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An analysis of the new IMO environmental regulation, Sulphur Cap 2020 | Case Study: M/T Aegean Dream

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List of Abbreviations

ADNOC	Abu Dhabi National Oil Company
API	American Petroleum Institute
ASTM	American Society for Testing and Material
B	Center of Buoyancy
BaP	Benzo-a-pyrene
BC	Black Carbon
BDN	Bunker Delivery Note
BS	British Standards Institute
CAPEX	Capital Expenditure
CARB	California Air Resources Board
CCAI	Calculated Carbon Aromaticity Index
CDU	Crude Oil Distillation Unit
CEMS	Continuous Emission Monitoring System
CFD	Contract for Differences
CFP	Cold Filter Plugging Points
CH_4	Methane
CIMAC	International Council on Combustion Engines
CO_2	Carbon dioxide
CO	Carbon monoxide
COT	Crude Oil Tanks
CP	Cloud Points
DM	Distillate Marine
DME	Dimethyl Ether
ECA	Emission Control Area
EEA	European Environment Agency
EGCS	Exhaust Gas Cleaning System
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EU	European Union
FAME	Fatty Acid Methyl Ester(s)
FCC	Fluid Catalytic Cracker
FNU	Formazin Nephelometric Unit
FONAR	Fuel Oil Non-Availability Report
G	Center of Gravity
GDP	Gross Domestic Product

GHG	Greenhouse Gas
GISIS	Global Integrated Shipping Information System
GPS	Global Positioning System
GRP	Glass Reinforced Plastic
H_2SO_3	Sulphurous Acid
H_2SO_4	Sulphuric Acid
HFO	Heavy Fuel Oil
HSFO	High Sulphur Fuel Oil
IFO	Intermediate Fuel Oil
IMCO	Inter-Governmental Maritime Consultative Organization
IMF	International Monetary Fund
IMO	International Maritime Organization
ISO	International Organization for Standardization
KPC	Kuwait Petroleum Corporation
LSMGO	Low Sulfur Marine Gas Oil
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
M	Metacenter
MARPOL	International Convention for the Prevention of Pollution from Ships
MCR	Maximum Continuous Rating
MDO	Marine Diesel Oil
ME	Main Engine
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
M/T	Motor Tanker
MV	Motor Vessel
NIOC	National Iranian Oil Company
NO_x	Nitrogen Oxides
NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
NPV	Net Present Value
NTU	Nephelometric Turbidity Unit
ODS	Ozone Depleting Substances
OPEC	Organization of the Petroleum Exporting Countries

OPEX	Operational Expenditure
PP	Payback Period
SCR	Selective Catalytic Reduction
SFOC	Specific Fuel Oil Consumption
SIP	Ship Implementation Plan
SOLAS	Safety of Life at Sea
SOMO	State Organization for Marketing of Oil
SO_x	Sulphur Oxides
SO_2	Sulphur dioxide
SO_3	Sulphur trioxide
STEO	Short – Term Energy Outlook
SW	Sea Water
PAH	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter
PSC	Port State Control
PSSAs	Particularly Sensitive Sea Areas
REBCO	Russian Export Blend Crude Oil
RM	Residual Marine
SECA	Sulphur Emission Control Areas
UAE	United Arab Emirates
UK	United Kingdom
ULSFO	Ultra Low Sulphur Fuel Oil
USEPA	United States Environmental Protection Agency
VGO	Vacuum Gas Oil
VLSFO	Very Low Sulphur Fuel Oil
WBT	Water Ballast Tank
WHO	World Health Organization
WTI	West Texas Intermediate
WTU	Water Treatment Unit

Glossary of Terms

Acid rain: Rain or any other form of precipitation that is unusually acidic, meaning that it has elevated levels of hydrogen ions (low pH). It can have harmful effects on people, plants, aquatic animals and infrastructure. Acid rain is caused by emissions of sulfur dioxide and nitrogen oxide, which react with the water molecules in the atmosphere to produce acids.

Alkalinity: The buffering capacity of a water body; a measure of the ability of the water body to neutralize acids and bases and thus maintain a fairly stable pH level.

Ballast: When the vessel is travelling empty of cargo and specific tanks (Ballast tanks) are filled with seawater for stability reasons.

Buffer tank: The buffer tank is used in the closed loop mode and collects the liquid that contains the most PM which is further pumped to the water treatment filter.

Capital Expenditure (CAPEX): It is used to describe funds that are utilized by the shipping company to acquire, upgrade, and maintain physical assets (i.e. vessels).

Sodium Hydroxide (Caustic soda - NaOH): Caustic soda is an ionic compound used as an additive to the fresh or seawater to increase the pH and is utilized in the scrubbing process.

Closed Loop Scrubber: In a closed loop scrubber, treated water (fresh water plus chemical additives) is circulated in order to keep the scrubbing process independent of the water’s salinity that the vessel is sailing in. The main difference between the open loop and the closed loop scrubber, is that the latter rather than discharging the washwater overboard, it cleans and recirculates it.

Deadweight tonnage (DWT): It is a measure of how much weight in tons the vessel can carry. It includes cargo, fuel, fresh water, ballast water, supplies, crew, passengers, etc.

Decanter – Recirculation tank: The decanter or recirculation tank receives the water from the water treatment filter and the system tank.

Deposit – Sludge tank: The deposit or sludge tank collects all the sludges that occur from the scrubbing process until pumped them ashore.

Dry scrubber: A dry scrubber, is a scrubber that does not use any liquid to carry out the scrubbing process of the exhaust gases. Usually it uses hydrated lime-treated granulates.

Emission Control Area (ECA): An area where specific measures apply to reduce sulphur emissions.

Gross Domestic Product: GDP measures the monetary value of final goods and services—that are bought by the final user—produced in a country in a given period of time (say a quarter or a year).

Holding tank: The holding tank receives the bleed-off water from the decanter – recirculation tank in closed loop mode. It is used in ports where the zero – discharge regulation is applied.

Hybrid Scrubber: The hybrid scrubber is both an open and a closed loop scrubber, meaning that at any time it can operate as any of either.

International Organization for Standardization (ISO): The International Organization for Standardization is an international standard-setting body composed of representatives from various national standards organizations. Founded on 23 February 1947, the organization promotes worldwide proprietary, industrial, and commercial standards.

Laden: When the vessel is loaded and travels with cargo.

Marine Environment Protection Committee (MEPC): MEPC addresses environmental issues under IMO's remit. This includes the control and prevention of ship-source pollution covered by the MARPOL treaty, including oil, chemicals carried in bulk, sewage, garbage and emissions from ships, including air pollutants and greenhouse gas emissions. Other matters covered include ballast water management, anti-fouling systems, ship recycling, pollution preparedness and response, and identification of special areas and particularly sensitive sea areas.

Net Present Value (NPV): It is the difference between the present value of cash inflows and the present value of cash outflows over a period of time.

Open Loop Scrubber: An open loop scrubber uses seawater as the medium for cleaning or scrubbing the exhaust gases through utilizing the alkalinity of it, usually without adding chemicals. The used water is discarded later in the ocean after being monitored and maybe after surpassing a cleaning process which normally is not required.

Operational Expenditure (OPEX): Is the money that the shipping company spends to maintain the ship running, including wages, consumables, bunker fuels, etc.

Particulate Matter (PM): A mixture of solid particles and liquid droplets found in the air, such as dust, dirt, soot, or smoke.

Particularly Sensitive Sea Area (PSSA): An area where specific measures apply to protect it from international shipping activities.

Payback period: The period in which the investment will recover its initial outlay in terms of profit.

pH: The pH is a scale used to specify how acidic or basic a water-based solution is.

Polycyclic Aromatic Hydrocarbons (PAHs): Hydrocarbons - organic compounds containing only carbon and hydrogen - that are composed of multiple aromatic rings. Must be measured in the scrubber's washwater prior to discharging overboard.

Port State Control: Port state control (PSC) is an inspection regime for countries to inspect foreign-registered ships in port other than those of the flag state and act against ships that are not in compliance. Inspectors for PSC are called PSC officers (PSCOs) and are required to investigate compliance with the requirements of international conventions, such as SOLAS, MARPOL, STCW, and the MLC.

Salinity: Salinity is the saltiness or dissolved inorganic salt content of a body of water. Substances that are dissolved in water are usually called solutes. The typical seawater has a salinity of 35 ppt or 35‰. The average density of seawater at the surface is 1.025g/ml.

Scrubber: A scrubber is an air pollution control device that can be used to remove particulates. In ships particularly it is used to the desulphurization of the exhaust gases of the combustion units, in order to comply with the new Sulphur Cap 2020.

Sludge: Sludges are produced during the closed loop scrubbing process and, in some cases, also in the open loop process and are mainly soot and oil compounds emitted from the combustion unit(s) that the scrubber is serving. Usually when talking about scrubbers for ships, the sludges are liquid, containing 5% dry matter and 95% wastewater including water, water-soluble substances from the scrubbing process, sulphates and salts from the alkali addition (i.e. caustic soda).

Suezmax: Is defined as the ship with the maximum dimensions that can transit the Suez Canal in a laden condition. The limiting factors of the Suez Canal are the beam, draft and height of the vessel.

System tank: The system tank supplies the recirculation pump and thus the scrubber, when operating in closed loop mode, with liquid.

Turbidity: Is a measure of the degree to which the water loses its transparency and hence is a measure of the water quality, due to the presence of polluting particulates such as PM.

Wet scrubber: A wet scrubber, is a scrubber which uses liquid to clean the flue gas stream. In terms of shipping this liquid is either chemically treated fresh or seawater and SO_x compounds react with it and form sulphates.

Chapter 1. Introduction

1.1 Background

Air pollution has been recognized as a matter of paramount importance over the last decades. The highly increased levels of harmful pollutants in the atmosphere have raised international awareness and resulted in the adoption of increasingly stricter measures aiming to reduce global air pollution.

During the previous century, industrial plants and road vehicles had been regarded as the major sources of air pollution and consequently became the centre of attention of environmental policies-makers, and thus were gradually regulated by a series of legislative provisions leading to a more environmentally friendly operation. While land-based emissions were regulated and reduced, the increase in maritime traffic, which currently accounts for more than 90% of the total global trade, turned the shipping industry into a major contributor to global air pollution. Hence, international awareness on ships' emissions increased, leading to the establishment of several protective measures with the aim of preserving the environment, the health and living standard of all living beings.

The International Maritime Organization (IMO) has made a great effort in the restructuring of the shipping industry aiming at the reduction of the adverse effects of maritime traffic in international waters and surrounding lands. Through its regulatory body for the prevention of maritime pollution (MARPOL) it has introduced several Annexes for the protection of the marine environment. On 1997, MARPOL was amended with the Protocol of 1997 and a new *Annex VI, Regulations for the Prevention of Air Pollution from Ships* was introduced [2]. The provisions of Annex VI, concern all member states of IMO that have ratified Annex VI and set limits internationally on ships' exhaust gas emissions; Annex VI focuses on Sulphur Oxides (SO_x), Nitrogen Oxides (NO_x) as well as other harmful substances while also introduce the Emission Controlled Areas (ECA) within which the adoption of stricter air emissions regulations was deemed necessary due to their sensitive ecosystem.

The latest amendment of Annex VI, the so called «Sulphur Cap», introduces a new global limit of 0.50% (m/m) sulphur content in bunker fuels that will come into effect on January 1, 2020 alongside with the existing 0.10% (m/m) limit within the designated ECA areas. This amendment has brought major challenges to the shipowners who shall find a way to comply with the stringent regulations as well as the refinery sector who has to adopt quickly and cover the intense shifts in fuel demand that are expected with the advent of IMO 2020 Sulphur Cap. Additionally, it has introduced a new market in the shipping industry of machinery that are able to treat onboard the exhaust gases of ships' and thus comply with the regulations of the revised Annex VI. These machineries are called Scrubbers and are considered one of the primary options to meet the requirements of the imminent Sulphur Cap.

1.2 Objective of this study

The objective of this research was to address the forthcoming Global Sulphur Cap 2020, to analyse the available compliance options and lastly carry out a technoeconomic analysis on the conformity to the regulation of a specific tanker ship owned by a Greek shipping company.

The first part of this study provides some information on the environmental impact of ships' emissions (focusing primarily on air emissions) and explains the future benefits that are expected to come with the adoption of stricter regulations. The environmental background is followed by a detailed presentation of the legislative framework around the upcoming regulation.

The second part of this research starts with an introduction around crude oil, as the production base of marine fuels. Right after, follows a detailed analysis of the different routes by which shipowners and operators can comply to the Global Sulphur Cap, focusing mainly on two of them, namely the installation of an Exhaust Gas Cleaning Systems (EGCS) or the use of compliant low-sulphur marine fuels.

The third part of this study is a case study of the new regulation based on its application on a specific tanker ship owned by a Greek shipping company. This part was carried out in collaboration with Arcadia ShipManagment Co. Ltd, a Greek shipping company based in Athens, Greece. The research was conducted on Aegean Dream, a suezmax oil tanker owned by Arcadia, and was based on the ship's specifications, operating profile and annual trade pattern. Considering the said elements, a comparison between the available compliance options (already presented in the 2nd part) was carried out, aiming to find the optimal solution by which the company can meet with Sulphur Cap 2020 requirements.

Chapter 2. Regulatory Framework

The upcoming IMO 2020 Sulphur Cap's regulatory framework is designated by the following regulations:

- IMO Revised MARPOL Annex VI, Regulation 14 (IMO, 2008b) – SO_x and Particulate Matter
- IMO Revised MARPOL Annex VI, Regulation 4 (IMO, 2008b) – Equivalence
- MEPC 259(68) – 2015 Guidelines for Exhaust gas cleaning systems
- EU Directive 2016/802/EU
- US Regulations

These provisions establish limits on the maximum permissible sulphur content of fuel oil used by ships as well as describe recognized methods of compliance and are further detailed below.

2.1 International Maritime Organization Regulations

The International Maritime Organization (IMO), formerly known as the Inter-Governmental Maritime Consultative Organization (IMCO), is a specialized agency of the United Nations responsible for regulating shipping [47]. The IMO was established following an agreement at a UN conference held in Geneva in 1948 and it came into existence ten years later, meeting for the first time in 1959. Headquartered in London, United Kingdom, the IMO currently has 174 member states and three associate members [47].
The IMO's primary purpose is to develop and maintain a comprehensive regulatory framework for shipping and its remit today includes safety, environmental concerns, legal matters, technical co-operation, maritime security and the efficiency of shipping [47]. IMO is governed by an assembly of members and is financially administered by a council of members elected from the assembly. The work of IMO is conducted through five committees and these are supported by technical subcommittees. IMO is the source of approximately 60 legal instruments that guide the regulatory development of its member states to improve safety at sea, facilitate trade among seafaring states and protect the maritime environment.
The regulatory body that is responsible for the development of IMO Sulphur Cap 2020 is MARPOL (short for maritime pollution) international convention which was developed to address environmental pollution from international shipping. MARPOL convention was initially signed in 1973 and today it comprises several provisions which are divided into six Annexes, each one addressing a potential source of pollution from ships.

2.3 MARPOL Convention

The *International Convention for the Prevention of Pollution from Ships (MARPOL)* is the main international convention aimed at the prevention of pollution of the marine environment caused by ships both from accidental and operational causes [46].

It was initially signed on November 1973 at IMO but did not come into force at the signing date. A series of tanker accidents that followed the years after, led to the adoption of Protocol of 1978 and the combined instrument entered into force on 2nd of October, 1983 [46]. Later, on 1997, MARPOL Convention was amended with the Protocol of 1997, and a new Annex VI, *Regulations for the Prevention of Air Pollution from Ships* was introduced [16]. MARPOL convention has been revised with several amendments since its adoption.

Currently, MARPOL includes six Annexes, each one of which deals with a particular group of ships' discharges and pollutants. In brief, MARPOL legislation is focused on the prevention of potential pollution caused by spillage or discharge of oil, noxious and harmful substances, sewage, garbage as well as exhaust gas emissions, all sourced from ships.

All ships that are flagged under or operate within the jurisdiction of countries that are signatories to MARPOL are subject to its requirements. Compliance to the legislation is inspected by flag Administrations or classification societies that are authorized to act on behalf of them. Flag Administrations are wholly responsible for vessels that are registered on their national ship registries but also have the authority to inspect through the *Port State Control* (PSC) inspection regime foreign-registered ships that berth on their national ports. As of 2019, 158 states have ratified MARPOL convention accounting for more than 99% of the world's shipping tonnage [48].

Figure 2-1 MARPOL signatory and non - signatory parties worldwide

Source: Camphuysen, C. J., Leeuw, J. et al. (Eds). (2011, November). Monitoring Chemical Pollution in Europe's Seas Programmes, Practices and Priorities for Research. Oslo, Norway: European Marine Board.

2.3.1 Annex VI

MARPOL **Annex VI**, first adopted in 1997, regulates the main air pollutants contained in ships exhaust gas, including Sulphur oxides (SO_x) and nitrous oxides (NO_x), and prohibits deliberate emissions of ozone depleting substances (ODS). MARPOL Annex VI also controls shipboard incineration, and the emissions of volatile organic compounds (VOC) from tankers.

Annex VI came into force on May 19, 2005 after acquiring the requisite number of signatories and presently comprises five chapters within which there are 26 regulations contained. *Regulation 14* to Annex VI introduced a worldwide limit on the sulphur content of marine fuels of 4.5 percent and a limit within designated SO_x emission control areas (SECA) of 1.5 percent [3]. The Baltic Sea was the inaugural SECA adopted under the Annex and was followed by the North Sea/English Channel SECA on November 22, 2007 [3].

The 58th IMO MEPC session, in October 2008, adopted significant changes to Annex VI under Resolution MEPC.176 (58) [3]. A global sulphur fuel limit of 3.5 percent became effective on January 1, 2012 and introduced further reductions in the fuel sulphur limits within SECAs, with a limit of 1.0 percent applicable from July 1, 2010, and 0.1 percent from January 1, 2015 [3]. Additionally, it was mandated via Regulation 14.8 to Annex VI that a Fuel Oil Availability Review shall be completed by 2018 to examine the possibility of reducing the 3.5% sulphur limit to 0.50% (m/m) by 2020 or 2025.

The outcome of the review was presented at MEPC.280 (70) where it was assessed that the global oil refinery sector can produce sufficient quantities of 0.50% sulphur content fuel oil.

Hence, it was decided that the new global sulphur limit shall be introduced on January 01, 2020 alongside with the existing 0.10% limit within the designated ECA areas. The progressive reductions in fuel sulphur content limits worldwide and within ECA areas are illustrated in Table 2-1.

At the present time, after the last amendments that were adopted on October 26,2018 under Resolution MEPC.305 (73), member states of IMO and signatories to the MARPOL convention will not be allowed (after January 1, 2020) to **use or carry for use on board** a ship, fuel oil exceeding 0.50% (m/m) sulphur content. Alternatively, carriage and use of not-complying fuels can only be allowed by on board installation and use of approved alternative means of compliance that are at least as effective in terms of emissions reduction as the prescribed sulphur limits [66]. The aforementioned regulations are further explained below.

Table 2-1 Sulfur limits inside and outside of ECA areas

Outside an ECA established to limit SOx and particulate matter emissions	Inside an ECA established to limit SOx and particulate matter emissions
4.50% m/m prior to 1 January 2012	1.50% m/m prior to 1 July 2010
3.50% m/m on and after 1 January 2012	1.00% m/m on and after 1 July 2010
0.50% m/m on and after 1 January 2020	0.10% m/m on and after 1 January 2015

Source: International Maritime Organization (2020)

2.3.1.1 Regulation 14

Regulation 14 to Annex VI places limits on the sulphur content of bunker fuels to restrict SO_X and particulate matter (PM) emissions and is applicable to all ships in service [66]. It concerns fuel oil used for combustion purposes, propulsion and operation on board and applies to all combustion units, both main and auxiliary engines together with units such boilers and inert gas generators as well [55]. Furthermore, the regulation specifies different limits when operating inside and outside an Emission Control Area.

During MEPC.280 (70) session that was held in October 2016, IMO introduced the IMO 2020 Sulphur Cap by establishing from January 01, 2020 a new limit of 0.50% (m/m) maximum sulphur content worldwide.

Under the light of the latest amendments that were adopted on October 26, 2018 under Resolution MEPC.305 (73), Regulation 14 to Annex VI states that:

General Requirements:

1. The sulphur content of fuel oil **used or carried for use on board** a ship shall not exceed 0.50% m/m[1].
2. The worldwide average sulphur content of residual fuel oil supplied for use on board ships shall be monitored taking into account guidelines developed by IMO.

Requirements within Emission Control Areas:

3. For the purpose of this regulation, an emission control area shall be any sea area, including any port area, designated by the Organization in accordance with the criteria and procedures set forth in appendix III to this Annex. The emission control areas under this regulation are:

    1. the **Baltic Sea** area as defined in regulation 1.11.2 of Annex I of the present Convention (SO_x only);
    2. the **North Sea** area as defined in regulation 1.14.6 of Annex V of the present Convention (SO_x only);
    3. **North American area** (entered into effect 1 August 2012) – as defined in Appendix VII of Annex VI of MARPOL (SO_x, NO_x and PM); and
    4. **United States Caribbean Sea** area (entered into effect 1 January 2014) – as defined in Appendix VII of Annex VI of MARPOL (SO_x, NO_x and PM).

4. While a ship is operating within an emission control area, the sulphur content of fuel oil **used on board** that ship shall not exceed 0.10% m/m

5. The sulphur content of fuel oil referred to in paragraph 1 and paragraph 4 of this regulation shall be documented by its supplier as required by regulation 18 of this Annex.
6. Those ships using separate fuel oils to comply with paragraph 4 of this regulation and entering or leaving an emission control area set forth in paragraph 3 of this regulation

[1] The carriage ban of non-compliant fuels for combustion purposes, propulsion or operation on board a ship will enter into force on 01 March, 2020.

shall carry a written procedure showing how the fuel oil changeover is to be done, allowing sufficient time for the fuel oil service system to be fully flushed of all fuel oils exceeding the applicable sulphur content specified in paragraph 4 of this regulation prior to entry into an emission control area. The volume of low sulphur fuel oils in each tank as well as the date, time and position of the ship when any fuel oil changeover operation is completed prior to the entry into an emission control area or commenced after exit from such an area shall be recorded in such logbook as prescribed by the Administration.

7. During the first 12 months immediately following entry into force of an amendment designating a specific emission control area under paragraph 3 of this regulation, ships operating in that emission control area are exempt from the requirements in paragraphs 4 and 6 of this regulation and from the requirements of paragraph 5 of this regulation insofar as they relate to paragraph 4 of this regulation.

2.3.1.2 Regulation 4

Regulation 4 to Annex VI allows flag Administrations to approve alternative means of compliance that are at least as effective in terms of emissions reduction as the prescribed sulphur limits [66]. This means that a ship may operate using a fuel with sulphur content higher than that allowed by regulation 14 as long as an approved machinery can reduce the SO_x emissions to a level that is equivalent to, or lower than, the emissions produced by compliant fuel [66].

According to the revised Annex VI, including the most recent amendments, Regulation 4 to Annex VI states that:

1. The Administration of a Party may allow any fitting, material, appliance or apparatus, such as SO_x scrubbers, to be fitted in a ship or other procedures, alternative fuel oils, or compliance methods used as an alternative to that required by MARPOL Annex VI.

2. The Administrations of Party that allow a fitting, material, appliance, apparatus or other procedures, alternative fuels, or compliance methods used as an alternative to that required by MARPOL Annex VI shall advise IMO on it. Notifications of use of equivalent provision from Parties are available through the Global Integrated Shipping Information System (GISIS) (Registration required for public users).

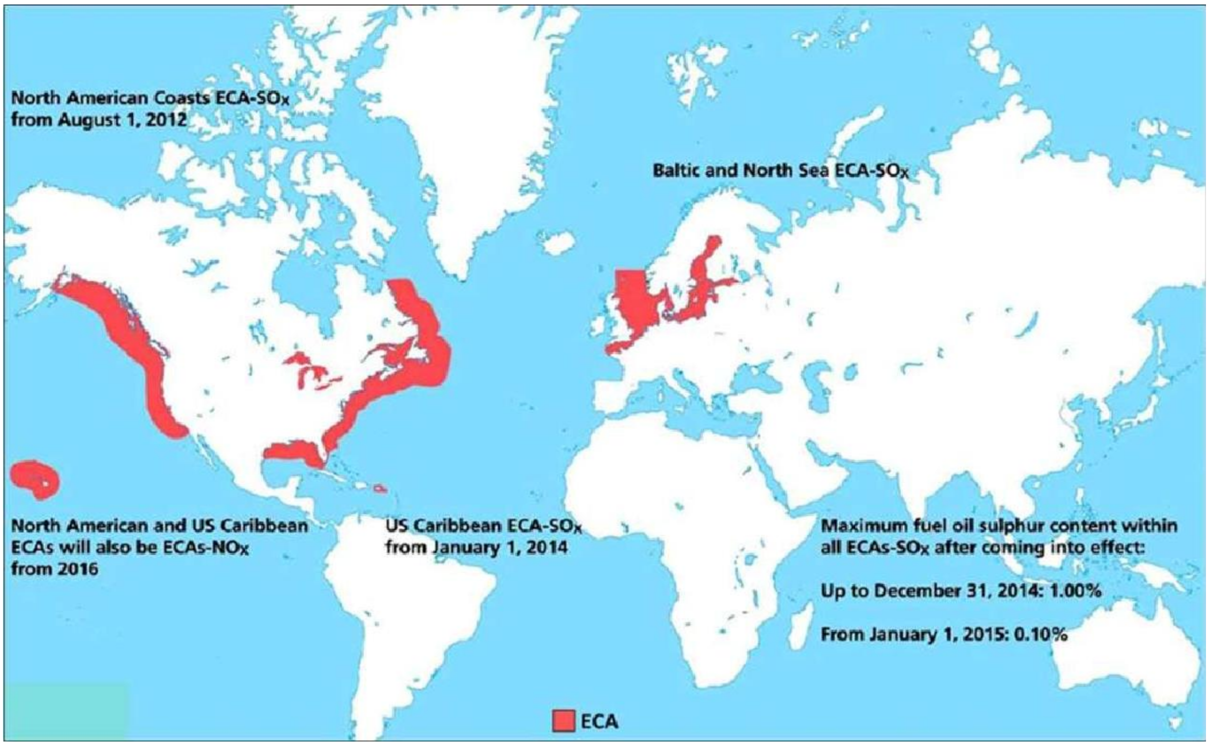
Any exhaust gas treatment system that is intended to be installed on board a vessel, must first be approved and verified by the Classification Society that acts on behalf of the Flag Administration; the scrubber system shall be manufactured and operate according to IMO's requirements, which are set out in the IMO Exhaust Gas Cleaning Systems Guidelines (MEPC 184(59) – 2009 Guidelines for Exhaust Gas Cleaning Systems).

2.3.2 Emission Controlled Areas (ECA)

As per MEPC.1/Circ.778/Rev.2 session of the IMO MEPC committee, **Emission Control Areas** (ECA) are defined under MARPOL Annex VI as areas where the adoption of special mandatory measures to regulate emissions from ships is required to prevent, reduce and control air pollution from NOX and/or SOX and/or particulate matter (PM) and their attendant adverse impacts on human health and the environment [45].

As per Regulation 14.3, the sea/port areas that have been designated under Appendix III of Annex VI as Emission Control Areas are illustrated in Figure 2-2.

Figure 2-2 Emission Control Areas in worldwide map



Source: Tran, Tien Anh. (2017). Research of the Scrubber Systems to Clean Marine Diesel Engine Exhaust Gases on Ships. Journal of Marine Science Research and Development. DOI: 10.4172/2155-9910.1000243

2.3.4 Particularly Sensitive Sea Areas (PSSAs)

The International Maritime Organization has laid down several areas as PSSAs linked to ecological, socio – economic, or scientific interests with the view of protecting them from possible international shipping activities. Such activities include operational discharges (ballast waters, wastewaters or solid waste), accidental or intentional pollution (oil spills and oil leaks) and physical damage to marine habitats or organisms (destruction of coral reefs or vessel collision with animals).

The criteria for specifying an area as particularly sensitive are displayed briefly in Table 2-2. At least one of them must be met with the according supporting documentation for an area to be established as PSSA.

Table 2-2 Defining PSSAs criteria

Criteria	
Ecological	Uniqueness or rarity
	Critical habitat
	Dependency
	Representativeness
	Diversity
	Productivity
	Spawning or breeding grounds
	Naturalness
	Integrity
	Fragility
	Bio – geographical importance
Social, cultural and economic	Social or economic dependency
	Human dependency
	Cultural heritage
Scientific and educational	Research
	Baseline for monitoring studies
	Education

Source: International Maritime Organization. (2005).

In addition to meeting the previously mentioned criteria, the area should be at risk from international shipping activities, such activities include key factors that are presented in Table 2-3.

Table 2-3 Key factors for PSSAs

Factors	
Vessel traffic characteristics	Operational factors
	Vessel types
	Traffic characteristics
	Harmful substances carried
Natural factors	Hydrographical
	Meteorological
	Oceanographic

Source: International Maritime Organization. (2005).

In the Table 2-4 all the currently listed PSSAs are displayed and in the Figure 2-3 are placed them in worldwide map.

Table 2-4 List of currently adopted PSSAs

The Great Barrier Reef including Torres Strait and the south – west part of the Coral Sea, Australia
The Sabana – Camaguey Archipelago, Cuba
Malpelo Island, Colombia
The sea around the Florida Keys, United States
The Wadden Sea, Denmark, Germany, Netherlands
Paracas National Reserve, Peru
Western European Waters
Canary Islands, Spain
The Galapagos Archipelago, Ecuador
The Baltic Sea area, Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland and Sweden
The Papahanaumokuakea Marine National Monument, United States
The Strait of Bonifacio, France and Italy
The Saba Bank, in the North-eastern Caribbean area of the Kingdom of the Netherlands
The Jomard Entrance, Papua New Guinea
Tubbataha Reefs Natural Park, the Sulu Sea, Philippines

Source: International Maritime Organization. (2005).

Figure 2-3 Map of currenlty listed PSSAs

Source: Retrieved from https://www.myseatime.com/upload/passports/1528722992-PSSA-areas.jpg

2.4 EU Directive

In order to mitigate the adverse effects of the shipping industry's Sulphur Oxides emissions and prevent further environmental pollution, the European Union has established its own regulatory framework for maximum permissible sulphur content in marine fuels.

The EU *Directive 1999/32/EC*, known as the '*Sulphur Directive*' designates limits on the maximum sulphur content of marine fuels used by ships operating within EU waters [16]. Following the progressive revisions of MARPOL *Annex VI* International Regulations, the Directive incurred several amendments through the years, inter alia, the *Directive 2009/30/EC* which mandated a limit of 0.10% (m/m) fuel sulphur content for ships that berth in EU ports after January 01, 2010 alongside with the existing IMO regulations inside and outside of ECA areas. The EU regulatory background was later amended with *Directive 2012/33/EU* where the Sulphur Cap's limit of 0.50% (m/m) sulphur content was introduced for operation within EU waters as well (i.e. outside ECAs) beginning on January 01, 2020.

The subsequent introduction of *Directive 2016/802/EU* led to the codification of the original 1999 Directive and the succeeding amendments and is currently in force as a single codified regulation.

The *EU Sulphur Directive* also permits the fitting of an EGCS, meeting the requirements of the IMO guidelines by providing emission reductions at least equivalent to the IMO's mandatory sulphur limits together with a **continuous** emission monitoring system.

As of today, the codified 2016/802/EU 'Sulphur Directive' requires inter alia compliance to the following regulations:

Article 6

1. Member States shall take all necessary measures to ensure that marine fuels are not used in the areas of their territorial seas, exclusive economic zones and pollution control zones if the sulphur content of those fuels by mass exceeds:

(a) 3,50 % as from 18 June 2014;

(b) 0,50 % as from 1 January 2020

This paragraph shall apply to all vessels of all flags, including vessels whose journey began outside of the Union.

2. Member States shall take all necessary measures to ensure that marine fuels are not used in the areas of their territorial seas, exclusive economic zones and pollution control zones falling within SO_x Emission Control Areas if the sulphur content of those fuels by mass exceeds:

(a) 1,00 % until 31 December 2014;

(b) 0,10 % as from 1 January 2015

This paragraph shall apply to all vessels of all flags, including vessels whose journey began outside the Union.

Article 7 - Maximum sulphur content of marine fuels used by ships at berth in Union ports

1. Member States shall take all necessary measures to ensure that ships at berth in Union ports do not use marine fuels with a sulphur content exceeding 0,10 % by mass, allowing sufficient time for the crew to complete any necessary fuel-changeover operation as soon as possible after arrival at berth and as late as possible before departure.

Member States shall require the time of any fuel-changeover operation to be recorded in ships' logbooks.

2. Paragraph 1 shall not apply:

(a) whenever, according to published timetables, ships are due to be at berth for less than two hours;

(b) to ships which switch off all engines and use shore-side electricity while at berth in ports.

Article 8 - Emission abatement methods

1. Member States shall allow the use of emission abatement methods by ships of all flags in their ports, territorial seas, exclusive economic zones and pollution control zones, as an alternative to using marine fuels that meet the requirements of Articles 6 and 7, subject to paragraphs 2 and 4 of this Article.

2. Ships using the emission abatement methods referred to in paragraph 1 shall continuously achieve reductions of sulphur dioxide emissions that are at least equivalent to the reductions that would be achieved by using marine fuels that meet the requirements of Articles 6 and 7. Equivalent emission values shall be determined in accordance with Annex I.

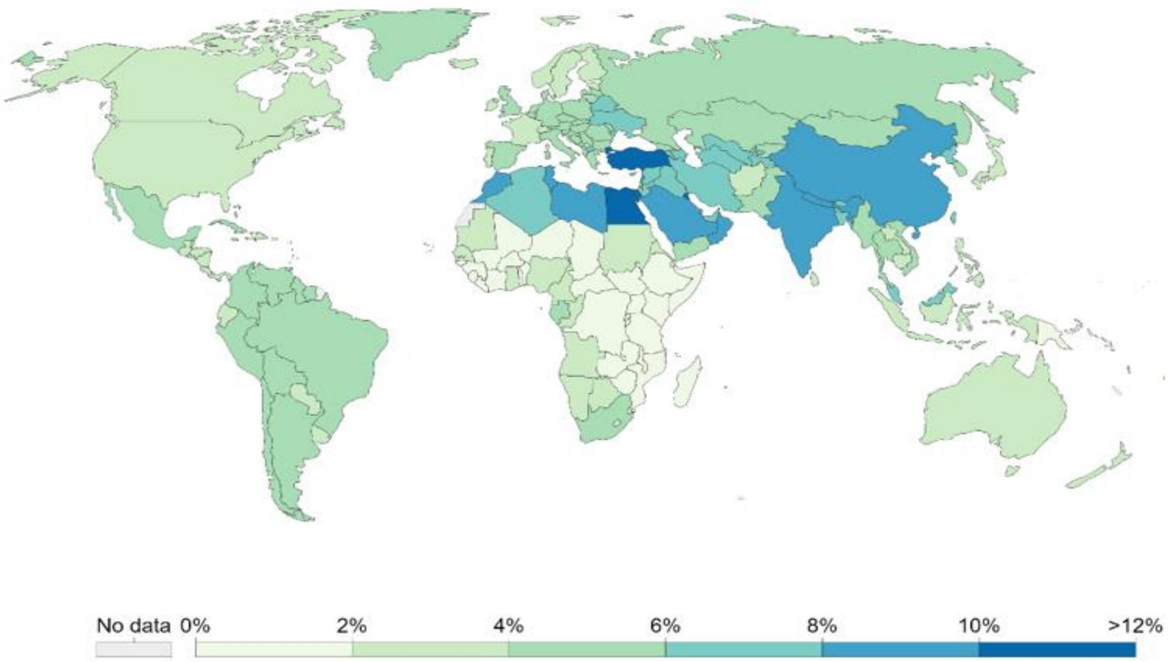
Chapter 3. Air pollution

Air pollution, from anthropogenic activities, is a global issue that affects human health and ecosystems. That effect is deriving mainly from the combustion of fuels that contain harmful contents and produce pollutant compounds like Sulphur oxides (SO2, SO3), Nitric oxides (NO,NO2), Carbon dioxide (CO2) and monoxide (CO), Polycyclic Aromatic Hydrocarbons (PAHs) and other elements such as Arsenic, Cadmium, Lead, Mercury and Nickel. According to World Health Organization (WHO), this is a reason for seven million premature deaths worldwide every year, which derives as a result from the combination of ambient and household air pollution [138].

3.1 Ambient air pollution

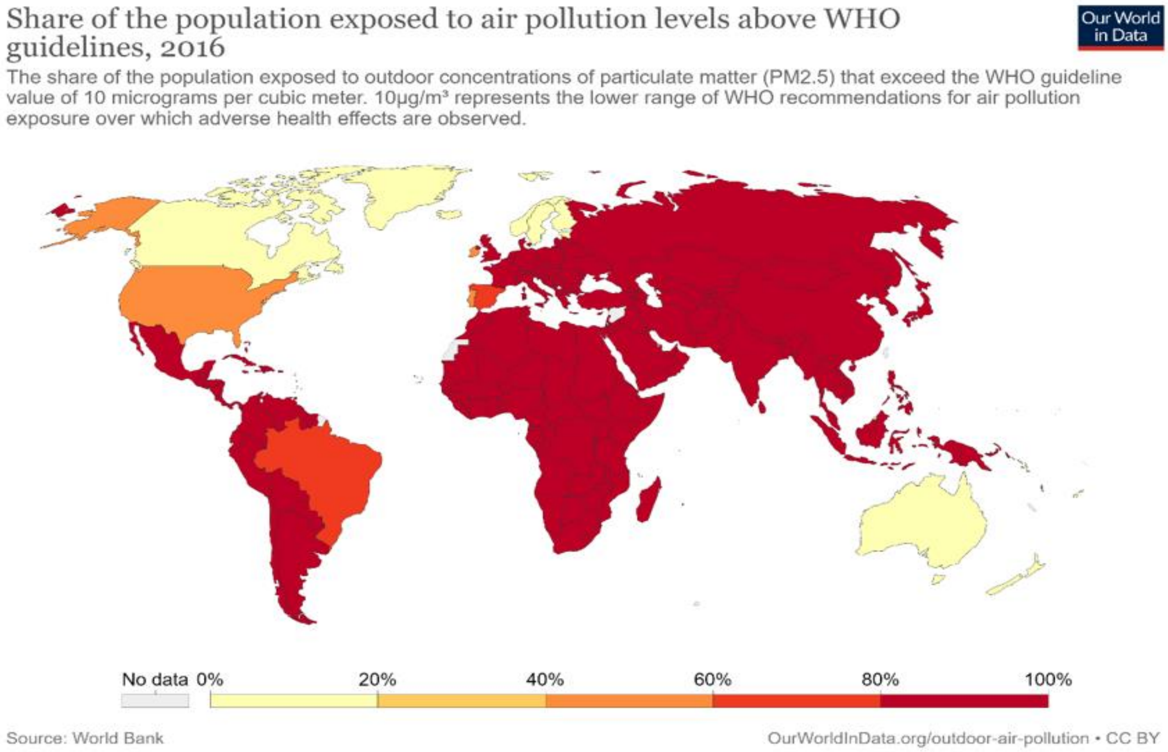
This pollution is responsible for an estimated 4.2 million deaths per year while it is dangerous for climate [138]. More than 90% of world's population live in places where air quality levels are over WHO limits. This phenomenon is being met worldwide in developing and developed countries, affecting more these with low- and middle-income, with its high point in Western Pacific and South-East Asia regions [138].

Figure 3-1 Share of deaths from outdoor air pollution, 2017.



Source: Ritchie, H., & Roser, M. (2019). Outdoor Air Pollution. Retrieved from https://ourworldindata.org/outdoor-air-pollution

Figure 3-2 "More than 90% of world's population live in places where air quality levels are over WHO limits."



Source: Ritchie, H., & Roser, M. (2019). Outdoor Air Pollution. Retrieved from https://ourworldindata.org/outdoor-air-pollution

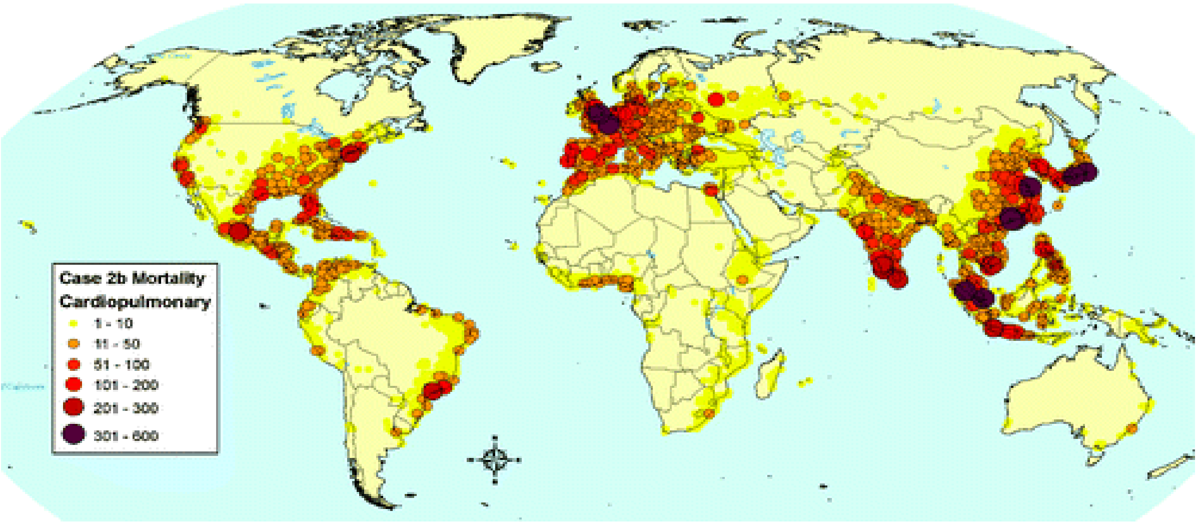
3.2 Household air pollution

WHO estimates that 3.8 million deaths globally per year are the result of this pollution [138]. Household air pollution derives from combustion of solid fuels for house activities such as heating and cooking, while it is being more observed in developing countries. This combustion, when taking place in inefficient stoves or open hearths produces hazardous pollutants that can cause illnesses, cancer and death.

3.3 Shipping impact to health

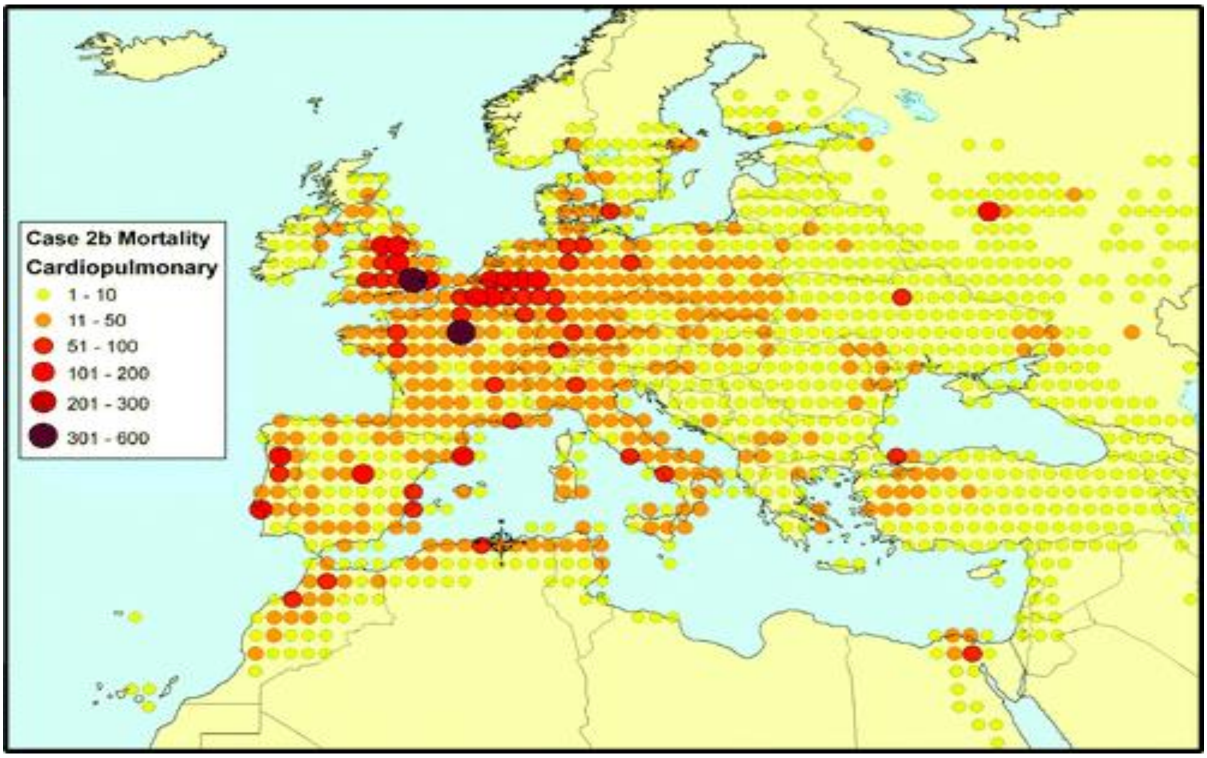
According to Federation for Transport and Environment, in 2005, shipping emissions in the seas of Europe were estimated at 1.7 million tons a year for Sulphur dioxide, 2.8 million tons of nitrogen dioxide and 195,000 tons of particulate matter [106]. Furthermore, according to the annual report of 2018 of this federation, shipping air pollution contributes to 400,000 premature deaths per year worldwide [106]. European Environment Agency (2013) also admits that, due to a study, specifically PM emissions form shipping are responsible for around 60,000 cardiopulmonary and lung cancer deaths annually, while most of them are being detected near coastlines in East Asia, Europe and South Asia [26], [18].

