubbers, BWTS and LNG retrofits where a high number of new components are added to space critical compartments
- Design process – The design process is rated with a complexity and capacity from 1-5. The design process is highly linked to the necessity of novel technologies as the novel technologies can be considered a basis for difficult retrofit projects.
- Prefabrication – The scale from 1-5 shows the number of prefabricated components and blocks needed for each retrofit.
- Outfitting – The difficulty of outfitting is determined by the amount of project manning, time and the location of the outfitting. If the project can be done enroute, the rating is low, if the project needs dry docking or a high number of hull modifications, the rating is high.
- Commissioning – The difficulty of commissioning is determined by the necessity and amount of as-built documentation and the number of necessary class approvals as newer and uncommon technologies can need more safety assessments and conformations.

Table 4 Difficulty of retrofits

Conversion	Novel Technology necessity	Design process	Prefabrication	Outfitting	Commissioning	Total
Scrubber	*****	*****	****	****	*****	4,6
SCR	***	**	**	***	***	2,6
LNG	*****	*****	*****	*****	*****	5
Methanol	****	***	***	***	*****	3,6
Fuel Cell	****	****	***	***	*****	3,6
Hybrid solutions	**	**	**	**	**	2
Flettner rotor	*	**	**	**	****	2,2
Air lubrication	*****	*****	***	*****	*****	4,6
Solar panels	*	*	*	*	*	1
BWTS	****	***	***	***	***	3,2

The most difficult projects can be considered in a declining order LNG, Scrubber and Air lubrication projects. The hardships to endure lie mostly in the complex design process as the number of new components and hull modifications lead to a vast number of class approvals, collisions and possible issues with compatibility with the original machinery.

The difficulty of a project also determines the possibility for profit. With a higher complexity retrofit project, the company with high levels of experience and engineering possibilities have major advantages. The more complex projects can be much more profitable as the number of design hours is higher, the possibility to earn more revenue on suppling the necessary components is higher and overall outfitting process is more extensive. The more profitable projects are also incorporated with a higher risk, which novel technologies can reduce or omit. The clear conclusion for every retrofit project with the complexity rating of over 3, is the necessity for novel technologies like 3D scanning. Without 3D scanning, the most difficult projects cannot be done in a feasible matter.

5 NOVEL APPROACHES AS THE FOUNDATION TO MODERN CONVERSIONS

The chapter will address a solution to a problem that many conversion companies must endure. As conversions and retrofits often take place on older vessels, the lack of documentation and drawings brings many complications to overall design process, production process as well outfitting. If the documentation is present, it is still difficult to add new systems in terms of use of space as well as compatibility wise.

Ships consist of many complex construction elements as well as piping, electrical systems and miscellaneous machinery components throughout the hull and superstructure. Often the issue comes from the lack of digital drawings or extreme cases of drawings being completely lost in the process of changing shipowners as well as the changing crew members misplacing them. The documentation can vary from general arrangements, machinery drawings, ventilation, piping, electricity etc. An extreme example of a vessel with no documentation can be seen on Figure 31, where the remains of a 700-year-old merchant vessel Koge needed to be lifted to a museum. The help of 3D scanning made the lifting possible without losing the structural integrity of the remains.

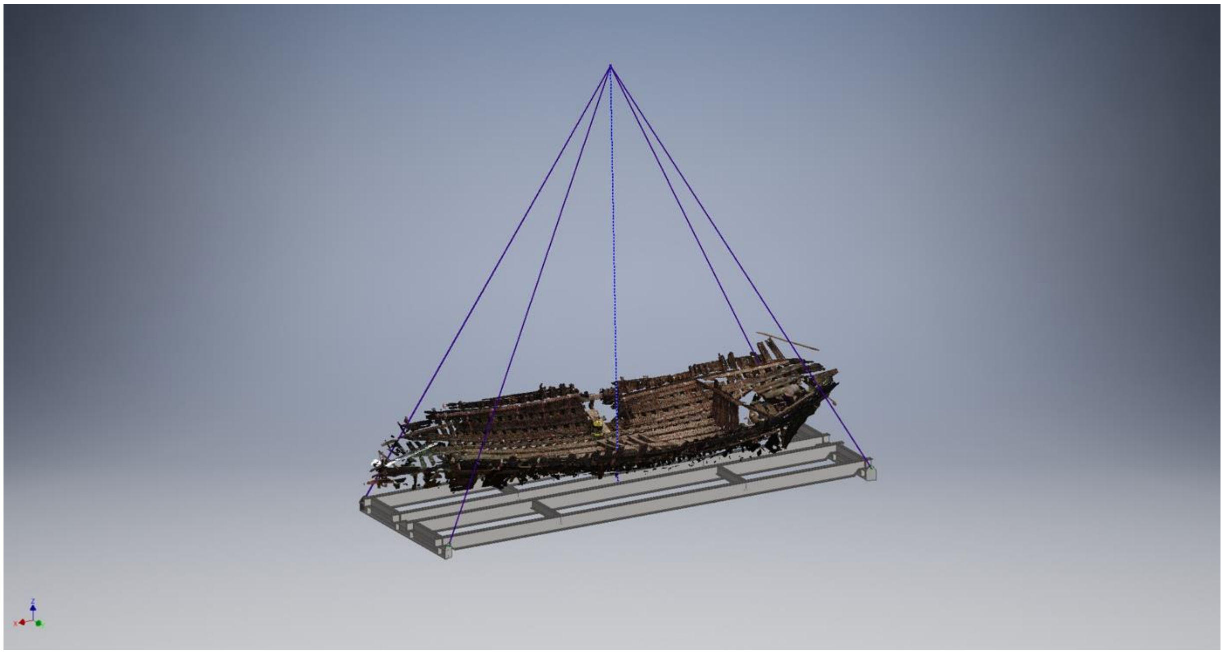

Figure 31 3D scan of Koge. Source: Author

Since machinery design is often very complicated, consisting of many different parts ranging from hull modifications, piping, electrical parts and various systems, accuracy is very important for budgeting, prefabrication as well as cutting down down-time during the outfitting. If the documentation or measurements are invalid, the conversion company as well as the shipowner could face complications in terms of higher cost of retrofit, longer down-time and as it is becoming more actual by the day – more waste and environmental setbacks.

The major game-changing solution to this issue is 3D scanning and augmented reality, which reduces the issue of non-compliant documentations of the existing vessel as well as reduces time for design and increases accuracy and helps engineers see the bigger picture in terms of system design, which leads to higher quality, system efficiency and ease of use.

Augmented reality, the mixture of real spaces with digital images and elements, will play an important part in future retrofits, as the utilization of AR can assist many steps of conversions and retrofits of ships, whether they are technical retrofits or interior retrofits. The help of AR helps with every stage of the retrofit from inspection to outfitting.

5.1 3D scanner

The main tool for reverse engineering is the 3D scanner, which has many different variations in terms of mobility, size of the scanned object, price and intended use. For marine retrofits, the following characteristics must be fulfilled:

- Mobility – the scanner must be light and mobile to ensure access to cavities as well as have the ability to be light enough to be carried around and taken onboard an airplane as the 3D scanning processes can be done globally as well as enroute.
- Range – the scanner used for ships has to have a medium distance range, meaning that the 3D scanners intended for civil engineers or geodesists could have a range too high as the distance of the 3D scan is limited by fire zones and distance between transversal bulkheads.
- Accuracy – As the cheaper 3D scanners on the market have a lower level of accuracy, which could lead to seriously expensive errors in engineering, accuracy of the 3D scanner is very important. This does unfortunately increase the price of the scanner.
- Ease of use – The scanning process itself must be simple and fast, as often the complex systems (ventilation, piping, electrical components, structure) a vast number of scans must often be taken within a short distance.
- Software – The 3D scan for a scrubber retrofit on a 314m container ship took 780 individual scans from the funnel top to the engine room. As the scan processing, which will be assessed in chapter 4.2, is a large-scale operation, the scanner producer provided software must be easy to use and intuitive.