Figure 3-3 . Cardiopulmonary mortality because of $PM_{2.5}$ shipping emissions globally



Source: Corbett, J.J., Winebrake, J.J., Green, E.H., Kasibhatla, P., Eyring, V., Lauer, A. (2007) Mortality from ship emissions: A global assessment, Environmental Science and Technology. doi:10.1021/es071686z

Figure 3-4 Cardiopulmonary mortality because of $PM_{2.5}$ shipping emissions in Europe



Source: Corbett, J.J., Winebrake, J.J., Green, E.H., Kasibhatla, P., Eyring, V., Lauer, A. (2007) Mortality from ship emissions: A global assessment, Environmental Science and Technology. doi:10.1021/es071686z

3.4 Shipping share in pollution

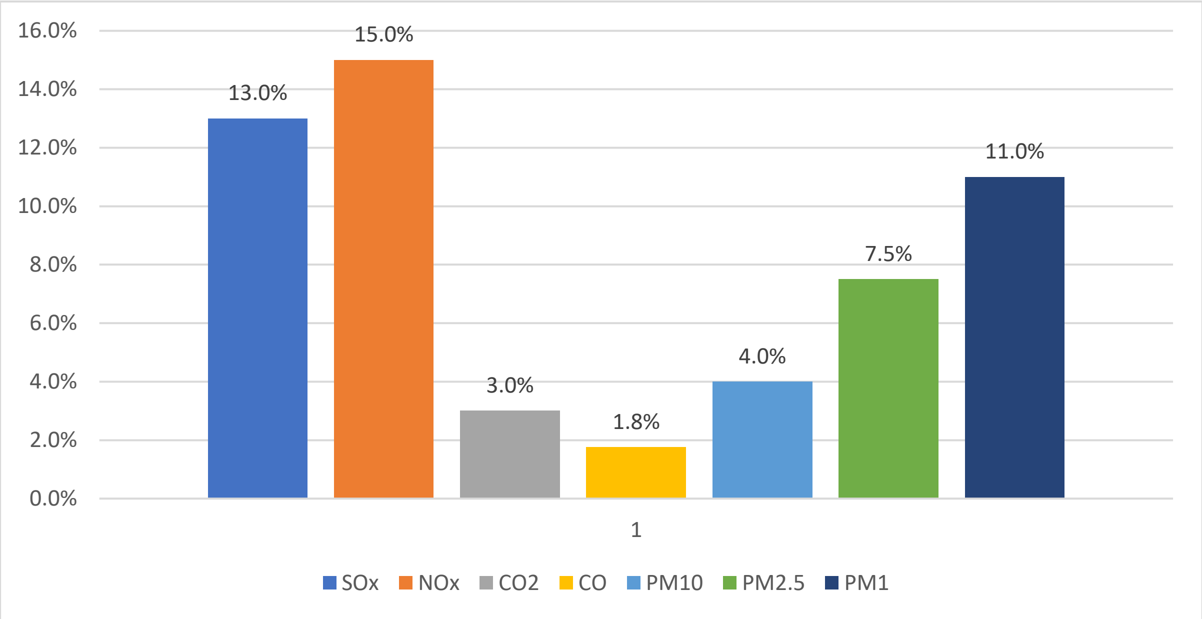
Shipping forms an important section of anthropogenic activities in which fuels are necessary in order to operate normally. Exhaust gases, that are being produced from marine diesel engines and boilers, comprise gaseous compounds. Some of which are classified as pollutants, while others as climate change agents and solid particles. It is crucial to be investigated the amount of damage these products cause. The Table 3-1 shows shipping emissions and their importance relative to other anthropogenic emissions:

Table 3-1 Shipping's contribution portion in air pollution

Air emissions	Contribution of shipping
SO_x	13% [54]
NO_x	15% [54]
CO_2	3% [54]
CO	1.5-2% [28]
PM_{10}	1-7% [6]
$PM_{2.5}$	1-14% [6]
PM_1	11% [6]

Note. Data for Shipping's contribution portion in air pollution from Annika K. J., Andreas B., Jennie Barthel S., Ing-Marie G. (n.d.), EEA (2019), IMO (2014). For CO, PM10 and PM2.5 in diagram was used mean value of emissions.

Figure 3-5 Contribution of shipping in air pollution.



It must be emphasized that harmful products of combustion are polycyclic aromatic hydrocarbons (PAH), black carbon (BC) whose effects are being examined later in this chapter. There can also be amount of Methane (CH4) in the emissions of the ship.

3.4.1 Products of combustion

Table 3-2 Aggregate Table of some crucial health, environmental and climate effects.

Pollutant	Health effects	Environmental effects	Climate effects
Sulphur Oxides (SO_X)	Aggravates asthma and can reduce lung function and inflame the respiratory tract. It forms a factor for cardiovascular disease. Can cause headache, general discomfort and anxiety.	Contributes to the acidification of soil and surface water. Causes injury to vegetation and local species losses in aquatic and terrestrial systems. Contributes to the formation of particulate matter with associated environmental effects. Damages buildings.	Contributes to the formation of sulphate particles, cooling the atmosphere.
Nitrogen Oxides (NO_X)	NO_2 can affect the liver, lung, spleen and blood. Can aggravate lung diseases leading to respiratory symptoms and increased susceptibility to respiratory infection.	Contributes to the acidification and eutrophication of soil and water, leading to changes in species diversity. Acts as a precursor of ozone and particulate matter, with associated environmental effects. Can lead to damage to buildings.	Contributes to the formation of ozone and particulate matter, with associated climate effects.
Carbon Monoxide (CO)	Can lead to heart disease and damage to the nervous system; can also cause headache, dizziness and fatigue.	May affect animals in the same way as humans. Acts as a precursor of ozone.	Contributes to the formation of greenhouse gases such as CO_2 and ozone.
Particulate Matter (PM)	Can cause or aggravate cardiovascular and lung diseases, heart attacks and arrhythmias, affect the central nervous system, the reproductive system and cause cancer. The outcome can be premature death.	Can affect animals in the same way as humans. Affects plant growth and ecosystem processes. Can cause damage and soiling of buildings. Reduced visibility.	Climate effect varies depending on particle size and composition: some lead to net cooling, while others lead to warming. Can lead to changed rainfall patterns.
PAHs, in particular Benzo-a-pyrene (BaP)	Carcinogenic. Other effects may be irritation of the eyes, nose, throat and bronchial tubes	Is toxic to aquatic life and birds. Bioaccumulates, especially in invertebrates	No specific effects.
Methane (CH_4)	Exposure to high levels of methane can cause: Suffocation, loss of consciousness, headache and dizziness, nausea and vomiting etc.	A climate change gas with twenty times the global warming potential of carbon dioxide.	Contributes to the formation of greenhouse.

Source: European Environment Agency (2013). Air quality in Europe — 2013 report (report No. 9). Retrieved from https://www.eea.europa.eu/publications/air-quality-in-europe-2013

3.4.1.1 Sulphur oxides (SOx)

Table 3-3 WHO Guidelines for SO2

WHO Guidelines for SO_2	
24-hour mean	20 µg/m^3
10-minute mean	500 µg/m^3

Source: World Health Organization (2006) Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulphur dioxide. Global update 2005, World Health Organization, Regional Office for Europe, Copenhagen, Denmark. Retrieved from: https://apps.who.int/iris/bitstream/handle/10665/69477/WHO_SDE_PHE_OEH_06.02_eng.pdf?sequence=1

Sulphur oxides are emitted when fuels containing sulphur are burned, which happens in the most activities that include combustion. An important factor of Sulphur oxides is a natural source, volcanos. Around 95% of these oxides emitted from the combustion of fossil fuel is Sulphur dioxide [32]. SO_2 is a colorless gas with a sharp odor, it is a toxic gas directly harmful to human health. It is heavier than air and at an atmospheric concentration of around 500 parts per billion (ppb), at which level it can be fatal. At 20 ppb or lower there should be no ill effects to a healthy person.

3.4.1.1.1 Health effects

Short-term exposures:

According to WHO, 2005, controlled studies involving exercising asthmatics indicate that a proportion experience changes in pulmonary function and respiratory symptoms after periods of exposure to SO_2 as short as 10 minutes [137]. Irritation of the eyes can also be caused. Based on these results, WHO came up with this SO_2 limit for 10 minutes period.

Long-term exposures:

According to European Environment Agency, 2013, the correlation between SO_2 exposure and some important medical conditions are being marked. These are Inflammation of the respiratory tract causes coughing, mucus secretion, aggravation of asthma and chronic bronchitis, and makes people more prone to infections of the respiratory tract. It is also a factor that can contributes to lung cancer. Furthermore, mortality and hospital admissions for cardiac disease increase on days with higher SO_2 levels. It is finally noted that Sulphur dioxide is a major precursor to $PM_{2.5}$, which is associated with significant health effects.

3.4.1.1.2 Environmental effects and acid rain

When SO_2 and NO_x are released into the atmosphere, react with water, oxygen, and other substances to form airborne sulphuric and nitric acid. These acidic compounds can be spread through wind over hundreds of kilometers and thus become part of the rain, the so-called acid rain. When acid rain reaches earth, it flows across the surface in runoff water, becoming part of water systems, and sinks into the soil [82].

Acid rain has many ecological effects, especially aquatic environments, by making waters more acidic, which results in more aluminum absorption from soil that is being carried into lakes and streams. That combination makes waters toxic to aquatic animals. Also, in an interconnected ecosystem, what affects some species eventually affects many more throughout the food chain, including non-aquatic species. Furthermore, Acid rain and fog also damage forests, especially those at higher elevations. The acid deposits rob the soil of essential nutrients such as calcium and cause aluminum to be released in the soil, making it difficult for trees to take up water. Trees' leaves and needles are also harmed by acids [82].

Acid deposits damage to physical structures as well, such as limestone buildings and cars. These effects are more noticeable on endangered monuments such as monuments in Acropolis of Athens, as air pollution and acid rain are eroding marbles. In addition, when it takes the form of inhalable fog, acid precipitation can cause health problems including eye irritation and asthma.

Figure 3-6 "These effects are more noticeable on endangered monuments such as monuments in acropolis of Athens"

Source: The story of Acropolis (2017). The Greek observer. Retrieved from https://thegreekobserver.com/greece/culture/article/29100/story-acropolis

3.4.1.2 Nitrogen dioxide (NO_2)

Table 3-4 WHO guidelines for NO_2

WHO Guidelines for NO_2	
Annual mean	40 µg/m^3
1-hour mean	200 µg/m^3

Source: World Health Organization (2006) Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulphur dioxide. Global update 2005, World Health Organization, Regional Office for Europe, Copenhagen, Denmark. Retrieved from: https://apps.who.int/iris/bitstream/handle/10665/69477/WHO_SDE_PHE_OEH_06.02_eng.pdf?sequence=1

Nitrogen dioxide is a reactive gas that is formed by high temperature combustion and by the oxidation of nitrogen monoxide. Nitrogen monoxide accounts for the most of NO_x emissions. A small part of NO_x emissions is directly emitted as NO_2, typically 5–10 % for most combustion sources [26].

3.4.1.2.1 Health effects

NO_2 is an air pollutant which primarily affects the respiratory system. Short-term exposure to NO_2 can affect the proper lung function of sensitive population groups, while long-term exposure can lead to more serious effects such as increased susceptibility to respiratory infection. Reduced lung function is also linked to NO_2 at concentrations currently found in cities in Europe and North America. It should be noted that as NO_2 is highly correlated with other pollutants, mainly with PM, it is difficult to differentiate the effects of NO_2 from those of other pollutants in epidemiological studies. It also found an association between long-term NO_2 exposure and respiratory symptoms and reduced lung function in children.

3.4.1.3 Carbon Monoxide (CO)

Fossil fuels are the main factor of carbon monoxide in atmosphere. Road transport was once a significant source of CO emissions, but the introduction of catalytic converters reduced these emissions sufficiently. CO concentrations tend to vary present variation that are related to traffic patterns. The highest CO levels are found in urban areas, typically during rush hours at traffic locations.

3.4.1.3.1 Health effects

Carbon monoxide enters the body through the lungs. In the blood it is linked to hemoglobin. Exposure to this pollutant can reduce blood's oxygen-carrying capacity, resulting the reduction of oxygen delivered to the body's organs and tissues. CO exposure threatens more people with cardiovascular disease. These people already have a reduced capacity for pumping oxygenated blood to the heart, which can cause them to experience myocardial ischemia (reduced oxygen to the heart), often accompanied by chest pain [26]. Short-term CO exposure can also make it difficult for them to correspond to oxygen demands of exercise or exertion. At extremely high levels, CO can cause death.

3.4.1.4 Particulate Matter (PM)

Table 3-5 WHO guidelines for PM

WHO Guidelines for PM	
Annual mean for $PM_{2.5}$	10 μg/m^3
24-hour mean $PM_{2.5}$	25 μg/m^3
Annual mean for PM_{10}	20 μg/m^3
24-hour mean PM_{10}	50 μg/m^3

Source: World Health Organization (2006) Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulphur dioxide. Global update 2005, World Health Organization, Regional Office for Europe, Copenhagen, Denmark. Retrieved from: https://apps.who.int/iris/bitstream/handle/10665/69477/WHO_SDE_PHE_OEH_06.02_eng.pdf?sequence=1

Particulate matter is the general term used for a mixture of particles (solid and liquid) suspended in the air, with a wide range of sizes and chemical compositions. $PM_{2.5}$ refers to 'fine particles' that have a diameter of 2.5 micrometers or less. PM_{10} refers to particles with a diameter of 10 micrometers or less and PM_1 to particles with a diameter of 1 micrometer or less [26]. PM_{10} includes the 'coarse particles' fraction in addition to the $PM_{2.5}$ fraction.

3.4.1.4.1 Health effects

When PM is inhaled and penetrated the lungs and blood stream, respiratory, cardiovascular, immune, and neural systems can be affected. Ultrafine particles (with diameters of 0.1 micrometers or less) can also penetrate the brain through the nose. Both chemical and physical interactions between PM and lung tissues can induce irritation or damage. The smaller the particles, the deeper they penetrate the lungs. PM's mortality effects are clearly associated with the $PM_{2.5}$ fraction, which in Europe represents 40–80 % of the PM_{10} mass concentration in ambient air [26]. The current levels of PM exposure experienced by most urban and rural populations have harmful effects on human health. Long term exposure to PM can lead to cardiovascular and respiratory diseases, as well as lung cancer.

3.4.1.5 Polycyclic Aromatic Hydrocarbons (PAHs)

PAHs are a group of chemicals that are formed during the incomplete burning of coal, oil, gas, wood, garbage, or other organic substances, such as tobacco and charbroiled meat. There are more than 100 different PAHs [104]. PAHs generally occur as complex mixtures (for example, as part of combustion products such as soot), not as single compounds.

3.4.1.5.1 Health effects

PAHs effects depend on the length of person's exposure, the type of PAH and how this exposure was done. People in some vulnerable groups are more endangered by these chemicals. Short term exposure can lead to symptoms as eye irritation, nausea and vomiting, diarrhea and confusion. Effects from chronic exposure may include cataracts, kidney and liver damage aplastic anemia and skin damage. There is also an increased risk for some types of cancer.

3.4.1.6 Carbon Dioxide (CO_2)

Carbon dioxide is a natural gas of environment and doesn't form a threat to health is small quantities. But burning fossil fuels increases CO_2 in atmosphere, which results a warming effect that could change earth's climate.

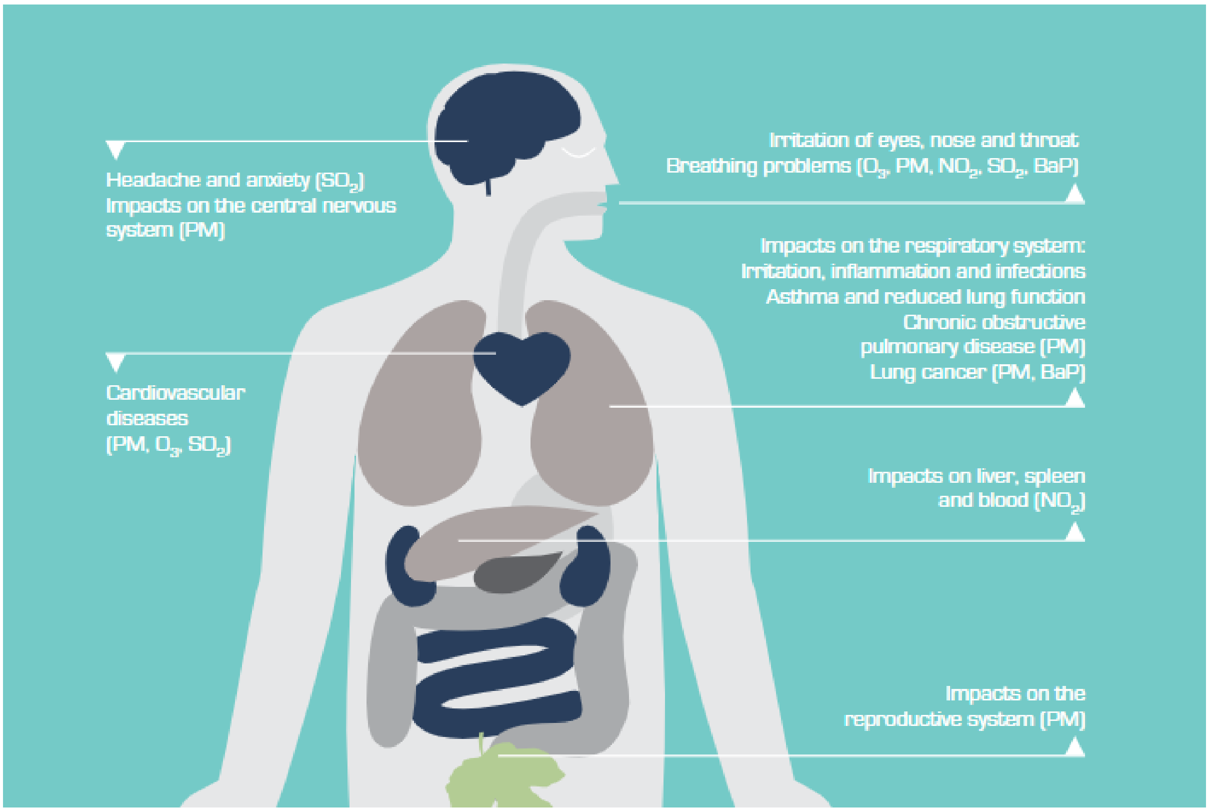
3.4.1.7 Black Carbon (BC)

Black carbon is the sooty black material emitted mainly by diesel engines, wood burning and power stations using heavy oil or coal. Additionally, it comprises an important portion of PM.

3.4.1.7.1 Health effects

There is no significant difference between the effects of BC exposure and those of $PM_{2.5}$ on the cardiovascular system in general. It can also be observed lung disfunction, such as asthma and children's development of the lungs can be affected.

Figure 3-7 Health effects on human deriving from air pollution



Source: European Environment Agency (2013). The impact of international shipping on European air quality and climate forcing (report No 4/2013). Retrieved from https://www.eea.europa.eu/publications/the-impact-of-international-shipping

3.4.2 Shipping pollution types

Shipping forms one of the oldest and important sectors of anthropogenic activities. But, as many of them, there are some impacts in nature. The most crucial impacts are presented below:

- Air pollution
- Water Pollution
- Oil pollution
- Sound pollution
- Wildlife collision

3.4.2.1 Air pollution

A detailed discussion has been done previously about air pollution from shipping and how this affects human health, environment and climate. It is useful to be reminded that shipping is an important factor of atmospheric pollution and climate change (3.5% to 4% climate change emissions [25]).

Figure 3-8. Air pollution from shipping.

Source: Biofuel Engine Research Facility. Shipping emissions and their impacts on air quality. Retrieved from https://research.qut.edu.au/berf/projects/shipping-emissions-and-their-impacts-on-air-quality/

3.4.2.2 Water pollution

Water is being threatened by multiple shipping operations. These are ballast water, wastewater and solid waste.

Ballast water is necessary for shipping operations, but it can cause ecological problems as this water contains a variety of biological materials and marine species. These can be bacteria, microbes, small invertebrates, eggs, cysts and larvae of various species. If these species survive, they can reproduce in the host environment and become invasive, threating native species. Spread of these species is now recognized as one of the greatest threats to the ecological and the economic wellbeing of the planet [49].

Wastewater includes blackwater (sewage) and greywater. Blackwater is wastewater from toilets and medical facilities, that harmful bacteria, pathogens, viruses, intestinal parasites, and harmful nutrients can be contained. Sewage discharged which is not treated inadequately, can cause bacterial and viral contamination of fisheries, which forms threat for public health. A serious threat is oxygen depletion, too. Greywater is wastewater from sinks, showers and cleaning activities aboard. This can also contain pollutant substances, as fecal coliforms, detergents, oil and grease, metals, organic compounds, petroleum hydrocarbons, nutrients, food waste, medical and dental waste [25].

Solid waste on ships include glass, paper, cardboard, aluminum, steel cans and plastics. Most hazardous for nature are plastics. Fish and sea mammals can mistake them for food, or they can be trapped in plastic ropes, nets and bags leading to drowning.

Figure 3-9 Sewage thrown in sea.

Source: Bluebird Marine Systems Ltd. MARPOL- International maritime pollution 1973-1978. Retrieved from: https://www.bluebird-electric.net/MARPOL_International_Convention_Marine_Pollution_1978.htm

3.4.2.3 Oil pollution

Oil pollution can be separated in two parts. First part concerning oil spills, following from an accident and bilge water, which resulting from engine maintenance activities and oil leaks and mixes with water in the bilge.

Oil spills are widely known for their dangerous effects in nature, despite the low frequency. These effects can be disastrous for a whole ecosystem as they last for years. Marine species exposed in PAHs (components in crude oil) can exhibit developmental problems, susceptibility to disease, and abnormal reproductive cycles [25]. Long-term effects must be considerable, as they can harm sea activities of the locals such as fishing, which can lead to economic and social issues.

Figure 3-10 Oil spill.

Source: Heather H., (2015, July 29). Scientists Find a Natural Way to Clean Up Oil Spills, With a Plant-Based Molecule. Smithsonian magazine. Retrieved from https://www.smithsonianmag.com/innovation/scientists-find-natural-way-to-clean-up-oil-spills-with-plant-based-molecule-180955815/

Bilge water must be filtered before being discharged, but even very low concentrations of oil can kill fish and causing chronic effects. This water is possible to contain wastes and pollutants containing high levels of oxygen-demanding material, oil and other chemicals [25].

3.4.2.4 Sound pollution

IMO marks that studies have shown that underwater-radiated noise from commercial ships may have both short and chronic negative effects on marine life, especially marine mammals. These animals' communication is being affected by noise made from ships, resulting consequences in their behavior and life.

3.4.2.5 Wildlife collision

There is danger for marine mammals to get struck by ships, causing injury or death. Most reports of collisions involve large whales [61], but many more species can be damaged. Collisions are a great threat for whales, for example between 1970 and 1999, 35.5% of recorded deaths were attributed to collisions [133].

3.5 Shipping community regulations

As it has been referred previously, serious effects of shipping were being detected. So, some decades ago, the decision of erasing or minimizing these effects entailed by the necessity of protecting humans, animals and atmosphere. This resulted in the establishment of organizations for environment protection. One very important occurrence was when the MARPOL Convention was adopted on 17 February 1973. After then, there are series of laws and regulations have been introduced over pollution from ships. Some important regulations are being presented below, according to the type of pollution.

3.5.1 Air pollution

MARPOL Annex VI was firstly adhered in 1997 in order to limit components of ship emissions, mainly Sulphur and nitrous oxides. These oxides are not only known as harmful for environment and health, but they are associated with formation of particulate matter as well.

3.5.1.1 Annex VI through years

Annex VI was forced on 19 May 2005, with implementation limit of 4.5% m/m (mass by mass) on sulphur oxide emissions from ship exhausts. Furthermore, special SO_x Emission Control Areas (SECAs, after named as ECAs) was established, with SO_x limit 1.5% m/m [56]. A few years later, on 1st of July 2010, limit of Sulphur oxides in ECAs was further decreased to 1.00% m/m. Additionally, on the 1st of January 2012 the limit non-ECAs was reduced to 3.5% m/m. Last modification about ECAs emissions was forced on the 1st of January 2015, as a decrease to 0.1% m/m. The regulatory authority for international shipping during its MEPC (Marine Environment Protection Committee) meeting for its 70th session in London, decided a global Sulphur limit of 0.50% m/m, which is forced since the 1st of January 2020. An occurrence of great importance was that directive 2005/33/EC adopted on 1st of January with a 0.1% maximum Sulphur content by ships at berth in European Union ports.

Figure 3-11 Progress of regulations for Sulphur content limits.

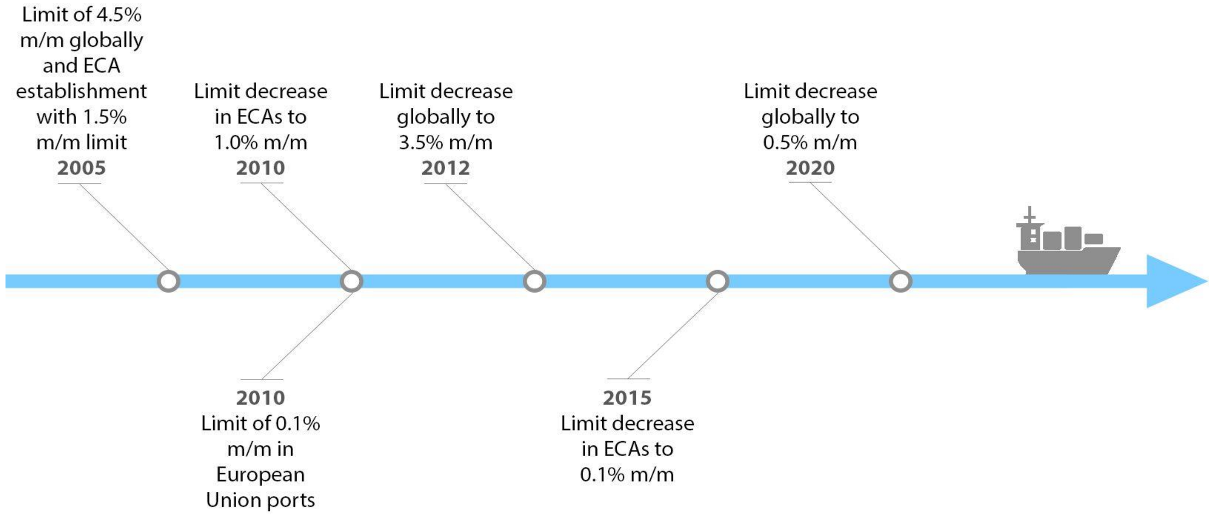
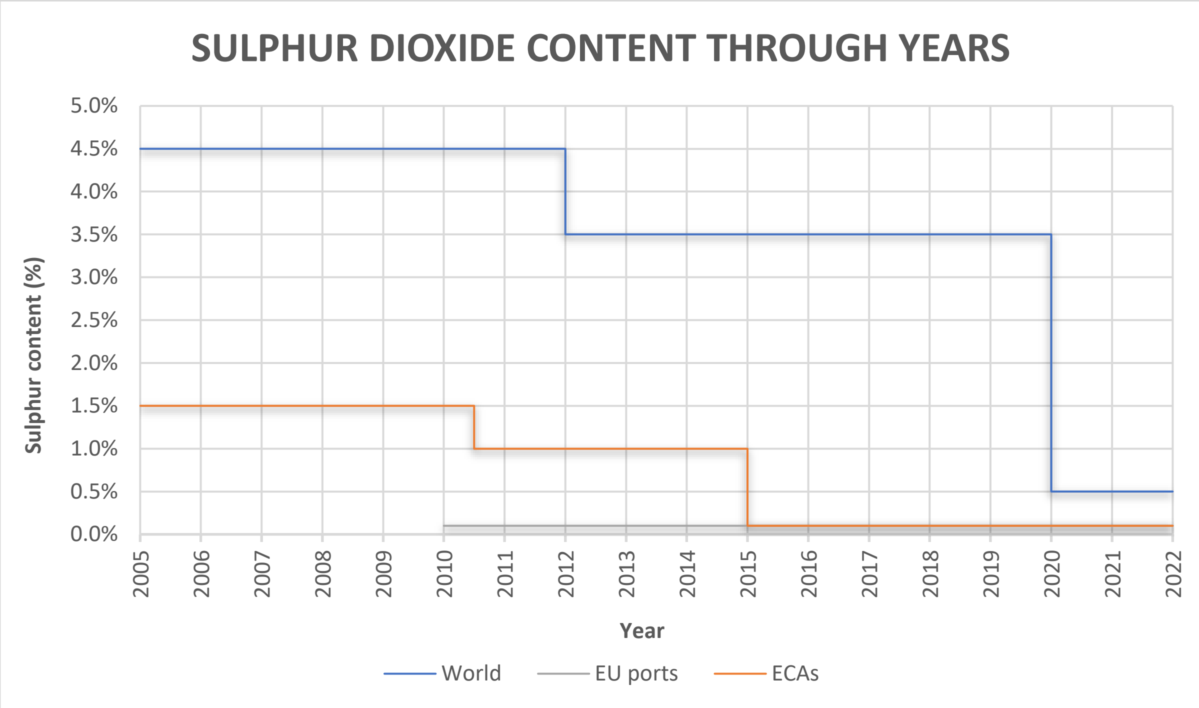


Figure 3-12 Reduction of SO_2, according to Annex VI regulations



3.5.1.2 NOx Limits

IMO also limited NOx emissions through NOx Technical Code 2008 (resolution MEPC.177(58) as amended by resolution MEPC.251. (66)). The NOx control was forced according to ship construction date. The table below shows the limits in each case (tier I, tier II and tier III).

Table 3-6 NOx emissions limits.

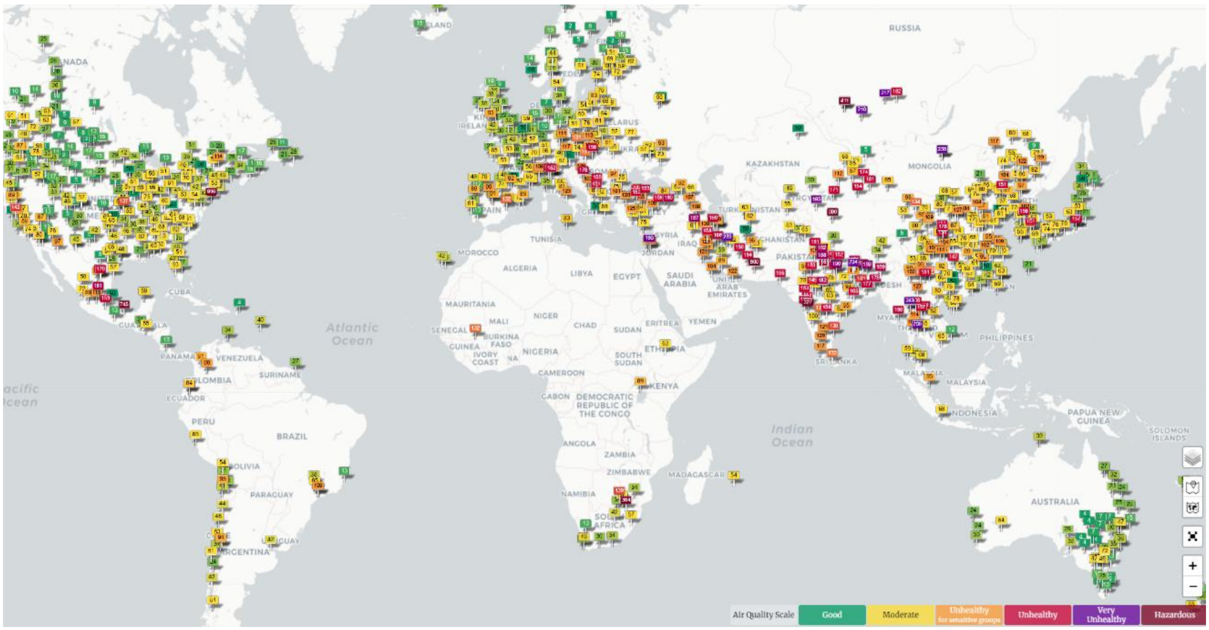
Tier	Ship construction date on or after	Total weighted cycle emission limit (g/kWh) N = Engine's rated speed (rpm)		
		n < 130	n = 130 – 1999	n > 2000
I	1 January 2000	17.0	45 $n^{(-0.2)}$ e.g., 720 rpm – 12.1	9.8
II	1 January 2011	14.4	44 $n^{(-0.23)}$ e.g., 720 rpm – 7.9	7.7
III	1 January 2016	3.4	9 $n^{(-0.2)}$ e.g., 720 rpm – 2.4	2.0

Source: International Maritime Organization. (n.d.). Nitrogen Oxides (NOx) – Regulation 13. Retrieved from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Nitrogen-oxides-(NOx)-%E2%80%93-Regulation-13.aspx

3.5.1.3 Particulate Matter Concentrations

As It has been referred already, Sulphur dioxide and nitrogen oxides are main factors to particulate matter formation, which is a main threat for humans' health derived from air pollution. Furthermore, PM is the main reason that WHO states that the major share of people lives in places that exceeds the WHO guidelines. So, reducing these pollutants aims also at reducing particulate matter concentrations.

Figure 3-13 Air quality based on PM2.5 concentration (16/02/2020).



Source: World's Air Pollution: Real-time Air Quality Index. Retrieved from https://waqi.info/#/c/10.339/24.148/3.2z

3.5.2 Water pollution

Annex IV of MARPOL firstly entered into force in September 2003 and the revised on 1st of August 2005. Annex VI forms a set of regulations concerning:

- The discharge of sewage into the sea.
- Ships' equipment and systems for the control of sewage discharge.
- The provision of port reception facilities for sewage.
- Requirements for survey and certification.

The revised regulations are about ships, engaged in international voyages, of 400 gross tonnage and above or which are certified to carry more than 15 persons. According to them, ships must be equipped with either an approved sewage treatment plant or an approved sewage comminuting and disinfecting system or a sewage holding tank [53].

Annex V of MARPOL is regarding the reduction of the amount of garbage discharged into the sea. It concerns all types of ships. All garbage is prohibited to be discharge into the sea, with some exceptions by regulations 4, 5 and 6 of the Annex (related to food waste, cargo residues, cleaning agents and additives and animal carcasses) [52].

A great discussion has also been about ballast water management, and series of guidelines have been developed in order to minimize the consequences from the reckless ballast water exchange.

3.5.3 Oil pollution

Annex I MARPOL contains regulations for the prevention of pollution by oil. IMO, with these measures, contributed to the safe construction and operation in order to minimize the amount of oil spilled in case of an accident. A significant enhancement in marine environment was noted because of the requirement for oil tankers delivered from 1996 onwards to be fitted with a double hull [50]. MARPOL introduced also innovations on allowable discharges of bilge water through the oily water separator, or oily waters from the cargo tanks, through the oil discharge and monitoring system that led to decrease of the air pollution.

3.6 Results from Annex VI

The fact that 70% of shipping emissions occur within 400km from land [27], combined with the significant portion of shipping in air pollution, led to the need of creating regulations that would shrink these consequences. IMO, through Annex VI regulations, is aiming at environmental protection and improvement of air quality and humans' health globally. The contribution of these regulations is being conceivable below.

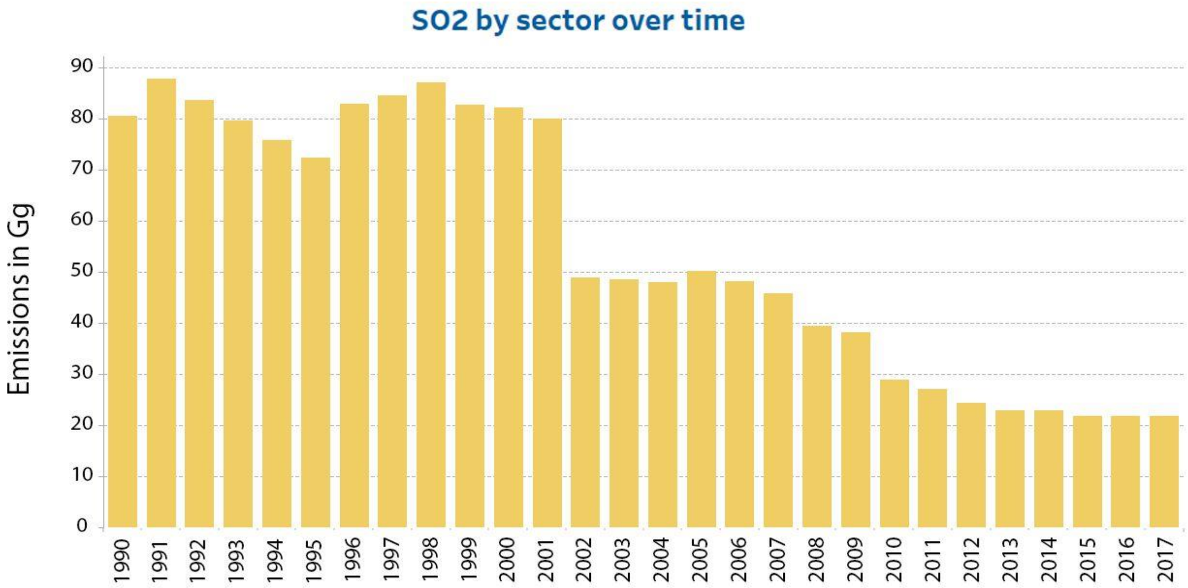
Figure 3-14 Air quality based on PM2.5 concentration (16/02/2020).

Source: World's Air Pollution: Real-time Air Quality Index. Retrieved from https://waqi.info/#/c/10.339/24.148/3.2z

3.6.1 SO_2 emissions variation over time

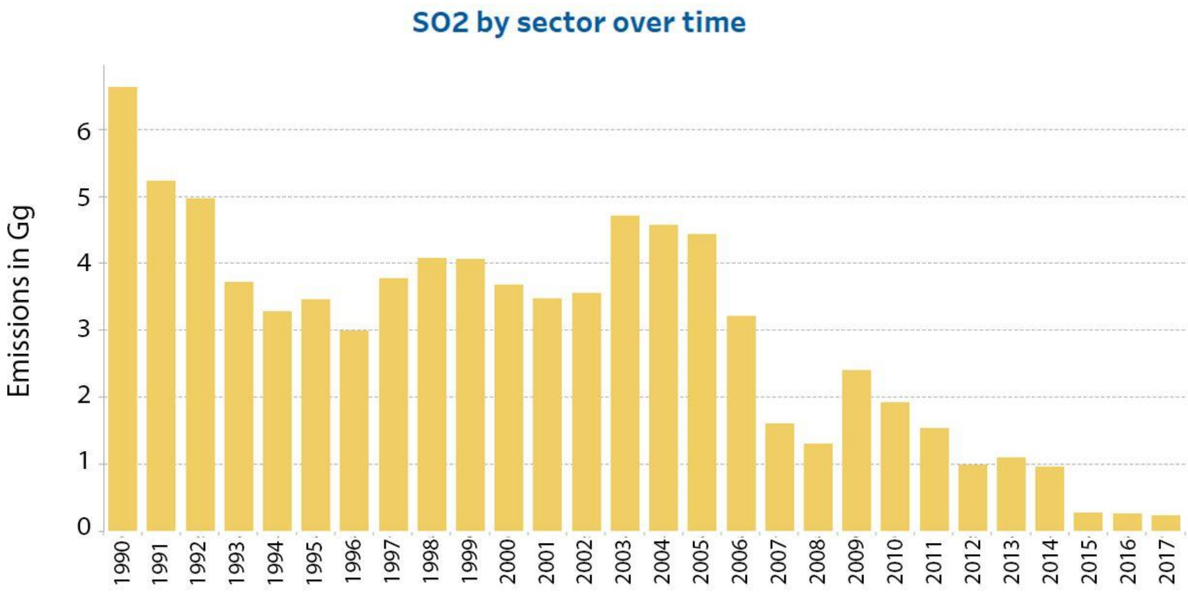
The process of regulations about Sulphur dioxide content in fuels, may be a crucial factor of the variation of SO_2 emissions in Europe. Examining the case of Italy (Mediterranean Sea is not an ECA) and Sweden (Baltic sea is ECA), can help to draw conclusions. The Figure 3-15 and Figure 3-16Figure 3-15 SO_2 from non-road transportation in Italy show the variation of SO_2 emissions deriving from the sector non-road transportation (over 90% of the world's trade is carried by sea [111]) from 1990 to 2017.

Figure 3-15 SO_2 from non-road transportation in Italy



Source: World's Air Pollution: Real-time Air Quality Index. Retrieved from https://waqi.info/#/c/10.339/24.148/3.2z

Figure 3-16 SO_2 from non-road transportation in Sweden



Source: World's Air Pollution: Real-time Air Quality Index. Retrieved from https://waqi.info/#/c/10.339/24.148/3.2z

Interesting observations are made comparing the Figure 3-15 with the Figure 3-16:

- Baltic sea has been an ECA since 2005. The three next years, SO_2 emissions were reduced considerably.
- In both countries', emissions show a reduction in 2010. This is justifiable for both countries since that is the year when all ships in ports of European Union had to comply with the 0.10% Sulphur limit and ECAs' limit decreased to 1.00%.
- Regarding Sweden's minimization of emissions in the 3 last years (2015-2017), it is possibly related to the last regulation about ECAs (limit decreased to 0.10%) that was applied on the 1st January 2015.

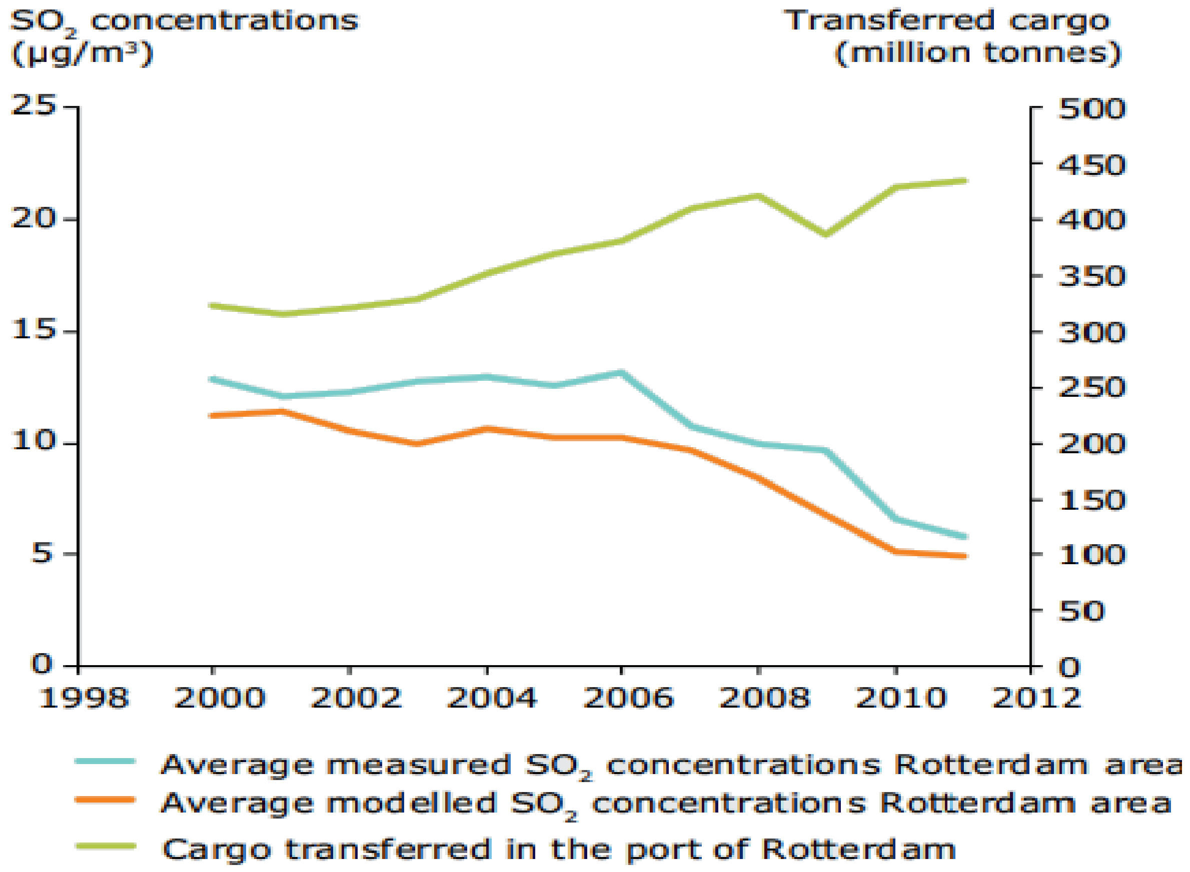
It is becoming definite that regulations are affecting the quantity of emissions. Additionally, ECAs are a significant factor for an improved air quality for the local area.

3.6.2 SO_2 concentrations in Rotterdam

Areas that are being the most affected from ship emissions are berths and the surrounding places. These areas must be more observed in order to appreciate the impact of these regulations. SO_2 concentrations in the port of Rotterdam are being examined, in parallel with transferred cargo, before and after the enforcement of the regulation about North Sea becoming an ECA (adopted July 2005, enforced 2006).

According to Figure 3-17, concentration levels appeared to be more or less constant from 2000 to 2006, while there was a great decreasing between 2007 and 2010. While in 2010, concentration was decreased about 50% comparing with 2000-2006 average concentration. This reduction is related to the regulation about EU ports that was applied that year (2010). It is crucial to be marked, the fact that transferred cargo was increased significantly in this period (2000-2011). So, these regulations have immediate and positive effects, providing better conditions for people who work or live in this area.

Figure 3-17 SO_2 concentrations in Rotterdam area.



Source: European Environment Agency (2013). The impact of international shipping on European air quality and climate forcing (report No 4/2013). Retrieved from https://www.eea.europa.eu/publications/the-impact-of-international-shipping

3.7 Impact of Sulphur reduction

The contribution of shipping to global Sulphur emissions can be identified as significant. Hence, this revision of the Regulation 14 is about to reduce substantially the total of Sulphur emissions globally. An interesting issue is to review the expected results in mortality caused by diseases directly connected with this pollutant.

Table 3-7 The expected reduction of mortality and childhood asthma with IMO 2020

	Without IMO 2020	**With IMO 2020**	**Rate of reduction**
Cardiovascular disease	349,000	226,800	35%
Lung cancer	54,300	39,500	27%
Total premature deaths	403,300	266,300	34%
Childhood ashtma	14,000,000	6,400,000	54%

Source: Sofiev, M., Winebrake, J.J., Johansson, L. (2018). Cleaner fuels for ships provide public health benefits with climate tradeoffs. https://doi.org/10.1038/s41467-017-02774-9

It appears that premature deaths, as well as childhood asthma, will significantly be decreased. This, combined with the fact that IMO is constantly revising the existing regulations, is a prove that shipping community remains always alert about the protection of human health and environment. Acting this way, shipping community fulfills its duty in order to provide next generation a healthier environment and, finally, a better standard of life to people globally.

Chapter 4. Crude Oil

4.1 Introduction

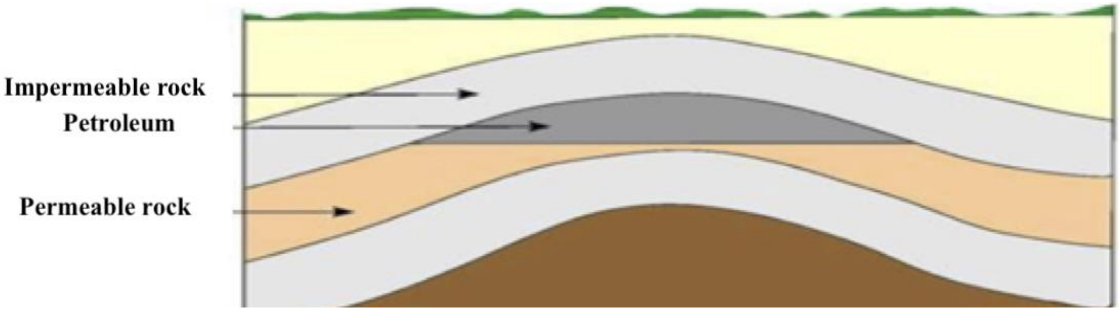
Crude oil, coal and natural gas play a dominant role in the global energy status quo [99]. They are extracted from huge onshore and offshore fields and together constitute the fossil fuels, a non – renewable energy source. Coal is the oldest and most abundant among fossil fuels, however, at the present time crude oil is the major energy source, accounting for around 39% of fossil energy, followed by coal and natural gas at 33% and 28% respectively [99]. Traditionally, Middle East countries were the world's largest oil producers with Saudi Arabia holding for a long time the first place among them. Improvement of the unconventional shale oil's extraction process though, brought USA lately in the top.

4.2 Etymology and Composition

Crude oil, commonly known as petroleum is a naturally occurring mixture of hydrocarbons that exists as a liquid in underground geologic formations [127]. While crude oil corresponds solely to the aforementioned definition, the term petroleum also covers all of the petroleum products [127]. The latter comprise a wide variety of products that are produced from the processing of crude oil and other liquids at petroleum refineries, from the extraction of liquid hydrocarbons at natural gas processing plants and from the production of finished petroleum products at blending facilities [127].

Crude oil composition can vary depending on its origin and extraction process, although hydrocarbons constitute its primary component (50% - 97%) [136]. Organic compounds such as nitrogen, sulphur and oxygen typically make up between 6%-10% of crude oil while metals such as copper, nickel, vanadium and iron account for less than 1% of the total composition [136]. Crude oil originates from a mixture of organic material and other sediments that were buried under high pressure and temperature for millions of years and transformed into fossil fuels, among others petroleum [108]. The latter was formed inside underground cavities and under the effect of high pressure it slowly moved towards the earth's surface and areas of lower pressure [108]. It continued its movement until encountering layers of rock that were impermeable [108]. The upward movement of oil stopped there and it gradually was accumulated under these impermeable layers, in huge reservoirs, a typical type of which is illustrated in Figure 4-1. These reservoirs can be found hundreds of meters beneath the earth's surface, either under the land or the ocean floor, and frequently contain both petroleum and natural gas [108].

Figure 4-1 Structure of a typical conventional oil reservoir



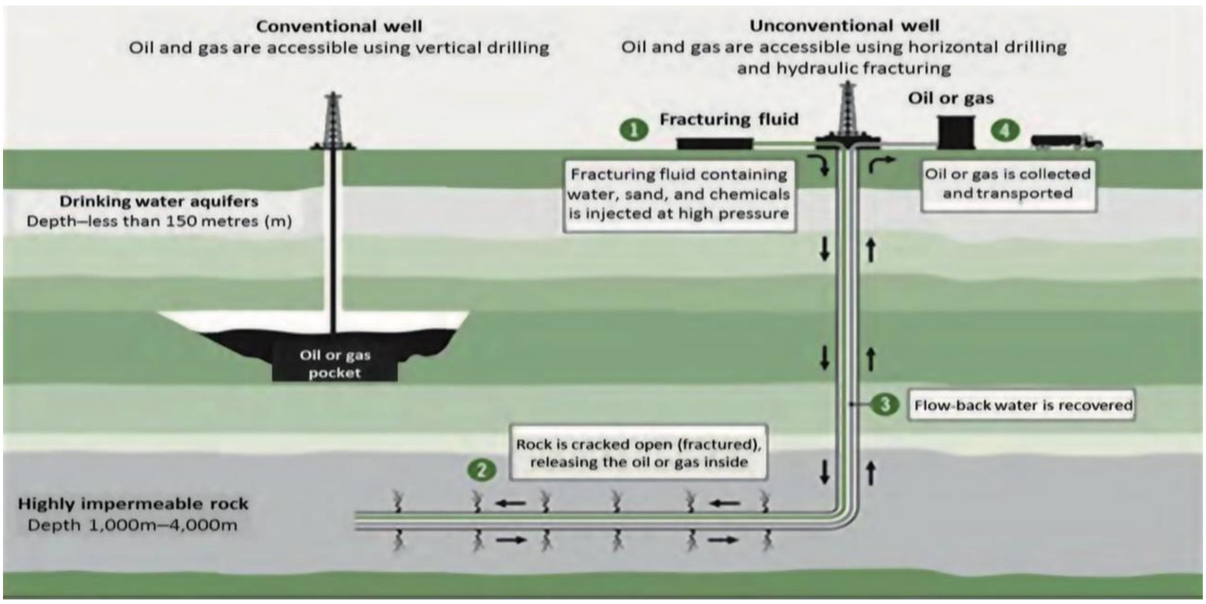
Source: Retrieved from https://www.essentialchemicalindustry.org

4.3 Extraction Process

Crude oil is extracted via drilling wells and then pumping the oil that is contained in the underground reservoir either using the earth's natural pressure or force it with artificial means towards the earth's surface. Before the beginning of any drilling process, geologists and engineers must first examine the underground formations to determine if they have found a - financially worthwhile to drill - petroleum reservoir, both in regard with the reservoir's quantity and its characteristics (permeability, porosity, depth etc.).

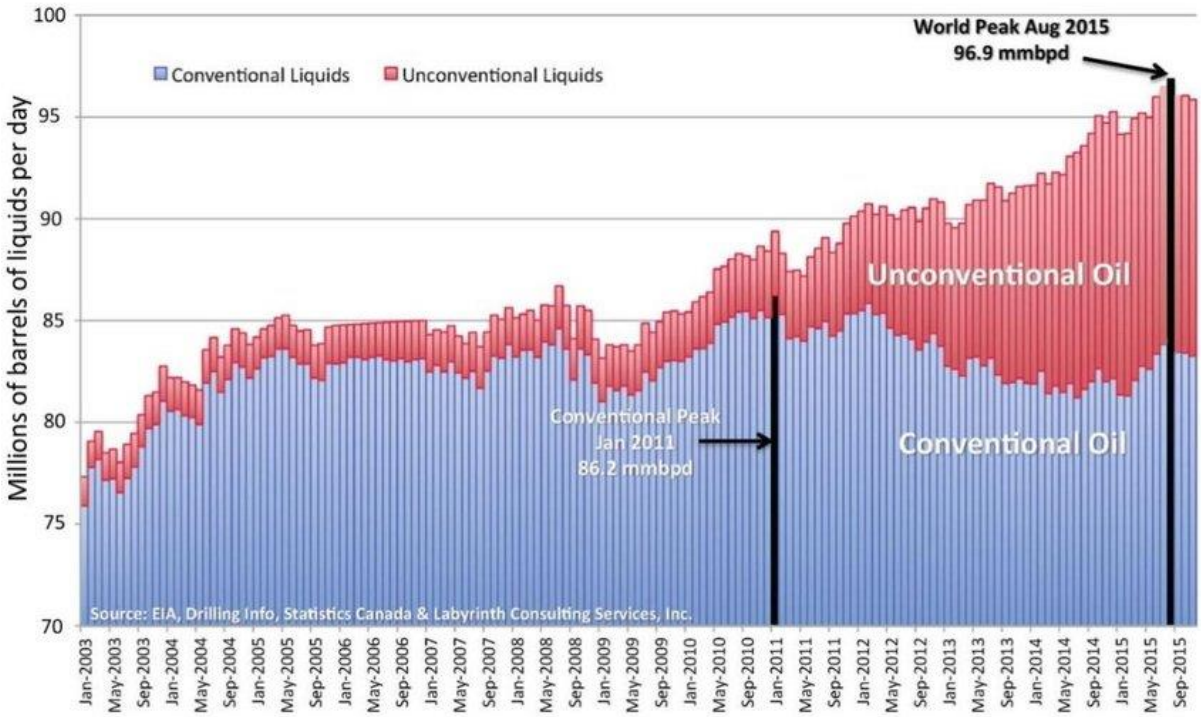
Petroleum reservoirs are classified as conventional and unconventional reservoirs [95]. In conventional oilfields, petroleum is usually accumulated in medium – depth reservoirs and is enclosed by rock formations of low permeability [95]. Extraction is performed usually via vertical drilling and the crude oil flows freely up the well due to the reservoir's natural pressure [125]. In unconventional reservoirs, petroleum is not so easily recoverable since it is trapped inside rock formations of low porosity and permeability, thus it cannot flow up the drilled well [23]. In this case, crude oil can be extracted by specialized methods, such as hydraulic fracturing, where water or gas in injected into the oil - containing rocks causing enough cracks until petroleum becomes adequately pumpable. Distinctive examples of unconventional oil deposits are shale oil fields and oil sands [23]. Due to the more complex extraction process and the higher production cost, unconventional oilfields were commonly not regarded financially worthwhile [23]. Oil extraction technology improvements though, together with high oil prices and gradual decline in old conventional oilfields' yields, ramped up the unconventional petroleum production in unprecedented rates during the last decade. A graphic illustration of petroleum reservoirs' classification and the evolution of unconventional drilling is depicted in Figure 4-2.

Figure 4-2. Comparison of extraction methods for conventional and unconventional Oil & Gas reserves



Source: Office of the Auditor General of Canada. (2012). Retrieved from https://pubs.ciphi.ca/doi/pdf/10.5864/d2016-013

Figure 4-3. Conventional vs Unconventional Petroleum liquids global production



Source: Rakonczai, János. (2018). Global and Geopolitical Environmental Challenges. Retrieved from https://www.researchgate.net/profile/Janos_Rakonczai/publication/331398136/

4.4 Global Crude Oil Production Data

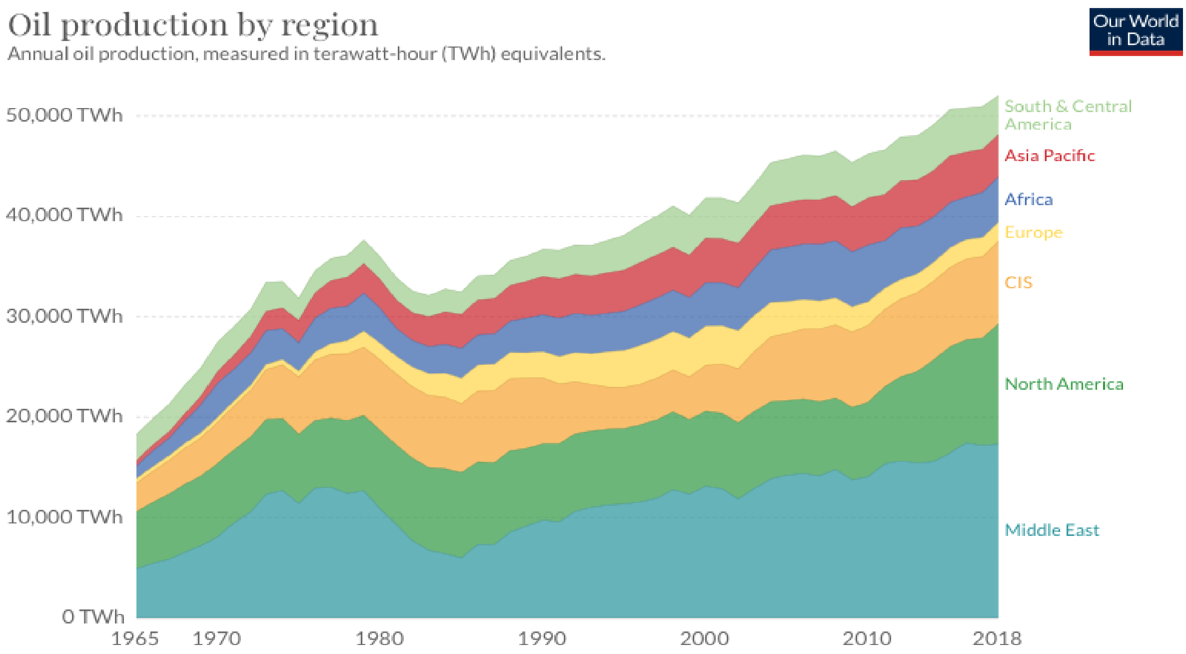
Middle East dominates for more than 50 years now the crude oil landscape supplying in the past more than 50% [99] of the global daily crude oil production and holds the largest proven oil reserves worldwide, as shown in Table 4-1 and Figure 4-4.

Table 4-1. Middle East's oil production

Field	Location	Discovered	Started production	Peaked	Recoverable oil, past and future (billion barrels)	Production (million barrels/day)
Ghawar Field	Saudi Arabia	1948[3]	1951[3]	2005,[4] disputed[5]	88-104[6]	3.8[7]
Burgan Field	Kuwait	1937	1948	2005[9]	66-72[8]	1.7[10]
Ahvaz Field	Iran	1958		1970s[11]	25 recoverable[12]	.750[13]
Upper Zakum oil field	Abu Dhabi, UAE	1963[14]	1982[15][16] (1967[14])	Production still increasing	21 recoverable [15][14])	0.750[15]
Gachsaran Field	Iran	1927	1930	1974	66[18]	0.480
Cantarell Field	Mexico	1976	1981	2004[19]	18-35 billion recoverable[8]	.772 [20]
Ku-Maloob-Zaap	Mexico	1979	1981	production still increasing		.867 [21]
Bolivar Coastal Field	Venezuela	1917	1922		30-32[8]	2.6-3[8]
Aghajari Field	Iran	1938	1940		28[22]	0.300

Source: List of oil fields. (n.d.). In Wikipedia. Retrieved January 20, 2020 from https://en.wikipedia.org/wiki/List_of_oil_fields

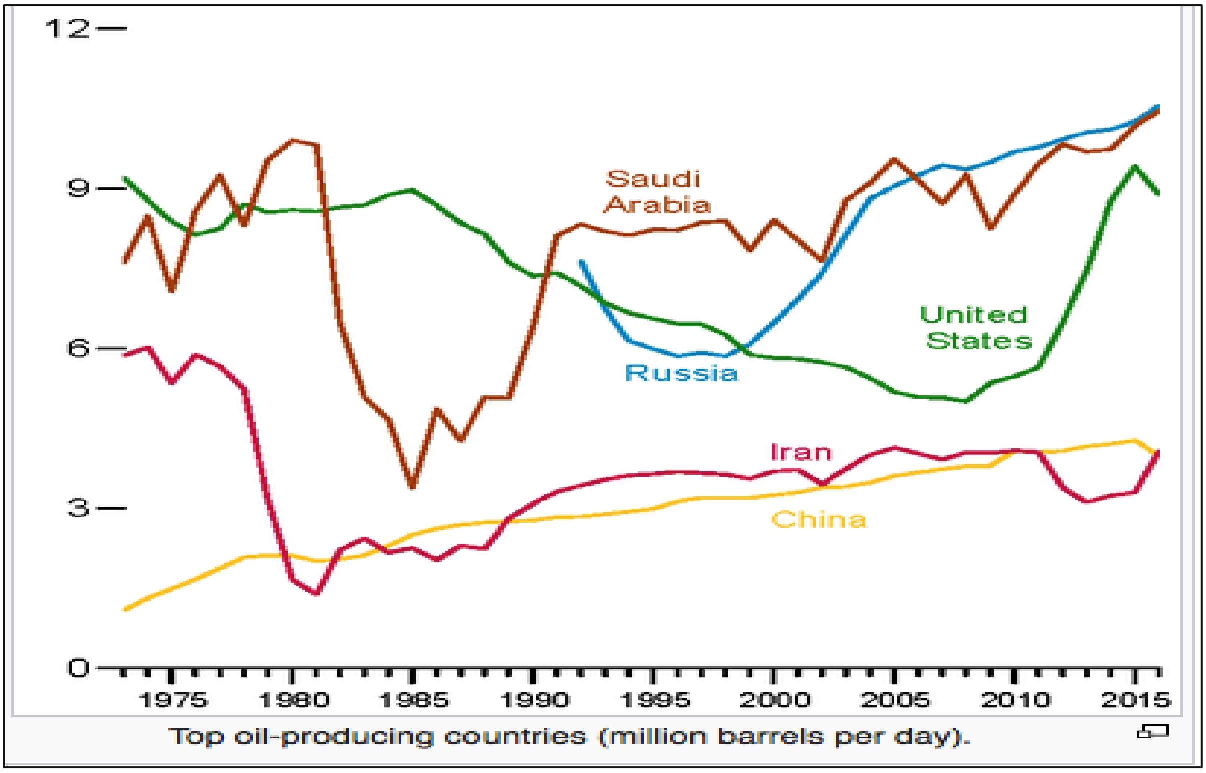
Figure 4-4. Global oil production by region



Source: Ritchie, H., and Roser, M. (2020). Fossil Fuels. Retrieved from: https://ourworldindata.org/fossil-fuels

Among oil producing countries, Saudi Arabia, USA and Russia steadily occupy the top 3 positions during the last decades, as illustrated in Figure 4-5.

Figure 4-5. Annual crude oil production of the 5 top-oil producers



Source: Petroleum. (n.d.). In Wikipedia. Retrieved January 22, 2020, from https://en.wikipedia.org/wiki/Petroleum#Unconventional_oil

4.5 Shale Oil

4.5.1 Generally

Shale Oil[2], officially known as Tight Oil, is light crude oil contained in petroleum – bearing formations of low permeability, often shale or tight sandstone [75]. In contrast to conventional petroleum reservoirs, shale reserves are not recoverable via conventional vertical well drilling, since the much lower permeability and porosity makes the trapped petroleum impossible to flow. Improvement of hydraulic fracturing – a controversial extraction method – during the 1990's though, meant the advent of a new era in the oil and gas industry and created the potential for exploration and exploitation of the vast unconventional shale oil reserves.

The purpose of hydraulic fracturing is to create fractures in relatively impermeable rock, such as shale, that allow gas or oil to flow back up to a well head on the surface [134]. At first stage, a well is vertically drilled until it makes it through the oil-containing rock formation, frequently at depths of 2000 m – 4000 m. The difference with traditional oil reserves is that unconventional drilling includes a 90-degree turn of the drill bit so that the drilling process continues for thousands of feet horizontally, alongside the oil deposit [11]. Once the horizontal drilling has been completed, the fracking process begins. Huge amounts of high-pressured mixture of water and chemicals is pumped deep down the shale rocks causing an array of fractures in the surrounding rocks, allowing for the gas or petroleum to flow easily back to the surface [134].

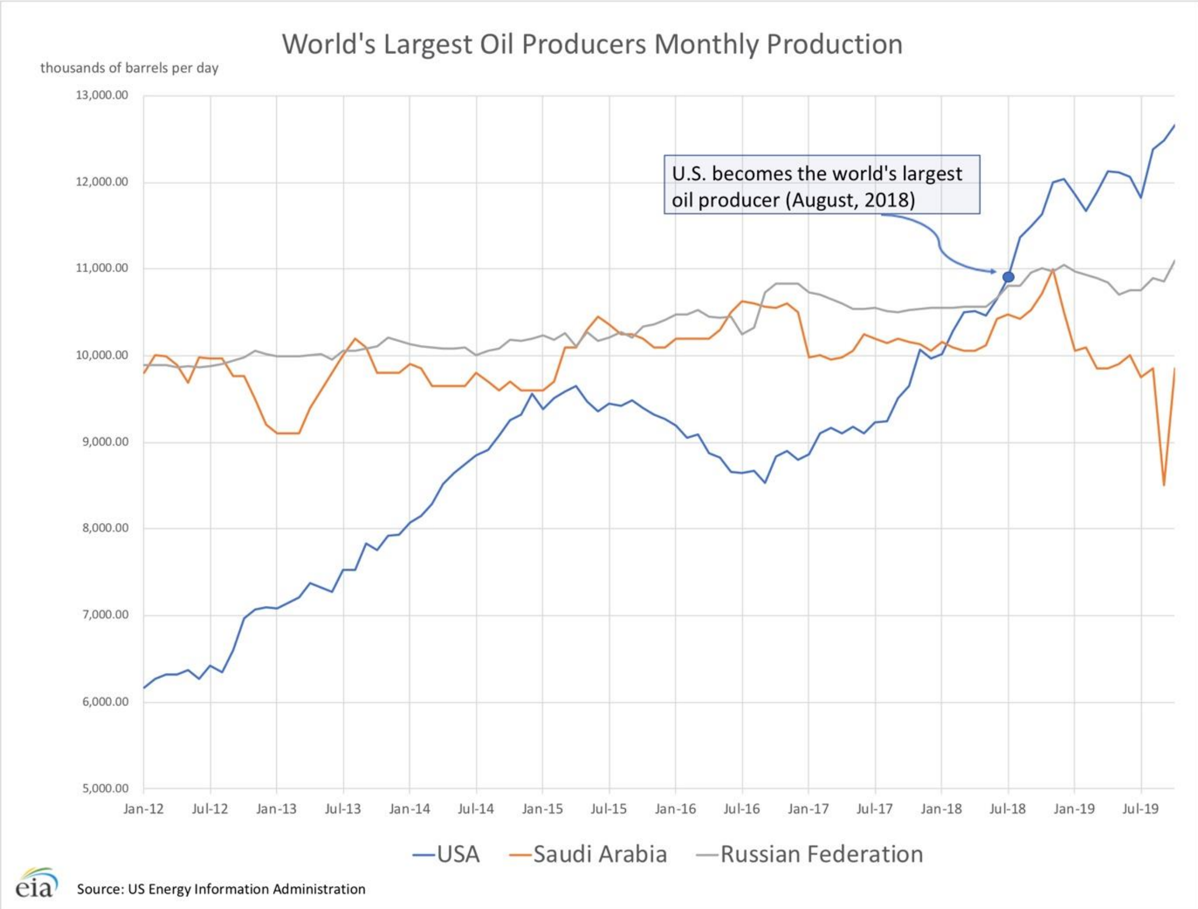
Shale oil drilling requires deeper and more complex wells, a large number of trucks and extra infrastructure in order to supply the millions of litres of fracturing fluid and consequently longer drilling times comparing to conventional drilling. Therefore, it is a capital-intensive investment with huge upfront expenses and high operating and labour costs. Indicatively, a conventional oilfield extraction, costs averagely between 30$ - 40$ a barrel, while, the break – even point in fracked shale oil is typically around 60$ a barrel, reaching sometimes 90$ a barrel, making shale oil production not economic viable [11].

[2] Shale oil, when referring to Tight oil, should not be confused with the homonymous shale oil that is produced from the kerogen rich sedimentary rocks, oil shales. Regarding the latter, U.S. has confirmed the existence of very large reserves of oil shales, although they still have not proved to be financially recoverable.

4.5.2 U.S. Shale Oil Revolution

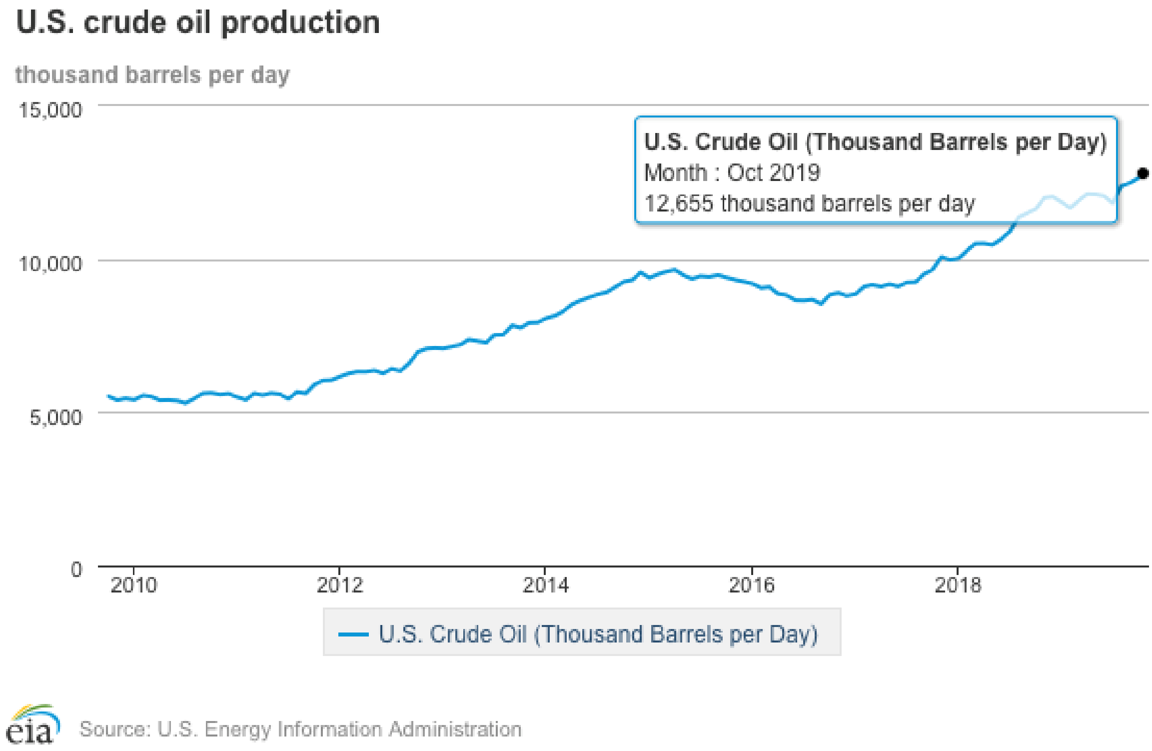
In August 2018, U.S. oil production reached a major milestone hitting an output of 11.3 million barrels per day thus becoming the world's largest crude oil producer [130]. Petroleum production of the United States exceeded those of Saudi Arabia and Russia for the first time in more than two decades as seen in Figure 4-6, introducing a new era towards U.S. energy independence. Since then, US oil industry has steadily ramped up production, reaching an all – time record of 12.6 million b/d during the fourth quarter (Q4) of 2019 [130], as illustrated in *Figure 4-7*. According to the IEA's Short – Term Energy Outlook (STEO), January 2020, U.S. crude oil production is expected to average 13.3 million b/d in 2020 and will continue to grow through the next years, due to the improvement of rig efficiency and well productivity.

Figure 4-6. Monthly oil production of Saudi Arabia, United States and Russia (2012-2019)



Source: Data for the United States and Saudi Arabia from US IEA (2020) and for the Russian Federation from the Russian Ministry of Oil (2020)

Figure 4-7. U.S. crude oil production (2010-2019)



Source: Data from U.S. EIA Monthly crude oil and natural gas production report (2020, January 31).

The remarkable growth in U.S. oil production, which grew more than double between 2012 and 2019, was driven mainly by the tremendous increase of the shale oil reserves' exploitation that was set off in 2011, commonly known as the U.S. shale oil boom. Shale Oil, officially called as tight oil, is the US oil industry's highlight of the last decade and the cornerstone of its unprecedented success in crude production.

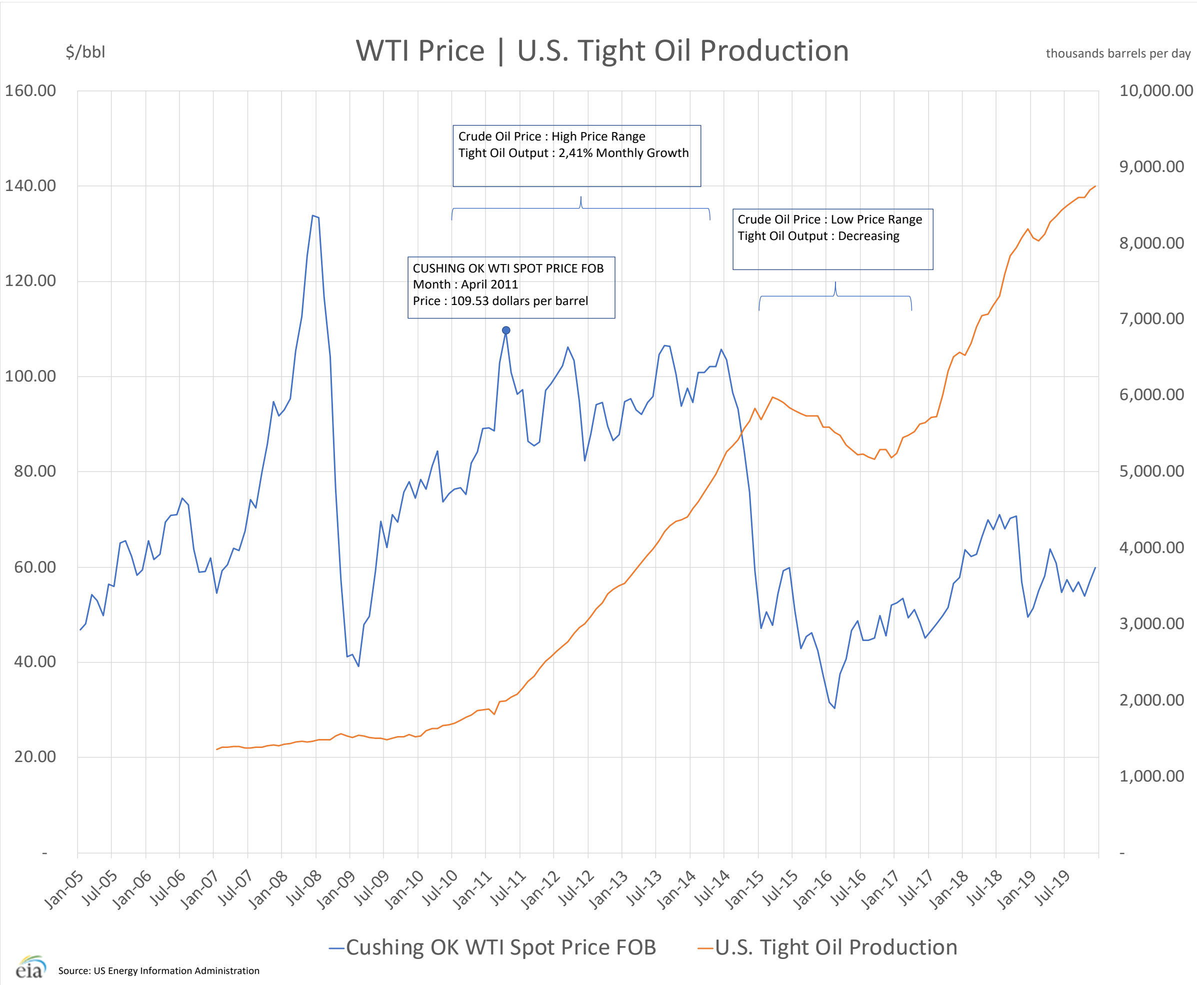
The phenomenal impact of US tight oil in the global energy landscape, necessitated a strong understanding of the reasons behind this noteworthy achievement of the US oil companies. The relatively young age of the latter though, made it difficult to determine the factors that led shale oil's extraction rates during the last 7 years to a surge. The four – part article series "*Moving the US shale revolution forward*" by Deloitte, was created in order to provide better insight of the factors of US shale's success, undertaking a thorough analysis of the operations and performance of several companies that are involved in US shales.

According to the first-out-of-four articles of Deloitte's research, "the advent and commercialization of hydraulic fracturing and horizontal drilling beginning in the Barnett region shale paved the way for rapid expansion in unconventional reserves", after 2011 [100]. The rise in crude oil price during the start of the decade, exceeding 100$ per barrel in 2011, prompted oil companies to start drilling shale oil reserves. The 3.6 billion barrels of US tight oil proven (at that time) reserves [113] and the 112 billion barrels [100] estimates of undiscovered tight oil gave the oil producers additional reassurance and incentive so as to boost their operations. As prices remained in the 80$ – 105$, they continued drilling wells and ramping up oil production, managing to maintain an average monthly production rate of growth of 2.41%, until late 2014 as seen in Figure 4-7.

This prolific era, between early-2011 and late – 2014, is characterized by rapid acquiring of know – how from the oil producers, who, through unique engineering designs and intense completion of the new wells managed to compensate the low quality of some shale formations and steadily increase productivity [100]. At the same time, the better management in time and expenses, lowered their breakeven cost and contributed indirectly in their productivity [100].

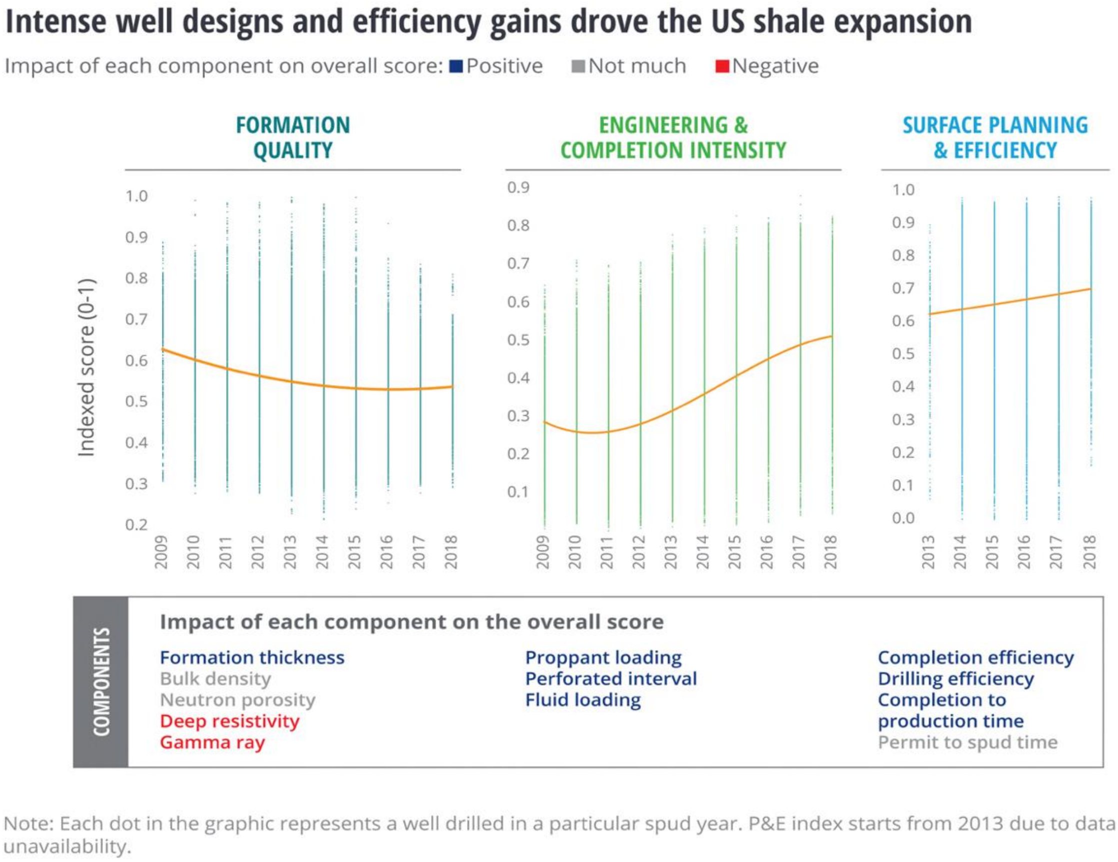
However, the steadily augmenting – until late 2014 – global oil oversupply, together with major producer Saudi Arabia's announcement of further increasing production, caused a dramatic downward course of crude's price [7] which completed with WTI plummeting to 30,6 $/bbl. in February, 2016, having lost 71% of its mid-2014 value (105,7 $/bbl.). Discouraging crude prices together with reduction in well productivity forced many integrated oil companies to scale back their activity in shales [100] (Figure 4-8). By limiting their operations up to drilling, and not pumping the oil out of the ground, the producers started cutting down the supply of crude oil, thus, pushing the prices upwards, aiming to surpass breakeven point. At the same time, many managed to improve their drilling and fracking methods, therefore leading to a strong comeback of the tight oil production by October 2016. Since then, the production is characterized by positive and steady rate of growth, reaching a record high output of 8.54 million barrels per day in August 2019 [124]. A graphic illustration of the oil companies' productivity evolution, based on key productivity indices, is presented in Figure 4-8.

Figure 4-8. US tight oil production in regard to WTI price



Source: Data for tight oil production from U.S. EIA Drilling Productivity Report for key tight oil and shale gas regions (2019, December) and data for WTI price from U.S. EIA spot prices for crude oil and petroleum products (2020, January)

Figure 4-9. Key performance indicators of US shale oil industry (2009-2018)



Source: Data from Deloitte analysis based on Enverus Drillinginfo database (2019, June 1)

According to U.S. IEA's latest data, total proved crude oil reserves in the United States at year – end 2018, set a new record, rising to 43.8 billion barrels (Table 4-2). Of all these, 22.93 billion barrels were the total proved reserves of the country's seven biggest tight oil plays, accounting for 52,36% of its total crude oil reserves (Table 4-3).

Table 4-2. U.S. proved reserves (2017-2018)

U.S. proved reserves, and reserves changes, 2017-18	
	Crude Oil (billion barrels)
U.S. proved reserves at December 31, 2017	39,2
Total discoveries	6,6
Net revisions	0,6
Net Adjustments, Sales, Acquisitions	1,2
Production	-3,7
Net additions to U.S. proved reserves	4,7
U.S. proved reserves at December 31, 2018	43,8
Percent change in U.S. proved reserves	11,9%
Notes: Oil includes lease condensate; wet natural gas includes natural gas plant liquids.	

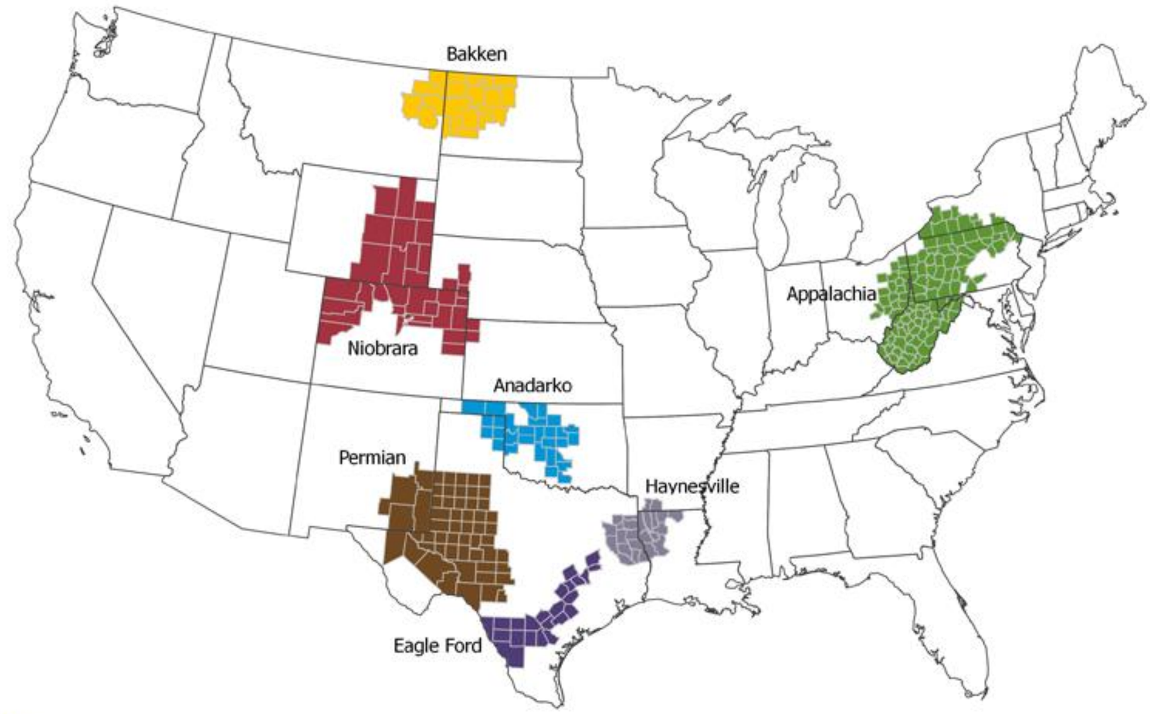
Source: U.S. Energy Information Administration, Form EIA-23L, Annual Report of Domestic Oil and Gas Reserves *(2019, December)*

Table 4-3. U.S. Seven Biggest Shale Plays

Crude oil and lease condensate production and proved reserves from major U.S. tight plays (2018)				
Basin	**Play**	**State(s)**	**2018 Production (million barrels)**	**2018 Reserves (million barrels)**
Permian	Wolfcamp/Bone Spring	NM, TX	922	11.096
Williston	Bakken/Three Forks	ND, MT, SD	458	5.862
Western Gulf	Eagle Ford	TX	449	4.734
Anadarko, S. Oklahoma	Woodford	OK	34	560
Appalachian	Marcellus*	PA, WV	17	345
Denver	Niobrara*	CO, KS, NE, WY	25	317
Fort Worth	Barnett	TX	2	20
Sub-total			**1.907**	**22.934**
Other			NA	NA
U.S. tight oil			**1.907**	**22.934**
Note: Includes lease condensate. Bakken/Three Forks tight oil includes fields reported as shale or low permeability on Form EIA-23L.				
***Other* includes fields reported as shale on Form EIA-23L not assigned by EIA to the Eagle Ford, Bakken, Barnett, Marcellus, or Niobrara resource plays.**				
*** The Niobrara estimate may contain some reserves from the Codell sandstone.**				
Source: U.S. Energy Information Administration, Form EIA-23L, *Annual Report of Domestic Oil and Gas Reserves,* 2017 and 2018 (Published on December, 2019)				

Source: U.S. Energy Information Administration, Form EIA-23L, Annual Report of Domestic Oil and Gas Reserves *(2019, December)*

Figure 4-10. US seven biggest tight oil plays

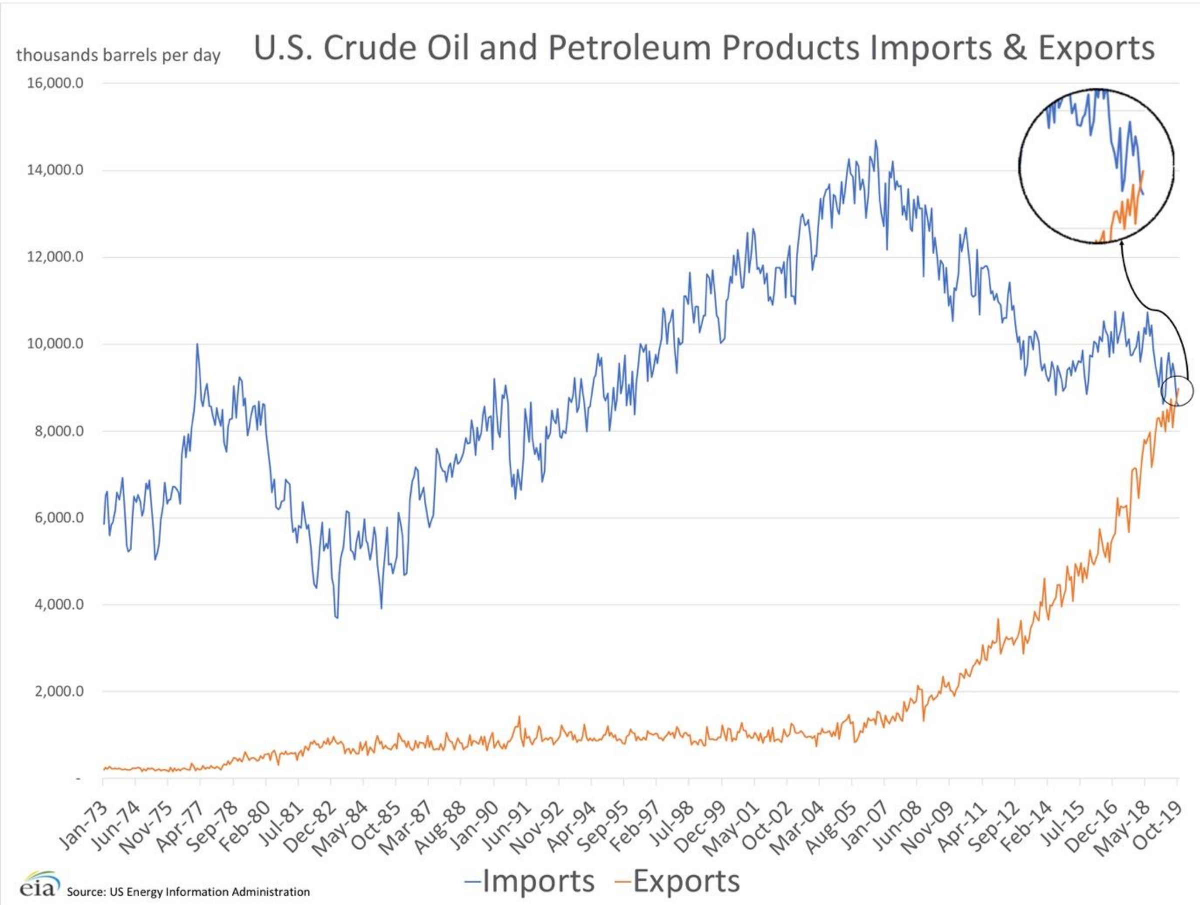


Source: U.S. Energy Information Administration, Form EIA-23L, Annual Report of Domestic Oil and Gas Reserves *(2019, December). Retrieved from https://www.eia.gov/naturalgas/crudeoilreserves/pdf/usreserves.pdf*

The United States consumes more than 20% of the world's 99 million barrels daily crude production, with China holding the 2nd spot at 13% and India in a distant 3rd at 5% [17]. America's energy dependence had always been its weak spot, the impact of which was put on display in an alarming way, during the 1973 Oil Crisis [17]. The superpower's susceptibility to foreign crude production and price volatility shaped the country's foreign policy and is the reason behind the US troops' intense presence in the Middle East as well the US Navy's 5th fleet operations in tense critical maritime trade chokepoints, such as the Strait of Hormuz and the Suez Canal [17].