An example of a suitable scanner is the Faro Focus S 70, which is a short-range scanner in the Faro catalogue, but compared to stationary and handheld scanners, it is still a medium range scanner with a range of 0.6m to 70m [69]. The accuracy of the scanner is ±1mm, which is sufficient for retrofitting projects.

The IP54 environmental protection and mobility makes it a suitable scanner for marine use, as it withstands dirt, rain and various temperatures (-20 to +55 ºC) [65] as the scanner could be susceptible to debris and precipitation when used on the outer decks as well as high and low temperatures both inside and outside of the vessel.

The point cloud processing can be done in Faro Scene software as well as Autodesk applications, which makes it a versatile scanner by not limiting the use of point clouds to the manufacturer catered software as much of engineering is done on multiple modelling and drafting programs depending on the field of conversions.

5.2 Scanning process

The scanning process is still very labor intensive throughout the stages from scan configuration to export. As the process is currently relatively manual, the possibilities for error are high. The following subchapter will go through the main characteristics of 3D scanning and how to optimize the process.

5.2.1 Configuration

Prior to the scanning process, the engineer must make ensure that the scanning configuration is in accordance with the desired object to be scanned. The following settings must be configured:

- Resolution – the number of points in a point cloud. If the measured object is of a simple geometry, then lower resolution is suggested to minimize the time for scanning and processing.
- Color – The point cloud can be either black and white or colored. The colored version can be converted into black and white but not vice versa. Black and white must be used in dark rooms and in big projects as the colors would eventually become disruptive. Colored scans are helpful for interior scans and for aesthetically oriented projects.
- Distance – The configured distance of the scan is important in 2 ways.
    - First when the scanning process cannot be done near the desired scanning object and there are other objects in the vicinity of the scanner and in the direction of the desired scanned object. This way the scanner leaves out the set range and only scans the object in the desired distance.
    - The second reason is for scanning reflective and shiny surfaces – if the surface is shiny, there will be more noise in the point cloud and the noise is expressed in reflected points away from the reflective surface.
- The angle of scan – The angle of the scan be limited in both vertical and horizontal direction. The principle of limiting the angle is similar to the point about distance. Rather than scanning in the whole 360-degree spectrum, the scan can be done for the area defined by the scanner i.e. a single component placed in front of the scanner.
- Quality/accuracy of the point cloud – this defines the number of points and their accuracy in the cloud. The accuracy of the points is determined by scanning the same point twice and finding the arithmetic mean of the points.

The parameters listed above have a strong impact on the time taken for a single scan. If the parameters are set to a maximum, a single scan cane take over an hour, if set to a minimum, approximately a minute. For marine use, it is suggested to rather have a high number of scans with lower quality than a low number of high-quality scans as the complex geometry of the machinery and structural components require multiple locations of scans.

5.2.2 Scanning process nuances

The scanning process itself is quite simple. The scanning itself is done by the scanner, but the suitable location must be carefully located by the engineer. The following aspects must be taken into account in marine 3D scanning:

- Preliminary routing – The engineer must find a logical way to move around in the vessel, they must take account the possible blind spots and shadows created by machinery, piping, electrical looming as well as structural components.
- The preliminary groundwork for scan processing and merging as there are 3 main ways of registering scans:
    - Registration markers – simple self-adhesive paper markers
    - Target spheres – usually magnetic spheres, easy to use but the spheres must not move during scans in one compartment, could lead to errors in point cloud registering.
    - Local geometry – fastest way of scanning, but the engineer must make sure that the scanner “sees” the objects in the next scan, otherwise it would be impossible to merge the scan without having common ground between scans i.e. when scanning two connected rooms, the door must be open. Especially important for scans in engine rooms, where the engine extends through multiple decks. The scanner must “see” upper deck surfaces.
- Vibration – the frequencies and vibration from the machinery on board a vessel could disable the ability to scan, alternative locations for scanning must be taken into account if it is impossible to scan i.e. near the main engine.
- Use of inclinometer or compass – if the ship is enroute or docked during high waves, the use of inclinometer is omitted as the ship could succeed the allowed deviation of incline. This is especially case sensitive on higher decks (monkey island, funnel top)

The process is location sensitive, having experience in scanning in challenging conditions will give the company a big advantage compared to companies new to the process. This leads to lower down times, inspection time and higher quality of the overall scan.

5.2.3 Processing of the cloud

Once the scanning process is done, the point cloud must be merged/registered in order to be exported and used by designers in CAD software or for visual inspection in Recap.

The first step is importing the raw scans. The engineer can opt for colorized or black and white scans, dark point filters. minimum and maximum distances between scanner and objects and the way the scan is being merged (markers, spheres, checkerboards, planes) prior to the registration of scans.

The next step is registration/merging. In naval architecture, where the number of scans could be very high, the registration is suggested to be done through vessel's geometry as this removes the necessity to constantly move markers. If the geometry is highly distinguishable, the software is able to register the scans autonomously.

The unrecognized scans will be registered as a cluster and the engineer must register them by hand. The overall use of clusters is important if the scan extends through multiple rooms/decks as every change to individual scan could result in changes to other scans. If the room/deck is registered as a cluster, it will remain untouched.

Once the scans have been hand-registered, a secondary more accurate level of registration is done by the software, during which the suitable level of accuracy must be selected as the high quality requires more computing power, which could make the work in CAD programs difficult.

5.2.3 Coordination of the cloud

The coordination of the cloud depends highly on the quality of existing documentation. If the vessel has a sufficient amount of high quality documentation then an example can be made from a scan in an engine room – 4 physical points on the main engine's foundation were marked, the scans were registered, the coordinates were taken from existing drawings and matched with selected points on foundations.

The second possible way is to register the scans, mark 4 points on different scans as far from each other as possible (in case of scrubber retrofit tank top, 4 points of the highest deck and funnel top), exporting scans as .rcp files, importing them to Autocad and positioning the scans according to the model or drawings. The coordinates given in Autocad can be exported back to the scanner's own software and the whole project will be coordinated.

5.2.4 Exporting the cloud

There are many possible export formats like rcp, pts, dxf, e57, xyz etc. In marine retrofits the most commonly used formats are .rcp and .xyz, which depends on the software used by the customer or design/engineering company. An .rcp exported cloud can be seen on Figure 32. The use of .xyz formats makes compression of the cloud possible, in which the cloud is divided into rows and columns called subsampling, which makes the later processing simpler and quicker in CAD programs.

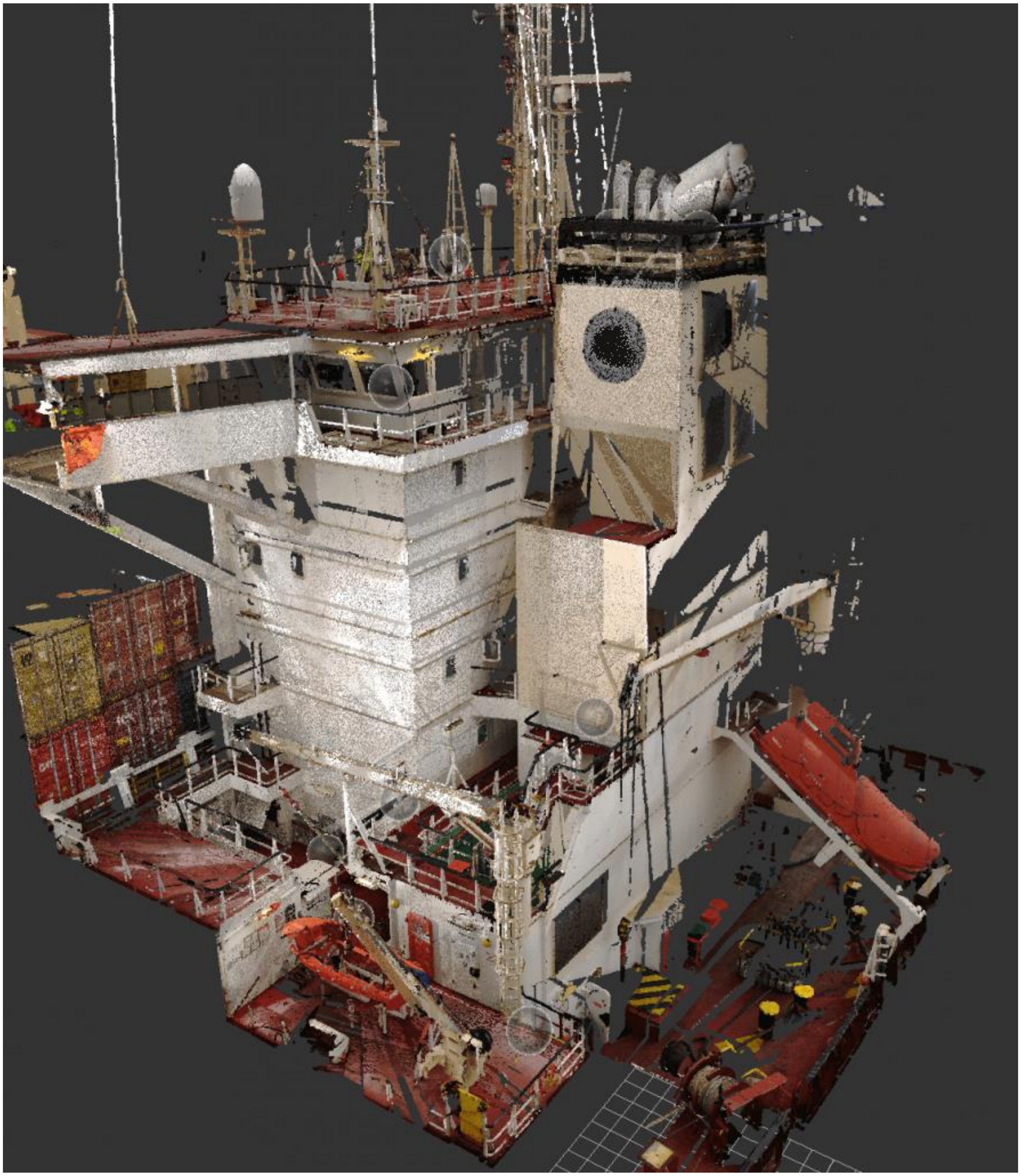

Figure 32 Registered point cloud. Source: Author

The other possibility is to export the project as a 3D scene (See Figure 33), where the 3D scene is in higher definition than a point cloud can be, but the scan is coordinated and has a possibility to measure points. This can find use in crew training, as preliminary design for shipowners and as an interactive for way of moving around in the ship for i.e. cruise ship passengers.

Figure 33 High definition 3D point cloud. Source: Author

5.2.5 Post-processing

The registered and coordinated 3D scan could include unwanted objects and points in the scan like people, furniture, insulation., which could complicate the work of an engineer as high amount of unwanted objects will increase the size of the scan and slow down the CAD program as well as stand in the way of possible modelled objects.

The fastest way is to use Autodesk Recap. The unwanted objects like bulkhead insulation must be selected with a selection box and deleted. The advantage of utilizing ReCap rather than scanner provided software is the speed of the process. The scanner provided software will start re-registering the whole scan, which in the case of 800 scans, could take a substantial number of hours and uses a high percentage of computers processing capacity.

5.3 Optimization of retrofitting stages through 3D scanning and AR

3D scanning and AR will play an even more important role in future retrofits as the technology advances. 3D scanning will make every stage of the conversion process more efficient and improve the quality and accuracy of the outcome. The vastly improving technology of 3D scanning and AR will help the retrofitting companies in every step of the project from inspection to outfitting.

The level on necessity, the possible potential and the main benefits of 3D scanning and augmented reality can be seen in Table 5.

Table 5 Novel Technology benefits

Stage	Level of necessity for novel technology		Benefit
	3D scanning	AR	
Inspection	****	**	Faster, more accurate inspection, low number of inspectors, infinite amount of measurements
Design	*****	****	Equipment placement, routing, collision checking, reverse engineering, class approvals
Prefabrication	***	***	Quality assurance, decreased number of drawings, faster prefab. process
Outfitting	****	***	Quality assurance, decreased number of drawings, high level of collision exemptions prior to outfitting (installation path clearing)
Commissioning	***	****	As built documentation, class approvals, crew training

5.3.1 Inspection

The first step to any conversion or a retrofit project is the inspection of the vessel, where the conversion or retrofit of new equipment will take place. A proper inspection process is a foundation to the whole project.

Main steps of an inspection are:

- Documentation review – Both system and constructional drawings are necessary for a technical retrofit project as the new installed systems must be compatible with existing machinery and the safety and serviceability must be ensured.
- Communication with the client – a clear understanding of the client's wishes must be achieved as the level of rework could lead to expenditures by the retrofitting company
- System compatibility review with the crew – the possibility of insufficient documentation leads to reviewing the existing equipment and machinery onboard a vessel with the crew to ensure the compatibility of the new retrofitted equipment

- Preliminary visual routing – in order to decrease the time taken for 3D scanning, preliminary visual routing must be done prior to the scanning process to limit the number of scans and to ensure the efficiency of the process
- 3D scanning – a range of scans must be taken on the given time onboard a vessel. An efficient 3D scanning process lays the foundation for every following stage of a retrofit

3D scanning

As the 3D scanning usually takes place during the inspection, it can be considered the basis of an inspection rather than an aid. The use of 3D scanning makes hand measurements obsolete as the point cloud can be used in the design process for infinite amount of measures as the engineer pleases. With capacious projects like scrubber retrofits, where a big amount of new equipment is connected to existing machinery, without proper documentation, hand measurements would not be feasible or possible. The 3D scanning also reduces the number of photographs taken by hand as the scanner takes a 360-degree image of the scenery after every individual scan.

The mobility of the scanner is important as the scans can be taken in spaces where it is difficult for a person to access. This can include manholes, tanks as well as overboard objects, which can be measured from afar with the help of the scanner.

A big scale scanning process (800 scans) takes up to two days for a scrubber project and a week for processing the point cloud, but leads to less time spent during the following stages and reduces the number of design errors.

With technical retrofits becoming more demanding, the 3D scanning process during the inspection becomes irreplaceable and companies utilizing and having the competence of 3D scanning and processing will have an advantage over companies buying in the service.