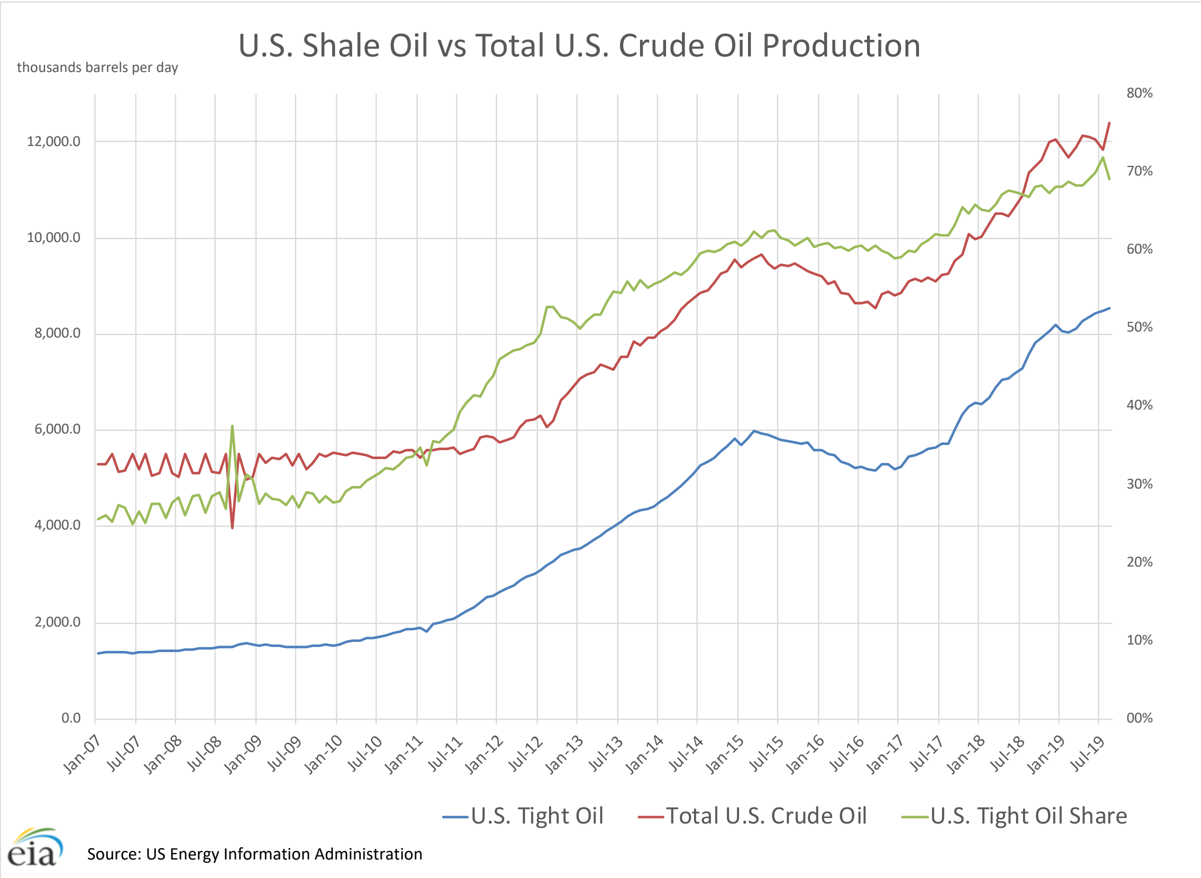
Shale revolution was a very big deal for the world's leading oil buyer. Not only did the US hit an all-time high crude output of 12.8 million b/d during November 2019 [126], they also managed to become a net petroleum exporter. According to a US Energy Information Administration report, during September 2019 the country exported 89,000 b/d more petroleum (crude oil and petroleum products) than it imported, marking a turning point in American energy history [41]. By comparison, a decade ago the United States was importing 10 million b/d more petroleum than it was exporting [41]. This is the first time than petroleum exports outstrip imports, since the EIA began keeping monthly records in 1973 [41]. According to the U.S. IEA's Short-Term Energy Outlook report for January 2020, US will remain a net petroleum exporter, maintaining a trade surplus of an averagely 800.000,0 barrels per day, during 2020 [126].

Figure 4-11. US becomes a net crude oil and liquids exporter for the first time since 1973



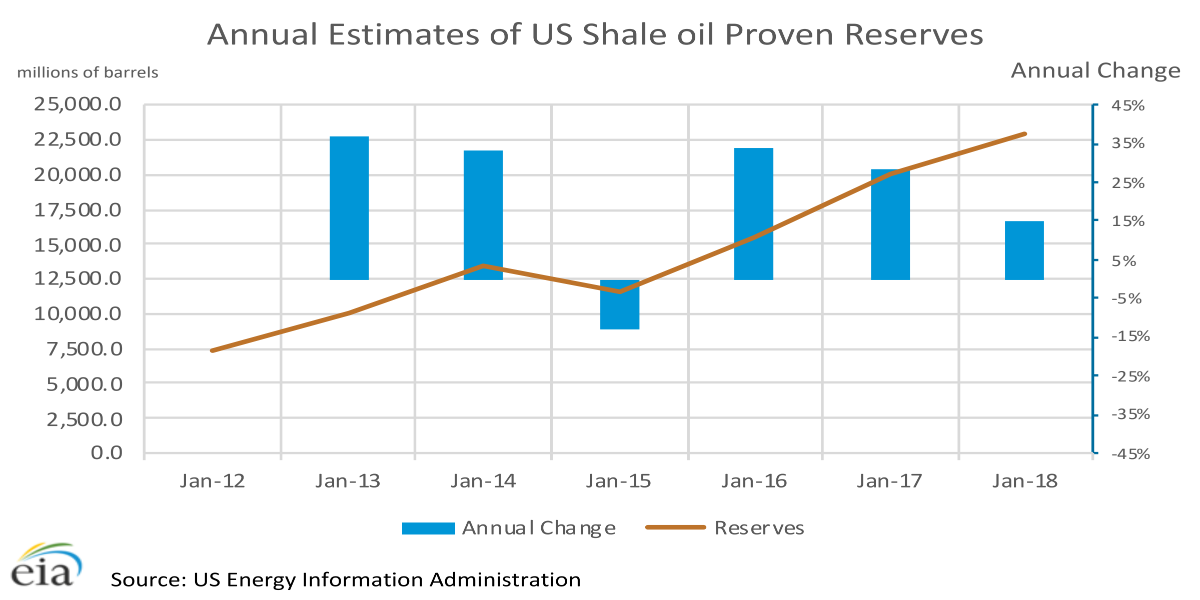
On July 2019, US shales' output rose to 8.64 million barrels per day [129], accounting for a record high 73,1% share of the country's daily total crude production (Figure 4-12). By the advent of 2020, almost 0.5 million barrels had been added to shale oil production, which reached a new high of 9.13 million barrels per day [129]. According to the IEA's forecasts, production of US crude is expected to average 13,3 million b/d in mid-2020 and 13,7 million b/d during 2021 [131], a growth the driver of which is going to be the increasing shale exploitation rates. The impetus that is gained from the growing annual estimates of the proven shale oil reserves (Figure 4-13) together with the IEA's forecast of augmenting extraction rates in the Permian Region of Texas and New Mexico [131] are expected to extend the shale revolution. According, to IEA's Annual Energy Outlook 2019, the US crude oil production's future trajectory will be mainly determined by oil prices, technological improvement and resource availability (Figure 4-14).

Figure 4-12. Shale oil revolution skyrockets US crude oil production



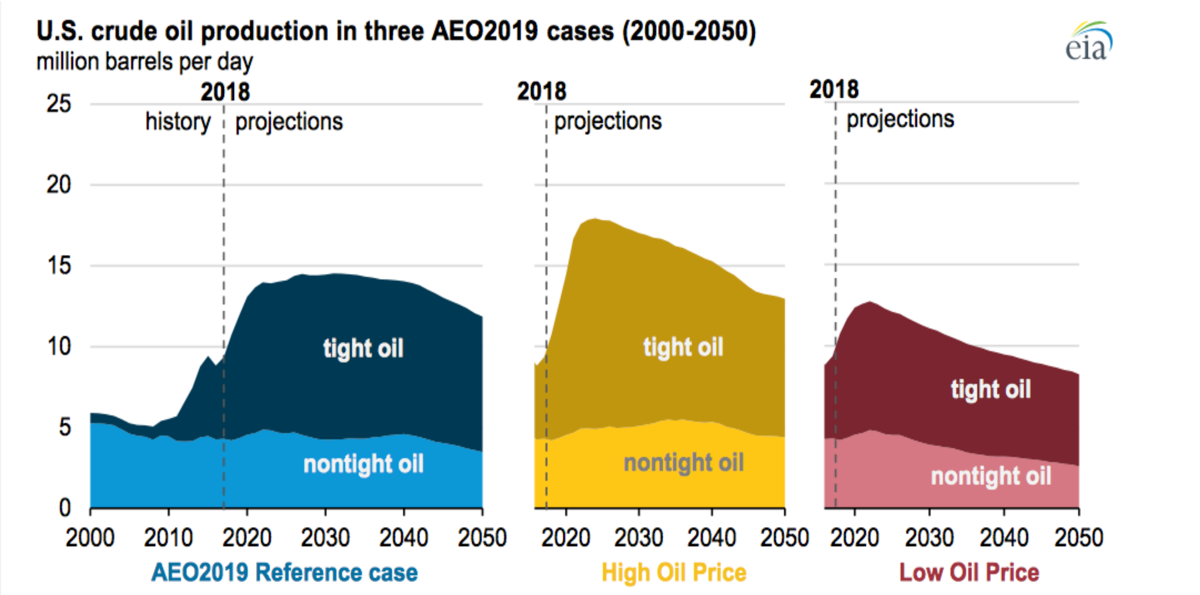
Source: Data for US tight oil and total crude oil production from U.S. EIA's database (2020)

Figure 4-13 US proven shale oil reserves changes (2012-2018)



Source: Data for US shale oil reserves (2012-2018) from U.S. EIA, Domestic Oil and Gas Reserves Annual Report, *(years 2012-2019)*

Figure 4-14 U.S. crude oil production projections up to 2050



Source: U.S. Energy Information Administration. (2019). Annual Energy Outlook 2019. *Washington, DC: U.S. Department of Energy. Retrieved from https://www.eia.gov/outlooks/aeo/pdf/AEO2020%20Full%20Report.pdf*

4.6 Crude oil classification

Crude oil pricing is based on, among others, production capacity, market and geopolitical conditions and its chemical properties. In regard to the latter, the two most important ones that acutely determine a crude's value are its density (measured as API[3] specific gravity) and its sulphur content (m/m).

Regarding the sulphur content, crude oil that contains less than 0.50% m/m sulphur is considered "sweet", while crude oil that has more than 0.50% m/m sulphur content is considered "sour". Due to the lack of the corrosive and generally un-wanted sulphur, sweet crude oil is easier to transport and refine, and suitable for low sulphur petroleum products such as gasoline and diesel oil, therefore it is priced at a premium over sour crude oils.

In respect to the API density, crude oil types are classified as follows:

- Light crude oil is defined as having an API gravity higher than 31.1
- Medium oil is defined as having an API gravity of 22.3 – 31.1
- Heavy oil is defined as having an API gravity below 22.3

Light crude oil typically receives a higher price than heavy crude oil on commodity markets because it produces a higher proportion of gasoline, diesel oil, namely high value-added products and does not require special treatment process during refining. Heavier crude oil receives a lower price because of lower yields in value-added products and the need for more time-consuming and resource-demanding refining process.

Overall, extracted crude oils are defined based on the combination of the aforementioned two properties e.g. light sweet crude, medium sour and et cetera.

4.7 Crude oil grades

There are approximately 550 global crude oil streams that can be identified as individual grades with a multiplicity of qualities and prices [44]. Among those, around 200 grades dominate the international oil markets, the majority of which are produced from the top 45 oil producer countries. Usually, an individual crude oil grade will originate from the combined production of various oil fields (with similar API gravities and sulphur content), however a few grades come from individual oil fields. For example, the Forties Blend, the largest crude oil stream in the UK is made up of oil from 70 fields spread over a large area of the North Sea. On the other hand, the Upper Zakum grade, the second largest crude oil stream of major oil producer Abu Dhabi, is mainly extracted from the Upper Zakum offshore oil field.

No two crude oil grades are identical. For this reason, oil companies provide for each grade a crude oil assay. The crude oil assay is a complete chemical evaluation of a specific crude oil

[3] API gravity is a commonly used index of the density of crude oil or petroleum products. API stands for American Petroleum Institute, the organization that created the index. API gravity calculation is based on the hydrocarbon's specific gravity. Crude oil's specific gravity is calculated as the ratio of its density to the density of water, with typical values of less than 1, since most crude grades are heavier than water. Typically, crude oil's API gravity will range between 15-45°. The higher the API value, the lighter (less dense and viscous) the hydrocarbon, and vice versa.

stream, that is necessary for refiners and traders in order to source the right grades, in respect to the clients' and market's needs. It includes an evaluation of more than 20 chemical properties as well as an assessment of petroleum products yields and information around the fractions' boiling temperatures. Due to the complexity of crude oil assays, a trading company will typically focus at first on the API gravity and sulphur content in order to source the desired crude quality. Below is listed an overview of the world's major oil producers and their main crude oil grades.

4.7.1 Middle East

4.7.1.1 Saudi Arabia

According to U.S. EIA estimates, Saudi Arabia produced during 2019 an average of 9.78 million b/d, becoming the world's 3rd largest crude oil producer, after U.S. and Russia. The kingdom is the largest exporter of petroleum liquids in the world and has roughly 16% of the world's proved oil reserves holding the 2nd position globally, after Venezuela [118]. Moreover, it is the biggest oil producer among OPEC members and Middle Eastern countries. Saudi Arabia is located near two of the world's most strategically important chokepoints, in regard to the global crude oil flow. On the east of the country and specifically between Oman and Iran is located the Strait of Hormuz, which connects the Persian Gulf with the Gulf of Oman and the Arabian Sea. This sea passage, which at its narrowest point reaches a 39 km width, had during 2016 a tanker traffic equal to an average crude oil and other liquids flow of 18.5 million b/d or 19% of the year's global petroleum liquids consumption [118].

Table 4-4 Saudi Arabia's crude oil0

Saudi Arabia 2018 Data		
	Unit	**Value**
Crude oil production[4]	(1,000 b/d)	10,317.30
Crude oil exports	(1,000 b/d)	7,371.50
Crude Oil Consumption	(1,000 b/d)	3,104.60
Proven crude oil reserves	(million barrels)	267,026.00
GDP at market prices	(million $)	782,484.00
Value of petroleum exports	(million $)	194,358.00

Source: Organization of the Petroleum Exporting Countries. (2019). OPEC Annual Statistical Bulletin 2019. *Table1.1. Vienna, Austria: Organization of the Petroleum Exporting Countries*

Saudi Arabia has about 130 major oil fields and natural gas fields, nevertheless more than half of its total oil reserves are contained in nine fields, all of them located in the northeast portion of the country [118] (Table 4-5). The country is home to the Ghawar field, the world's largest oil field in terms of production as well as of total remaining reserves (around 75 billion barrels according to U.S. EIA's estimates).

[4] Including share of production from the Saudi-Kuwait Neutral Zone

Table 4-5. Saudi Arabia's biggest oil fields production

Major oil fields in Saudi Arabia			
Field	**Location**	**Production capacity as of 2017 (million b/d)**	**Crude grade**
Ghawar	onshore	5.8	Arab Light
Safaniya	offshore	1.2	Arab Heavy
Khurais	onshore	1.2	Arab Light
Manifa	offshore	0.9	Arab Heavy
Shaybah	onshore	1	Arab Extra Light
Qatif	onshore	0.5	Arab Light
Khursaniyah	onshore	0.5	Arab Light
Zuluf	offshore	0.68	Arab Medium
Abqaiq	onshore	0.4	Arab Extra Light

Source: U.S. Energy Information Administration. (2017, October). Country Analysis Brief: Saudi Arabia. Retrieved from https://www.eia.gov/international/content/analysis/countries_long/Saudi_Arabia/saudi_arabia.pdf

Saudi Arabia produces a range of five crude oil grades as displayed in Table 4-6, from super light to heavy. Light crude streams come mainly from its onshore fields, whereas medium and heavy grades are produced from its offshore fields.

Table 4-6. Saudi Arabia's major exported oil grades

Saudi Arabia’s Crude oil Grades		
Crude oil Grade	**API Gravity**	**Sulphur Content**
Arab Heavy	28.0°	2.80%
Arab Medium	31.0°	2.55%
Arab Light	33.0°	1.77%
Extra Light	40.0°	1.09%
Super Light	51.0°	0.01%

Source: Crude Grades. (n.d.). Retrieved from https://www.mckinseyenergyinsights.com/resources/refinery-reference-desk/crude-grades/

Figure 4-15. Saudi Arabia's Oil & Gas pipeline network

Source: U.S. Energy Information Administration. (2017, October). Country Analysis Brief: Saudi Arabia. Retrieved from https://www.eia.gov/international/content/analysis/countries_long/Saudi_Arabia/saudi_arabia.pdf

4.7.1.2 Iraq

Iraq is the second-largest producer in OPEC and one of the top holders of proved oil reserves in the world. Iraq has nine supergiant fields (defined as holding more than 5 billion barrels each) and 22 known giant fields (over 1 billion barrels).

Table 4-7. Iraq's crude oil

Iraq 2018 Data		
	Unit	**Value**
Crude oil production	(1,000 b/d)	4,410.00
Crude oil exports	(1,000 b/d)	3,862.00
Crude Oil Consumption	(1,000 b/d)	704.40
Proven crude oil reserves	(million barrels)	145,019.00
GDP at market prices	(million $)	212,407.00
Value of petroleum exports	(million $)	68,192.00

Source: Organization of the Petroleum Exporting Countries. (2019). OPEC Annual Statistical Bulletin 2019. *Table1.1. Vienna, Austria: Organization of the Petroleum Exporting Countries*

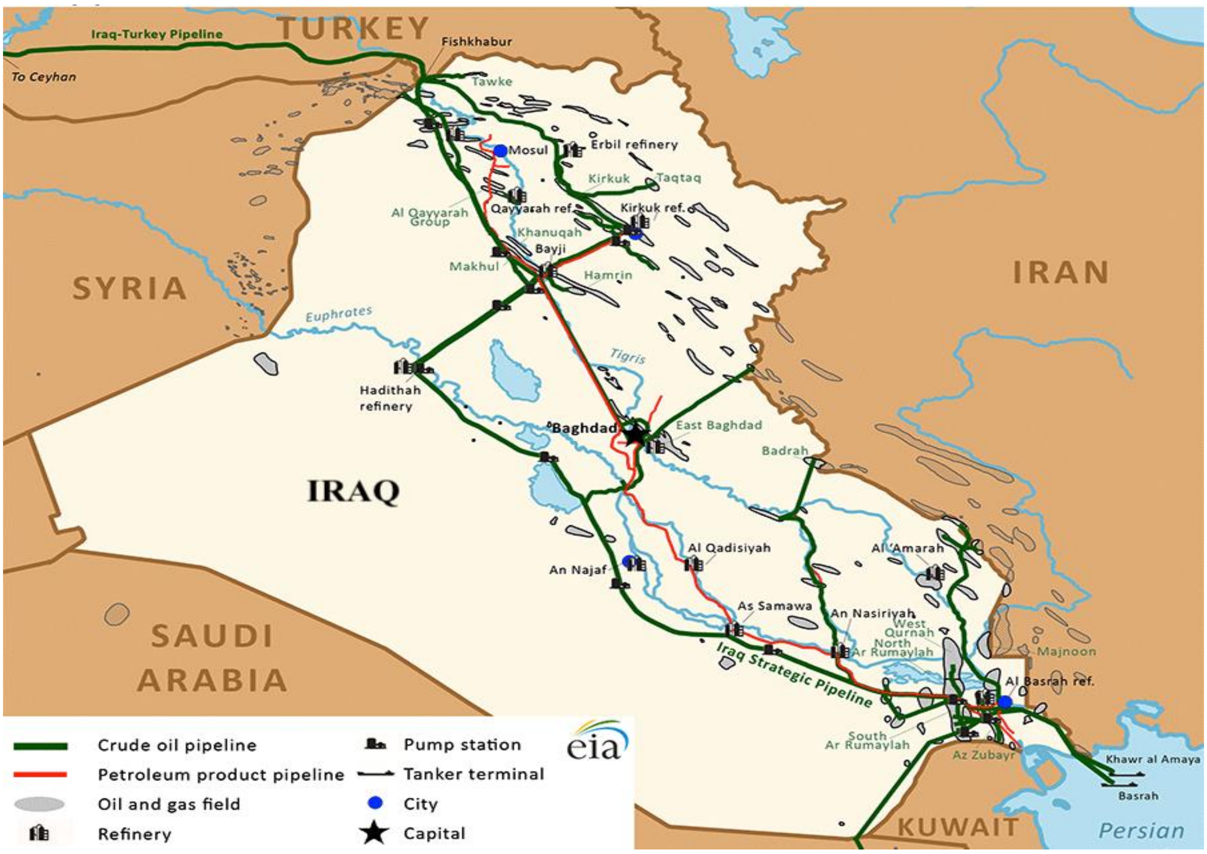
Iraq exports three grades of crude oil: Basrah Heavy, Basrah Light, and Kirkuk as seen in Table 4-8. In addition to these three grades, Iraq plans to introduce a Basrah Medium grade, but this addition is being for now on hold due to limited storage availability in the country's southern export and storage terminals (S&P Global Platts, 2018). The new grade is expected to have an API gravity of 29-30 degrees and around 2% Sulphur content, as announced by SOMO Deputy Director General Ali Nazar al-Shatari. According to the Iraqi oil ministry, the new logistics infrastructure will attain better stability in Iraq's grades specifications and help the country's plans to boost its southern exports to 6 million b/d by 2023.

Table 4-8. Iraq's major exported crude oil grades

Iraq's Main Crude oil Grades		
Crude oil Grade	**API Gravity**	**Sulphur Content**
Basrah Heavy	24.03°	3.83%
Basrah Light	29.88°	2.93%
Kirkuk	34.20°	2.24%

Source: U.S. Energy Information Administration. (2019, January). Background Reference: Iraq. Retrieved from https://www.eia.gov/international/analysis/country/IRQ/background

Figure 4-16. Iraq petroleum infrastructure



Source: U.S. Energy Information Administration. (2019, January). Background Reference: Iraq. Retrieved from https://www.eia.gov/international/analysis/country/IRQ/background

4.7.1.3 Iran

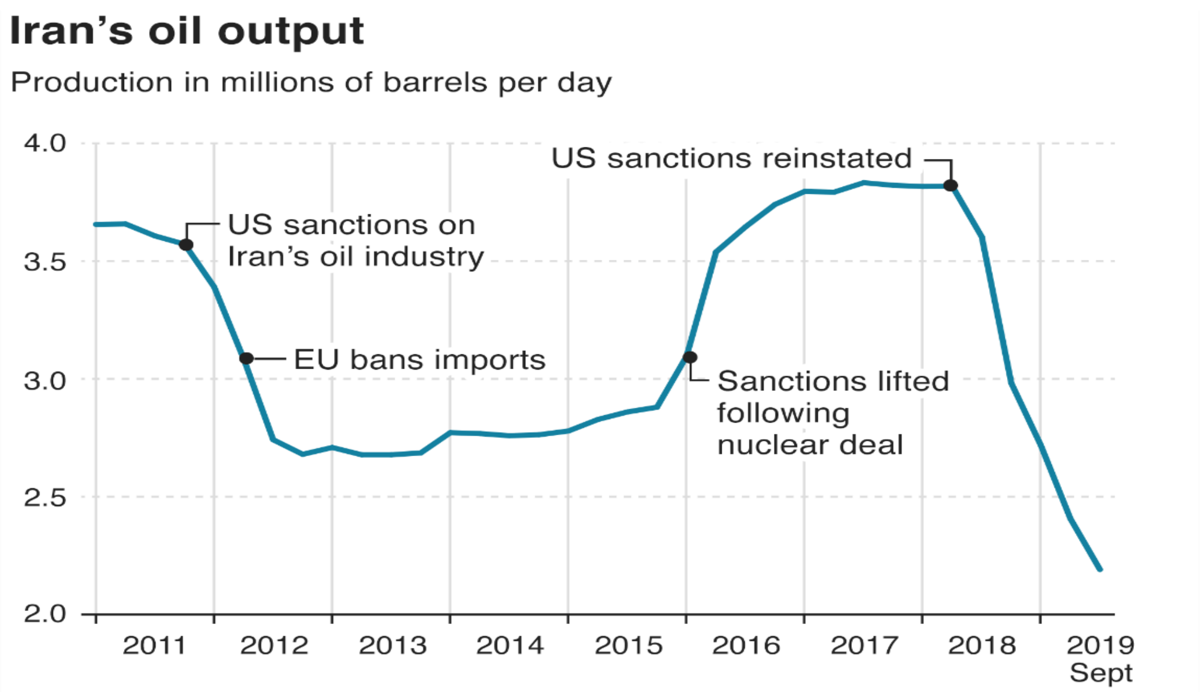
Iran is one of the founding members of the Organization of the Petroleum Exporting Countries (OPEC). Middle-East's second largest country is the holder of the world's fourth-largest proven crude oil reserves and the world's second-largest deposits of natural gas. Iran's economy was badly affected for several years by sanctions imposed by the international community over the country's nuclear programme (BBC News, December 2019). The reinstatement of U.S. sanctions in 2018 reduced Iran's crude output from 3.8 million b/d during August 2018 [87] to 2.2 million b/d in October 2019 [90], causing serious contraction in the country's GDP and oil exports.

Table 4-9 Iran's crude oil

Iran 2018 Data		
	Unit	**Value**
Crude oil production	(1,000 b/d)	3,553.00
Crude oil exports	(1,000 b/d)	1,849.60
Crude Oil Consumption	(1,000 b/d)	1,854.30
Proven crude oil reserves	(million barrels)	155,600.00
GDP at market prices	(million $)	418,582.00
Value of petroleum exports	(million $)	60,198.00

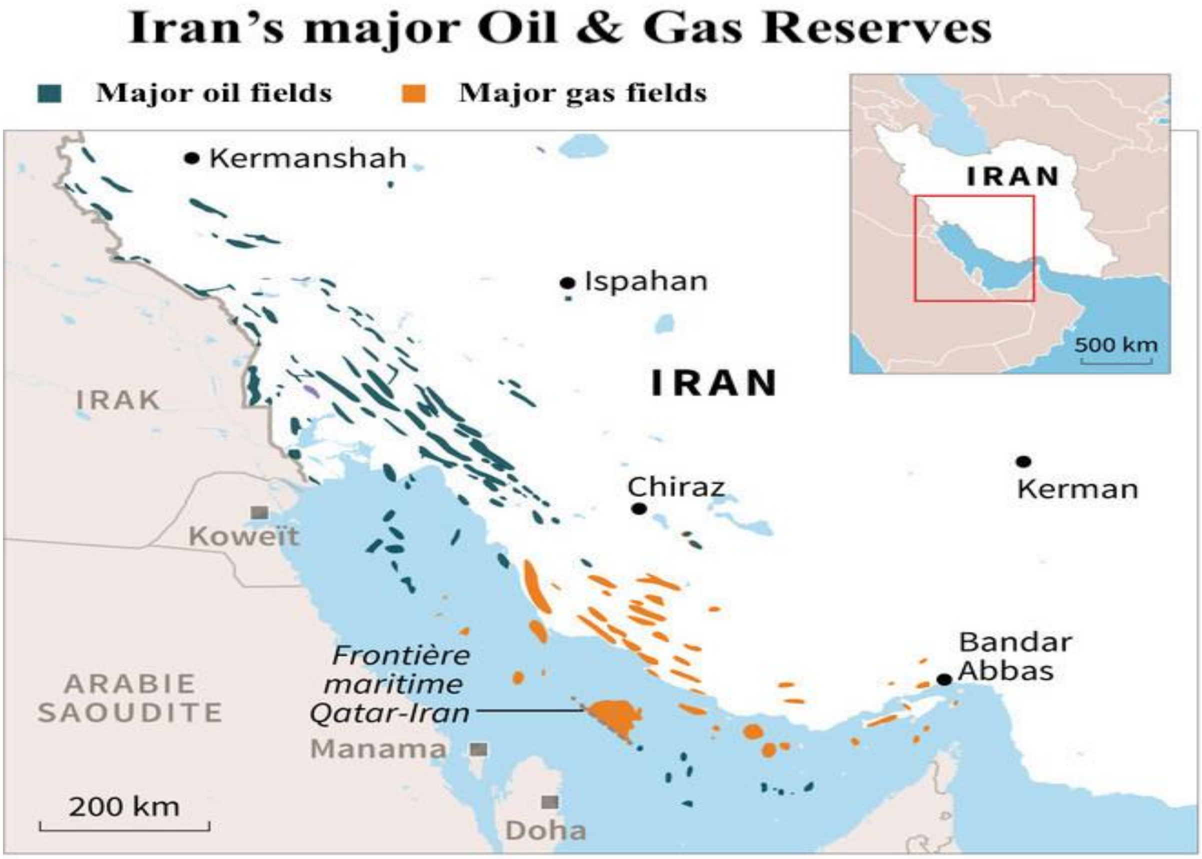
Source: Organization of the Petroleum Exporting Countries. (2019). OPEC Annual Statistical Bulletin 2019. *Table1.1. Vienna, Austria: Organization of the Petroleum Exporting Countries*

Figure 4-17. U.S. sanctions effect on Iran's oil output



Source: BBC News. (2019, December). Six charts that show how hard US sanctions have hit Iran. Retrieved from https://www.bbc.com/news/world-middle-east-48119109

Figure 4-18. Iran's biggest Oil & Gas reserves



Source: OPEC Says Iran's Oil Production Down By 1.65 Million bpd Since US Sanctions. (2019, November). Retrieved from https://en.radiofarda.com/a/opec-says-iran-s-oil-production-down-by-1-65-million-bpd-since-us-sanctions/30272297.html

Most Iranian reserves are located in onshore fields in the southwestern part of the country, an area with an aggregate production of about 85% of Iran's total crude oil output [121]. The National Iranian Oil Company (NIOC), Iran's state-owned oil and gas company produces several crude oil grades, out of which the most-traded are Iranian Heavy and Iranian Light.

Table 4-10. Iran's main crude oil grades

Iran's Main Crude oil Grades		
Crude Grades	**API Gravity**	**Sulphur Content**
Soroosh/Nowruz	18.90°	3.88%
Iranian Heavy	29.60°	2.24%
Forozan	30.40°	2.21%
Sirri	33.00°	1.83%
Iranian Light	33.60°	1.46%
Lavan Blend	35.40°	1.67%

Source: National Iranian Oil Company (NIOC). (n.d.). Crude Oil Specifications. Retrieved from https://www.nioc-intl.com/EN/CrudeSpec.aspx

4.7.1.4 Kuwait

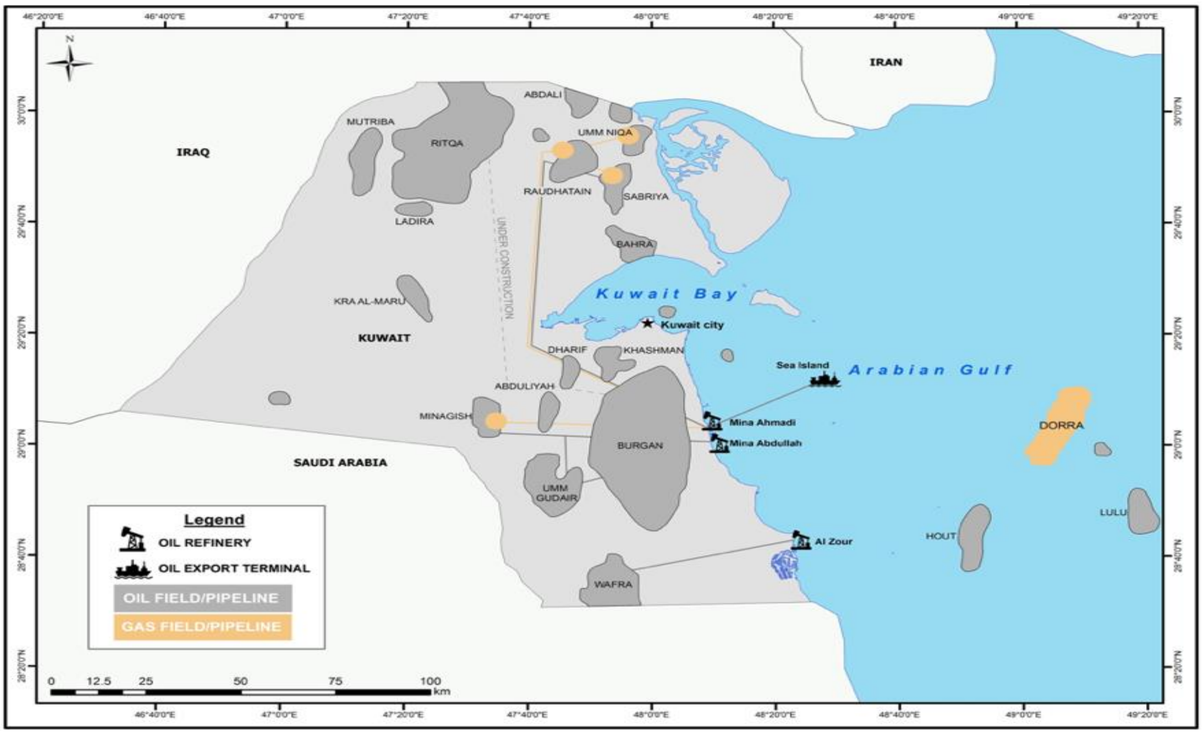
Despite its small size (about 6,900 sq. miles), Kuwait maintained during 2019 the 4th largest daily crude oil production among OPEC members [90]. Kuwait holds the 6th position globally in terms of proved oil reserves among oil, accounting for nearly 6% of the world's total proved reserves [88]. Kuwait's economy is heavily dependent on crude oil exports revenues, which accounted for roughly 71% of the government's total revenues in 2018, according to IMF estimates [59]. The country's state-owned oil company, Kuwait Petroleum Corporation (KPC) plans to raise crude oil production to 4 million b/d by end of 2020 [65].

Table 4-11. Kuwait's crude oil production

Kuwait 2018 Data		
	Unit	**Value**
Crude oil production	(1,000 b/d)	2,736.60
Crude oil exports	(1,000 b/d)	2,050.00
Crude Oil Consumption	(1,000 b/d)	352.90
Proven crude oil reserves	(million barrels)	101,500.00
GDP at market prices	(million $)	141,705.00
Value of petroleum exports	(million $)	71,931.00

Source: Organization of the Petroleum Exporting Countries. (2019). OPEC Annual Statistical Bulletin 2019. *Table1.1. Vienna, Austria: Organization of the Petroleum Exporting Countries*

Figure 4-19. Kuwait's major oil fields and infrastructure



Source: Kuwait Institute of Scientific Research (2018)

Kuwait has several oil fields spread across the country's territory as illustrated in Figure 4-19. Nearly half of Kuwait's total petroleum production comes from the Burgan field, which is the second-largest oil field in the world in terms of proved reserves, only surpassed by Saudi Arabia's Ghawar field.

Kuwait produces a range of light to heavy crudes which are blended into a single grade, producing Kuwait Blend, a medium sour crude. The crude stream is exported to foreign markets via Mina Al-Ahmadi terminal.

Table 4-12. Kuwait's crude oil grades

Kuwait's Crude oil Grades		
Crude oil Grade	**API Gravity**	**Sulphur Content**
Kuwait Blend	30.20°	2.72%

Source: Crude Grades. (n.d.). Retrieved from https://www.mckinseyenergyinsights.com/resources/refinery-reference-desk/crude-grades/

4.7.1.5 United Arab Emirates (UAE)

The United Arab Emirates comprises seven emirates – Abu Dhabi, Ajman, Dubai, Fujairah, Ras Al-Khaimah, Sharjah and Umm Al-Quwain – located along the southeast coast of the Arabian Peninsula. According to OPEC data, UAE was the third-largest crude oil producer during 2019, among OPEC members [90]. The Emirates are heavily dependent on petroleum exports revenues, which in 2018 accounted for more than 55% of the government's annual revenues, according to IMF estimates [58].

Table 4-13. United Arab Emirates crude oil

UAE 2018 Data		
	Unit	**Value**
Crude oil production	(1,000 b/d)	3,008.30
Crude oil exports	(1,000 b/d)	2,296.50
Crude Oil Consumption	(1,000 b/d)	885.20
Proven crude oil reserves	(million barrels)	97,800.00
GDP at market prices	(million $)	414,179.00
Value of petroleum exports	(million $)	74,940.00

Source: Organization of the Petroleum Exporting Countries. (2019). OPEC Annual Statistical Bulletin 2019*. Table1.1. Vienna, Austria: Organization of the Petroleum Exporting Countries*

Among the seven emirates, Abu Dhabi and Dubai are the major oil producers with the majority of produced oil coming from Abu Dhabi oil fields. The latter is home to Upper Zakum oilfield, which with an estimated 50 billion barrels of proven oil reserves is the fourth-largest oilfield in the world. Abu Dhabi produces mainly three crude oil grades: Murban, Upper Zakum and Das Blend, with Murban grade being the flagship crude of the country. Das blend crude stream was introduced in 2014 and is a blend of two pre-existing streams – the Umm Shaif and Lower

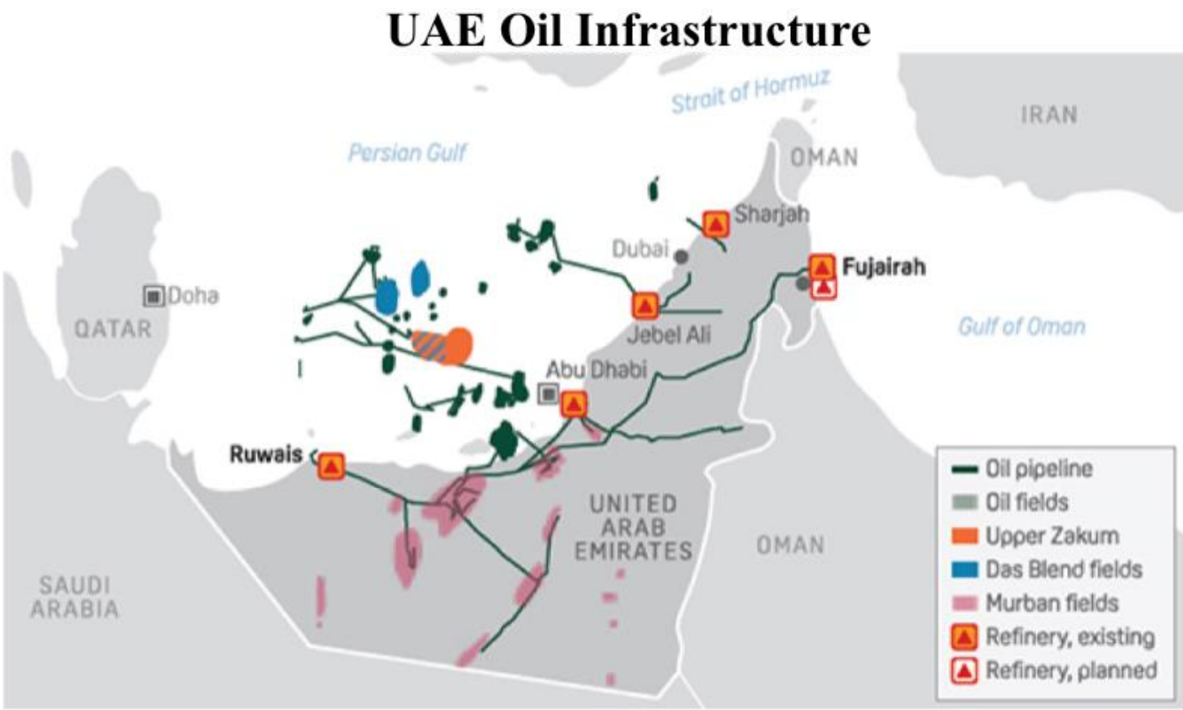
Zakum crude oil streams. In 2018, Abu Dhabi National Oil Company (ADNOC) introduced Umm Lulu, a new light sweet crude oil stream, with initial production of 50,000 b/d and plans of increasing it in the future (Reuters, 2018). Dubai is exporting the Dubai grade, otherwise known as Fateh grade.

Table 4-14. United Arab Emirates crude oil grades

UAE Main Crude oil Grades		
Crude oil Grade	**API Gravity**	**Sulphur Content**
Abu Dhabi		
Murban	40.31°	0.77%
Upper Zakum	34.11°	1.95%
Das Blend	38.79°	1.14%
Umm Lulu	38.70°	0.70%
Dubai		
Dubai (or Fateh)	31.00°	2.10%

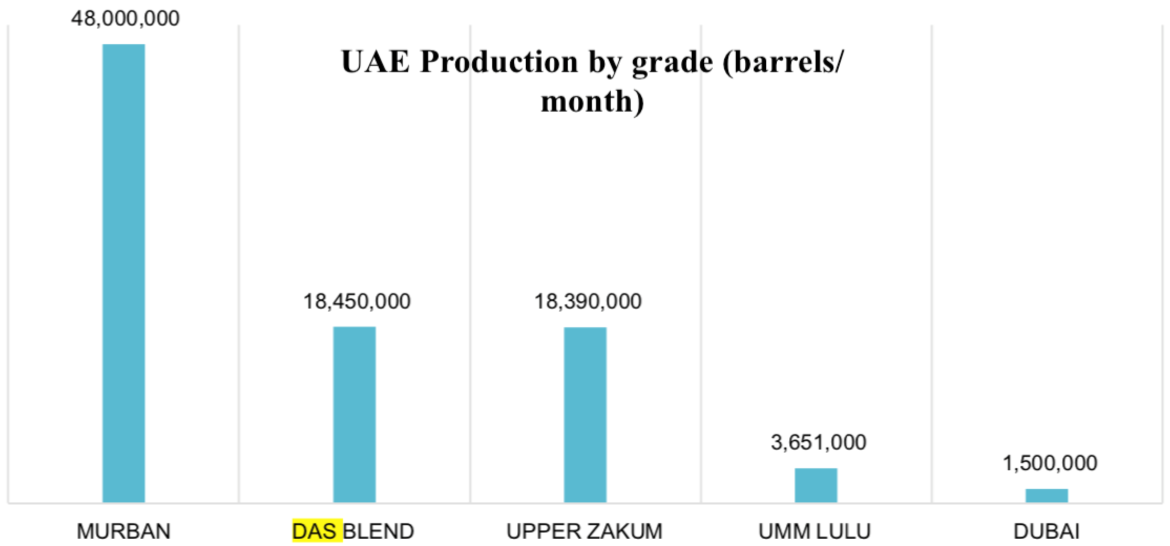
Source: Abu Dhabi National Oil Company. (ADNOC) (n.d.). Product Specifications: Crude and Condensates. Retrieved from https://www.adnoc.ae/en/doing-business-with-us/product-specifications#F0EE107F71DE4FA5AB31CEACB2CA5864

Figure 4-20. United Arab Emirates oilfields and pipelines network



Source: S&P Global Platts

Figure 4-21 UAE's oil grades monthly production

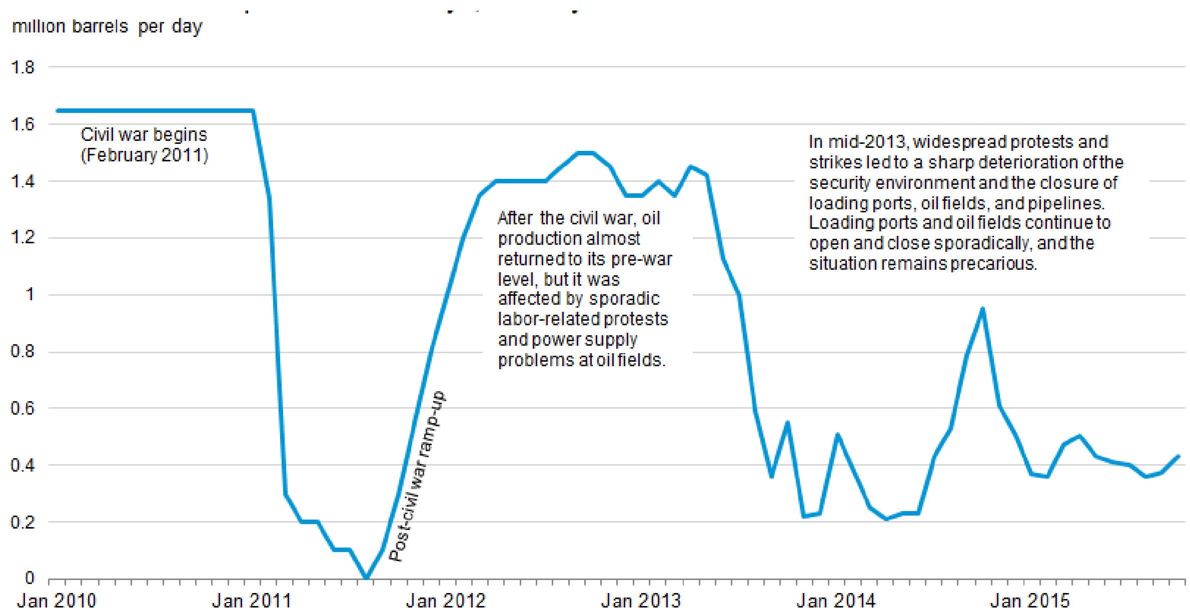


Source: S&P Global Platts

4.7.1.6 Libya

Libya is a member of OPEC and holds the largest proved crude oil reserves in Africa. Libya's economy is heavily dependent on crude oil and gas exports revenues, which accounted for nearly 96% of the government's total revenues in fiscal year 2012, according to IMF estimates. Libya's hydrocarbon production and exports have been substantially affected the past years (Figure 4-22) by civil war, protests and shutdown of oil terminals and facilities caused by the country's militia forces that gained power after Gadhafi's overthrow in 2011.

Figure 4-22. Social unrest and internal conflicts' negative effect in Libya's crude oil production (2010-2015)



Source: U.S. Energy Information Administration. (2015, November). Short-Term Energy Outlook.

Table 4-15. Libya's crude oil

Libya 2018 Data		
	Unit	**Value**
Crude oil production	(1,000 b/d)	951.20
Crude oil exports	(1,000 b/d)	998.50
Crude Oil Consumption	(1,000 b/d)	214.80
Proven crude oil reserves	(million barrels)	48,363.00
GDP at market prices	(million $)	49,716.00
Value of petroleum exports	(million $)	17,141.00

Source: Organization of the Petroleum Exporting Countries. (2019). OPEC Annual Statistical Bulletin 2019. *Table1.1. Vienna, Austria: Organization of the Petroleum Exporting Countries*

Libya produces and exports several different crude oil streams, the majority of which are sweet crudes of light to medium density.