The main advantages of 3D scanning during inspection:

- Low number of engineers on site during the inspection (project manager and 3D scanning engineer)
- No need for hand measurements
- Possibility to measure objects not accessible by man
- One-time inspection needed

Augmented reality

With a prefabricated 3D model of the main components of a large system, the location of the new components can be visualized inside different compartments of a vessel. That can help the engineers and project managers determine the most suitable locations for new equipment in terms of practicality, accessibility and the aesthetic point of view prior to the inspection.

Naval architecture is moving towards virtual reality mock-ups in shipyards, augmented reality will become the direction of conversion and retrofitting companies as the digital elements combined with existing scenery of a vessel can be combined and the shipowners and crew can have more understanding of the equipment to be retrofitted its location and preclude and include conditions of their own in the earliest stages.

The main advantages of AR during inspection:

- Visualization of clients wishes
- Visualization of preliminary pipe routing and equipment placement possibilities

5.3.2 Design

The design process of a ship conversion process is usually the most capacious and time consuming. The engineering/design process is also the most reliant on proper inspection, measurements and modelling software, which can be combined with 3D scans and augmented reality.

The main design processes of a major retrofit:

- **Basic Design** – the first stage of a retrofit, where a lot of communication with the client and class society takes place to ensure the efficiency of detail design
    - GA updates
    - Preliminary pipe routing
    - Preliminary electrical arrangement update
    - Collision checking
    - Safety plans
    - Class approval (Safety, Stability, Environmental aspects)
- **Detail Design** – A high level of engineering ranging from hull modifications, electrical design, equipment foundations, ventilation, CFD etc.
    - Equipment arrangement
    - Detailed hull modification drawings
    - Detailed equipment production drawings
    - Detailed pipe, electrical and ventilation routing
    - Collision checking
    - Class approvals

3D scanning

3D scanning is becoming an inseparable part of the design process. The 3D scanning in the design process helps the engineers in two main ways – reverse engineering and overall adaption of new systems.

The 3D scans will reduce the necessity for engineers to participate in vessel inspections as the point clouds accompanied by 360-degree high definition pictures give engineers the holistic understanding of the vessel and the sections in which the design will take place. The engineer can move around in the assembled point cloud and come back to every necessary location unlike with one-time inspections.

The biggest upside for engineers is the possibility to build new equipment and structures inside the point cloud as seen on Figure 34. This helps the engineer create a new technical solution with ±1 [mm] accuracy, which reduces surplus of materials, reduces the number of on-site modifications to zero if done correctly and reduces the amount of surplus back-up material to be transported to the yard/site.

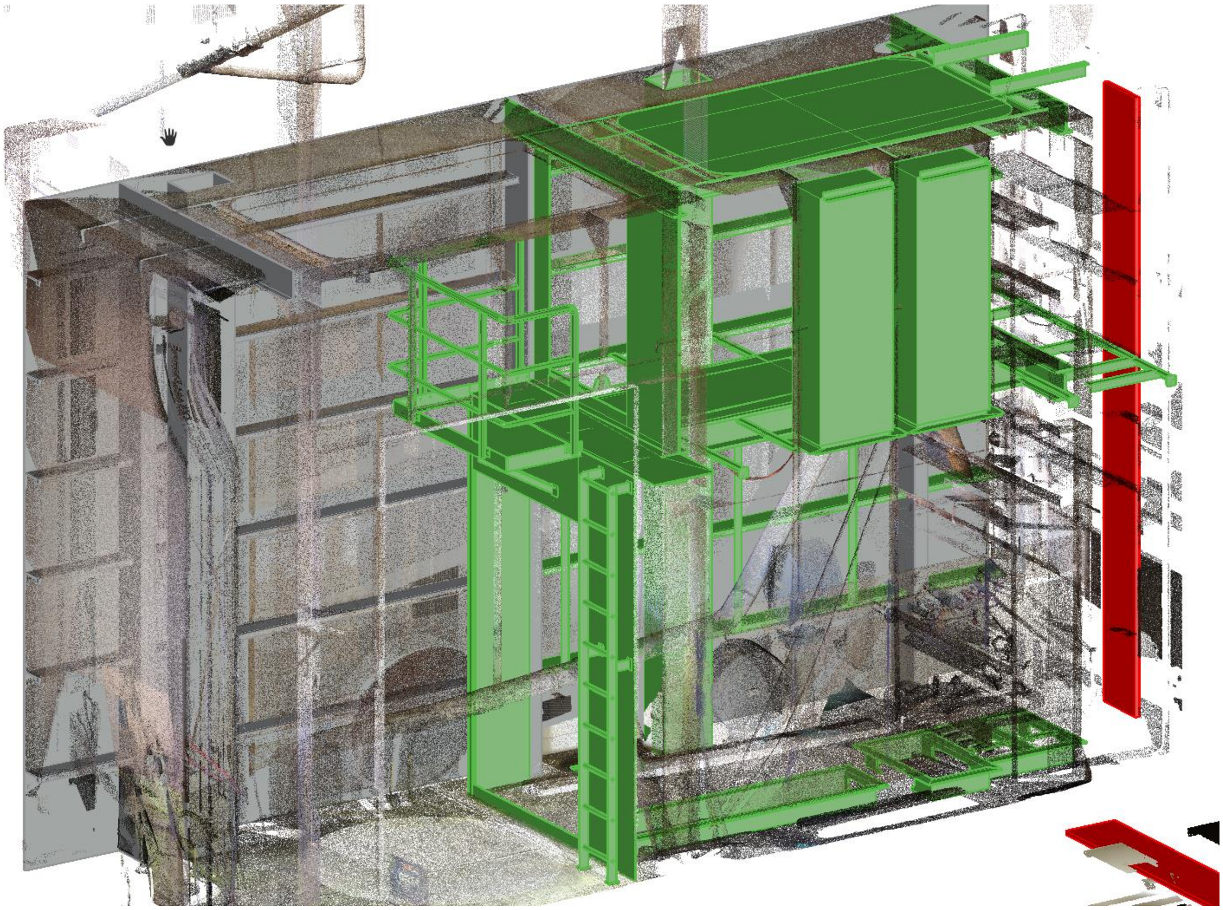

Figure 34 New model inside a point cloud. Source: Author

The second biggest advantage of using point clouds is the ability to reduce the number of collisions to zero. The new equipment modelled into the point cloud can show the engineer the possible collision of existing equipment and the new to be retrofitted component as seen on Figure 35 [70]. This can be considered to be one of the biggest advantages of 3D scanning and utilization of point clouds as the documentation often does not show trivial components like ventilation foundations and brackets. This also omits the issue of older documentation revisions held by the shipowners as the 3D scan shows the current situation of systems and their location.

Figure 35 Point cloud and 3D model collision. Source: Alfa laval

If the ship is lacking original documentation, the 3D scanned point clouds help engineers recreate old equipment found in the vessel, especially details with complex geometry. The reverse engineering aspect is the key to restoring and repairing historical ships as well as newer ships with outdated and out of production equipment that cannot be replaced with an alternative. The last part is especially significant in conversions of old navy ships, where state of the art technology was used during building, which never became widely spread in commercial vessels.

The point cloud can be considered a very strong tool in 3D modelling of a ship's hull and systems, which can be considered as a different scope from the retrofitting job as the next retrofit projects can be done with existing 3D models and as built documentations. For shipowners, that means possible savings in following retrofit projects and the decrease of design and inspection capacity.

The main advantages of utilizing 3D scanning in the design stage:

- Holistic point of view without being on site
- CAD Modelling of existing ship and its equipment
- Unlimited amount of measurements
- Visualization of new equipment compatibility with existing equipment/machinery
- Collision reporting
- Accuracy level of ±1 [mm]
- Reverse engineering possibilities
- As built documentation compilation from model and point cloud

Augmented reality

The augmented and virtual reality is going to be a major game-changer in ship repairs and conversions as the projects take place globally and designers are usually stationary in offices. The visual aids will help engineers have a more “hands-on” approach to their systems.

For interior retrofits, usually virtual reality is used for mock-ups, as the only components for a mockup are an empty space and the VR goggles. Augmented reality can be utilized in a different and even a more realistic way. An example of a cabin conversion can be brought out. The conversion company must build a simple cabin mock-up without any furniture and the engineers, designers and the client can find the most suitable design for the selected space without having to do any additional modifications to the simple mock-up.

For technical retrofits, the augmented reality has a slight disadvantage compared to virtual reality as building a mock-up for i.e. an engine room is senselessly expensive, but the augmented reality can be used on site once the outfitting starts to confirm the design prior to final outfitting, which will be discussed in subpart 4.4.4. Putting the surroundings aside, augmented reality can be used to visualize an assembly in its actual scale and understand aspects unseen on a computer screen.

The engineers can also use augmented reality for preparations of future maintenance guidelines by disassembling the equipment, which also leads to better maintainability of the equipment as the engineer can see its shortcomings prior to the actual maintenance, which could lead to bad user experience or rework of the components.

The main advantages of AR during the design stage:

- Virtual hands-on approach
- Possibility for mock-ups
- Maintenance guideline assembly possibility

5.3.3 Prefabrication

Prefabrication can range from single pipes to whole grand blocks during a retrofit. The process is highly dependent on the proper design and engineering stage, but the modern technological proceeding can help the prefabrication stage, especially AR.

The main prefabrication processes of a major retrofit:

- Fabrication of grand blocks, blocks, assemblies, subassemblies, piping, electrical components
- Quality control of prefabrication
- Project documentation follow up, as built documentation
- Revision and documentation check
- Design modifications

3D scanning

3D scanning is a strong tool in quality control during the prefabrication stage of the retrofit. The point cloud of the finished product can be used whether it is a single item or an assembly. The point cloud of the fabricated assembly or item can either measured and inspected by hand in i.e. ReCap or a faster way can be suggested:

- 3D scanning of a prefabricated assembly must be done.
- Registration and coordination of the scans
- 3D model and point cloud accordance check - The deviations between the 3D model and the 3D point cloud can then be checked

The main advantages of 3D scanning during the prefabrication stage:

- Fast quality assurance
- As built documentation compilation speed

Augmented reality

Augmented reality can help project managers, engineers and outfitters. The use of augmented reality can reduce the use of drawings and help understand the location of each part inside the assembly as the prefabricated assemblies can be complex as seen on Figure 36. Adapting augmented reality will not omit the use of drawings as the accuracy level of augmented reality is still low but can help understand the bigger picture, which will reduce the time of prefabrication as well as decrease the amount of errors due to misreading of difficult drawings. The augmented reality's advantage over drawings can be especially high in difficult conditions like higher decks, overboard work, dark locations etc., in which the use of drawings can be difficult or even impossible.

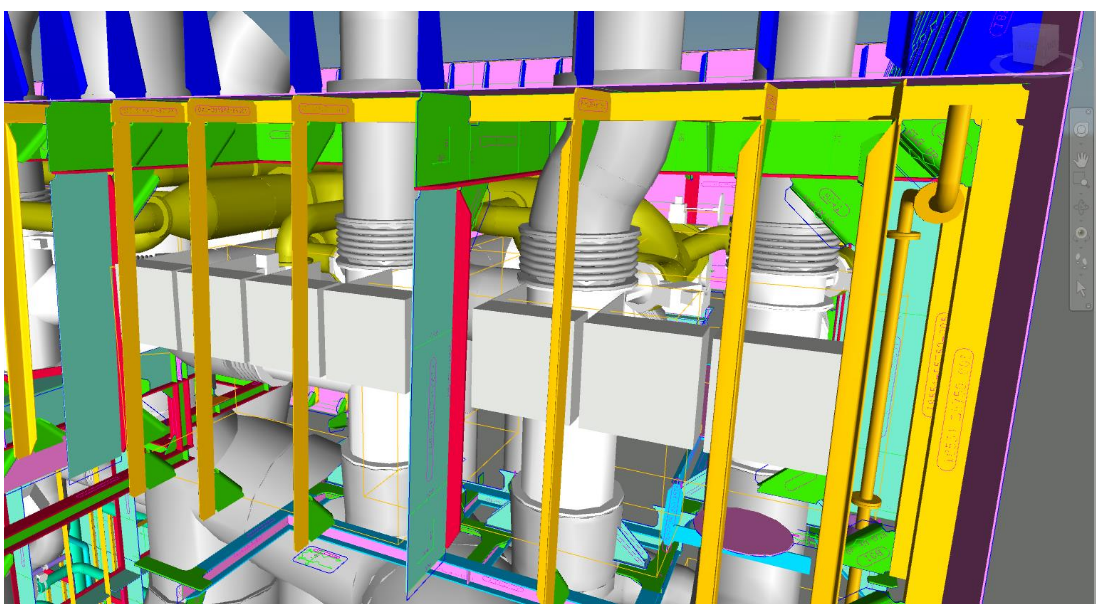

Figure 36 Funnel top of a scrubber. Source: Author

The main advantages of AR during the prefabrication stage:

- Reduction of drawings on site
- Possibility to use AR, where drawings cannot be used
- Reduction of human error

5.3.4 Outfitting and commissioning

The final step of a major retrofit project is outfitting and commissioning. The outfitting is the most time-sensitive stage of any project as the downtime of the vessels translates directly into unearned profit. Digital advancements can raise the quality of the work as well as reduce time in ports and dock, which means that the vessel can return to its operations faster and utilizing these novel advancements can hold an edge for retrofitting companies with such competence.

The main outfitting and commissioning processes of a major retrofit:

- Equipment outfitting
- Hull modifications
- Quality control
- Design and drawing alterations
- Trials
- Class approval
- As built documentation

3D scanning

3D scanning can be used for both outfitting and commissioning. As the outfitting is a time sensitive operation, 3D scanning can help with quality control and in cases of production errors, reduce the time for reworks.

The possibility to use a point cloud has a very substantial advantage in outfitting time consumption. The possible collisions that were assessed in the design subpoint can be reduced en route to the outfitting location.

As for a scrubber retrofit, the extent of the installation is from the sea chest to the top of the funnel, the quality control requires a substantial amount of time and effort. 3D scanning will help the engineer by comparing the point cloud with the as built equipment on the vessel. The process is similar to the prefabrication process quality assurance.

The commissioning of the vessel can be aided by 3D scanning by making the as-built documentation package as accurate as possible and less time consuming by using the 3D model of the new equipment and the vessel modelled with the help of the point cloud.

The main advantages of utilizing 3D scanning in the outfitting and commissioning stage:

- Ease of quality assurance
- As built documentation compilation simplicity

- Faster design alterations
- As built documentation package compilation simplicity
- Simplicity of new retrofits with new accurate documentation and 3D models

Augmented reality

Augmented reality can help the project managers, engineers, the outfitters, the ship's crew and will play a bigger role in the coming years as the technology advances as well as the knowledge of the retrofitting company.