Table 4-16. Libya's main crude oil grades

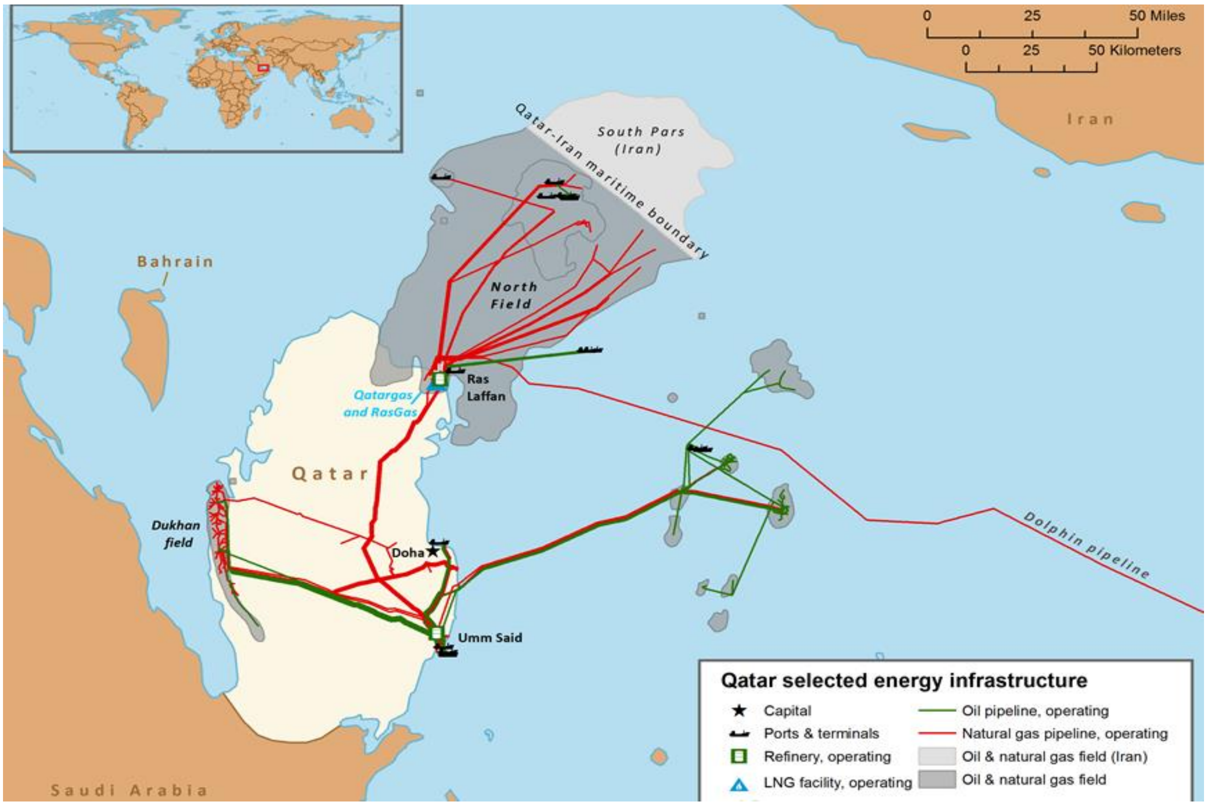
Libya's Main Crude oil Grades		
Crude oil Grade	**API Gravity**	**Sulphur Content**
El Sharara	43.1°	0.08%
Brega	42.0°	0.22%
Zuetina Blend	41.5°	0.31%
Sirtica	41.0°	0.40%
Sarir	38.0°	0.83%
Amna	37.0°	0.17%
Es Sider	36.2°	0.49%
Al-Jurf	30.0°	1.90%
Bouri	26.3°	1.91%

Crude Grades. (n.d.). Retrieved from https://www.mckinseyenergyinsights.com/resources/refinery-reference-desk/crude-grades/

4.7.1.7 Qatar

Qatar was for a long a member of OPEC, however it terminated its membership in January 2019. The small Arab country is the largest exporter of liquefied natural gas (LNG) in the world, and the government's revenues are heavily dependent on crude oil and LNG exports, according to U.S. IEA. All of the country's oil and gas activities are operated by Qatar Petroleum, the state-owned petroleum company of Qatar. According to data analytics web provider, Trading Economics, the small Arab country produced an average of 1.52 million b/d of crude oil during 2019. Qatar's proven oil reserves were estimated in 2015 at roughly 25.2 billion barrels, according to U.S. IEA's data [114].

Figure 4-23. Qatar Oil & Gas infrastructure



Source: U.S. Energy Information Administration (2015, October). Qatar: International energy data and analysis Report. Retrieved from

Qatar produces and exports two individual crude grades, Qatar Marine and Qatar Land, both of them sour grades.

Table 4-17. Qatar's main exported crude oil grades

Qatar's Crude oil Grades		
Crude oil Grade	**API Gravity**	**Sulphur Content**
Qatar Marine	32.00°	2.17%
Qatar Land	40.00°	1.35%

Source: Qatar Petroleum Company. (n.d.). Crude Oil. Retrieved from https://qp.com.qa/en/marketing/Pages/RP_CrudeOil.aspx

4.7.2 West Africa

4.7.2.1 Nigeria

Nigeria is currently the largest oil producer in Africa and 6th among OPEC members. The country has the second largest proved crude oil reserves in Africa. Nigeria's economy is heavily dependent on crude oil and gas exports revenue, which accounted for roughly 58% of the government's total revenues in 2014, according to IMF estimates. Nigeria's oil production has declined in the last years due to public unrest and violence that has surged due to the increasing power of paramilitary forces (Figure 4-24).

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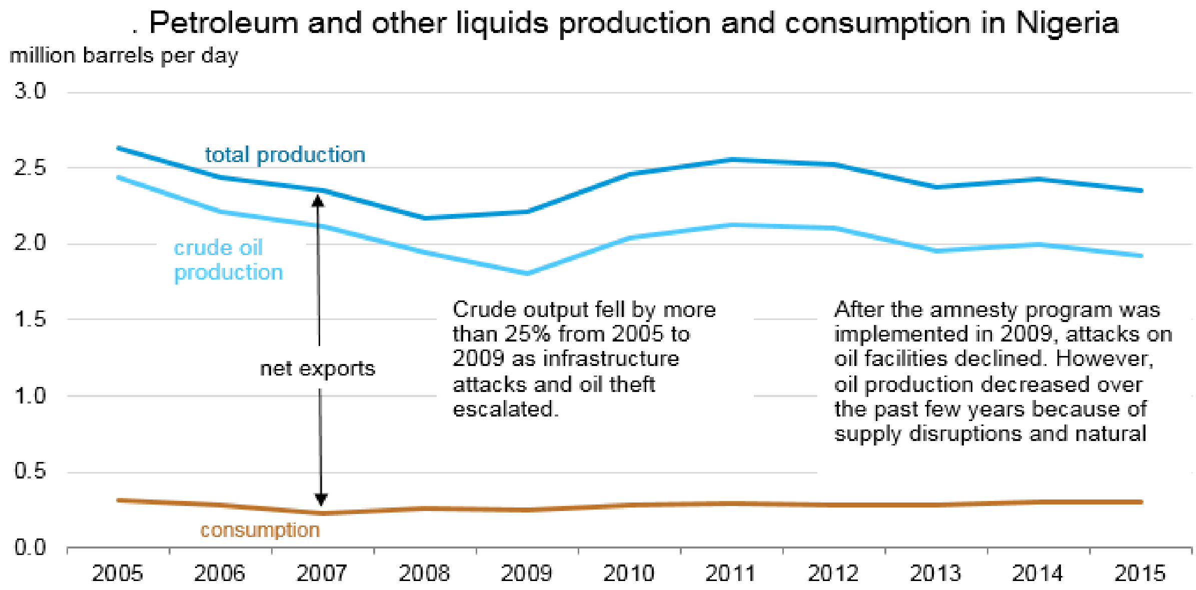
Figure 4-24. Public unrest and violence outbreaks' negative effects on Nigerian crude oil output



Source: U.S. Energy Information Administration. (2016, May). Country Analysis Brief: Nigeria. Retrieved from https://www.eia.gov/international/content/analysis/countries_long/Nigeria/nigeria.pdf

Table 4-18 Nigeria's crude oil

Nigeria 2018 Data		
	Unit	**Value**
Crude oil production	(1,000 b/d)	1,601.60
Crude oil exports	(1,000 b/d)	1,979.50
Crude Oil Consumption	(1,000 b/d)	445.50
Proven crude oil reserves	(million barrels)	36,972.00
GDP at market prices	(million $)	417,410.00
Value of petroleum exports	(million $)	54,513.00

Source: Organization of the Petroleum Exporting Countries. (2019). OPEC Annual Statistical Bulletin 2019. *Table1.1. Vienna, Austria: Organization of the Petroleum Exporting Countries*

Nigeria produces and exports several crude oil grades, the majority of which are sweet and of light to medium API gravity.

Table 4-19. Nigeria's main crude oil grades

Nigeria's Main Crude oil Grades		
Crude oil Grade	**API Gravity**	**Sulphur Content**
Oso	49.2°	0.03%
Agbami	47.9°	0.04%
Akpo	45.8°	0.07%
Okono	41.9°	0.06%
Yoho Light	40.5°	0.06%
Qua Iboe	37.6°	0.10%
Amenam	37.0°	0.17%
Brass Blend	*36.5°*	*0.13%*
Pennington	35°	0.08%
Escravos	33.7°	0.16%
Bonny Light	32.9°	0.16%
Zafiro Blend	30.0°	0.25%
Forcados	30.0°	0.15%
Bonga	28.6°	0.25%

Source: Data from McKinsey Energy Insights (2020), ExxonMobil database (2020), Equinor database (2020) and America Hope Petroleum

Figure 4-25. West African oil producing countries

Source: U.S. Energy Information Administration

4.7.2.2 Angola

According to OPEC's 2019 data, Angola is the second-largest oil producer in Africa and 7th among OPEC members. The country experienced an oil production boom between 2002 and 2008 as exploitation of deep-water fields began to take off [123].

Table 4-20. Angola's crude oil

Angola 2018 Data		
	Unit	**Value**
Crude oil production	(1,000 b/d)	1,473.30
Crude oil exports	(1,000 b/d)	1,420.60
Crude Oil Consumption	(1,000 b/d)	120.80
Proven crude oil reserves	(million barrels)	8,160.00
GDP at market prices	(million $)	99,150.00
Value of petroleum exports	(million $)	36,323.00

Source: Organization of the Petroleum Exporting Countries. (2019). OPEC Annual Statistical Bulletin 2019. *Table1.1. Vienna, Austria: Organization of the Petroleum Exporting Countries*

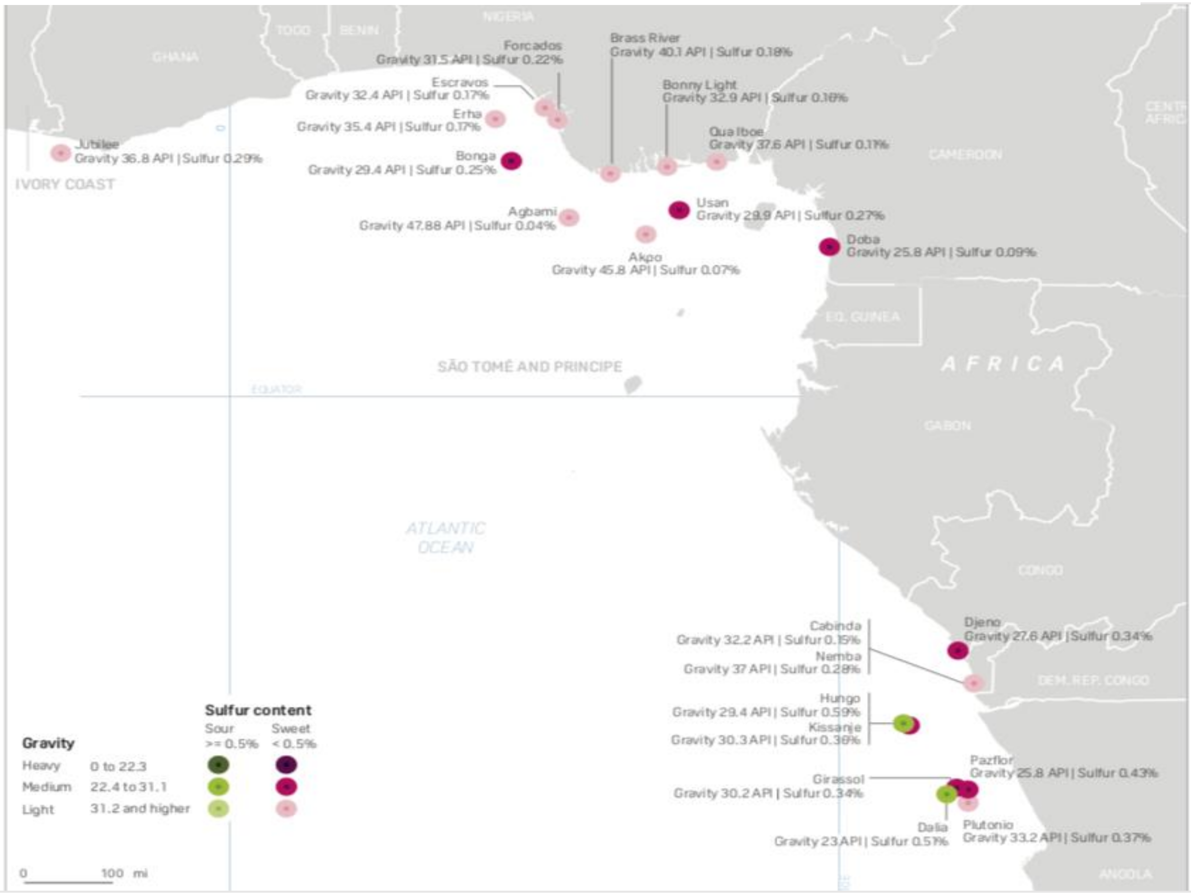
Angola produces several crude streams the majority of which have and light to medium density and in general low sulphur content.

Table 4-21. Angola's main crude oil grades

Angola's Main Crude oil Grades		
Crude oil Grade	**API Gravity**	**Sulphur Content**
Nemba	38.7°	0.19%
Palanca Blend	37.2°	0.18%
Xicomba	34.9°	0.36%
Saxi Batuque Blend	33.9°	0.26%
Cabinda Blend	32.0°	0.12%
Kissanje Blend	31.3°	0.40%
Girassol	30.2°	0.34%
Hungo Blend	29.5°	0.60%
Saturno	27.6°	0.80%
Pazflor	24.1°	0.41%
Dalia	22.9°	0.50%

Source: Data from SonAngol Group (2020) and Equinor database (2020).

Figure 4-26. West African crude oils delivery points



Source: S&P Global Platts

4.7.2.3 Congo

The majority of Congo's crude oil production comes from offshore oil fields. The country is a member of OPEC and ranks among the lowest positions in terms of petroleum production, among the oil cartel's members. Congo's economy is heavily dependent on crude oil exports revenues, which accounted for almost 87% of the government's total revenue in 2011, according to IMF estimates.

Table 4-22 Congo's crude oil production

Congo 2018 Data		
	Unit	**Value**
Crude oil production	(1,000 b/d)	323.50
Crude oil exports	(1,000 b/d)	307.10
Crude Oil Consumption	(1,000 b/d)	8.50
Proven crude oil reserves	(million barrels)	2,982.00
GDP at market prices	(million $)	10,160.00
Value of petroleum exports	(million $)	4,455.00

Source: Crude Assays. (n.d.). Retrieved from https://www.totsa.com/pub/crude/index2.php?expand=1&iback=1&rub=11&image=africa

Congo produces three crude grades, the most traded of which is the medium sweet Djeno crude oil.

Table 4-23 Congo's crude oil grades

Congo's Crude oil Grades		
Crude oil Grade	**API Gravity**	**Sulphur Content**
N'kossa	39.93°	0.06%
Kitina	36.40°	0.11%
Djeno	27.6°	0.34%

Source: Crude Assays. (n.d.). Retrieved from https://www.totsa.com/pub/crude/index2.php?expand=1&iback=1&rub=11&image=africa

4.7.2.4 Cameroon

Cameroon has the lowest crude oil production among African countries. According to data analysis web provider, Knoema, Cameroon's crude production averaged at 70,000 b/d during 2019. The country produces two sweet crude grades.

Table 4-24 Cameroon's crude oil grades

Cameroon's Crude oil Grades		
Crude oil Grade	**API Gravity**	**Sulphur Content**
Kole	30.98°	0.33%
Lokele	20.20°	0.45%

Source: Crude Assays. (n.d.). Retrieved from https://www.totsa.com/pub/crude/index2.php?expand=1&iback=1&rub=11&image=africa

4.7.3 North Africa

4.7.3.1 Algeria

Algeria is a major crude oil and natural gas producer in Africa and has been a member of OPEC since 1969. Petroleum exports revenues are the driving force of the country's economy, accounting for more than 30% of the government's total revenue during fiscal year 2016, according to IMF data [57].

Table 4-25. Algeria's crude oil production

Algeria 2018 Data		
	Unit	**Value**
Crude oil production	(1,000 b/d)	1,040.10
Crude oil exports	(1,000 b/d)	571.00
Crude Oil Consumption	(1,000 b/d)	431.40
Proven crude oil reserves	(million barrels)	12,200.00
GDP at market prices	(million $)	178,259.00
Value of petroleum exports	(million $)	26,092.00

Source: Organization of the Petroleum Exporting Countries. (2019). OPEC Annual Statistical Bulletin 2019. *Table1.1. Vienna, Austria: Organization of the Petroleum Exporting Countries*

Algeria extracts petroleum form several oil fields, the production of all which combines into one individual light sweet grade, the Sahara blend.

Table 4-26. Algeria's crude oil grades

Algeria's Crude oil Grades		
Crude oil Grade	**API Gravity**	**Sulphur Content**
Saharan Blend	45.30°	0.10%

Source: U.S. Energy Information Administration. (2019, March). A Background's Reference: Algeria. [PDF file]. Retrieved from https://www.eia.gov/international/content/analysis/countries_long/Algeria/Algeria_background.pdf

4.7.4 Latin America

4.7.4.1 Venezuela

Venezuela is a member of OPEC. The country holds the largest proven oil reserves in the world, surpassing Saudi Arabia's humongous reserves by more than 30 billion barrels of crude oil as seen in Table 4-27 Venezuela's crude oil production. Venezuela's financial welfare relies heavily on petroleum exports revenues, which during 2018 constituted 99% of the government's total income (Table 4-27 Venezuela's crude oil production).

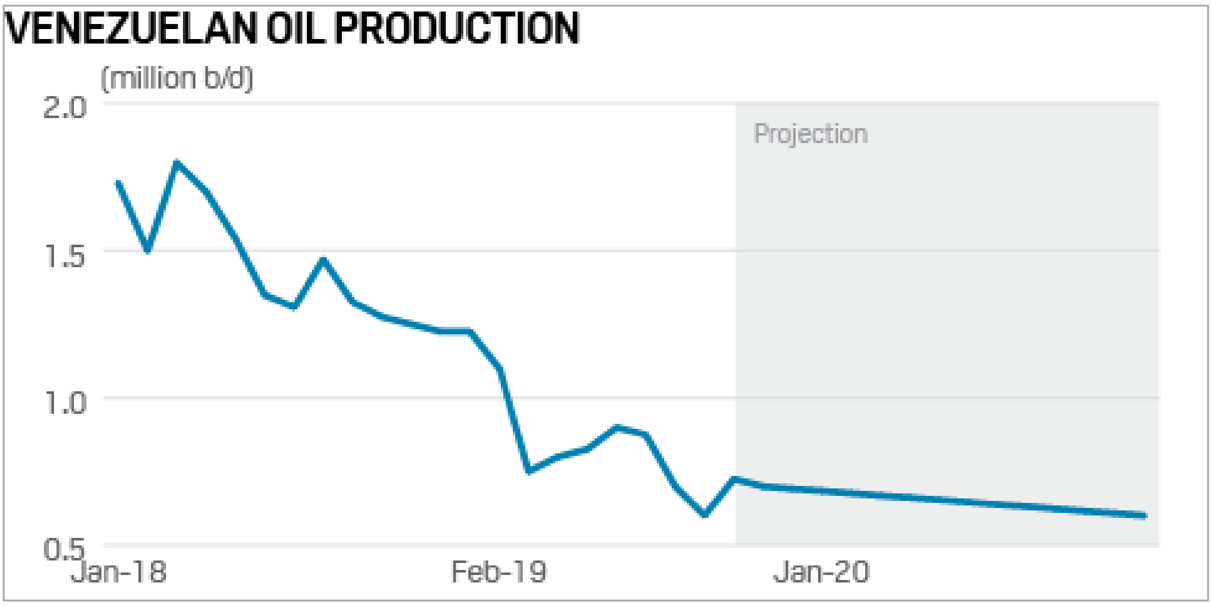
The last years, U.S. government has imposed severe financial sanctions on several high-ranking Venezuelan officials associated with Nicolás Maduro's administration, Venezuelan banks and companies. The latest sanctions included the country's state-owned oil company – PdVSA – operations, causing a tremendous decline in the country's oil production, as seen in Figure 4-27 Venezuela's oil production According to OPEC data, Venezuela's daily oil production fluctuated at around 660,000 b/d during Q4 2019 [90].

Table 4-27 Venezuela's crude oil production

Venezuela 2018 Data (Source)		
	Unit	**Value**
Crude oil production	(1,000 b/d)	1,510.20
Crude oil exports	(1,000 b/d)	1,273.10
Crude Oil Consumption	(1,000 b/d)	402.00
Proven crude oil reserves	(million barrels)	302,809.00
GDP at market prices	(million $)	98,468.00
Value of petroleum exports	(million $)	34,674.00
Value of exports	(million $)	34,996.00

Source: U.S. Energy Information Administration. (2019, March). A Background's Reference: Algeria. [PDF file]. Retrieved Organization of the Petroleum Exporting Countries. (2019). OPEC Annual Statistical Bulletin. Table1.1,. Vienna, Austria: Organization of the Petroleum Exporting Countries

Figure 4-27 Venezuela's oil production



Source: U.S. Energy Information Administration. (2019, March). A Background's Reference: Algeria. [PDF file]. Retrieved Organization of the Petroleum Exporting Countries. (2019). OPEC Annual Statistical Bulletin. Table1.1,. Vienna, Austria: Organization of the Petroleum Exporting Countries

Most of Venezuelan crude oil reserves are heavy and sour, thus requiring somewhat expensive refining and processing. Hence, they cannot be processed everywhere, but only in specialized facilities making traders and refineries to turn to grades of better quality in the international crude oil markets.

Table 4-28. Biggest oil reserves' holders in the world

Top 8 countries for proved oil reserves, Jan. 2017	
Country	**Billion barrels**
Venezuela	300.9
Saudi Arabia	266.5
Canada	169.7
Iran	158.4
Iraq	142.5
Kuwait	101.5
United Arab Emirates	97.8
Russia	80.0

Source: U.S. Energy Information Administration. (2019, January). Country Analysis Executive Summary: Venezuela *[PDF file]. Retrieved from https://www.eia.gov/international/content/analysis/countries_long/Algeria/Algeria_background.pdf*

Table 4-29. Venezuela's main crude oil grades

Venezuela's Main Crude oil Grades		
Crude oil Grade	**API Gravity**	**Sulphur Content**
Tia Juana Light	31.9°	1.18%
Lagomedio	31.6°	1.26%
Mesa	30.5°	0.85%
Lagotreco	30.4°	1.28%
Mesa 28	28.0°	1.18%
Leona	25.3°	1.52%
BCF-24	23.7°	1.88%
Menemota	20.7°	2.07%
Cerro Negro	16.0°	3.34%
BCF-17	13.5°	2.30%
Tia Juana Heavy	12.3°	2.82%
Bachaquero-13	12.2°	2.80%
Laguna	10.9°	2.66%
Boscan	10.9°	2.66%

Source: Venezuela Crude oil specifications. (n.d.). Retrieved from https://blacklion-trading.com/venezuela-crude-oil-2/

4.7.5 North Sea Fields

North Sea area is home to one of the most extensive and complex offshore oil and gas extraction projects in the world. More than 256 oil fields have been drilled and are producing crude oil of generally light to medium density and low sulphur content. Norway leads the crude production race extracting roughly 1.5 million b/d during 2018, according to Norwegian Petroleum Directorate's estimates [80]. The United Kingdom is second, with an average production of 1.09 million b/d in 2018, as stated in UK's Oil & Gas Authority reports [84]. Both countries produce several individual crude oil grades. Most grades come from the combined production of several oil fields, the streams of which travel and mix inside an extensive subsea pipelines network and end up in a few oil terminals in both countries (Figure 4-28). Despite, the low production volumes comparing to the big oil producers such as Saudi Arabia, North Sea produces some of the most well-known grades traded in the international oil markets. Brent blend, Ekofisk blend, Forties blend and Oseberg blend are a long time now the driving force of the North Sea's oil scene and together make up the basis for the price assessment of Brent Price Index, the reference price for 70% of the world's crude oil output.

Table 4-30. Norway's main crude oil grades

Norway's Main Crude oil Grades		
Crude oil Grade	**API Gravity**	**Sulphur Content**
Snohvit (Condensate)	63.7°	0.01%
Ormen Lange	62.5°	0.00%
Gudrun Blend	50.8°	0.07%
Njord	46.6°	0.05%
Skarv	44.3°	0.18%
Jotun	41.5°	0.17%
Aasta Hansteen	40.7°	0.03%
Draugen	40.0°	0.15%
Oseberg	39.6°	0.20%
Statfjord	39.5°	0.22%
Gullfaks	39.2°	0.20%
Goliat Blend	39.0°	0.19%
Ekofisk	38.9°	0.21%
Gina Krog	38.8°	0.25%
Alvheim blend	34.9°	0.17%
Troll	34.5°	0.18%
Norne Blend	29.6°	0.30%
Grane Blend	29.0°	0.59%
Johan Sverdrup	28.0°	0.80%

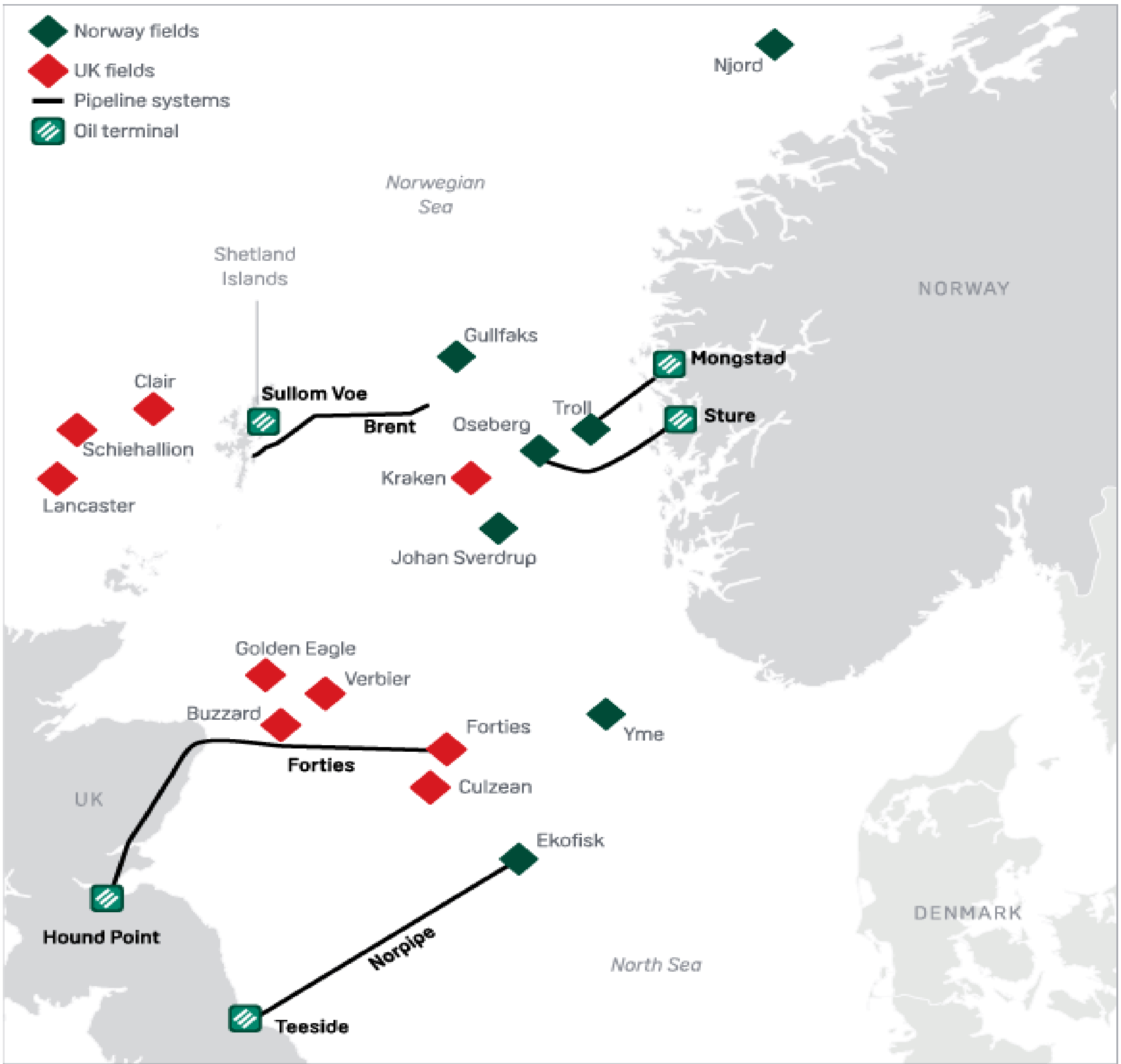
Source: Crude oil assays. (n.d.). Retrieved from https://www.equinor.com/en/what-we-do/crude-oil-and-condensate-assays.html

Table 4-31. UK's main crude oil grades

UK Main Crude oil Grades		
Crude oil Grade	**API Gravity**	**Sulphur Content**
Forties Blend	40.1°	0.67%
Mariner Blend	15.2°	1.10%
Brent Blend	40.1°	0.35%
Triton Blend	36.9°	0.39%

Source: Crude oil assays. (n.d.). Retrieved from https://www.equinor.com/en/what-we-do/crude-oil-and-condensate-assays.html

Figure 4-28. North Sea's oilfields and pipelines

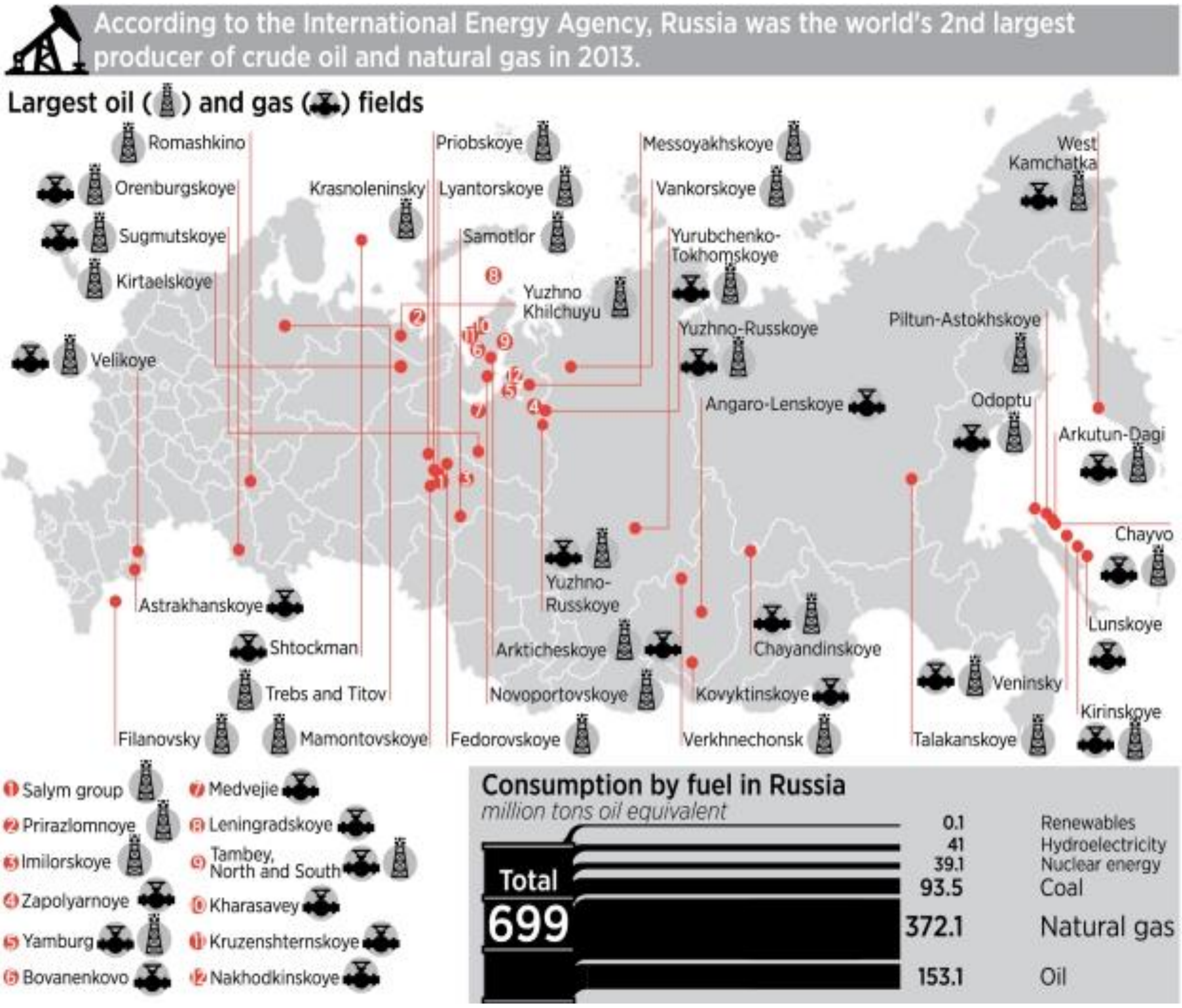


Source: S&P Global Platts

4.7.6 Russia

As of 2020, Russia is the second-largest crude oil producer in the world. Most of the country's oil production comes from oilfields in West Siberia and the Urals-Volga regions (Table 4-33). During the last years, new exploration projects in Arctic regions and East Siberia have begun and petroleum engineers' estimates have shown promising commercially recoverable reserves. The Siberian country has some of the world's largest proven oil reserves, amounting for roughly 80 billion barrels, according to U.S. IEA 2017 estimates [117].

Figure 4-29. Russia's major oil fields and gas reserves



Source: U.S. Energy Information Administration (2020) and BP (2020).

Russia is producing several different crude oil grades. The Russian Export Blend Crude Oil (REBCO) is the country's primary export blend and comes in two main qualities, Urals Blend and Siberian Light.

Table 4-32. Russia's main crude oil grades

Russia's Main Crude oil Grades		
Crude oil Grade	**API Gravity**	**Sulphur Content**
Urals blend	31.0°	1.40%
Sokol	35.5°	0.28%
ESPO blend	36.0°	0.47%
Sakhalin blend	42.5°	0.16%
Arctic Oil (ARCO)	24.0°	2.30%
Siberian Light	35.8°	0.57%
Novy Port	30.0-35.0°	0.10%

U.S. Energy Information Administration. (2017, October). Country Analysis Brief: Russia. Retrieved from https://www.eia.gov/international/content/analysis/countries_long/Russia/russia.pdf

Table 4-33. Russian oil production by region

Russia's oil production by region, 2016	
Region	**Thousand b/d**
Western Siberia	6,294
Khanty-Mansiisk	4,830
Yamal-Nenets	977
Other West Siberia	487
Urals-Volga	2,498
East Siberia and the Far East	1,338
Krasnoyarsk	426
Irkutsk	364
Sakhalin	344
Yakutia	204
Other + Arctic offshore	689
Total	**10,818**

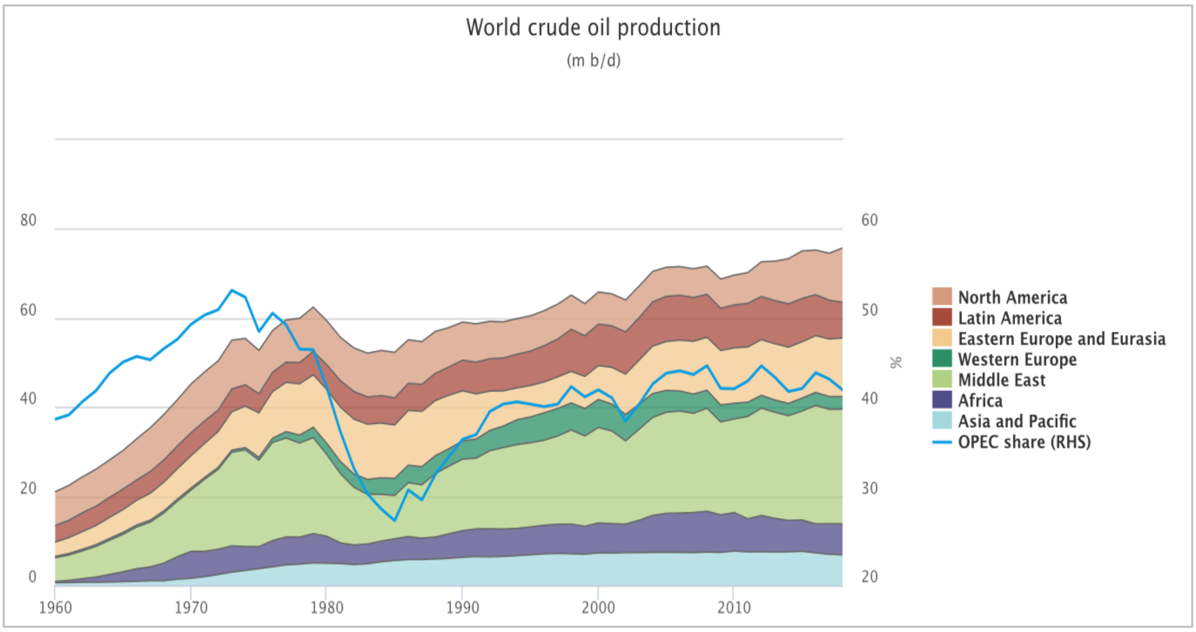
Source: U.S. Energy Information Administration. (2017, October). Country Analysis Brief: Russia. Retrieved from https://www.eia.gov/international/content/analysis/countries_long/Russia/russia.pdf

4.8 The role of OPEC

The Organization of the Petroleum Exporting Countries (OPEC) is a permanent, intergovernmental Organization created on September 1960, by Iran, Kuwait, Saudi Arabia and Venezuela. The five founding members were later joined by ten other countries. As of 2020, the organization consists of fourteen of the world's major oil-exporting nations. Initially, OPEC has its headquarters in Geneva, Switzerland, however since September 1, 1965, it is based in Vienna, Austria.

OPEC's objective is to provide technical guidance, economic aid and market intelligence to its members; moreover, it aims to coordinate the petroleum policies of its members and adjust their crude oil supply in an effort to exert influence in global oil prices, and maintain them to levels that will be beneficial for the organization's members. OPEC's members aggregate oil production amounts to a huge share of total global oil production, thus giving the oil cartel a critical role in the global oil scene and therefore the energy landscape. According to the organization's latest data, its members hold more than 75% of the world's total proven petroleum reserves.

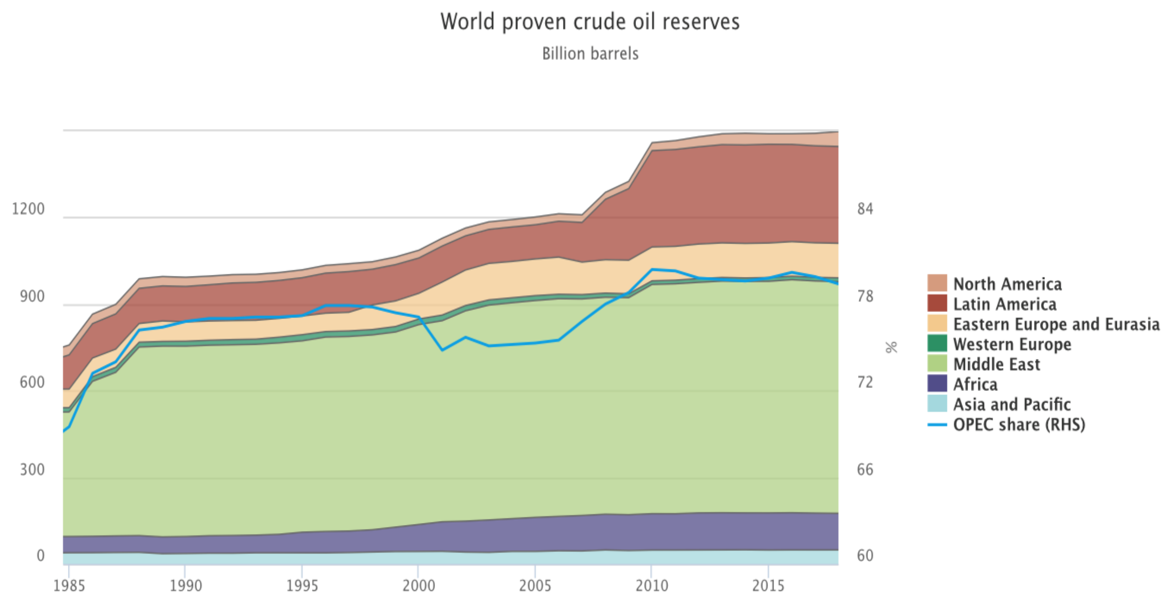
Figure 4-30. World crude oil production (1960-2015)



Source: Organization of the Petroleum Exporting Countries. (2019). OPEC Annual Statistical Bulletin 2019. *Vienna, Austria: Organization of the Petroleum Exporting Countries*

During 2018, the oil cartel's aggregate crude oil production fluctuated around 31.8 million b/d [90]. Top oil producers Russia and U.S. are not members of the organization, thus having the ability to freely manage their production and are not constrained by other nations' interests and decisions. The shale oil boom that started in 2011 in the U.S. reduced the oil cartel's share in the global oil production, thus lessening its influence in the oil markets. As countermeasures to the U.S. ever-increasing power, OPEC took advantage of its members' low break-even costs and oversupplied the market in an effort to reduce oil prices and put under financial pressure countries with high break-even cost e.g. Canada's costly oil-sands reserves.

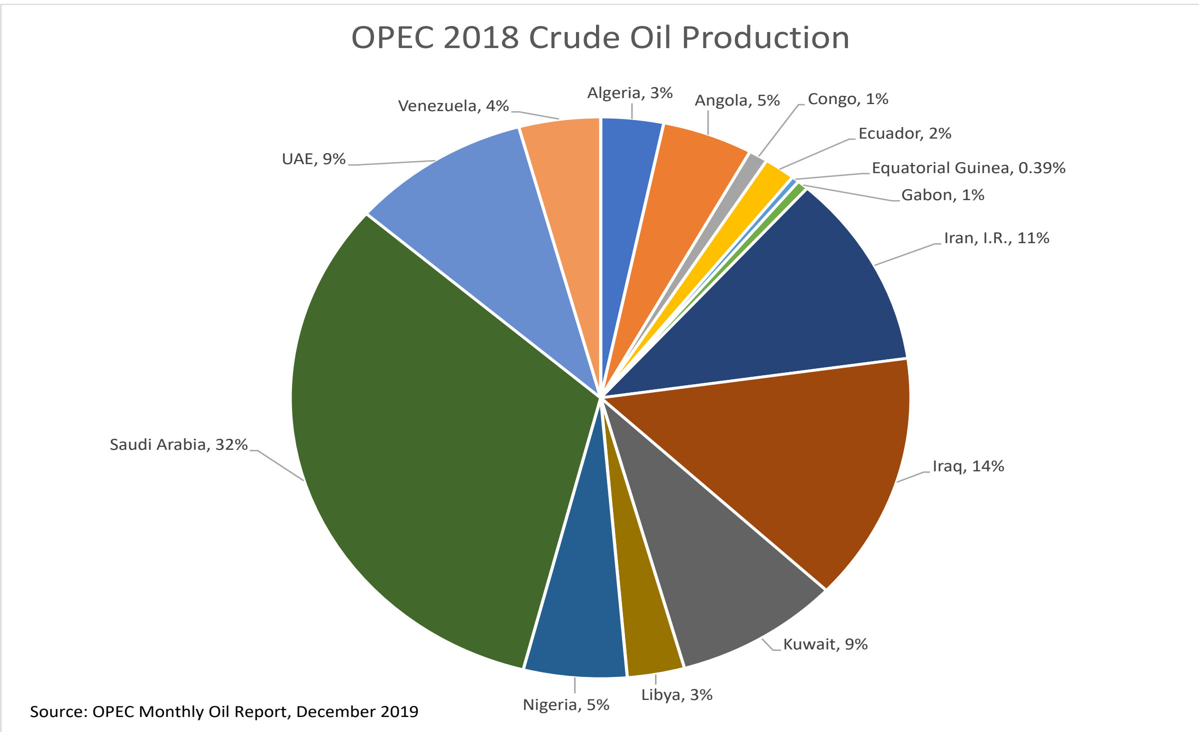
Figure 4-31. World proven oil reserves (1975-2017)



Source: Organization of the Petroleum Exporting Countries. (2019). OPEC Annual Statistical Bulletin 2019. *Vienna, Austria: Organization of the Petroleum Exporting Countries*

OPEC members meet at least twice a year and decide upon each country's quotas regarding crude oil production, according to markets conditions. Since every member is responsible for reporting its monthly crude production, there is room for "cheating" upon the pre-determined quotas. Nevertheless, regular violation of the organization's official policies may lead to the termination of a country's membership.

Figure 4-32. OPEC monthly crude oil production during 2018



Source: Organization of the Petroleum Exporting Countries. (2019, December). OPEC Monthly Oil

4.9 Crude oil Pricing and Benchmarks

Crude oil has long now become the world's most actively traded commodity, reaching in 2016 a market value of around $549 billion. The international oil trade is based on approximately 200 individual crude grades which vary in terms of quality, properties, market share and region of origin. The multiplicity of the available grades makes it difficult to price them, thus the international pricing system is based on the use of reference prices called benchmarks.