During the outfitting, AR can be used the same way as with the prefabrication process of the assemblies, where the outfitter or the site engineer can visualize the location of the component and therefore reduce the amount of understanding the complicated drawings. As machine vision advances, the augmented reality can also aid the outfitters in finding the right component to install as well as i.e. the orientation of a pipe elbow. By having the technology dictate the coordinates of a component, the reduction in continuous back-and-forth between drawings will make the progress more efficient as well as reduce human errors.

Augmented reality during the commission will become an inseparable part as the necessity for post-conversion training will reduce. As addressed in subchapter 5.4, the engineers will start making digital service manuals, which will reduce the necessity for customer service calls and make the remote repair assistance possible. This will reduce the costs of shipowner and the equipment supplier as well as make the life cycle of the equipment greener by reducing the transportation footprint of the equipment supplier's customer service.

The main advantages of AR during the outfitting and commissioning stage:

- Reduction of drawings on site
- Possibility to use AR, where drawings cannot be used
- Decrease of human error
- Crew preparation possibility for outfitting
- Crew training possibility prior to outfitting

5.4 Future of 3D scanning and AR

The 3D scanning and augmenter reality are still vastly developing technologies. In the last decade, the technologies have seen a rise in users, manufacturers and have become more versatile in every engineering field. As the prices reduce, there will be more demand for both 3D scanners and augmented reality goggles and software. The technology advancements have been impressive, but there are still shortcomings, which must be addressed and improved in the coming years to become a true game changer in the marine repair and conversion market.

3D scanning

3D scanning is a growing industry with a predicted annual compounded growth rate of 25.7% until 2025 and with a market value of up to $53.4 million [71]. The number grows for marine scanning as the predicted shipping rate grows and as the IMO regulations require harder technological solutions for existing vessels. The number of companies providing 3D scanning grows as the price for mobile 3D scanners reduces as the price for a suitable scanner addressed in subchapter 5.1 is approximately $40 000 at the moment, which makes the companies opt for a 3D scanning service rather than doing it in-house.

The biggest expectation for the future of 3D scanning lies in software and autonomy. The current software has short comings in rendering and meshing of 3D objects in CAD software. The scanned items/rooms must be built by hand as the machine vision is not capable of self-meshing complex structures with high quality. A mesh of a simple rudder can be seen on Figure 37.

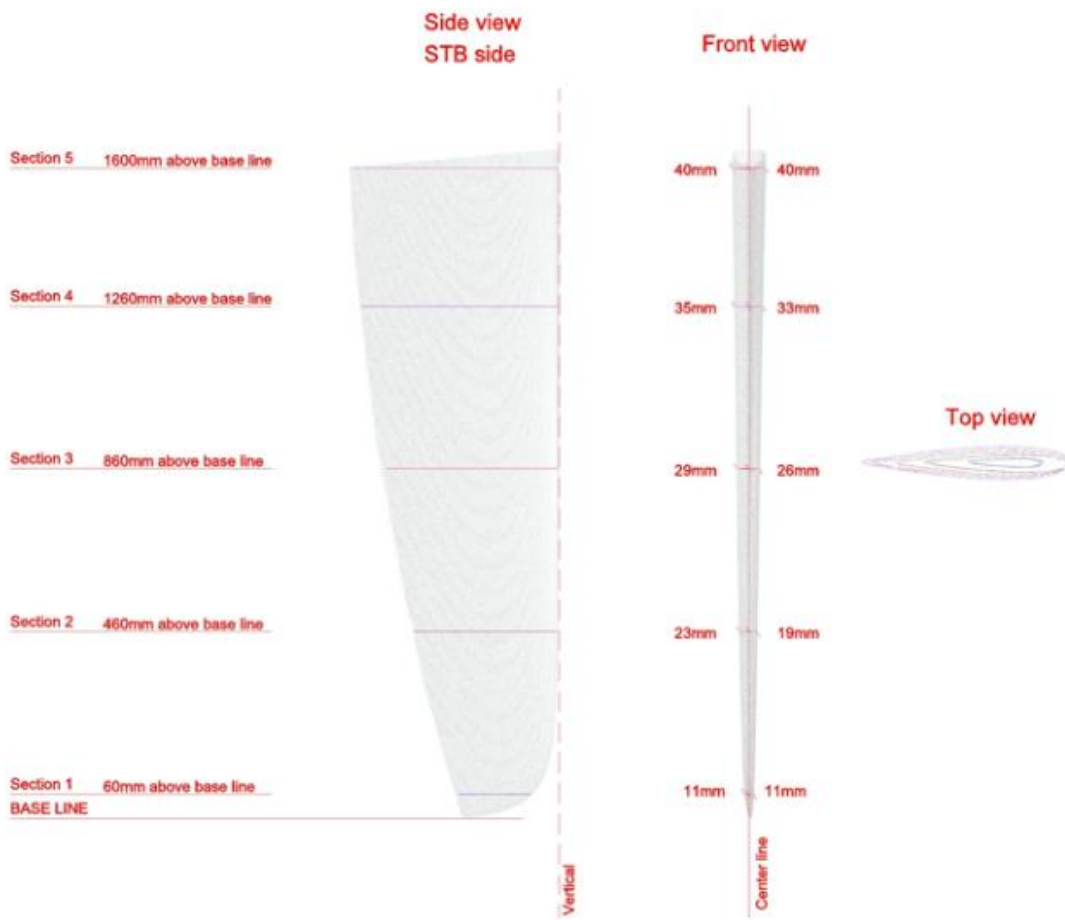

Figure 37 Rudder mesh. Source: Author

The geometry of the rudder was meshed by SolidWorks. As seen on Figure 38, the meshing capabilities are still limited as the mesh quality is lacking even with a single component, when using a Faro scanner produced point cloud and SolidWorks as a meshing tool. The scan of the rudder was done by using the highest resolution setting. In a scan for whole compartment of a ship, the resolution would have to be set to a lower setting. This would lead to even more “noise” in the mesh.