4.9.1 Benchmark definition

According to U.S. EIA, "a benchmark crude is a specific crude oil that is widely and actively bought and sold, and to which other types of crude oil can be compared to determine a price by an agreed-upon differential." The agreed-upon differential of a specific crude stream may vary between different markets and generally depends on various factors such as its quality (API gravity and sulphur content) and transportation (if included) costs from production to delivery point [33]; its global character has inevitably pegged crude pricing to international market conditions, thus factors of geopolitical uncertainty or supply/demand disruptions are immediately reflected on oil prices. Use of benchmarks as initial reference point makes it easier for buyers and sellers to compare and value oil grades with dissimilar characteristics and from different parts of the world, thus making the oil trade an activity of global range.

In order for a crude oil grade to be used as a global benchmark it has to satisfy a number of criteria, including a stable and abundant production, a transparent and liquid market located in a geopolitically and financially stable region, adequate storage to encourage market development as well as provide arbitrage opportunities [33].

Benchmark prices are assessed from price assessment agencies such as Platts or Argus. Each price index (benchmark) is assessed from the spot (usually) market's transactions of (a) specific crude stream(s) and reflect overall market sentiment and trading activity.

Only a handful of oil grades can be called 'benchmark' or 'marker' grades. The most widely used benchmarks are the Brent Index, the West Texas Intermediate (WTI) and the Dubai Index.

4.9.2 Main Benchmarks

4.9.2.1 Dubai

The Dubai crude oil is a "medium sour" crude oil extracted from Dubai. It has an API gravity of 31 degrees a sulphur content of 2% (m/m). Initially, the Dubai index was assessed based only on the Dubai grade's transactions. However, the declining production of the latter, forced price assessment agencies to create the Dubai basket and include in their calculations the Murban, Al-Saheen and Upper Zakkum grades, thus securing the physical liquidity of the Dubai Index base streams. Together with the Oman Index they are generally used as benchmarks for pricing Middle East oil exports to the Asian markets, and their prices are published at a regular basis by pricing agency Platts. The Saudi Arabia state-owned oil company Saudi Aramco, prices its oil exports to Asia based on a differential against the average of the Dubai/Oman price indices.

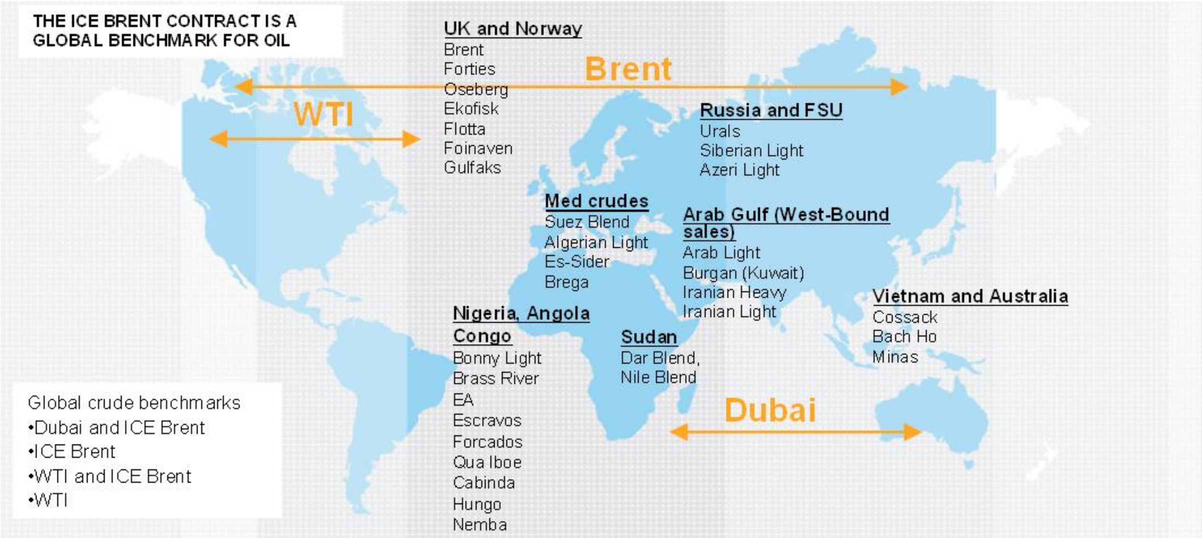
4.9.2.2 Brent benchmark

First and foremost, when referring to Brent it is important what Brent is being referred to: Dated Brent, Brent futures, Brent CFDs or the Brent blend crude oil that is produced from North Sea oil fields [33]? Dated Brent is a price assessment of physical, light North Sea crude oil cargoes that have been assigned specific delivery dates. It includes production from several oil fields that in total form four different crude oil streams, the Brent Blend, the Forties stream, the Oseberg stream and the Ekofisk stream. The otherwise called BFOE crude oil has four predetermined delivery points: Sullom Voe terminal in the Shetland Islands, Hound point in the UK, Sture Terminal in Norway, and the ConocoPhillips terminal at Teesside in the UK, each one corresponding to one of the said four different streams, arranged in the same order. The BFOE crude oils are a little less light and sweet than WTI, however remain ideal for making gasoline and distillate fuels. Despite the declining production of North Sea fields, the Dated Brent price index is used as the reference price for the two thirds of the traded crude oil globally, being the most used oil benchmark in the world. Most middle east oil producers such as Saudi Aramco, price their crude oil exports to Europe on a price differential to the Dated Brent based index. Brent crude oil is traded on the Intercontinental Exchange Brent futures market.

4.9.2.3 West Texas Intermediate

The West Texas Intermediate (WTI) grade is a “light sweet” crude oil that is sourced from U.S. oil fields, primarily in Texas, Louisiana and North Dakota. It is refined mostly in the Midwest and Gulf Coast regions, and every WTI trade contract has Cushing, Oklahoma as predetermined delivery point. Most of WTI crude oil is consumed in North America. Its high quality makes it excellent for making gasoline, thus it is used as the major pricing benchmark of crude oil in the United States. WTI is traded on the New York Mercantile Exchange and on a global scale it is the second most traded oil benchmark behind Brent.

Figure 4-33. Crude oil pricing around the world



Source: Kurt, D. (2020, January). Benchmark Oils: Brent Crude, WTI and Dubai. Retrieved from https://www.investopedia.com/articles/investing/102314/understanding-benchmark-oils-brent-blend-wti-and-dubai.asp

4.10 Uses of Crude Oil

Crude oil is the feedstock for thousands of products, among those, plastics, lubricating oils, tar, asphalt and fertilizers. Fuels oils used for heating and electricity generation are also produced from crude oil as well as transportation fuels such as gasoline, diesel oil and jet fuel. According to U.S. IEA, in 2018, gasoline consumption averaged about 9.33 million b/d, which was equal to approximately 45% of total U.S. petroleum consumption, with distillate fuels (mostly diesel fuel and heating oil) holding the 2^{nd} position with a total of 20% of U.S. crude consumption. Crude oil is transformed into various products through fractional distillation and several other treatment processes, as appropriate, that take in place in refineries. The produced intermediate or finished products are called petroleum products.

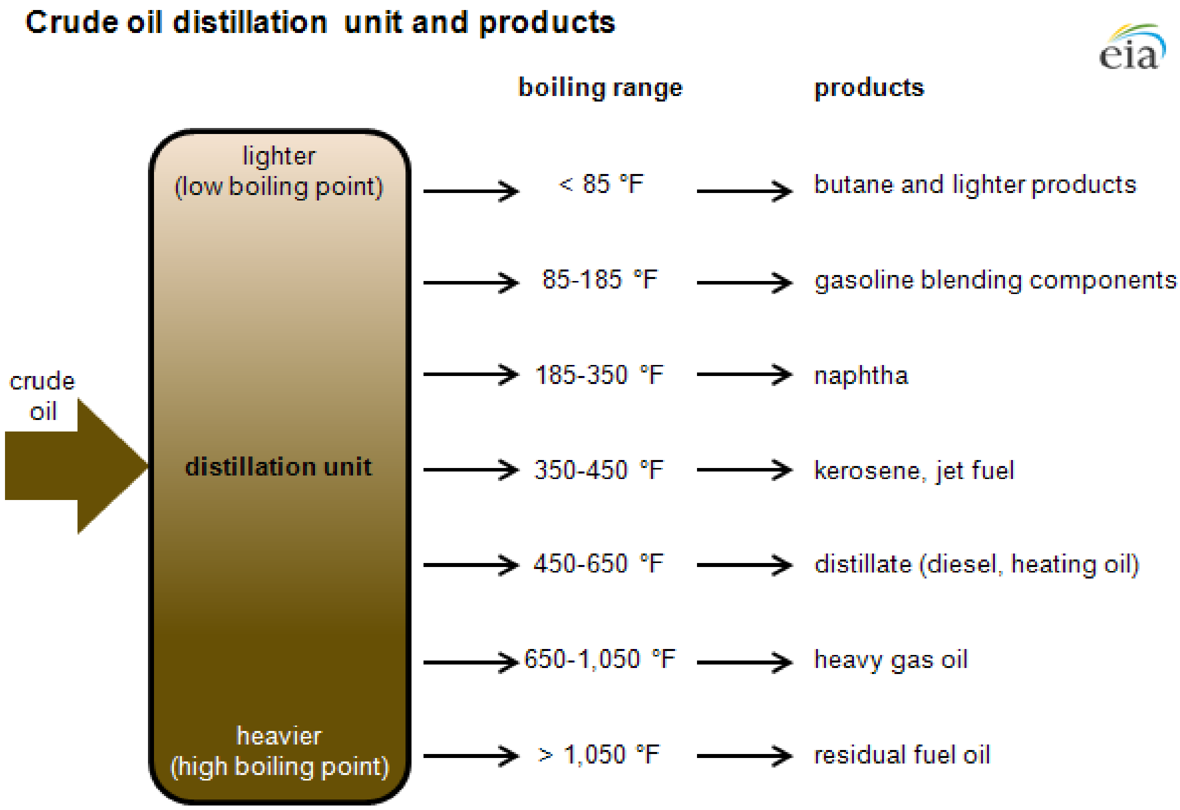
Maritime transport, as the most cost-effective way to move en masse goods and raw materials around the world, is dominating the world trade, constituting over 90% of the annual commodity transportations. Marine fuels, the driving force behind maritime trade, are key petroleum products, which similarly to all fuel oils, are produced via crude distillation.

4.11 Crude Oil Distillation Process

Crude oil in its raw form is a mixture of hundreds of hydrocarbons of different type with various chain lengths and properties. In order to make use of the earth's vast crude oil fields those hydrocarbons must be separated. Hence, the process of fractional distillation was developed in the late 1870's, being the oldest among the processes that take place in refineries worldwide. Fractional distillation takes place inside the Crude Oil Distillation Unit (CDU) and its operation is based on the different temperature ranges which the contained hydrocarbons vaporize. In a nutshell, the crude oil is gradually heated and when the temperature exceeds the boiling point of a particular component, that fraction passes into the gas phase. By gradually increasing the temperature, heavier and longer-chain hydrocarbons follow the vaporization process and the individual resulting gaseous fractions are then cooled down and liquified again. The separated components undergo further treatment (e.g. desulphurization, hydrotreating etc.) until they are ready to leave the refinery as finished petroleum products. Fractions that are separated from the crude oil in this way are distinguished as distillates. The remaining components in the distillation unit which do not pass into the gas phase, namely the residues, form what we call residual fuel oil or heavy fuel oil.

Residual Fuel Oils consist of the bottom residues of atmospheric and/or vacuum distillation that are dissolved with varying amount of "cutters", either from atmospheric and vacuum distillation units, such as Atmospheric Gas Oil and Vacuum Gas Oil respectively, or with fractions coming from Fluid Catalytic Cracking process, the so called Cycle Oils [9]. Depending on the ratio of residues to "cutters", residual fuel oils are classified into various grades, albeit they usually irrespectively of grade contain a high amount of the crude oil's impurities such as sulphur compounds and trace metals. All these, together with their high viscosities and ignition temperatures necessitate the use of proper combustion equipment [43].

Figure 4-34. Crude oil distillation unit and products



Source: U.S. Energy Information Administration (2012, July). Crude oil distillation and the definition of refinery capacity. Retrieved from https://www.eia.gov/todayinenergy/detail.php?id=6970

Chapter 5. Marine Fuels Background

5.1 Fuel Oils

In a general sense, the term fuel oil refers to a wide variety of petroleum-based products that are produced through crude oil distillation and can be used as fuel feedstock in a burner or furnace for the generation of heat or in an engine for the generation of power. In a stricter sense, the term is regularly used to describe the heaviest and most viscous fuel oil that can be obtained through crude oil distillation, often mentioned as residual fuel.

Fuel oils specifications have long now been standardized based on the requirements of the end consumers (i.e. industries, machinery etc) as well as on several regulations that designate their properties and usage taking into account factors such as safety and protection of the environment. Hence, the various petroleum products that accrue through crude oil distillation incur afterwards further treatment (usually depending on the fuel market needs) so as to be finally classified into the respective standardized grades. Despite the fact that various classification systems are nowadays in use, there is also a general trend to distinguish fuel oils between distillate and residual fuels, depending on how they are produced during the stage of crude distillation.

5.1.1 Fuel Oils Classification

Although different organizations may designate different specifications for the categorization of crude oil extracted fractions, a universal standard (which also is the one in use in US markets) is the classification of fuel oils into 6 fuel grades. The classes are numbered 1 through 6 and the fuel oils are classified depending on their properties and purpose. Generally, moving to a higher fuel grade number (from 1 to 6) is accompanied by an increase in the boiling point, viscosity, more impurities and to as less environmentally friendly fuel that is harder to handle [62]. Price is also usually higher in the lower fuel grade numbers [62].

- **No 1** – A distillate fuel oil, the lightest in the distillate category. It consists of the kerosene fraction that boils-off after the heavy naphtha cut, having a boiling range of 175 – 325°C [62].
- **No 2** – A distillate fuel oil consisting of the Light Gas Oil cut with a boiling range of 250 – 350 °C. It is used as home heating oil and is similar to the diesel oil used in trucks cars but of lower quality (i.e. lower cetane number and higher sulphur content) [36]. It is often used as solvent in the formulation of residual fuel oils as well as forms part of the fuel composition used in slow-speed marine engines [43].
- **No 3** – A distillate fuel oil consisting of Light Gas Oil material which has been rarely used since the mid-20th century and has been merged by ASTM into fuel grade No 2 [93].

- **No 4** – A residual type fuel oil, the lightest in the residual's category, sometimes being referred to though to as heavy distillate. It has the lowest ratio of pitch to Heavy Gas Oil [43] and consists of VGO range residual material blended with distillates such as fuel oil No. 2 (in a ratio lower than those in No 5 & 6 fuel grades). It has a pour point of approximately -7°C and low viscosity, properties than usually place it at a price higher than the succeeding No. 5 & 6 grade fuel oils [43].

- **No 5** – A residual type fuel oil with a higher pitch to Heavy Gas Oil ratio than fuel No. 4 [43]. It may consist mainly of Vacuum Gas Oil material (residual) but usually is a blend of about 80% of it and enough fuel No. 2 [37] to adjust viscosity so that it can be pumped without preheating [93] (down to temperatures of about 10 °C) [43]. Preheating is either way required though prior to the burner in order to achieve proper combustion [43].

- **No 6** – A residual type fuel oil that has the highest ratio of pitch to Heavy Gas Oil [43] and consists mainly of the Vacuum Residuum material, the heaviest among residual cuts. Small amount of fuel No. 2 may also be added in order to get it to meet specifications [37]. It is a high-viscosity residual oil requiring preheating both before pumping and combusting [36].

5.2 Marine Fuels

5.2.1 General Information

Marine fuels otherwise known by the market term "bunker fuels" comprise a huge challenge for the shipowners and operators, both due to their high purchase cost (constituting as much as 70% of a voyage's cost) and the stringent regulatory framework that define their management and use aboard the ship. For decades, the available marine fuels were being supplied in the market under the term "bunker fuels", distinguished as bunker A, B and C fuel types [109]. Bunker A was generally synonymous with No. 2 fuel oil, bunker B was generally synonymous with No. 4 or No. 5 fuel oils and bunker C, the most commonly used bunker fuel, was generally synonymous with No. 6 fuel oil [109].

The stepwise tightening of marine fuels regulations often in dissimilar ways depending on the region and the varying requirements of different marine combustion units created the need for various fuel compositions establishing a wide variety of fuel grades. As a result, national and international organizations such as the American Society for Testing and Materials (ASTM), the British Standards Institute (BS) and the International Organization for Standardization (ISO) recognized the need to classify and develop standardized specifications for marine fuels (Newbery, 1996; Thomas, 1981) [109]. Although various international standardized classification systems were developed throughout the years, the most widely acknowledged is the ISO structure [109].

5.2.2 ISO 8217 Marine Fuels Classification Standard

The *ISO 8217:2017 "Petroleum Products – Fuel (class F) – Specifications of Marine Fuels"* is a globally recognized standard that specifies the requirements for fuels for use in marine diesel engines and boilers, prior to conventional onboard treatment (settling, centrifuging, filtration) before use [60]. This document (the latest edition of which was issued in 2017) specifies seven categories of distillate marine (DM) fuels (one of which is for diesel engines used for emergency purposes) and six categories of residual marine (RM) fuels [60]. The separation of fuels into residual and distillates is based on the way they are produced during fractional distillation and the term "fuels" is used to include the following [60] :

- hydrocarbons from petroleum crude oil, oil sands and shale;
- hydrocarbons from synthetic or renewable sources, similar in composition to petroleum distillate fuels;
- blends of the above with a fatty acid methyl ester(s) (FAME) component where permitted. [60]

The distillate fuels are categorized as DMX, DMA, DFA, DMZ, DFZ, DMB and DFB while residual fuels are characterized as RMA, RMB, RMD, RME, RMG and RMK [5]. Key contrast among the two main categories are the divergence in their viscosities and sulphur content, which are both much higher in the six residual grades. The ISO 8217 standard several fuel characteristics, including viscosity, density, cetane index/CCAI, sulphur, flash point, acid number, total sediment, carbon residue, cloud point, pour point, cold filter plugging point, appearance, water, ash, lubricity, vanadium, sodium, cat fines etc.[5]. All -except a few - of these characteristics are applicable for both type of oils.

Figure 5-1. ISO 8217:2017 Fuel Standard for Residual Marine Fuels

Characteristic	Unit	Limit	Category ISO-F-										
			RMA	RMB	RMD	RME	RMG				RMK		
			10	30	80	180	180	380	500	700	380	500	700
Kinematic viscosity at 50 °C	mm²/s	Max	10,00	30,00	80,00	180,0	180,0	380,0	500,0	700,0	380,0	500,0	700,0
Density at 15 °C	kg/m³	Max	920,0	960,0	975,0	991,0	991,0				1010,0		
CCAI	–	Max	850	860	860	860	870				870		
Sulfur	mass %	Max	*The purchaser shall define the maximum sulfur content in accordance with relevant statutory limitations.*										
Flash point	°C	Min	60,0	60,0	60,0	60,0	60,0				60,0		
Hydrogen sulfide	mg/kg	Max	2,00	2,00	2,00	2,00	2,00				2,00		
Acid number [c]	mg KOH/g	Max	2,5	2,5	2,5	2,5	2,5				2,5		
Total sediment – Aged	mass %	Max	0,10	0,10	0,10	0,10	0,10				0,10		
Carbon residue – Micro method	mass %	Max	2,50	10,00	14,00	15,00	18,00				20,00		
Pour point (upper) [d] – winter	°C	Max	0	0	30	30	30				30		
Pour point (upper) [d] – summer	°C	Max	6	6	30	30	30				30		
Water	volume %	Max	0,30	0,50	0,50	0,50	0,50				0,50		
Ash	mass %	Max	0,040	0,070	0,070	0,070	0,100				0,150		
Vanadium	mg/kg	Max	50	150	150	150	350				450		
Sodium	mg/kg	Max	50	100	100	50	100				100		
Aluminium plus silicon	mg/kg	Max	25	40	40	50	60				60		
Used lubricating oil (ULO): – Calcium and zinc; or – Calcium and phosphorus	mg/kg	–	Calcium > 30 and zinc > 15 or Calcium > 30 and phosphorus > 15										

Source: International Organization for Standardization. (2017). Petroleum Products – Fuel (class F) – Specifications of Marine Fuels *(ISO 8217:2017). Retrieved from https://www.iso.org/standard/64247.html*

Characteristic		Unit	Limit	Category ISO-F-						
				DMX	DMA	DFA	DMZ	DFZ	DMB	DFB
Kinematic viscosity at 40 °C		mm²/s [a]	Max	5,500	6,000		6,000		11,00	
			Min	1,400	2,000		3,000		2,000	
Density at 15 °C		kg/m³	Max	–	890,0		890,0		900,0	
Cetane index		–	Min	45	40		40		35	
Sulfur [b]		mass %	Max	1,00	1,00		1,00		1,50	
Flash point		°C	Min	43,0	60,0		60,0		60,0	
Hydrogen sulfide		mg/kg	Max	2,00	2,00		2,00		2,00	
Acid number		mg KOH/g	Max	0,5	0,5		0,5		0,5	
Total sediment by hot filtration		mass %	Max	–	–		–		0,10 [c]	
Oxidation stability		g/m³	Max	25	25		25		25 [d]	
Fatty acid methyl ester (FAME) [e]		volume %	Max	–	–	7,0	–	7,0	–	7,0
Carbon residue – Micro method on the 10 % volume distillation residue		mass %	Max	0,30	0,30		0,30		–	
Carbon residue – Micro method		mass %	Max	–	–		–		0,30	
Cloud point [f]	winter	°C	Max	–16	report		report		–	
	summer	°C	Max	–16	–		–		–	
Cold filter plugging point [f]	winter	°C	Max	–	report		report		–	
	summer	°C	Max	–	–		–		–	
Pour point (upper) [f]	winter	°C	Max	–	– 6		– 6		0	
	summer	°C	Max	–	0		0		6	
Appearance				Clear and Bright [g]					[c]	
Water		volume %	Max	–	–		–		0,30 [c]	
Ash		mass %	Max	0,010	0,010		0,010		0,010	
Lubricity, corrected wear scar diameter (WSD) at 60 °C [h]		μm	Max	520	520		520		520 [d]	

Source: International Organization for Standardization. (2017). Petroleum Products – Fuel (class F) – Specifications of Marine Fuels *(ISO 8217:2017). Retrieved from https://www.iso.org/standard/64247.html*

Figure 5-2. ISO 8217:2017 Fuel Standard for Marine Distillate Fuels

The worldwide establishment of the ISO standard led to a remarkable reduction in the variability of marine fuel characteristics, an achievement that contributed to the improvement of marine engines' efficiency and integration with bunker fuels as well as amplified the implementation of important maritime environmental regulations. The adoption of a universal standardized nomenclature system eliminated past misconceptions and confusion around fuel distinction and clarified the available fuel grades and their purpose both to the buyers (shipowners) and the suppliers (oil majors and trading companies) as well as the marine engines' manufacturers.

5.2.3 Maritime "Market" Fuel Classification

Despite the establishment of the standardized ISO fuel nomenclature system there is a diverse range of terms that are still used in the market to describe the available marine fuel grades. For the sake of clarity, an effort towards a clear description of the most used terms was deemed necessary.

In the maritime field the most common fuel naming system includes the following terms:

- MGO (Marine Gas Oil)
- MDO (Marine Diesel Oil)
- IFO (Intermediate Fuel Oil)
- HFO (Heavy Fuel Oil)

5.2.3.1 Marine Gas Oil (MGO)

MGO describes marine fuels that consist **exclusively** of distillates and falls within the DMA and DMZ categories of ISO 8217. Marine Gas Oil usually consists of a blend of various distillates and is equivalent to No. 2 Fuel Oil and Bunker A. MGO is based on the lighter distillates and has a low viscosity, thus does not have to be heated prior to pumping. MGO (e.g. DMA, DMZ grades of ISO 8217) unless otherwise specified has a maximum 1.0% m/m sulphur content but is also available in lower contents in order to comply with special regional regulations (such as the 0.10% sulphur limit inside ECAs). The ECA compliant MGO specifically, is available in the markets under the name LSMGO (Low Sulphur Marine Gas Oil) and has a maximum sulphur content of 0,10% m/m.

5.2.3.2 Marine Diesel Oil (MDO)

MDO is generally composed of various blends of distillate fractions and a small portion of residual fractions and falls within the DMB category. Unlike Heavy Fuel Oil, Marine Diesel Oil does not have to be heated during storage. MDO has maximum sulphur content of 1.5% , although it is available in a range of 0.10%-1.5% sulphur in the bunker market. The different blending ratios of Marine Diesel Oil can be controlled directly by processes in the refinery or by blending ready-made marine fuels.

5.2.3.3 Intermediate Fuel Oil (IFO)

The **Intermediate Fuel Oil** (IFO) Grade system refers to blends of residual fuel oils with variable amounts of distillates in order to adjust viscosity to the desired values. The IFO grade system specifies only the viscosity at a specific temperature (usually 50 °C) including a viscosity range of 30-700 centistokes (cSt). Comparing to MDO, IFO blends have higher proportions of residual fuel oil. In relation to the ISO 8217 Fuel Standard, the IFO grade system can be used equivalently to refer to the Residual fuel grades denoted in the ISO classification. For example IFO 180 shall correspond to RME 180 or RMG 180 and IFO 380 to RME 380 or RMK 380. Typically, IFO with a viscosity designation 380+ will have properties similar to Bunker C, namely (almost) pure residual fuel.

5.2.3.4 Heavy Fuel Oil (HFO)

HFO is a broad term that is used in various different ways. In a stricter sense, it is equivalent to No. 6 fuel oil or Bunker C, describing a fuel type that consists (almost) entirely of pure residual material. In a general sense though, this term is used to refer to any marine fuel grade that falls within the Residuals category of the ISO standard, and is typically characterized by high viscosity and high sulphur content. Summarizing, taking into account the definition of IFO classification, HFO and IFO terms are used synonymously within the shipping industry, namely to describe fuel grades that fall within the Residuals category of the ISO standard, with the difference that the IFO term is also followed by the value of the fuel's viscosity (e.g. IFO 380). Additionally, the HFO term is regularly substituted by the term High Sulphur Fuel Oil (HSFO), when it is intended to highlight the high sulphur content of Residual Marine Fuels.

In practise, the six Residual fuel grades as defined in the ISO 8217 standard (RMA to RMK) are Intermediate Fuel Oils, namely blends with a high ratio of residual oil to distillates, depending on the desired viscosity at a set temperature (50 °C). Low viscous grades such as the RMD 80, RME 180 contain about 70%-90% residual fuel and 10%-30% distillates while more viscous grades (e.g. RMG 380 and above) comprise of about 90%-100% residual fuel and the remaining amount of distillate fuel. The most widely used products are IFO 380, accounting for 70% of the total volume of heavy bunker oils supplied, followed by IFO 180, constituting approximately 25% of the volume of bunker oil on the market (Lewis, 2002). The other grades account for the remaining 5% (Moldestad et al. 2007).

Summarizing the fuel naming subject, the ISO nomenclature system is the official distinction system of the various fuel grades that can be used in marine applications. The bunkering market though, uses mainly the IFO grade system in order to refer to residual fuel oils and the terms MGO and MDO for distillate fuel oils. Finally, a large share of Classification Societies and maritime literature uses the generic term Heavy Fuel Oil (HFO) in order to refer to any residual type fuel oil. A typical example of how bunker fuels are presented in the fuel market is illustrated in Figure 5-3. The included terms VLSFO & ULSFO that are included in preciously mentioned Figure, will be elaborated later in this chapter.

Considering all the above, in this research from now on the generic terms HFO or residual oil will be used in order to refer to any of the Residual Marine Fuel grades of the ISO standard as were described above.

Figure 5-3. Typical marine fuels classification

- **IFO380** & **IFO180** are Max **3.5% Sulfur** Bunkers (RME, RMF, RMG, RMH, RMK, etc.)
- **VLSFO** is Max **0.5% Sulfur** fuel (Also known as IMO2020 grade bunkers)
- **LS380** & **LS180** are Max **1.0% Sulfur** Bunkers
- **ULSFO** is Max **0.10% Sulfur** Fuel Oil for Compliance with 2015 ECA Regulations
- **MGO** is, unless otherwise specified, a Max **1.50% Sulfur** "Clear and Bright" Distillate (DMA, DMZ, etc.)
- **LSMGO** is Max **0.10% Sulfur** Distillate (DMA, DMZ) for Compliance with 2015 ECA Regulations
- **MDO** is Max **1.50% Sulfur** Distillate (DMB)

Source: Marine fuels. (2020, February). Retrieved from www.shipandbunker.com

5.3 Marine fuels during the Sulphur Cap Era

The ever-increasing stringent environmental legislation in maritime trade has brought major changes in the structure of shipping. The establishment in 2015 of the 0.10% (m/m) maximum fuel sulphur content for operation inside sensitive areas (ECA) led shipowners into using compliant fuels such as MGO with low sulphur content (< 0.10% m/m). High price of MGO and several technical issues regarding the use of a distillate fuel in residual fuel type-designed marine engines pushed refiners into developing residual type compliant fuels, leading to the introduction of Ultra Low Sulphur Fuel Oils (ULSFO), namely fuels with max. sulphur content of 0.10% (m/m) and with properties that meet the requirements of Table 2 (Residual Fuels) of the ISO 8217 Standard.

The very recent introduction of the long-awaited IMO 2020 Sulphur Cap had a similar effect in the bunker market, although with a much bigger impact in all contracting parties, mainly due to the global character of the regulation. As noted above, the increased cost of burning MGO along with the various technical issues that would arise due to the fuel's low viscosity, led refiners into developing innovative fuel blends, of residual type and low sulphur content (< 0.50 % m/m). The new fuels were introduced in the market having a max. 0.50% (m/m) sulphur content under the name Very Low Sulphur Fuel Oils (VLSFO) and by the end of 2019 started getting their own share in the bunker market.

Nevertheless, the development of new residual type low sulphur fuels was accompanied with positive as much as negative outcomes. As for the positive ones, shipowners were offered an alternative solution instead of using low sulphur MGO/MDO as compliant fuel. The distillate MGO's low viscosity, thus not requiring heating during storage or pumping, implied a complicated fuel changeover process when transiting in or out of ECA areas, with potential compatibility issues in various ship machinery such as fuel pumps, centrifuges, purification system etc. Pump leakages, increased machinery wear, the likelihood of MGO contamination due to HFO residues "coated" pipes as well as potential need for extra fuel tanks made MGO seem a rather complicated option, not to mention the considerable increase in fuel expenses. Supply of compliant residual type - therefore of a high viscosity - bunker fuels meant a more simplified operation with little changes in respect with the usual operation with the 3,5% max sulphur HFO.

On the other hand, the introduction of VLSFO and ULSFO came with a lot of new concerns as well. Theoretically, low sulphur residual fuels could be produced through desulphurization of the heavy fuels oils (HFO), however the high cost of the desulphurization process together with the inadequate refinery infrastructures made the process non-sustainable from a financial viewpoint. The new low sulphur fuels are residual and distillate fuel blends, although there is no specific guidelines in the way that these blends shall be produced. VSLFO and ULSFO appeared on the market during the latter stage of the ISO 8217 Standard revision, thus it was not possible to revise the standard's tables and define specifications for 0,50% and 0,10% maximum sulphur content residual type fuels. Nevertheless, the new fuel blends will still need to meet the ISO standard's requirements, and thereby will be classified in accordance with Tables 1 & 2 for Distillate and Residual Marine fuels.

The problem in this case is that due to the lack of a standard "mixing recipe" of the new fuels, it is anticipated that they will present considerable variability in their characteristics, principally in the viscosity and density. On one hand, the fuel blends can be distinguished as residual or distillate type based on the ground criterion of whether they need heating during storage or not, on the other hand fuel blends that could be typically characterized as distillates - since they probably meet most of the requirements of Table 1 (ISO 8217) - they might however exceed the max. 11.0 cSt viscosity limit for a few centistokes. As a result, these fuels will be supplied as low viscous Residual type fuels such as the RMB 30 or RMD 80 grades. As a matter of fact, fuel testing agencies have taken sample of thousands of 0,50% compliant VLSFO and have reported viscosities that lie between 30 cSt and 500 cSt accompanied with considerable variance in density as well. This phenomenon was also confirmed by MAN Energy Solutions' fuel tests (Table 5-1). In brief, bunker suppliers expect a particularly unstable fuel regime comparing to the old one where the 380 & 180 cSt fuel grades used to dominate the heavy fuels market.

The emergence of fuel blends that originate from several different fuel batches with different characteristics, will make onboard fuel mixing a very dangerous practise, since the different fuel batches might not homogenize well and thus lead into serious combustion problems. Ultimately, since VLSFO it totally new, it is anticipated that there will be considerable logistics and availability problems in a lot of bunkering hubs, a fact that will probably lead the new fuel into very high prices, at least for the first months after the implementation of the IMO regulation.

Summarizing, choosing the newly introduced low sulphur residual type fuels as a compliance option, must be given adequate consideration, and shipowners shall plan ahead in order to be properly prepared. A more detailed analysis of the new fuels' potential risks and some indicative measures are denoted in the following chapter.

Table 5-1 Variability among a different VLSFO batches

Source: MAN Energy Solutions

0.50% S VLSFO	Kin. Viscosity at 50°C, cSt	Density at 15°C, kg/m³	Pour point, °C	Cat fines, Al+Si, ppm	MAN Energy Solutions comments
Fuel 1	45	990	27	< 15	Unusual viscosity (low) to density (high) relationship. Note: high pour point.
Fuel 2	360	969	<24	55	Al+Si: above average. Pour point may be high.
Fuel 3	7.4	885	-24	28	Very low viscosity and density. High Al+Si.
Fuel 4	215	942	30	45	Al+Si: above average. Note: high pour point.
Fuel 5	60	985	< -3	33	Al+Si: above average. Unusual viscosity (low) to density (high) relationship

Chapter 6. Compliance with the IMO Sulphur Cap by use of Low-Sulphur Fuels

The unanimous decision of IMO MARPOL convention's signatory parties to introduce a 0.50% max. fuel sulphur content limit at January 1st, 2020, put shipowners and vessel operators in a challenging situation with only a short time to prepare their fleet in view of the new environmental regulation. At the same time, refiners were pushed into developing "cleaner" fuels which could also meet the global merchant fleet's technical requirements taking into account factors such as vessel's efficiency, overall machinery compatibility and stable fuel quality. IMO's decision to allow the use of alternative means of compliance such as sulphur abatement technologies (i.e. scrubber), gave shipowners the option to continue burning heavy fuel (HFO), provided that they have installed a functioning and certified exhaust gas treatment system onboard.

This chapter is a key part of this research and comprises a detailed analysis of the leading pathways through which the maritime industry can meet the requirements of IMO's Sulphur Cap mandatory regulation.

Considering what has been mentioned so far, ship compliance can be attained through:

1. Low-Sulphur compliant fuels (VLSFO, LSMGO, ULSFO)
2. Exhaust Gas Cleaning System (EGCS) and use of HFO
3. LNG
4. Alternative fuels e.g. LPG, ethane, methanol, CNG, biofuel, solar power & fuel cells

The majority of the world fleet is anticipated to turn to the use of low sulphur fuels, followed by those who will opt to install scrubbers and continue burning HFO, although in a much smaller extent. Switching to LNG implies huge capital expenditure, thus, it is expected to be adopted by a very small number of shipowners. Regarding the use of alternative fuels, considering that they are not yet adjusted for marine application, this solution will probably be applied to a few vessels worldwide.

Based on the foregoing, it was regarded wiser that this research will focus on the first two options (low sulphur fuels or EGCS) giving an emphasis in technical challenges as well as financial pros and cons.

The majority of the bunkering hubs offer the following low sulphur fuels:

- LSMGO – Max. 0,10% Low Sulphur Marine Gas Oil
- ULSFO – Max. 0,10% Ultra Low Sulphur Fuel Oil (commonly known as ECA fuel)
- VLSFO – Max. 0,50% Very Low Sulphur Fuel Oil (commonly known as IMO 2020 fuel)

Considering the general rule of thumb, the lower the fuel's sulphur content, the higher the distillate proportion, therefore the price of the fuel as well, a feature that under normal market conditions will likely place the three aforementioned fuels in the following price ascending order: VLSFO, ULSFO, MGO.

Concerning the vessels which are mostly operated inside ECAs and/or make regular in-and-out of ECA transitions, those will be operated mainly on the 0,10% options (ULSFO, MGO) in order to avoid frequent fuel changeover, expecting MGO to be the predominant option.

In respect to the 0,50% worldwide limit, VLSFO is regarded to be the best option both due to lower expected price and better compatibility in marine machinery.

Given the above and the fact that most merchant vessels sail on the high seas, it is anticipated that the majority of the world fleet will use VLSFO to operate outside ECAs and MGO inside ECAs.

It was deemed therefore necessary to provide directions on the transition into 0,50% sulphur fuels as well as information and guidance against VLSFO's potential issues and challenges. Regarding ships that trade within ECAs, guidelines on the fuel changeover procedure will be included. For the convenience of the readers, the foregoing will be preceded by a brief presentation of a typical ship fuel system's technical background.

6.1 Technical Background

The fuel oil system of a ship is generally comprised of the fuel tanks, the fuel oil transfer system and the fuel treatment system.

6.1.1 Fuel Tanks

Every merchant vessel burning fuel oils is fitted with three types of fuel tanks: bunker tanks, settling tanks and service tanks.

6.1.1.1 Bunker Tanks

These are the biggest fuel tanks in terms of capacity present on board the ship. They are used to store all fuel oils that are bunkered for ship propulsion as well as operation of all combustion units aboard. Modern vessels have separate dedicated tanks for low sulphur (e.g. MGO) and high sulphur fuel (e.g. HFO) in order to avoid fuel mix-up, with HFO tanks usually outnumbering MGO bunker tanks. A typical Suezmax tanker has two HFO storage tanks at the starboard[5] side and two more at the port side of the ship together with two MGO tanks in total. Bunkered fuel specifications especially pour point[6] and viscosity[7] demand a minimum tank temperature in order to prevent wax formation and potential problems regarding pumpability. For this reason, bunker tanks are fitted with heating coils, which typically use as a heating medium steam that is produced via the ship's exhaust gas boiler.

HFO's high viscosity requires a typical tank temperature of around 40 ºC (~ 10 ºC above pour point), with the necessitated steam consumption though, to be heavily depended on the ambient outside temperature. MGO has a much lower pour point and viscosity, therefore much lower heating needs and can easily be pumped at 20 ºC [73]. However, an average tank temperature of 30 ºC is advised, especially during winter conditions, to prevent wax formation where the fuel meets outside temperatures [2]. Bunkering capacity varies from ship to ship, even between sister ships. Normally, the maximum filling is in the range of 85% to 90%, and subsequent fuel expansion from tank heating should be strictly always taken into account, before commencing any bunkering procedure [34].

[5] Port and starboard are nautical terms of orientation that deal unambiguously with the structure of vessels. Both terms always refer to the same portion of the vessel's symmetrical structure, and do not depend on which way the observer is facing. Starboard side is to the right of an observer that is facing towards the vessel's bow, that is, facing forward towards the direction the vessel is heading when underway, and the port side is to the left of such an observer.

[6] Pour point is an important cold flow characteristic that determines the temperature below which the fuel ceases to flow (perceived as turning solid) rendering the fuel unusable. Ships have reported solidified fuels in tanks when reaching colder regions. The energy required in order to transfer the solid wax back to a liquid is significant and exceeds what normal onboard heating capacity and arrangements can manage. (CIMAC Guidelines, Cold flow properties, 2015-01 (1st edition)

[7] Viscosity is a measure of an oil's resistance to flow. It decreases (thins) with increasing temperature and increases (or thickens) with decreased temperature. An oil's viscosity is measured most commonly by kinematic viscosity and reported in a unit called the centistoke (cSt).

6.1.1.2 Settling Tanks

As the name implies, settling tanks provide, among others, a settling function for the fuel's impurities, such as water and sludge. It's a pre-cleaning stage, whereby the heavier-than-fuel solids and water migrate to the bottom of the tank under the influence of gravity. Settling tanks are succeeding the storage tanks, from which they are transferred via a fuel oil transfer pump and its associated suction strainer. Normally, a ship will have a "two settling tank" arrangement, one for low sulphur fuel and the other for high sulphur fuel.

Besides the "settling function", these tanks provide a heating function, a de-aeration function and a thermal stabilizing action [34]. Just like the storage tanks, so are the settling tanks fitted with steam coils, by which fuel is heated at the desired temperature. As soon as the bunker fuel has filled the settling tank, it is typically heated to approximately 72 ºC, or 6 ºC below the fuel flash-point, whichever is lower [34]. It is important that the tank temperature is maintained in the appropriate range, otherwise the fuel's impurities might not precipitate properly

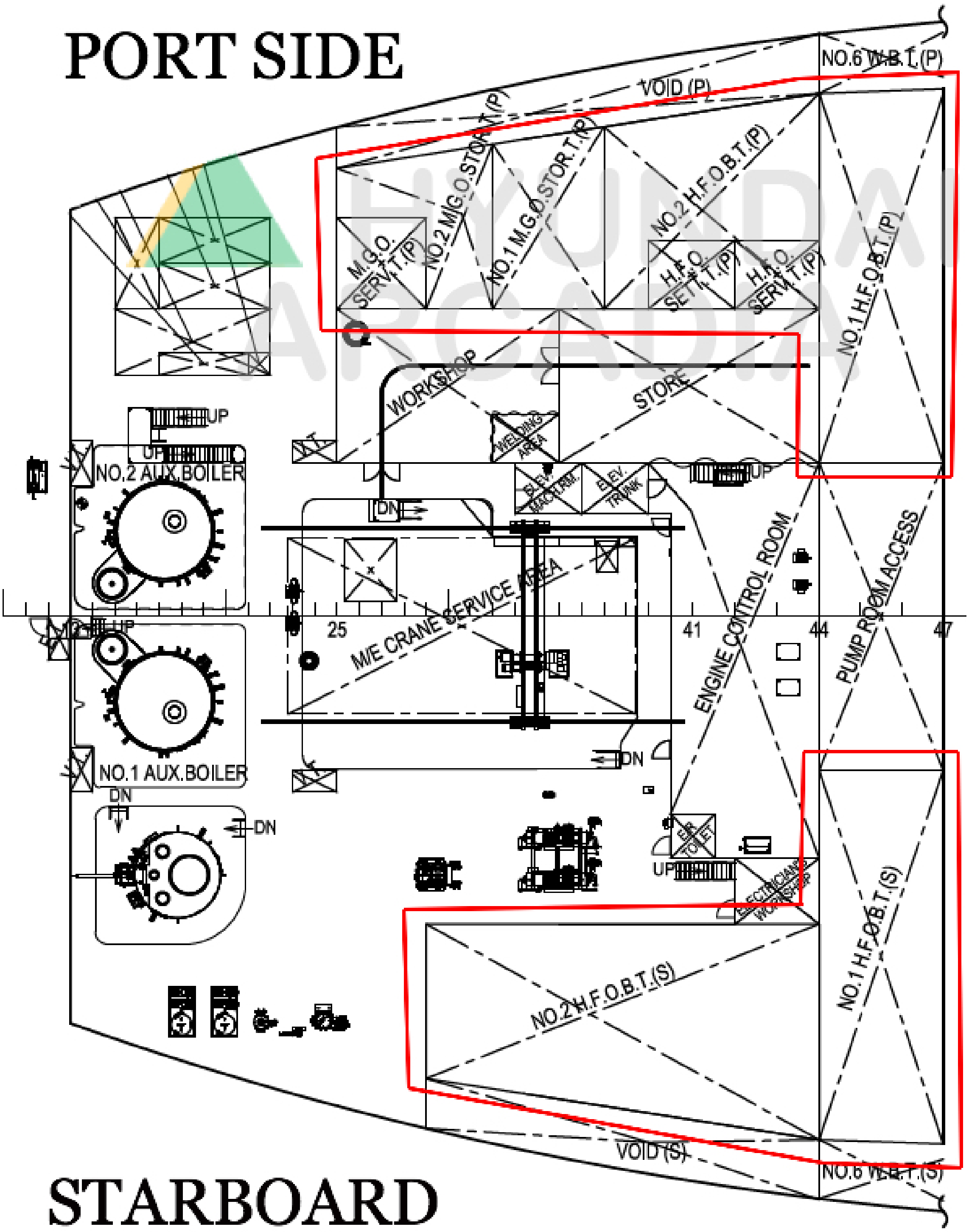
The settling tanks have a sloping bottom with a drain valve at the lower point by which sludge and water can be drained at regular intervals [39]. Gravity based operation of the tank's cleaning action, implies that ship's movements can stir up the contents of the tank and move settled sludge and water towards the tank's fuel outlet [39]. For this reason, pump suction shall not be in the vicinity of the sludge space [101]. The longer the fuel remains inside in the settling tank, the better it will be prepared for the next stage.

6.1.1.3 Service Tanks

According to IMO SOLAS Regulation II-1/26.1, a service tank is "a fuel oil tank which contains only fuel of a quality ready for use i.e. fuel of a grade and quality that meet the specifications required by the equipment manufacturer". Service tanks (or day tanks) are succeeding the purifier/clarifier system and are the last cleaning stage before the fuel is fed is to the consumers. They serve a very important role in the overall treatment of fuel oil, providing a final precipitation for water and solids as well as heating of the fuel to a higher temperature [8]. For this reason, there are equipped with steam heating coils, which after the tank filling, gradually heat the fuel oil to around 80 ºC - 85 ºC.