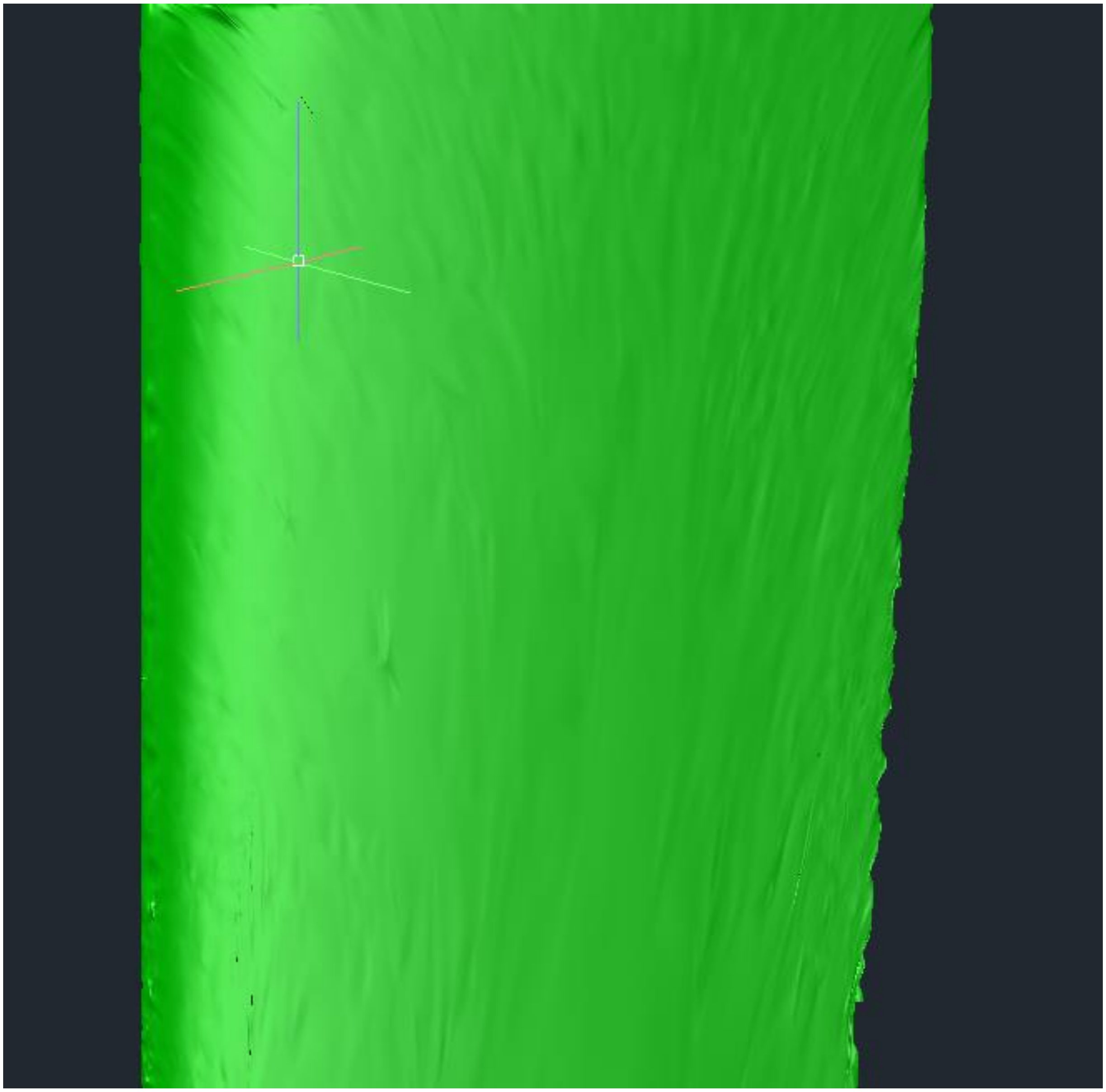

Figure 38 Meshed rudder. Source: Author

The perfect case scenario would be converting the 3D scanned room or object directly into a 3D solid rather than importing a point cloud into a compatible 3D modelling software like AutoCad or SolidWorks and hand modelling the required object according to the scan. The on-site registering of scans must also become smoother and autonomous as the coordination and point cloud registering is still done in a substantial amount by an engineer.

The advancements in machine vision would make quality assurance much faster and efficient as the current possible technique described in subpoint 5.3.3 and 5.3.4 are done manually currently. As the machine vision advances in the 3D scan processing software, the program should point out the possible errors according to the set deviation.

As the autonomous vehicle technologies advance, the 3D scanning must adapt autonomous scanning process with either drones or autonomously moving tracked vehicles, which would register the necessary area for scanning and carry through the job by itself. At the moment the process is done by hand by the 3D scanning engineer – they place the scanner in desired location and initiate the scanning. If the 3D scanner could move autonomously, the engineer could utilize the necessary time taken for hand scanning to other required inspection tasks. The autonomy could also make the process of i.e. scanning a tank safer as the engineer does not have to access the confined spaces, where oxygen levels could be low and dangerous gasses could be present.

Augmented reality

Augmented reality is not as well known to the ordinary user as virtual reality, apart from the game Pokemon Go, but due to its versatile field of use in different industries, its market share is expected to be almost 7 times bigger than virtual reality. The AR market is estimated to reach $46.6 Billion by the year 2024 and is estimated to have a CAGR of 46.6% over the next 4 years [72].

The biggest expectation for the future advancements in augmented reality for engineers lie in the stages brought out in subchapter 5.3. Augmented reality will become a major aid in product visualization throughout the building stages as the technology becomes more widespread and advanced as the current shortcomings are for both hard- and software. The field of view, resolution of the display and machine vision capabilities are still lacking. Once the market becomes wider and more advanced, the technology will become an irreplaceable digital aid in the retrofitting business.

Product visualization, quality assurance and crew training are the main directions in which the augmented reality will have the biggest impact. The product visualization will help engineers understand the holistic picture of its system whether it is in the office or on site as well as having the possibility to use visual mock-ups for understanding and meeting customer needs.

The quality assurance aspect will play a major role from prefabrication to commissioning. As the machine vision becomes more intuitive and the AR goggles advance in accuracy, the augmented reality will make the overall conversion and build process far more efficient and faster as the necessity for vigorous use of drawings would be omitted as well as reduce the human errors in drawing readings.

For crew training, the digital user and service manuals, which have already been implemented in some extent in automotive engineering, will make the commissioning of the system, the everyday use and servicing of the system much simpler and cheaper. The ship owners will opt for suppliers with competent visual user manuals and user support as it keeps the costs down as well as possible down times.

5.5 Conclusion

As the retrofitting and conversion jobs become more complex, the use of modern engineering aids becomes more imminent by the day. The emerging market is driven by the lack of documentation on the behalf of the shipowner, capacity of the engineering hours due to complex system design and the world changing to a more remote work environment.

For marine retrofits, the 3D scanner must be chosen accordingly as there are many variations for different uses. The suitable scanner found was Faro S70. The main aspects to consider for a marine 3D scanner were bought out:

- Mobility – the scanner must be light and mobile to ensure access to confined spaces
- Range – the scanner used for ships has to a distance range of up to 70 meters
- Accuracy – Moderate accuracy levels of up to ±1m should be considered
- Ease of use – The scanning process itself must be simple and fast, as the number of scans can be big
- Environmental protection – The scanner must withstand a range of temperatures, debris and precipitation
- Software – The registration of scans must be fast and the point cloud must be compatible with a variety of engineering software.

The 3D scanning process of a marine project can differ from land-based scanning projects. The following aspects must be considered with marine 3D scans in order to lower down times, inspection time and increase the quality of the overall scan.:

- Preliminary routing – A logical way must be found around the vessel as constructional elements and equipment create blind spots
- Processing registration groundwork – Use of local geometry rather than target spheres and registration markers is suggested in scanning a vessel, as it makes the scanning process as fast as possible (crucial as scan numbers can range up to 800-1000 scans), but common ground between each scans must be seen.
- Vibration – The frequencies and vibration from the machinery on board a vessel could disable the ability to scan, alternative locations for scanning must be taken into account
- Use of inclinometer or compass – Even a docked ship has pitch and roll, the use of inclinometer is omitted as the ship could succeed the allowed deviation of incline

The main advantages of utilizing 3D scanning in retrofitting were bought out in each step of a retrofitting project. The biggest overall advantages can be seen during the design phase as it lays groundwork for a successful prefabrication and outfitting stage, but the advantages of 3D scanning can be seen throughout the retrofitting phase:

- Less manpower for inspections, less overall expenditures (travel cost, salary)
- Higher safety levels during inspection – scanner is able to reach tanks, manholes and scan objects that are not easily accessible from afar.
- Possibility to sell the point cloud and designed 3D model of the vessel post project

- Collision reporting – fewer errors, less expenditures
- Higher accuracy level
- Reverse engineering possibilities
- Higher and simpler quality assurance possibilities
- As built documentation compilation simplicity
- Faster design alterations

The main advantages of utilizing augmented in retrofitting were bought out in each step of a retrofitting project. Augmented reality is still not as popular as 3D scanning in marine retrofits, but can be utilized as a very powerful tool. Augmented reality can be most helpful during outfitting and early design stages, as it helps engineers have a virtual hands-on approach to their designed systems. Other important advantages include:

- Possibility to use AR, where drawings cannot be used (heights, dark areas, heavy weather conditions)
- Crew training possibility prior to outfitting
- Visualization of preliminary pipe routing and equipment placement possibilities
- Possibility for mock-ups
- Maintenance guideline assembly possibility

3D scanning and augmented reality are strong engineering tools in every step of a modern retrofitting job from initial inspection to post retrofitting customer service. The technologies make the work more accurate, help with quality control, lessen the need for complex drawings and can become the new direction in customer service by utilizing AR as a servicing guide, which reduces the necessity for service calls globally and reduces the cost for shipowner.