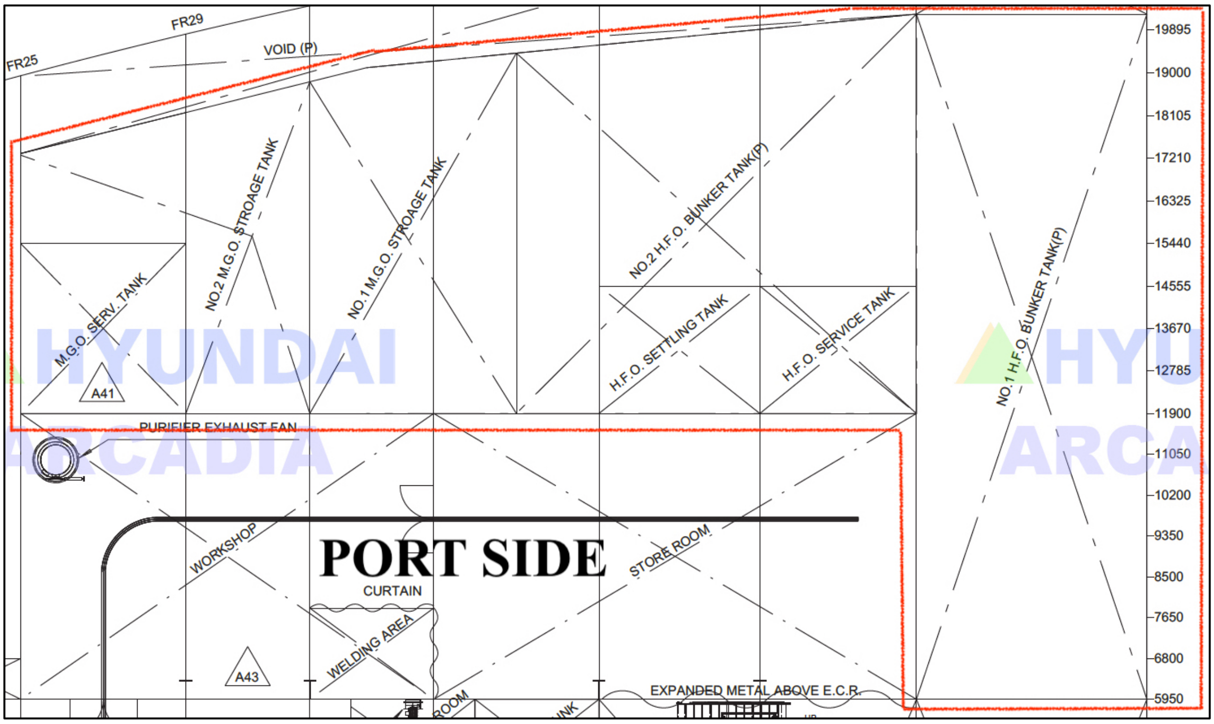
SOLAS Regulation II-1/26.1 states that "two fuel oil service tanks for each type of fuel used on board necessary for propulsion and vital systems or equivalent arrangements shall be provided on each new ship, with a capacity of at least 8 h at maximum continuous rating of the propulsion plant and normal operating load at sea of the generator plant". In simpler words, modern vessels shall have at least two service tanks, one for low sulphur and one for high sulphur fuel, arranged in a way that they can operate independently of each other and with adequate capacity in regard to the daily consumption. When a service tank is full, there is generally a return line allowing overflow back to the settling tank.

Figure 6-1. Top view of the Engine room's 2nd deck of M/T Aegean Dream



Source: Reprinted with kind permission of Arcadia ShipManagement Co. Ltd.

Figure 6-2. Port side of the Engine room's 2nd deck of a suezmax tanker



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6.1.2 Fuel Oil Treatment System

Daily marine fuel consumption during 2019 fluctuated at an average of 5 million b/d, out of which 65% was residual fuels, commonly known as HFO (Flowers, 2019). A long time now, heavy fuel oil dominates the bunker fuel market, and is the fuel according to which, marine machinery's specifications are typically designed. Heavy fuel does not though arrive at ships in the purest form. It normally contains water, ash, heavy metals and cat-fines, all of which are delimited according to ISO 8217 requirements, and it is usually further contaminated with sludge and dirt from the tank themselves. If not treated, these impurities could lead to serious wear and damages in the fuel oil system components and the main engine, therefore on-board fuel cleaning is considered a necessary procedure. Cat-fines in particular, can easily cause main engine failure and extra cost of hundred thousands of dollars for repairs and spare parts.

Cat-fines (catalytic fines), are small, hard and abrasive particles that are normally present in bunker fuels, although limited according to ISO 8217 fuel standard requirements. They originate from the catalytic cracking processes in the refineries where a catalyst is used to break down complex hydrocarbons into simpler molecules, thus are almost always present in residual fuels [68]. Most catalysts being used in these processes are based on aluminium and silicon oxides [68]. RMK & RMG grades have the maximum allowed cat-fine content among all grades of ISO 8217:2017 standard, amounting to 60 ppm (aluminium & silicon). The maximum recommended cat-fines content before the engine is 15 ppm, although lesser values are generally advised [68]. Therefore, it is important that the ship's fuel treatment system is able to obtain sufficient cleaning of the bunkered fuel, otherwise cat-fines may enter the engine with the fuel and cause serious and costly damages.

Partial cat-fine cleaning is carried out in the settling and service tanks, where heavier impurities (including cat-fines) precipitate at the tank's bottom under the influence of gravity. The main fuel cleaning on board though, is performed in the fuel centrifugal separators, namely the ship's purifier and clarifier system.

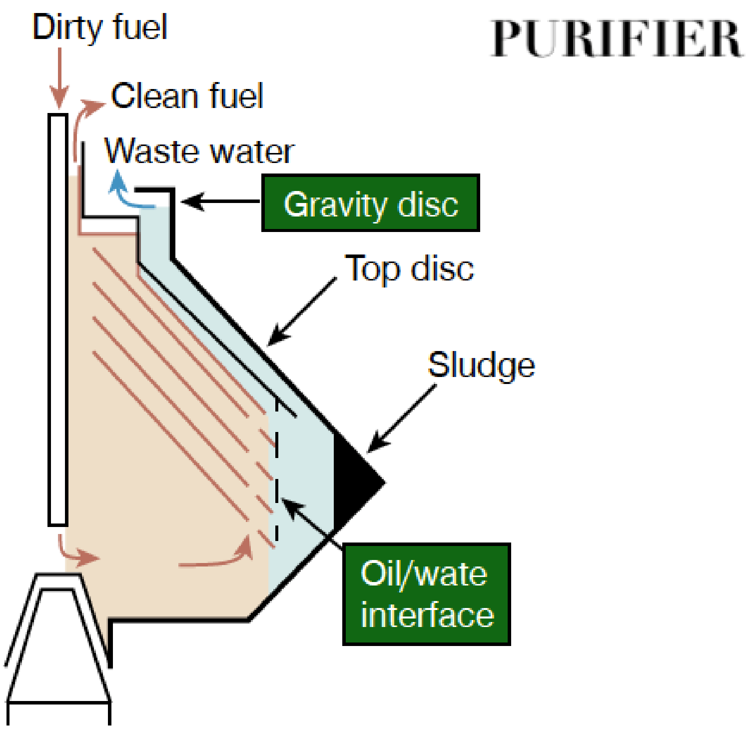
In respect to the fuel's typical flow path from storage to consumption, fuel separators are located between the HFO settling and service tank(s). Following treatment in settling tank, the fuel is pumped out by the purifier inlet pump. The inlet pump delivers the fuel to a heater, which raises the fuel temperature at around 80 ºC, and thence to the purifier [38]. After filtered in the purifier, the fuel enters the clarifier for additional removal of finer particles (e.g. cat-fines), until it is ready to enter the service tank.

6.1.2.1 Purifier

The purifier's operation is based on the difference between the fuel's and its impurities' densities and the use of the centrifugal force that is generated as a result of the arrangement's fast spinning. The purifier consists of a number of perforated discs of inverted bowl shape, stacked one over the other (known as disc stack) and one special gravity disc, all of them rotating in high speed around a vertical shaft powered by an electric motor [15]. The untreated fuel contains a mix of oil, water and solids, which the centrifuge separates into three layers [86]. The purifier has two outlet pipes, one for discharging the purified fuel and one for the separated water. Within the water outlet there is a gravity disc, which controls the radial position of the fuel-water interface, and thus directly affects the purifier's cleaning efficiency [86].

A set of gravity discs is supplied with each machine and the optimum size to be fitted depends on the density of the untreated oil [86]. During operation, the fuel's solids (cat-fines etc.) will accumulate on the walls of the bowl, thus regular discharge is required. Modern ships are fitted with automatic separators that automatically adjust the oil-water interface without the need of gravity discs and are able to discharge the accumulated sludge without stopping purifier's operation. Generally, purifiers are designed for maximum engine load operation, and thus maximum fuel consumption. However, the longer the fuel stays in the separator, the better it will be cleaned, meaning that lower fuel flows are heavily recommended e.g. in the range of 25% - 35% as seen in Table 6-1.

Figure 6-3. Purifier Cross-section



Source: Alfa Laval

Table 6-1 Purifier efficiency range

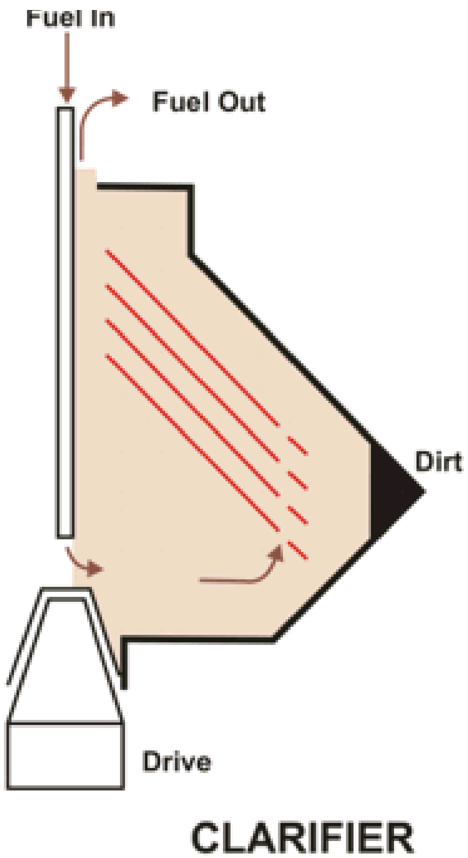
Size range of particles (microns)	5 – 6	6 - 8	8 - 10
Particles in feed oil to purifier	1,600	13,600	6,400
Particles after purification			
100% throughput	1,600	1,100	440
50% throughput	910	760	400
25% throughput	150	90	60

Source: The Standard P&I Club, American Bureau of Shipping (ABS)

6.1.2.2 Clarifier

Basically, the centrifugal clarifier is placed right the purifier and is the second stage of the separation process, with the consecutive double separation being the one that is normally followed by most vessels. Clarifier's operation is akin to the purifier's with the main manufacturing differences though being the lack of a gravity disc and the presence of a sealing ring to keep the impurities intact until discharge [35]. Contrary to a purifier which separates fuel from water and solids, a clarifier only removes solids, however with a much better efficiency in finer particles. Fuel oil enters the arrangement untreated from the top and exits it cleaned from the clarifier's outlet pipe. During operation, centrifugal force forces the fuel through the disc stack driving the denser impurities towards the periphery of the machine and the clean fuel towards the center of the bowl and finally to the clarifier's oil outlet [86]. The combination of the purifier/clarifier in series arrangement is generally recommended, since clarifier is able to withhold much finer and lighter particles than the purifier and especially the very dangerous cat-fines [35]. This does not apply though when automatic purifiers with no gravity discs are used, in which case the combination of two purifiers in parallel arrangement and corresponding feed rates is preferred.

Figure 6-4. Clarifier cross-section



Source: Operational information: Centrifugal separators. (n.d.). Retrieved from http://www.marinediesels.info/2_stroke_engine_parts/Other_info/purifiers.htm

6.1.3 Fuel Oil Transfer System

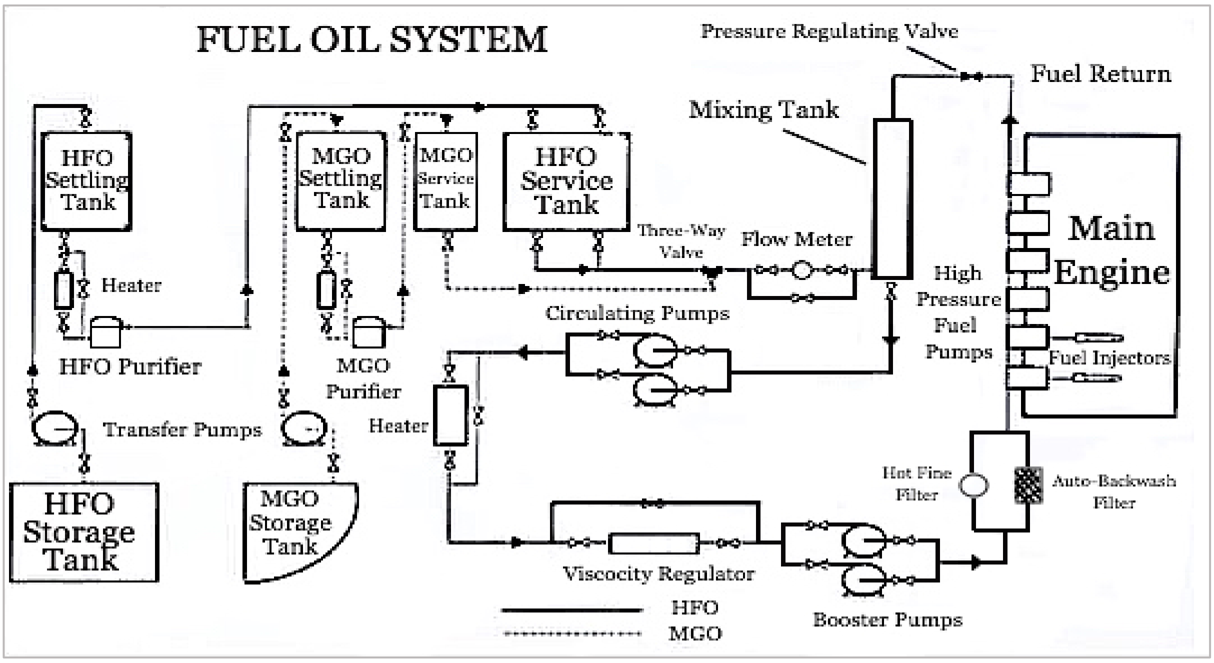
Fuel oil flow is driven by numerous pumps along its course from storage tanks to consumption, a typical example of which is illustrated in Figure 6-5.

First in line are the transfer pumps (different for HFO and MGO), which take suction from the corresponding storage tank and deliver the fuel via a suction filter to the settling tank, as appropriate. After treatment in the settling tank, the fuel oil is pumped to the service tank via a heater and the purifier/clarifier system's pump. The ship's MGO & HFO service tanks' fuel outlets converge to a three-way valve (commonly known as change-over cock) which is used to change-over between the two fuels and vice versa. The regulated outflow is measured by a flow meter prior to entry in the mixing tank. The otherwise known as mixing column provides a smooth change in the fuel's viscosity when changing from HFO to MGO (or vice versa) and acts as an absorber for the pressure shocks that are coming from the return line [67].

The mixing tank's outflow is pumped out by the circulating pumps which deliver the fuel to the booster pumps via a heater and a viscosity regulator. Normally, there are two circulating and two booster pumps, however, at any time only one pump (of each type) is in operation and the other in standby. The viscosity regulator (or viscotherm) measures the fuel's temperature and adjusts the steam supply to the fuel heater according to the desired fuel viscosity [67].

The booster pump raises the fuel's pressure at the necessary level and delivers the fuel to the distribution manifold through either a hot fine filter or an auto-backwash filter [67]. Both filters, besides contributing to the cat-fines abatement, can also indirectly act as indication of inadequate cleaning in the centrifugal separators.

Figure 6-5. A typical marine fuel oil system



6.2 Preparations and Challenges

In view of January 1st, 2020, ships not fitted with scrubbers should prepare to start burning cleaner fuels. Shipowners will need to schedule their plan in advance in order to secure their fleet's smooth transition into VLSFO. Considering the complexity of the task, IMO is encouraging shipowners and ship operators to develop ship implementation plans, outlining how the ship may prepare in order to comply with the required sulphur content limit of 0,50% by 1 January 2020. This preparation should be made for all ships in a timely manner and it should include all the necessary ship modifications, crew training and operational planning in order to ensure a smooth transition and consistent compliance to the new regulation.

In this context, the Marine Environment Protection Committee (MEPC) of IMO, at its 73rd session (October 2018), recognizing the need for guidance, approved the "Guidance on the development of a ship implementation plan for the consistent implementation of the 0,50% sulphur limit, under MARPOL Annex VI" (circular MEPC.1/Circ.878). Due to the importance of its content, IMO's guidelines will be appended verbatim in the annex, and in the present chapter only the key points of the document will be quoted (hereafter the IMO's SIP). In short, the IMO's guidelines consist of three appendices:

- Appendix 1: An indicative example of a ship's implementation plan
- Appendix 2: Information regarding the VLSFO & MGO's impact on ship machinery
- Appendix 3: Recommendations on fuel tank cleaning

Following the foregoing guidelines, IMO furtherly issued on MEPC 74th session, the "2019 Guidelines for consistent implementation of the 0.50% sulphur limit, under MARPOL Annex VI" (hereafter IMO 2019 Guidelines); similarly to IMO's SIP, these guidelines will be utilized for the writing of this chapter, and will be annexed in their official form in the appendix.

It is important to be noted though that, "a ship implementation plan is not a mandatory requirement. A lack of a ship implementation plan or an incomplete ship implementation plan should not be considered as "clear grounds" for a more detailed inspection." (IMO, MEPC.1/Circ.878, 2018). That means, that, neither is it the IMO's abovementioned guidelines obligatory to be followed, nor are the shipowners obliged to deploy ship implementation plans in general. Nevertheless, they are heavily recommended to do so.

Among others, major marine engine manufacturer MAN Energy Solutions, has issued its own guidelines on how to prepare and operate on 0,50% fuels. The manufacturer's "0.50% S fuel operation 2020" paper includes detailed information and recommendations regarding the transition on sulphur cap compliant fuels. Considering the company's expertise, it was deemed wise that emphasis in the foregoing paper (hereafter MAN Guidelines) is to be given, bearing in mind that MAN's accumulated knowledge can constitute a high quality and insightful source for this chapter's subject.

6.2.1 Pre – January 2020 Preparations

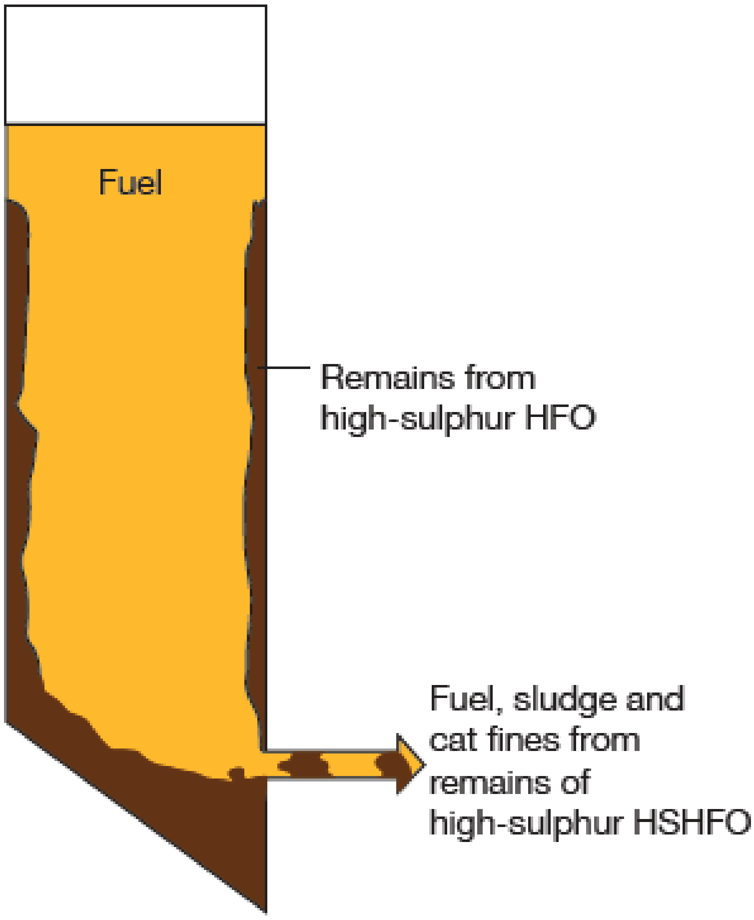
At the 70th session of MEPC, it was agreed to "1 January 2020" as the effective date of implementation for ships to meet the global 0,50% m/m sulphur content of fuel oil requirement. For shipowners that intend to turn to the use of low sulphur fuels, it means that the full ship change-over to VLSFO must be finished the latest by 1st of January 2020, with no exceptions to be allowed. The complexity of the attempt and the uncertainty around the new fuels, together with the number of the affected vessels (approximately …), necessitate the timely preparation of shipping companies, as early as possible in 2019. The ship implementation plan should be based, among others, on the vessel's technical characteristics, operating and trading profile, elements that vary between a company's vessels, thus it is advised to be prepared separately for each one of them. Depending on the vessel, it may prove necessary that a number of installations and machinery modifications should be carried out on board, hence, an effort to clarify those was considered indispensable.

6.2.1.1 Fuel Tank modifications

6.2.1.1.1 Tank cleaning

As previously stated, most ships have been operating mainly on high sulphur residual fuels, commonly known as HFO. According to IMO's SIP, "such fuels tend to adhere to the inside of fuel tanks forming layers of semi-solid substances containing sediments and asphaltenic sludge with dangerously high concentrations in cat-fines and sulphur; such residues will also typically have solidified and settled in various parts of the fuel oil service system including pipelines, settling and service tanks" (Figure 6-6). However, some of the fuels complying with the 0.50% sulphur limit are expected to be very paraffinic due to the fractions' types that will be blended with the fuel in order to lower its sulphur concentration. As quoted in IMO's SIP, "in case that such fuels are loaded into HSFO fuel tanks that have not been cleaned, there is a possibility that they could dissolve and dislodge the sediments and asphaltenic sludge that have precipitated along the fuel system and tanks". Tank bottom's sediment dissolving could cause serious wear (due to cat-fines) in the ship's engines but also contaminate several hundred tons of subsequently bunkered VLSFO. Thereby, HFO tanks cleaning is considered necessary.

Figure 6-6. Dirty residues in HFO tanks



Source: MAN Energy Solutions. (2019, July). Fuel tank cleaning (Service Letter SL2019-674/JAP). Retrieved from https://marine.man-es.com/docs/librariesprovider6/service-letters/sl2019-674.pdf?sfvrsn=c7bcc3a2_4

6.2.1.1.1.1 Manual Cleaning

Fuel tank cleaning can be done by emptying the tanks (stripping) and manually cleaning the fuel residues and accumulated impurities from the tank's walls and bottom. In this way, tank cleanliness can visually be verified while at the same time it is good opportunity for the ship's crew to inspect the overall tank coating and heating coils condition and carry out any maintenance or repairs that may come into display. Moreover, the fuel oil system components (purifiers, valves, filters and etc.) and especially the main engine will be protected against a potential mass abruption of the accumulated sludge and precipitated cat-fines. Manual tank cleaning can either be done during dry-docking or whilst in service.

6.2.1.1.1.1.1 Manual Cleaning during dry-docking

Regarding dry-docking, it would be the ideal scenario since the process can be done with much more flexibility. Tank stripping and disposal of the removed fuel residues ashore will be easier and with less concerns since the whole process will be exempted from the complexity of the fuel system and the need to operate the ship at the same time. Additionally, specialized cleaning personnel can be outsourced which due to better and faster tank cleaning, could bring significantly down the overall cost of the operation [79]. Ship crew should take into account though, that after dry-docking the whole fuel system has to flushed in order to prevent VLSFO contamination, thus adding a few more days in the whole process. Nevertheless, it is highly unlikely tank cleaning can coincide with the dry-docking of the beforehand scheduled special and intermediate surveys [79]. In addition, it is also true that global shipyard capacity is way behind the 50.000-60.000 of ships that are anticipated to need tank cleaning by January 1, 2020.

6.2.1.1.1.1.2 Manual cleaning in service

Manual cleaning whilst in service will likely be the predominant option. The procedure can be carried out either by outsourced specialized staff that will board the vessel for a few days or by the ship's crew. Since the announcement of sulphur cap regulation, many companies providing tank cleaning services at sea have emerged, although with a relatively high cost, therefore it is expected that the task will be normally undertaken by the ship's crew.

In advance of the cleaning process, the emptying of all HFO fuel tanks (bunker, settling and service) has to take place. The tanks should be emptied as much as possible, in order to reduce fuel wasting and ease the cleaning process [79]. Furthermore, it is necessary that the ship engineers should schedule the next bunkerings bearing in mind that at least one or two bunker tanks should be empty at each time; each finished bunker tank should be right after filled with VLSFO. Regarding the settling tanks, if more than one are present on the ship then then planning will not be difficult, since when the one will undergo cleaning the other will be in use. Otherwise, the engineer might have to switch to MGO while the HFO settling tank is undergoing cleaning. The same applies for the service tanks.

The time and work involved in cleaning HFO tanks cannot be defined precisely, as it will vary depending on:

1) the time since the last cleaning of the tanks
2) the condition of the tank coating
3) the size of the ship crew and its experience in the cleaning process
4) the size of the tanks
5) the weather since it can heavily affect permit or not of entrance in the fuel tanks
6) the availability of on shore facilities for fuel waste disposal as well as HFO offloading, should the ship have full bunker tanks

If the cleaning is done by the ship's existing crew, it would likely take a minimum of 4 days per tank (IMO, 2018). Of course, tanks need to be empty before they can be cleaned, hence the time needed to drain tanks needs to be taken into account when estimating the overall time required. In addition to cleaning tanks, all of the pipework in the fuel oil service system needs to be flushed. Flushing the remaining pipework and fuel oil service system after all tanks have been cleaned could take another 1 to 2 days, as stated in IMO SIP.

Overall, a typical suezmax tanker that has an HFO tank arrangement of four bunker tanks, one settling and one service tank, is expected to need at least 25 workdays in order to be ready to operate on VLSFO. Having successfully cleaned the tanks it will be necessary to ensure proper and appropriate disposal of the tank cleaning residues in accordance with the requirements of MARPOL ANNEX I, including the completion of all appropriate documentation for proper disposal at approved reception facilities (John Taylor, 2019). As outlined in North P&I Club's publication "Preparing for the Big Switch: Compliant VLSFO Products", who is going to bear the expenditure for the overall tank preparation, will depend on the wording of the charter party.

6.2.1.1.1.2 Cleaning by use of specialized additives

After the introduction of ECAs, many companies involved in marine chemicals started promoting fuel additives, claiming that they can be added in fuel tanks and gradually remove the solidified HFO residues from the walls and bottom of the tanks, without disrupting ship operation. Considering the average 1$ per treated ton of fuel cost of the fuel additive [1], it was forwarded as a very lucrative option against the much costlier and complex manual cleaning. Notwithstanding the tremendous benefits of not requiring any planning and work to clean the tanks, exempted also from the associated dangers and off-hire time, this practice shall receive the same attention before commencing it, although, in a slightly different way.

Due to the dilutant function of these additives, the sediment and asphaltenic sludge that has precipitated in various parts of the fuel system, will gradually dissolve and end up to the fuel consumers. As stated in MAN ES Service Letter SL2019-674/JAP, the tank bottom's sediment could contain cat-fines as high as 19,000 ppm in adverse situations, and generally a range of 4,000 to 19,000 ppm can be expected. Comparing to the 15 ppm maximum cat fines limit at the main engine inlet, it is obvious that sufficient removal of the dissolved impurities before entering the engines, is of utmost importance.

Therefore, during the cleaning process, the vessel's engineers should closely monitor the operation of the centrifugal separators and filters and be in a state of readiness in case of unexpected issues. In order to minimize machinery damage risk, it is recommended that fuel samples are taken regularly before and after the separators as well as at the main engine inlet. The whole process should be performed under the guidance of the cleaning additive manufacturer, while a pre-cleaning tank condition assessment is deemed necessary. The duration of the whole procedure cannot be predefined since several bunkerings are expected to be needed until the tanks are ready to fill with VLSFO.

6.2.1.1.1.3 Cleaning by regular flushing of the fuel system

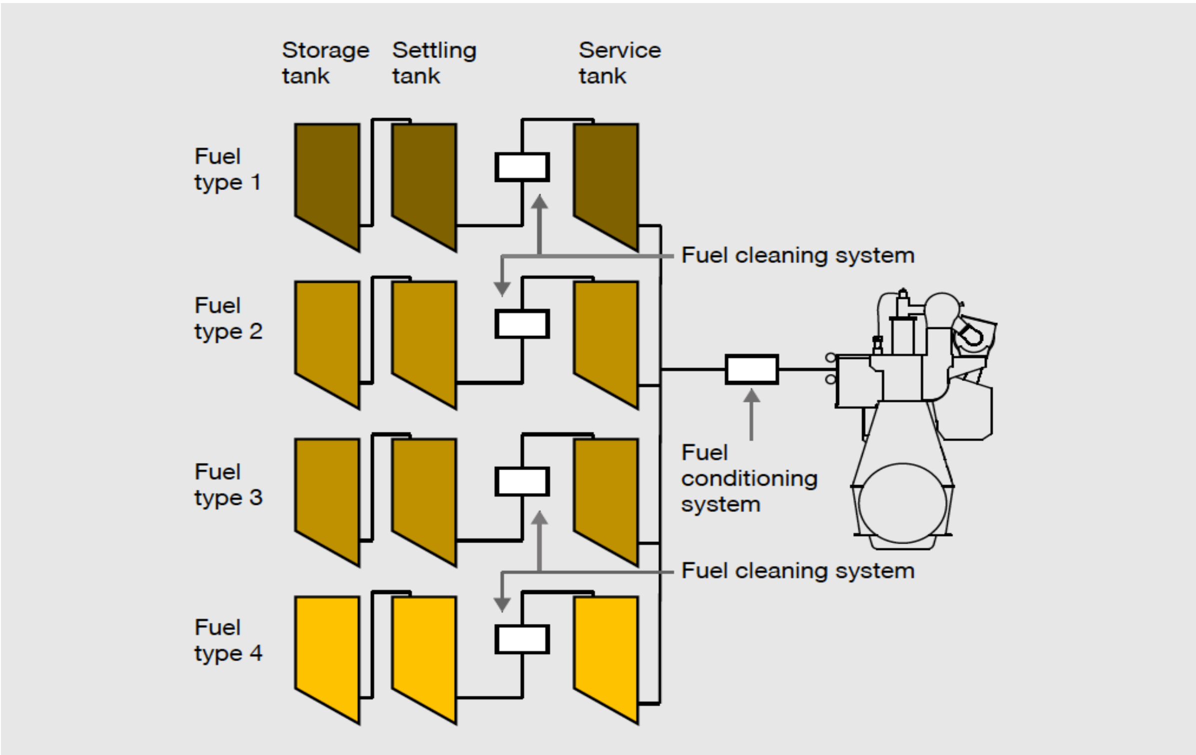
Another solution that has come into display for tank preparation, is bunkering the dirty tanks with VLSFO and waiting until the whole fuel system has been flushed of the sulphur, cat fines and other settled impurities. Random fuel sampling before separators and the main engine inlet together with the auto-backwash filter indication can confirm when the fuel has been cleaned from the unwanted impurities and if the ship has achieved compliance to the sulphur cap requirements. Like with fuel additives, the simple flushing of the fuel system is likely to lead to mass abruption of sediment and cat-fines, which could damage the purifiers, clog filters and cause serious wear in engine cylinders and pistons and other components. Misconception regarding the cleanliness of the fuel system is also possible, therefore it is not recommended to be adopted.

6.2.1.1.2 Tank Arrangement

The newly introduced VLSFOs are expected to present considerable variability in their specifications, among different refiners and bunkering ports. The lack of regulation on the VLSFO production procedure and the flexible fuel standardization have opened the way for an unstable low sulphur fuels landscape; bearing in mind the mass transition into VLSFO that will take place concurrently during the late 2019, VLSFO bunkers are anticipated to present varying quality and characteristics, for the first months after January 2020. Consequently, mixing different VLSFO batches on-board carries the risk of incompatibility issues that could cause excessive sludge production, filter clogging, engine malfunction and in the worst-case scenario of loss of power. For this reason, fuel suppliers are greatly discouraging any VLSFO mixing on-board the vessel.

Complete fuel flexibility can be achieved via a segregated fuel system whereby fuel commingling could be avoided along the whole fuel flow-path. The smart fuel system shall have multiple and equal number of bunker, settling and service tanks for VLSFO as well as separate fuel pipelines and treatment systems for each of the VLSFO lines (Figure 6-7). Thus, a new VLSFO bunker batch can be loaded in one of the empty individual fuel lines, while the ship is operating on VLSFO from the service tank of a different line. For newbuilds, a flexible fuel system should be considered from the beginning in order to facilitate the management of different fuel types. For the existing fleet though, modifying the whole fuel system is an expensive and complex retrofit, and in many cases impossible due to the lack of space. Hence, the ship engineers should give special attention and care on the VLSFO handling and the change-over procedure between incompatible bunkers, which will be explained in detail below.

Figure 6-7. Flexible fuel system Arrangement



Source: MAN Energy Solutions. (2019). 0,50% S fuel operation [PDF file]. Retrieved from https://marine.man-es.com/docs/librariesprovider6/test/0-50-s-fuel-operation.pdf

6.2.1.2 Procurement of VLSFO

Depending the ship's contract type (spot or time chartered), the shipowner or the charterer respectively, has to secure VLSFO supply both at the initial changeover's time (after tank cleaning) as well as steadily after January 2020. Bearing in mind the mass transition that will take place during the Q4 of 2019 and the relative unreadiness of bunker suppliers, high VLSFO prices and limited availability in many bunkering hubs are expected. Shipowners and charterers are advised to make long-term supply agreements with bunker suppliers and not rely on the spot market.

6.2.2 Post – January 2020 Challenges and Recommendations

6.2.2.1 Fuel chemistry

Traditionally, for the residual fuels, blending was principally in terms of viscosity control but then, with the greater availability of high-density refinery products, density also became a blending factor. The introduction of Sulphur cap has changed the primary blend target from viscosity and density to Sulphur regulation.

Whereas viscosity and/or density are at a relatively consistent level within the same fuel grades in the pre-2020 fuels, the implications of this mean that marine fuels post 2020 are expected to result in a wide variability of fuel formulations and characteristics alike.

Residual marine fuels' chemical composition is difficult to define since different crude oil feedstock and different production processes lead to varying quality and properties of the resulting marine fuels. Nevertheless, the quality and behavior of a bunker fuel much depends on the feedstocks' asphaltenes content and their aromaticity level.

The generic term 'asphaltenes' covers a wide range of heavier hydrocarbon structures of high molecular weight and high carbon/hydrogen ratios, the exact constituents being dependent on the crude source and choice of blend stocks. Asphaltenes are present in all residual fuels and a typical VLSFO batch will have an asphaltene content of 3%-10% (m/m) (IMO Guidelines).

The aromaticity level of a marine fuel depends on its ratio between saturates (paraffins and naphthenes) and aromatics, where aromatics content greater than 50% constitutes an aromatic fuel while lower values give a paraffinic character to the blend. Resins are compounds of similar structure to asphaltenes and they represent an "intermediate" between asphaltenes and saturates/aromatics.

As asphaltenes have a substantial aromatic character, they tend to be stabilized by the presence of resins and aromatic oil fractions (e.g. FCC Cycle Oils have an aromatic content of more than 80%). Contrarily, higher concentration of saturates, which usually dominate among paraffinic oil fractions (e.g. atmospheric gas oils) has detrimental effects on asphaltenes; the latter will gradually break apart from the colloidal state and begin to agglomerate (or flocculate), and finally break the fuel's equilibrium and precipitate as asphaltenic sludge.

In brief, residual marine fuels tend to be characterized as paraffinic or aromatic, according to the overbalance or not of their aromatics content. Mixtures of paraffinic blends (e.g. vacuum distillation bottom) and aromatic blends (e.g. high atmospheric gas oil), can result either in an aromatic fuel or a paraffinic one, depending on the residues/"cutter" aromatics content, their blend ratio as well as the order of blending. The unfavorable interaction of paraffinic compounds with asphaltenes, can create serious problems in the fuel's stability and mixing capacity.

6.2.2.2 Stability

The stability of a fuel is defined by its resistance to breakdown and precipitate asphaltenic sludge, despite being subjected to forces, such as thermal and ageing stresses, while storaged under normal operating conditions (MAN Guidelines). Stability relates primarily to the potential for asphaltenes to precipitate and lead to the formation of sludge. This has the potential to block filters and pipes leaving with an un-pumpable residue.

If the fuel is aromatic, then the asphaltenes will remain in suspension and will not affect the fuel's combustion quality. If the fuel is paraffinic though, the fuel's cohesion can be adversely affected and the asphaltenes may precipitate and accumulate to the tanks and fuel system as sludge. Once the fuel's equilibrium has been disrupted there is little chance to reverse the process. The fuel refiners and suppliers are responsible for delivering a stable and homogenous fuel, with the anticipated combustion behavior.

6.2.2.3 Compatibility

Compatibility is the term used when evaluating if two (or more) fuels can be mixed without asphaltenes coming out of suspension. If two fuels are commingled together and the resulting blend remains stable (i.e. does not precipitate asphaltenic sludge), the fuels would be termed compatible. On the other hand, if the resulting blend is unstable, then the component fuels are said to be incompatible, even though each component is individually stable. Commingling in the same tank an aromatic VLSFO batch with a paraffinic VLSFO batch has the likelihood of creating an unstable blend, where asphaltenes will disperse and precipitate into asphaltenic sludge.

In a general sense, having an unstable fuel or having mixed two incompatible fuels, will have the same effect, namely excessive production of asphaltenic sludge. The accumulation of this sludge in tanks' bottom and pipelines can lead to operational problems of separators, filter clogging and in the worst-case disruption of the fuel supply to the engine, causing fuel starvation. As mentioned before, mixing two incompatible VLSFO batches shall therefore be avoided at the maximum possible extent.

6.2.2.4 Viscosity

The 0,50% VLSFO is expected to present wide variation in viscosity comparing to HFO, the two-thirds of which were being supplied at 380 centistokes. The ISO 8217:2017 standard designates only maximum limits regarding the residual fuels and bearing in mind that fuel production process is unregulated, shipowners shall expect VLSFO batches with normal viscosities (around 380 cSt) as well as with unusually low values e.g. 50 cSt-100 cSt. Ship crew must be aware of the received fuel's viscosity and adjust the heater as. Low fuel viscosity could be a problem for the fuel system's pumps, and possibly lead to insufficient pumping and fuel leakages. The purifier/clarifier can also be affected, with possible deterioration in their separation efficiency. Even more important is the fuel's viscosity at the engine inlet, which has a desired range of 2 cSt – 20 cSt. Should the fuel be too thick or too thin, that could in inadequate combustion and lower overall efficiency.

6.2.2.5 Density

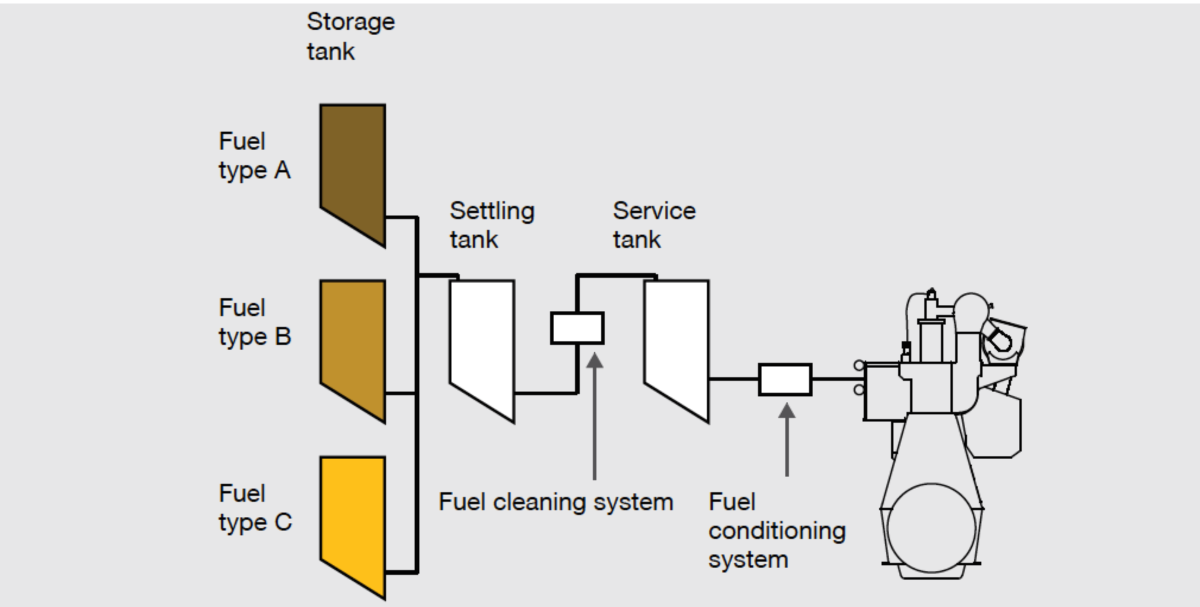
Like viscosity, VLSFO density is expected to vary between suppliers and ports, even within the same fuel grades. The ship engineers should pay attention in the bunkered fuels' characteristics and appropriately adjust the centrifugal separators, in case they are of the classic type with the gravity discs. If a wrong gravity disc is fitted in the purifier, the solids and water separation efficiency can be adversely affected; that would lead into supplying the main engine with a fuel high in cat-fines and possible subsequent wear in the cylinders and pistons.

6.2.2.6 Tank Management

Typically, a ship has at least 2-4 bunker tanks, one settling tank and one service tank dedicated for high sulphur fuels as seen in Figure 6-8. If there are not any completely empty bunker tanks then the new VLSFO batch has to loaded on top of another batch, risking incompatibility issues. In that case, the selected bunker tank has to be emptied to the greatest possible extent, preferably resulting to a mixing ratio of 80:20 or 90:10 and avoiding high-risk ratios of 50:50 or lower. Generally though, due to the number of available storage tanks, the engineer can prevent such incidents and schedule in advance the consuming of one of the storage tanks.

Regarding the settling and service tank, a change-over between the storage tanks of different VLSFO batches means that the two fuels will inevitably come into contact inside the settling and the service tank. In that case, the change-over has to be preceded by a spot testing (ASTM D4740) of the previous and the following fuel batch. In case that the two batches prove incompatible, the settling and service tank have to emptied as much as possible, so that only the un-pumpable tank heel (usually under 2%) will be mixed with the new fuel. Since, the engines need continuous and uninterrupted fuel feeding from the service tank, the ship crew can also intervene the VLSFO change-over with MGO, thus not needing to worry about possible loss of power due to insufficient fuel feeding or unwanted VLSFO commingling.

Figure 6-8. Simple fuel system arrangement



Source: MAN Energy Solutions. (2019). 0,50% S fuel operation [PDF file]. Retrieved from https://marine.man-es.com/docs/librariesprovider6/test/0-50-s-fuel-operation.pdf

Chapter 7. Compliance with IMO Sulphur Cap by use of Exhaust Gas Cleaning System

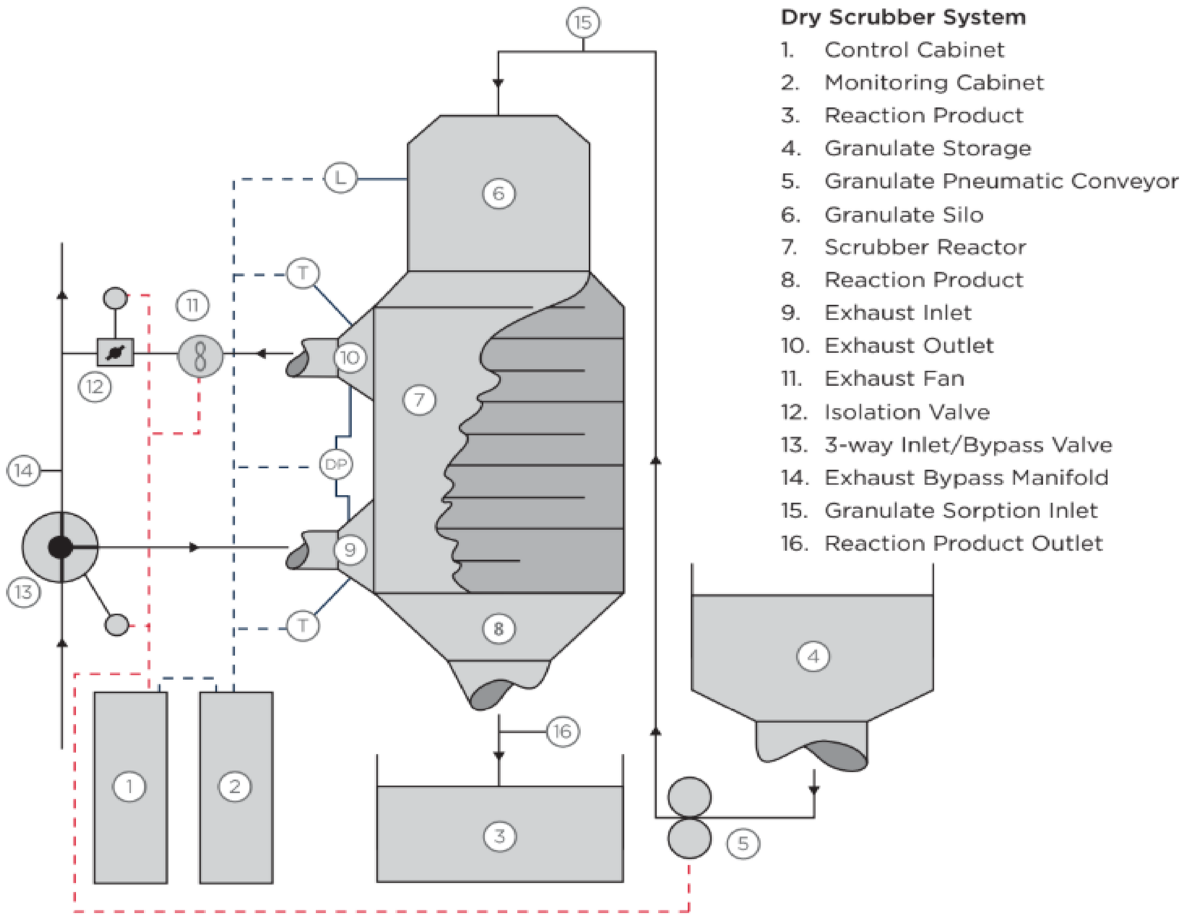
The ship owners that will not employ a fuel-change solution (e.g. VLSFO) as their main fuel to comply with the new IMO 2020 regulation, an Exhaust Gas Cleaning System (EGCS) is a matter of necessity. Also known as scrubbers, these systems are a viable solution, both economically and environmentally, to remove most of the Sulphur Oxides (SO_x) and reduce Particulate Matter (PM) from the exhaust gas of ship's combustion units.

There are two basic concepts commonly proposed for shipboard application of EGCS: the dry and the wet scrubber type. The basic principles for the dry and wet scrubbing concept are described further in this section.