The market for 3D scanning and augmented reality will grow substantially in the coming years, which will lead to widespread use and the vast advancements in the technology. As the 3D scanning market has a global CAGR of 25.7% [71] and augmented reality has a global CAGR of 46.6% in until the year 2024 [72] suggests that now is the time to become competent in utilizing these novel technologies. As the market share grows, the more experience companies with firsthand experience will become more valuable.

The main directions to move forward in the future for these technologies is the higher accuracy, lower price and autonomy of both systems. The companies already utilizing these technologies will have an edge on companies buying in the service as the future sees an inevitable widespread utilization of these technologies as the complexity of retrofits makes the utilization of the technologies listed inevitable.

6 CONCLUSION AND DISCUSSION

The key research questions have been discussed and answered. The main key drivers for retrofitting were targeted. The possible solutions to meet the future regulations and help shipowners make their vessels more efficient were addressed and their features discussed. The hardships for retrofitting companies during these retrofits were brought out and solutions were found.

6.1 Research outcomes

It was concluded that the changing regulations, fuel prices and society's environmental awareness will drive the retrofitting industry for years to come. In the near future, the retrofitting companies will see a major growth in scrubber, battery powered hybrid and ballast water treatment system conversions.

The biggest drivers of conversion are the expanding ECAs as well as the Tiers for NOx emissions on vessels. The expansion of the ECAs is directly linked to fuel prices as the ECA mandates the shipowners to use either scrubbing technologies or operation on low Sulphur fuel or opt for hybrid solutions. The ballast water treatment system market is directly driven by the hardening regulations both by the IMO and national marine laws, which makes the BWTS an unavoidable system on globally operating vessels.

The possible solutions to meet these restrictions and regulations is to retrofit either more efficient systems onboard existing vessels or to retrofit systems which clean either emissions or discharges. Most feasible solutions for exhaust gas cleaning are scrubbers for SECA requirements and SCRs for NOx tiers. As far as efficiency and alternative fuels go, the most feasible option for adapting new fuels is LNG, as it meets the SECA and NOx tier requirements as well as has a steady fuel price, but the issue comes from fuel storage on different types of vessels. The infrastructure of LNG bunkering is also forecasted to grow. The battery powered hybrid retrofits are the future of existing short distance ferries as the battery technology prices reduce. The retrofitting process is straightforward and has a high feasibility. For future BWTS retrofits, the most promising technology in which to focus on is UV+filtration based systems.

Table 6 concludes the drivers of conversion brought out in chapter 2 and the suitable technical solutions for them brought out in chapter 3. The market potential [74-78] for each solution was combined with retrofit suitability based on the hardships and characteristics of each solution's retrofit brought out in chapter 4.

Table 6 Future retrofit potential

Driver(s)	Solution Type	Technical Solution	Market Potential (CAGR) [%]	Retrofit Suitability	Retrofitting Difficulty	Future Retrofit Potential	Potential Advantage Through Novel Engineering Solutions
ECA	Exhaust Gas Cleaning	Scrubber	36,1	5	4,6	180,5	5
ECA		SCR	2	5	2,6	10	3
ECA, Fuel Price, EEDI & SEEMP	Alternative Fuel	LNG	15	1	5	15	5
ECA, Fuel Price, EEDI & SEEMP		Methanol	5,62	3	3,6	16,86	4
ECA, Fuel Price, EEDI & SEEMP		Fuel Cell	4	3	3,6	12	4
Fuel Price, EEDI & SEEMP	Misc. Efficiency Increasing Technologies	Flettner Rotor Sail	6,53	4	2,2	26,12	1
Fuel Price, EEDI & SEEMP		Air Lubrication System	4,5	2	4,6	9	5
Fuel Price, EEDI & SEEMP		Solar Panels	4	5	1	20	1
ECA, Fuel Price, EEDI & SEEMP	Electricity	Battery powered hybrid	13,2	5	2	66	3
BWM Conventio n	Ballast Water Management	BWTS	10	5	3,4	50	4

The three most potential fields of work for the upcoming years for retrofitting companies (See Table 6) were brought out:

- BWTS retrofits – Driven by the BWT Convention. Expected to grow from $4.57 billion to $8.9 billion by the year 2027 with a steady 10% CAGR [54].

- Scrubber installations – Driven by ECAs and fuel prices. Expected to grow up to $10 billion with a 36.1% CAGR until the year 2026 [52].
- Hybrid solutions – Driven by ECAs and fuel prices. The market is expected to triple in value from $5.2 billion to $15.6 billion with a CAGR of 13.2% over the next 10 years [53].

The BWTS market shows a growth up to the year 2027, which is directly mandated by the law and can be considered unflappable as the shipping volumes grow. The scrubber market has shown a growth regardless of the worldwide COVID-19 pandemic and a momentary decrease of fuel costs. As the fuel prices rise, the necessity for scrubbers will grow. Battery powered hybrids are considered a fast-growing market as the market size is forecasted to triple in the following decade. As the battery technology advances, the market can expect broadening to other ship types as it is mostly dominated by short-fare ferries with the current advancements.

As the number and complexity of technical retrofits grows, the key foundation to every future retrofit will be 3D scanning and augmented reality. The way to utilize these solutions were brought out in every step of a retrofitting job from initial inspection to post retrofitting customer service. Table 6 shows a high necessity of novel technologies for the 3 most potential retrofit directions. The technologies make the work more accurate, help with quality control, lessen the need for complex drawings and can become the new direction in customer service by utilizing AR as a servicing guide, which reduces the necessity for service calls globally and reduces the cost for shipowner. The use of 3D scanning and AR is becoming an irreplaceable engineering tool in difficult marine retrofitting projects.

6.2 Discussion and future considerations

The directions in technical retrofits in the following 30 years could change as the fuel prices fluctuate extremely or a stricter approach to shipping emissions and discharges is taken. The possible future technologies for fuel cells, batteries and solar energy could lead the way, but trends have shown that as long as fossil fuels are widely available and the technical solutions are in accordance with the regulations, the vast use of fossil fuels will continue.

The author found it surprising that despite the COVID-19 pandemic and its impact on the economy of the shipping world especially the cruise industry, the number of scrubber orders still grew, which shows that the regulations enforced are effective.

As the 3D scanning market grows, the author hopes to see a leap in both 3D scanning technology and the more widespread use of augmented reality. The meshing possibilities of 3D scanning are still not as developed for marine use scanners as engineers would like. In the future, as the machine vision and mesh software advances, the possible meshing of ships constructional elements and systems would omit the need for hand modelling of the hull and equipment, which would reduce the time spent on the design process as well as the as built documentation substantially. The author believes that the quality control method for marine use scanners like Faro S 70, should match the possibilities for hand-held scanners like Nikon MMdx with Nikon Focus, where the quality reporting is done by the software when combined with a 3D model.

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