7.1 Dry Scrubbers

A dry scrubber does not use any liquid to carry out the scrubbing process, but instead exposes hydrated lime-treated granulates to the exhaust gas to create a chemical reaction that removes the SO_x emission compounds. The dry scrubbers are usually used in industrial plants [3]. A schematic of it is shown in Figure 7-1.

Figure 7-1 Dry scrubber system



Source: American Bureau of Shipping (2018). Advisory on exhaust gas scrubber systems.

7.2 Wet Scrubbers

In this category, the exhaust gases are treated with liquid, usually water either chemically treated fresh or seawater, and SO_x compounds react with parts of the wash liquid. There are further categorized by their operation as open loop, closed loop, and hybrid systems. The latter offers both methods of scrubbing; open and closed loop according to preference.

Wet scrubbers are more acceptable for ships due to their lower price and smaller unit dimensions [92].

The Sulphur Oxides generated in the combustion process due to the sulphurous fuel are dissolved and removed by the scrubber water following simple chemical reactions:

$$SO_2 + H_2O \rightarrow H_2SO_3 \text{ (sulphurous acid)}$$

$$SO_3 + H_2O \rightarrow H_2SO_4 \text{ (sulphuric acid)}$$

7.2.1 Open loop Scrubber

An open loop scrubber uses seawater as the medium for cleaning or scrubbing the exhaust gases through utilizing the alkalinity of it, usually without adding chemicals. The used water is discarded later in the ocean after surpassing a cleaning process. Thus, the effectiveness of an open loop scrubber depends on the chemistry of the water that the vessels is operating in [3].

Dedicated pumps (seawater pumps) provide the whole system with seawater which passes through pipes to the main scrubbing tower, where it is usually sprayed through nozzles in order to maximize the efficiency of the process. The cleaned exhaust gases may pass through a demister or water droplet separator to remove heavy water particles from the gas, which reduces the potential for steam generation as they exit in the atmosphere through the funnel. The washwater that was used before might be cleaned before discarded into the ocean. Passing through hydro-cyclones or separators is a great method to isolate the residuals, such as PM. The removed residuals must be retained onboard in a dedicated tank to be discarded ashore. There have been set discharge limitations by the IMO and various regional and U.S. Federal regulations, so the pH of the washwater discharge must be measured and adjusted to the ideal level prior to overboard discharge. Monitoring of turbidity and Polycyclic Aromatic Hydrocarbons (PAHs) are also mandatory.

Nevertheless, several countries and ports, such as Singapore, China and Fujairah in the United Arab Emirates, have already banned the use of open loop scrubbers, from the start of 2020 and more are to come. In such occasion, the washwater must be stored onboard and be discharged elsewhere.

Below, Table 7-1 summarizes the countries and ports that have or will prohibit the use of open loop scrubbers.

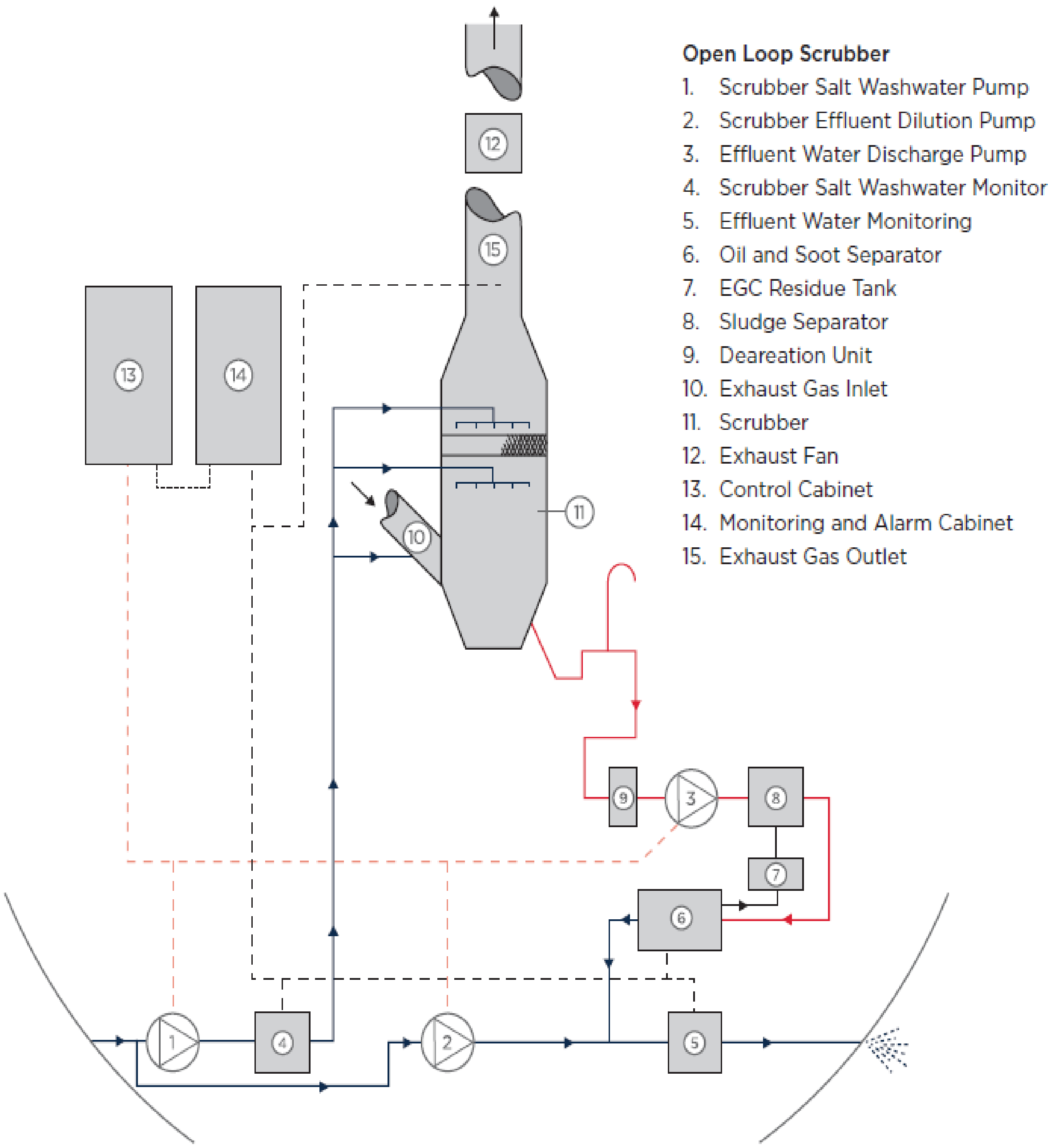
Table 7-1 Countries and ports that have banned the use of open loop systems

Country	Port	Open loop EGCS discharge allowed
Bahrain	Bahrain	No
Belgium	All ports	No
PR China	Inland river ECAs, Port areas within coastal ECAs and Bohai Sea	No
Egypt	Suez Canal	No
Germany	Inland Waterways, canals and ports within inland waterways	No
Gibraltar	Gibraltar	No
Ireland	Dublin and Waterford	No
Latvia	All ports	Conflicting advice
Lithuania	All ports	Conflicting advice
Malaysia	All ports	No
Pakistan	Karachi	No
Panama	Panama Canal	No
Portugal	All ports	No
Singapore	Singapore	No
United States	Californian Ports and Waters	No
United States	Connecticut Ports and Waters	No
United States	Hawaii Ports and Waters	Yes - conditional
United Arab Emirates	Abu Dhabi Ports	Yes - conditional
United Arab Emirates	Fujairah	No

Source: No scrubs: More ports declare ban on EGCS discharges (2020, January 22). Retrieved from https://www.nepia.com/industry-news/no-scrubs-more-ports-declare-ban-on-egcs-discharges-update/

A schematic of an open loop scrubber is presented on Figure 7-2.

Figure 7-2 Open loop scrubber system



Source: American Bureau of Shipping (2018). Advisory on exhaust gas scrubber systems.

Specifically, as it can be seen in Figure 7-2, the sea water is sucked through the scrubber salt washwater pump (1) directed into the scrubber salt washwater monitor (4) which measures the pH and finally ends up in the scrubbing tower (11) where it meets with the exhaust gas inlet flow (10).

After the scrubbing process the washwater passes through a deaeration unit (9) in order to remove oxygen and other dissolved gases. With the help of a pump (3) it is then headed to the sludge separator (8) where the residuals are separated and then headed to the EGC residue tank (sludge tank) (7). Continuing, in the oil & soot separator (6) the filters constrain the last residues, which are also headed to the sludge tank and the washwater is practically cleaned.

It is important to notice that for the open loop operation, the utilization of the oil and soot separator and thus the sludge tank is not mandatory and can be avoided.

Finally, the treated water is mixed with fresh seawater directly with the scrubber effluent dilution pump (2), monitored (5) in terms of pH, PAHs, turbidity and temperature and then discharged to the sea while complying fully with IMO regulations.

The cleaned exhaust gases escape from the scrubbing tower via a funnel with the help of the exhaust fan (12) which minimizes the pressure drop (backpressure) between the inlet and outlet condition.

The system has low operating costs as no additional water treatment is required. However, seawater flow rate is relatively high. Combined with the required pressure due to the difference in height of the highly placed scrubber and the seawater pumps, the power needed for scrubbing is a running cost that cannot be ignored. In certain cases, in areas where the seawater alkalinity is too low or restricted outlet criteria are in force, the system cannot be used, and running on low sulphur fuel or utilizing a different scrubbing method is required [92].

7.2.2 Closed loop Scrubber

In a closed loop scrubber, treated water (fresh water plus chemical additives) is circulated in order to keep the scrubbing process independent of the water's salinity that the vessel is sailing in. The additives usually are sodium hydroxide ($NaOH$) or magnesium oxide (MgO) forming a sulphate in the following process [69]:

$$H_2SO_3 + 2NaOH + \frac{1}{2}O_2 \rightarrow Na_2SO_4 + H_2O$$

$$H_2SO_4 + 2NaOH \rightarrow Na_2SO_4 + H_2O$$

The major difference between the open and closed loop systems is that in the latter, rather than going overboard, most of the circulating washwater is processed after it leaves the scrubber tower to make it suitable for recirculation as the scrubber washwater medium [3]. Finally, there is a bleed-off of saturated water, which is then replaced with fresh and dosed with caustic soda ($NaOH$) to restore its alkalinity prior to returning to the scrubber tower.

In the case of closed loop system, more tanks are required. These include a process tank or buffer tank, a holding tank through which discharge to sea is prohibited and also a storage tank capable of regulating its temperature between 20º and 50ºC for the sodium hydroxide which is usually used as a 50% aqueous solution.

It has been proven that a closed loop scrubber requires less washwater flow than an open loop to achieve the same scrubbing efficiency, since the pH of the water can be adjusted through dosing $NaOH$.

In freshwater scrubbers, since SO_2combines with a salt, it does not react with the natural bicarbonate of seawater and hence there is no release of CO_2. The following reactions describe the closed loop operation:

$$2NaOH + SO_2 \rightarrow Na_2SO_3 + H_2O \text{ (sodium sulfite)}$$

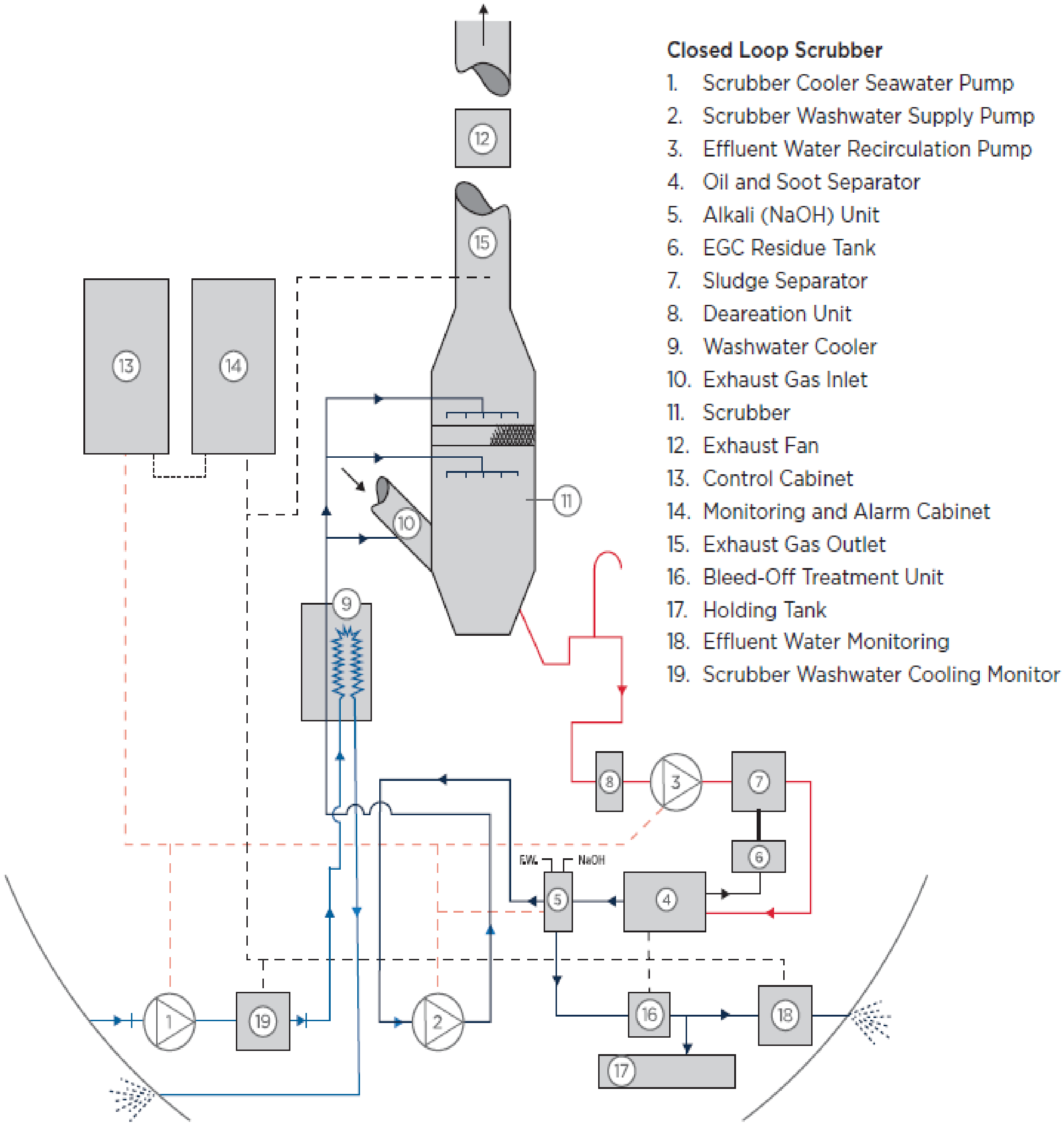
$$Na_2SO_3 + SO_2 + H_2O \rightarrow 2NaHSO_3 \text{ (sodium hydrogen sulfite)}$$

$$NaOH + H_2SO_4 \rightarrow NaHSO_4 + H_2O \text{ (sodium hydrogen sulfate)}$$

$$2NaOH + H_2SO_4 \rightarrow Na_2SO_4 + 2H_2O \text{ (sodium sulfate)}$$

A schematic of a closed loop scrubber is displayed in Figure 7-3.

Figure 7-3 Closed loop scrubber system



Source: American Bureau of Shipping (2018). Advisory on exhaust gas scrubber systems.

The basic internals of the closed loop system are the same with those of the open loop, but the cleaning process differs. As discussed before, the washwater is circulated in the system. Firstly, after it has cleaned the exhaust gases, as in the open loop system, it is headed to the deaeration unit (8), sludge separator (7), oil and soot separator (4) and the residues are collected to the EGC residue tank (sludge tank) (6).

Even though for the open loop system the oil and soot separator are not mandatory, for the closed loop system, this Water Treatment Unit (WTU) is considered necessary or else the washwater turbidity[8] would exceed the set limits and cause incompliance due to the saturation of the water.

In the case of the open loop system, the treated water in this stage would leave the system and be replaced by new sea water. Yet in the closed loop operation this treated water heads into the alkali unit (recirculation tank) (5) where it is dosed with fresh water (F.W.) and $NaOH$to regain its properties (proper pH). A bleed-off quantity of water is mandatory to be extracted from the system for the circulating water not to get saturated.

Following this process, the washwater is directed with the scrubber washwater supply pump (2) to the washwater cooler (heat exchanger) (9), which utilizes the temperature of the seawater, prior to be employed again in the scrubbing tower.

The bleed-off water that was extracted, is cleaned in the bleed-off treatment unit (16) and there are two choices, either to discharge it in the sea if it meets the criteria of pH, PAHs, turbidity and temperature, or to carry it in a holding tank (17) if zero discharge in the area is mandatory and unload it ashore.

The exhaust gases escape from the scrubbing tower as in the open loop system with the help of the exhaust fan (12).

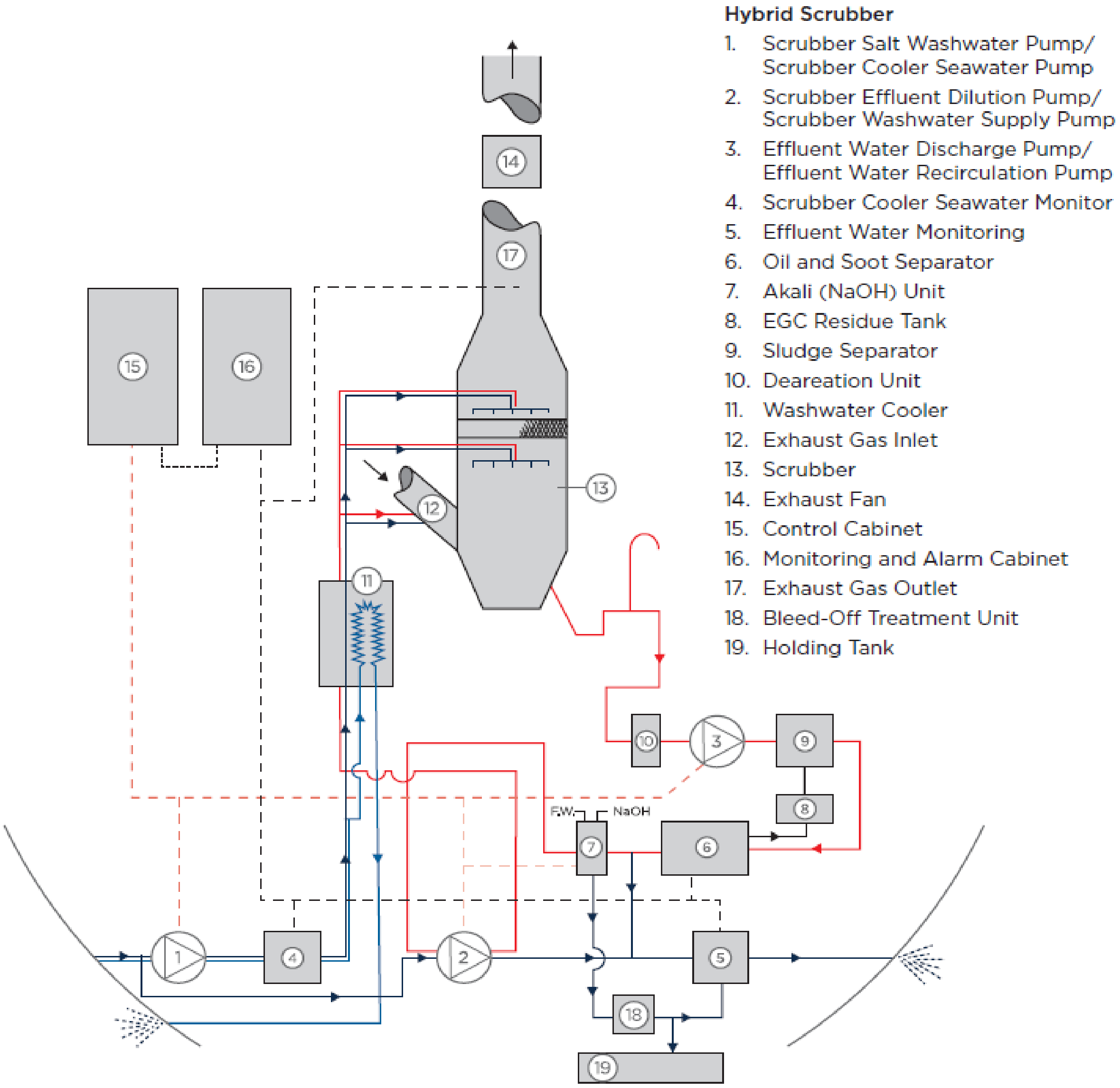
[8] Turbidity is a measure of the degree to which the water loses its transparency and hence is a measure of the water quality, due to the presence of polluting particulates such as PM.

7.2.3 Hybrid Scrubber

As mentioned before, the hybrid scrubbers combine the function of both open and closed loop, thus providing the advantages of both systems. Open loop systems offer the avoidance of purchasing and handling caustic soda, and the avoidance of processing washwater. Closed loop systems advantages include the scrubber working with the same efficiency independently of where the vessel is operating, and there is little or no water discharge making it best suited for coastal, port and inland waters [3].

A schematic representation of a hybrid scrubber can be seen in Figure 7-4.

Figure 7-4 Hybrid scrubber system



Source: American Bureau of Shipping (2018). Advisory on exhaust gas scrubber systems.

The hybrid scrubbers are suitable for long and short voyages around the world using only the lower costing Heavy Fuel Oil (HFO) all the time As the system can run on lower costing fuels for longer periods of time and around the world, they can overcome their high initial costs in order to economically meet with the international regulations. On the other side, there is a need for more structural modifications to employ this system as it combines both the equipment for closed and open loop operation. Thus, requires large storage space for chemicals and additives and the installation cost and time are higher.

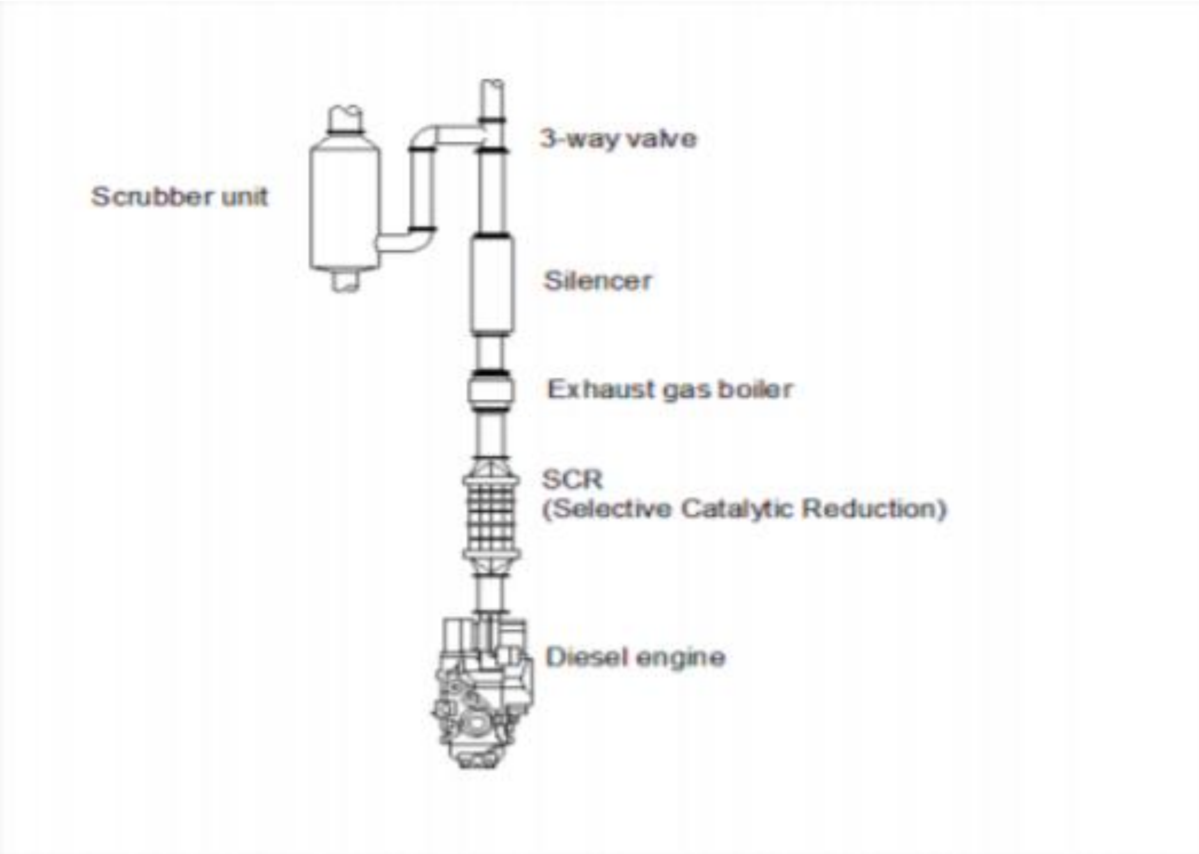
Usually, hybrid scrubbers have integrated GPS in the control system to switch automatically from open to closed loop.

Hybrid systems are hence proving to be the most popular because of their ability to cope with different conditions.

7.2.4 Connected E/G stream inlets

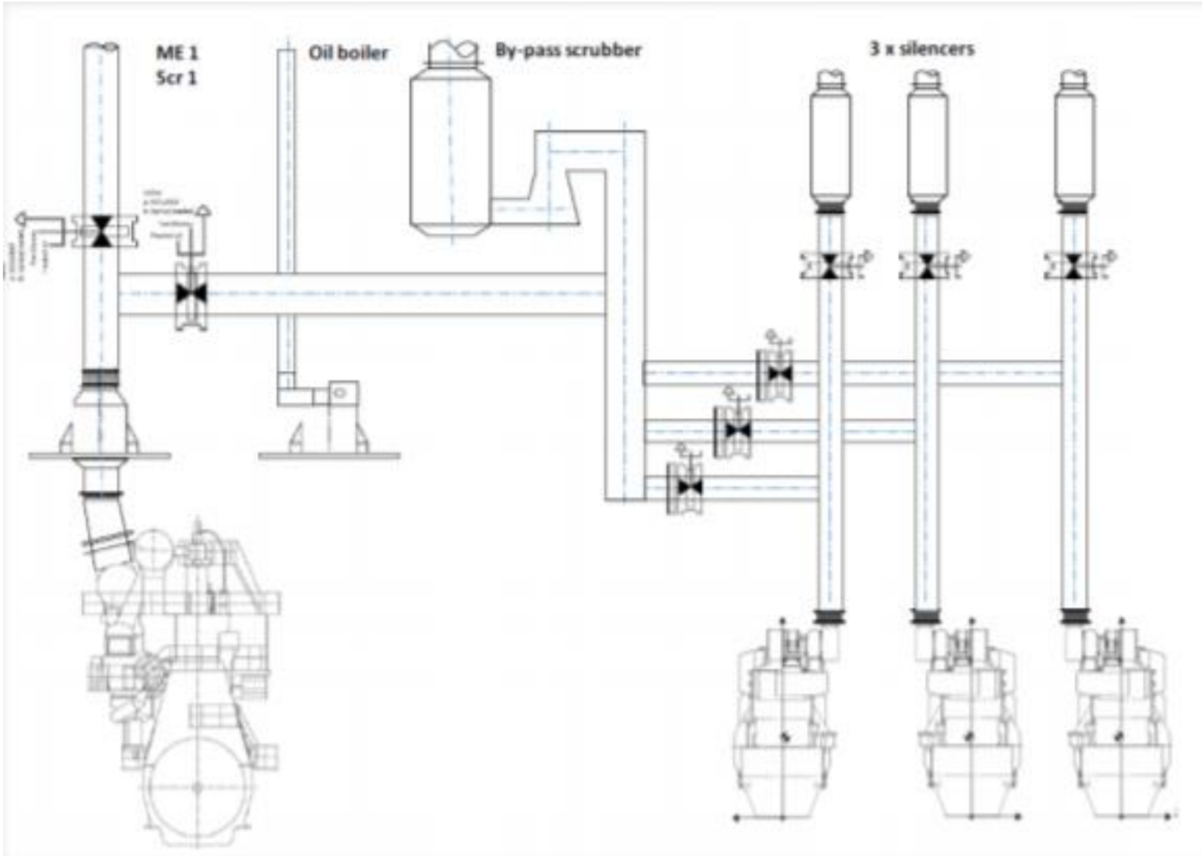
The scrubber can be further categorized in terms of the machinery that it serves. In the occasion that it has only one exhaust gas entry from an individual combustion unit, the EGCS can be characterized as single stream inlet. Multi-stream inlet scrubbers are typically installed so one scrubber can serve multiple internal combustion units. Such integrated systems require isolation and bypass arrangements so that any engine not in operation can be isolated, or in case of scrubber failure, the scrubber can be bypassed if they are not designed for operation in a dry condition [4].

Figure 7-5 Single stream inlet



For example, if the EGCS serves only the Main Engine (ME) of the vessel, it is labeled as single stream inlet. In any other event, serving both the ME, the boilers and/or the generators, characterizes it as multi-stream inlet.

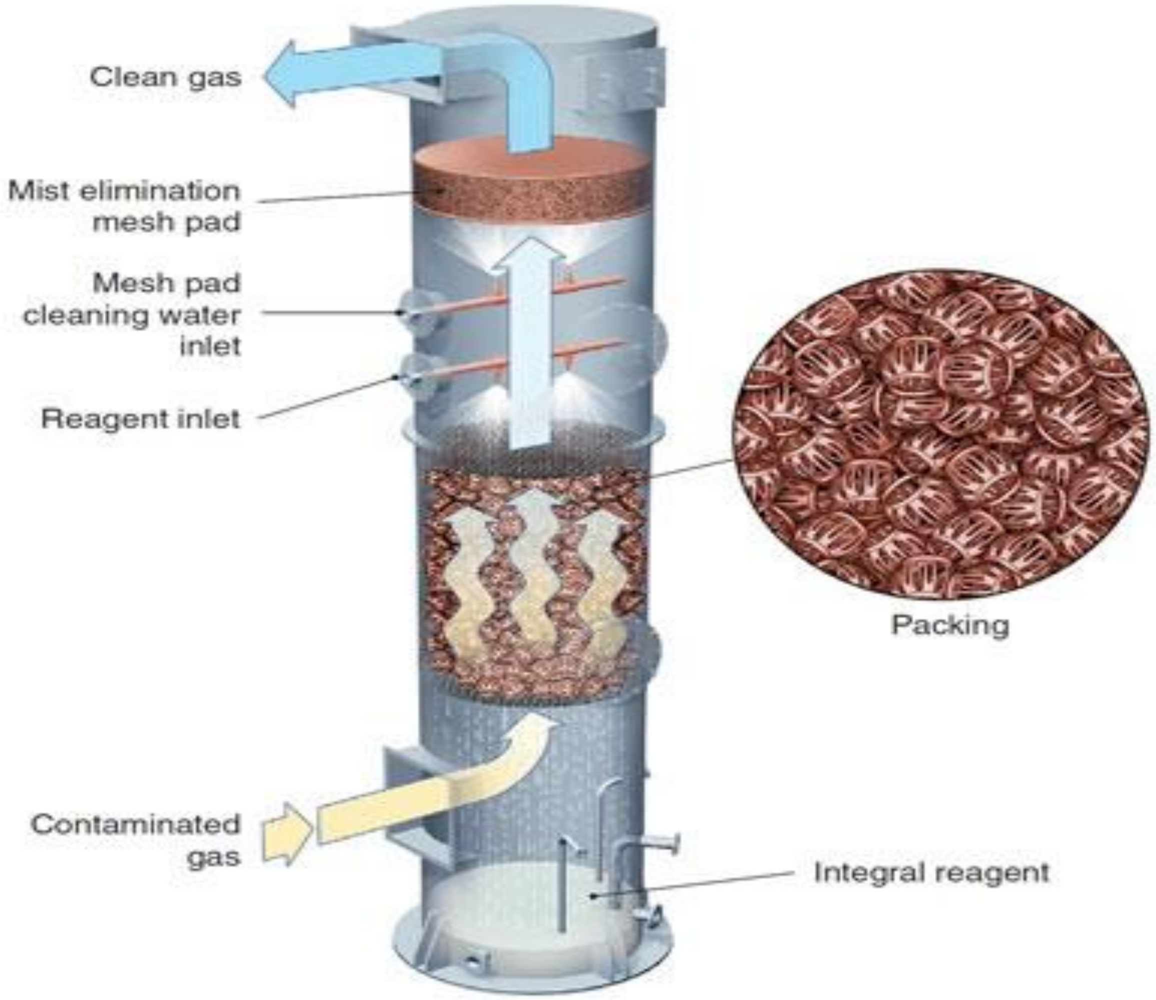
Figure 7-6 Multi - stream inlet



7.2.5 Packing materials

Generally, a scrubber with a packed bed means that the scrubbing tower is stuffed with packing material for several reasons. Packed beds were created to improve contact between two phases in a chemical process and are designed to remove gaseous or vaporous pollutants from an air stream. In a well-structured packing, the contact surface between gas and the scrubber liquid (seawater or fresh water) is maximized. This enables optimal efficiencies, and thus low operational costs [76].

Figure 7-7 I - type scrubber with packing matterial



Source: Packed bed scrubber. Retrieved from https://www.nedermanmikropul.com/en-gb/products/wet-scrubbers/packed-bed-scrubber

The scrubber may not have any packing material at all, and the scrubbing process is utilized through the improved fluid dynamics of it.

7.2.6 Shape

The EGCS are also categorized by their shape. Each scrubber company produces its own shape to cover their customer needs, with the most popular being the I – type and the U – type.

The I – type is in line with the exhaust gas pipe and usually is narrower in width and higher in height than the U – type. Most scrubbing I – type systems can run in dry mode and a bypass system is not needed. The bypass system is applied when the EGCS fails to scrub the exhaust gases, so a valve closes the path to the scrubber and redirects the 'dirty' exhaust gases to the funnel. Hence, the footprint of the system is considerably smaller. Also, packing materials are not usually used in this type of systems.

The U – type is wider in width and shorter in height than the I – type, as mentioned before. Unlike the I – type, it has a bypass system since dry mode is not applicable and each exhaust gas discharge medium has its own bypass line. Packing materials are usually used in this type of scrubbers.

Other scrubber types are for example the Clean Marine's CleanSOx Compact, which is smaller and lighter than the other types of the company due to implementing a unique gas recirculation technology.

Figure 7-8 U - type scrubber

Source: U – type EGCS. Retrieved from https://cleanmarine.no/product/u-type/

Figure 7-9 CleanSOx Compact

Source: CleanSOx Compact. Retrieved ftom https://cleanmarine.no/product/cleansox-compact/

7.3 Installation

There are several key consideration factors to ensure that the scrubber system that is selected, fulfills the vessel needs.

7.3.1 Space constraints

Especially when the scrubber is mounted on a retrofit vessel careful planning and managing of the unoccupied space is needed, since it is usually a large piece of equipment. Apart from that, the space that its auxiliary equipment will occupy must be taken into consideration especially when it is a closed loop or hybrid system. The auxiliary equipment consists of pumps, heat exchangers, water treatment units, monitor units, chemical tanks, holding tanks, sludge tanks, etc. Hence, a lot of work must be put into accommodating the new machinery regarding the installation of new pipes, enlargement of the funnel to fit the scrubbing tower, the rearrangement of the engine room and choosing the appropriate capacities of the tanks.

7.3.2 Power Availability

The addition of the new machinery that was mentioned before, arises the fact that it needs additional electrical power to operate. Hence, an electrical load analysis in all the operation modes of the ship (seagoing, manoeuvring, cargo loading / unloading, etc.) will determine if the vessel's existing power plant can handle the scrubber's electrical load.

7.3.3 Materials

The high temperatures and the extremely corrosive environment that govern the nature of the scrubber require the meticulous selection of the materials for the tanks, pipes and the other equipment. Typical materials that are used in scrubbers for the marine industry are presented in Table 7-2.

Table 7-2 Common materials for EGCS

Component	Materials
Scrubber reaction chamber	Super austenitic stainless steel – SMO 254 (6 Moly)
Washwater lines (effluent, bleed-off)	Glass Reinforced Plastic (GRP)
	Super duplex stainless steel
Water lines (scrubbing, cooling, reaction, makeup water)	Glass Reinforced Epoxy (GRE)
	Carbon steel with polyethylene (PE) lining

NaOH dosage line (supply)	Stainless steel – SS 316L
Sludge lines	Glass Reinforced Epoxy (GRE)
	Glass Reinforced Plastic (GRP)
	Fiber Reinforced Plastic (FRP)
Valves (Exhaust, bypass, isolation)	Nickel alloys
System tank	Steel with epoxy coating
NaOH storage tank	Mild steel with phenolic resin coating
Holding tank	Mild steel with pure epoxy coating
Sludge tank	Plastic
	Steel with synthetic coating
Recirculation tank (Buffer tank)	Mild steel with pure epoxy coating
Exhaust gas manifold	Yard standard for exhaust pipes
Exhaust inlet pipe	Yard standard for exhaust pipes
Exhaust outlet from EGCS	Duplex 1.4462
Droplet catcher	Duplex 1.4462

Source: American Bureau of Shipping (2019, December). Practical considerations for the installation and operation of exhaust gas cleaning systems.

7.3.4 Backpressure

Exhaust gas backpressure is defined as the exhaust gas pressure that is produced by the combustion units to overcome the hydraulic resistance of the exhaust system in order to discharge the gases into the atmosphere. Some scrubber units may generate backpressure and thus the engine needs to use more power to overcome it hence additional fuel consumption, due to lower turbocharger efficiency. So, the fuel consumption of the engine is slightly increased. Except for that, backpressure might be dangerous for the combustion units, especially the boilers, if it exceeds specific limits set by the manufacturers.

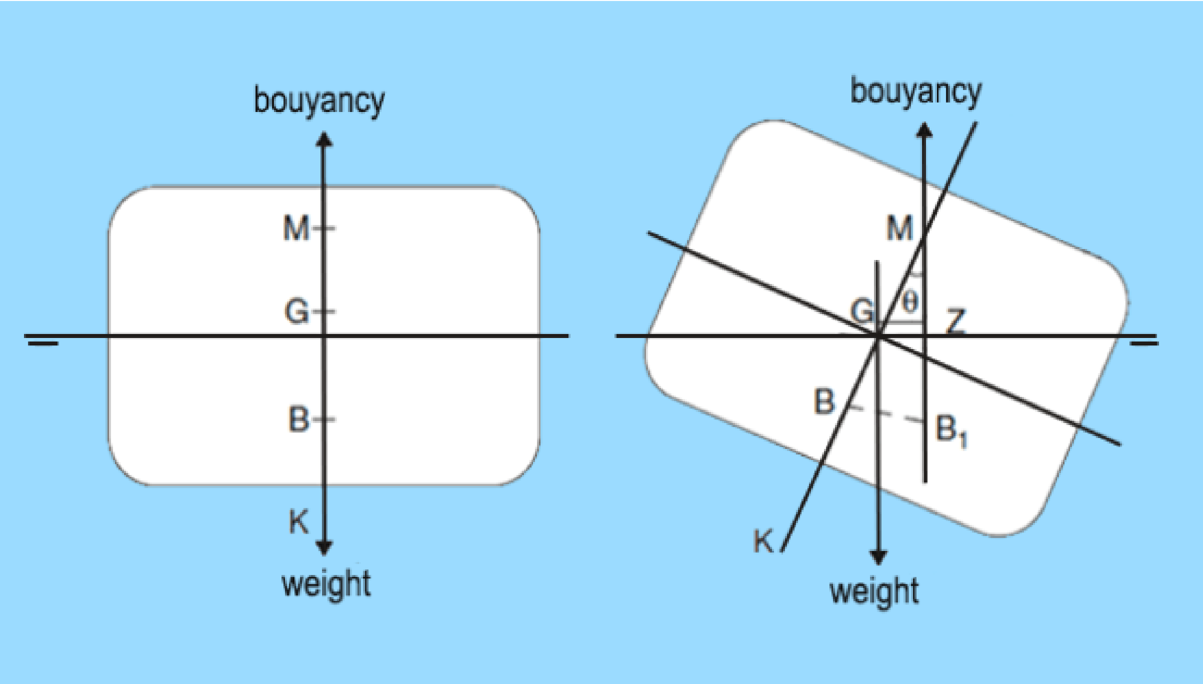
7.3.5 Stability

Stability is the vessel’s ability to return to an upright position after being heeled (rolled sideways) by an external force.

- Center of gravity (G): The center of gravity of a body is the point at which the entire weight of the body may be considered as concentrated such that, if supported at that point, the body would remain in equilibrium.

- Center of buoyancy (B): Centre of buoyancy of a ship is defined as being at the geometric center of the underwater volume of the ship at a particular instant and is the point through which the total buoyancy force (B) is considered to act vertically upwards [135].
- Metacenter (M): When a ship heels, the center of buoyancy of the ship moves laterally. It might also move up or down with respect to the water line. The point at which a vertical line through the heeled center of buoyancy crosses the line through the original, vertical center of buoyancy is the metacenter. The metacenter remains directly above the center of buoyancy by definition.

Figure 7-10 Stable equilibrium of a ship



Source: Ships stability – understanding intact stability of ships. (2019, December). Retrieved from https://www.marineinsight.com/naval-architecture/intact-stability-of-surface-ships/

When the vessel heels to an angle θ, the center of buoyancy shifts from B to B_1. The distance between the weight and B_1 times the buoyancy force, results in a moment that brings the vessel back to its original upright position and is called uprighting moment.

When moving the center of gravity to the right direction (port side) or upwards, the distance between the weight and B_1 lessens, resulting in smaller uprighting moment.

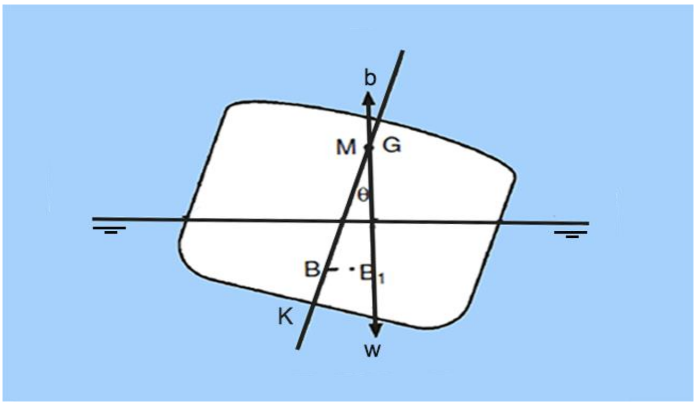
In the occasion that the center of gravity is moved to the left direction (starboard side) or downwards, the distance between the weight and B_1 increases and results in greater uprighting moment.

It comes as a logical outcome that a ship's stability is directly affected from the GM height (the distance between the center of gravity G and metacenter M – metacentric height [74]) in a way that:

1. GM > 0 means that the ship is stable, as seen in Figure 7-10 Stable equilibrium of a ship, where the uprighting moment contributes positively.

2. GM = 0 means that the ship is neutrally stable, where no uprighting moment is generated and hence the ship will remain in the heeled position.

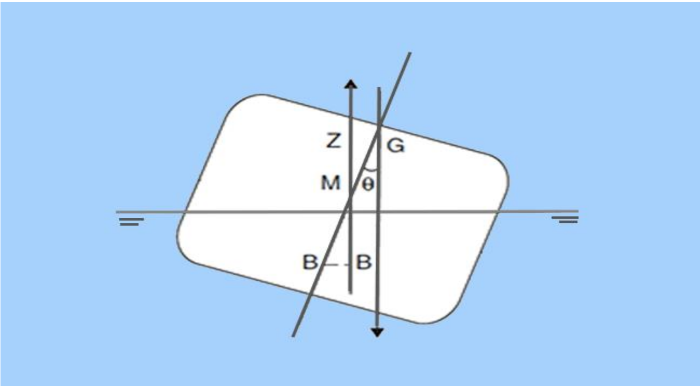
Figure 7-11 Neutral equilibrium of a ship



Source 7-1 Ships stability – understanding intact stability of ships. (2019, December). Retrieved from https://www.marineinsight.com/naval-architecture/intact-stability-of-surface-ships/

3. GM < 0 means that the ship is unstable, where the uprighting moment acts clockwise and forces the ship to capsize.

Figure 7-12 Unstable equilibrium of a ship



Source 7-2 Ships stability – understanding intact stability of ships. (2019, December). Retrieved from https://www.marineinsight.com/naval-architecture/intact-stability-of-surface-ships/

It can be understood from the above that when a scrubbing system is retrofitted it will affect the center of gravity and thus the stability of the vessel, which in most cases will be reduced.

7.4 Ballast

Ballast generally is a material that is used to provide stability to a structure. In naval terms, ballast is, in the most cases, seawater and is stored in the vessel's ballast tanks. When the vessel is empty of cargo it cannot travel, since it is light in weight and the center of gravity moves upwards and towards the metacenter, thus reducing the stability in the way that was discussed before. Also, there is a danger that the propeller will not be fully emerged into the water, since the draft[9] of the vessel will be minimum. Hence, to overcome these problems, specific tanks (ballast tanks) are filled with seawater. The Water Ballast Tanks (W.B.T.) can be seen in the Figure 7-13 and Figure 7-14.

Figure 7-13 Top view of Aegean Dream – Water Ballast Tanks are symbolized as W.B.T.

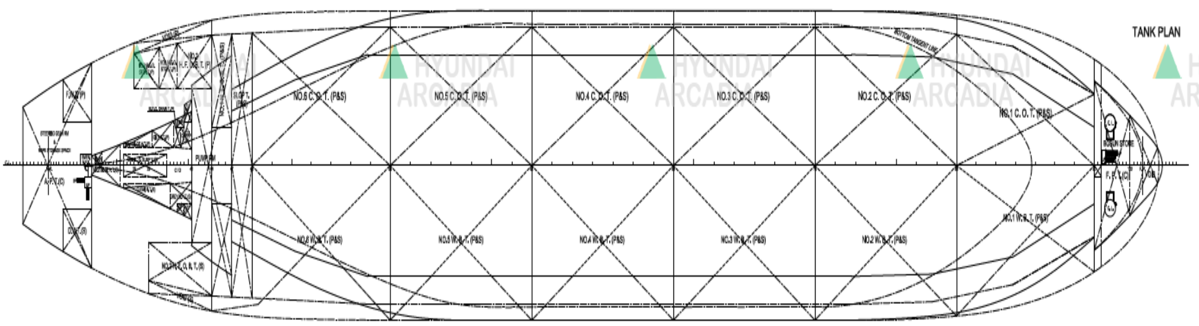
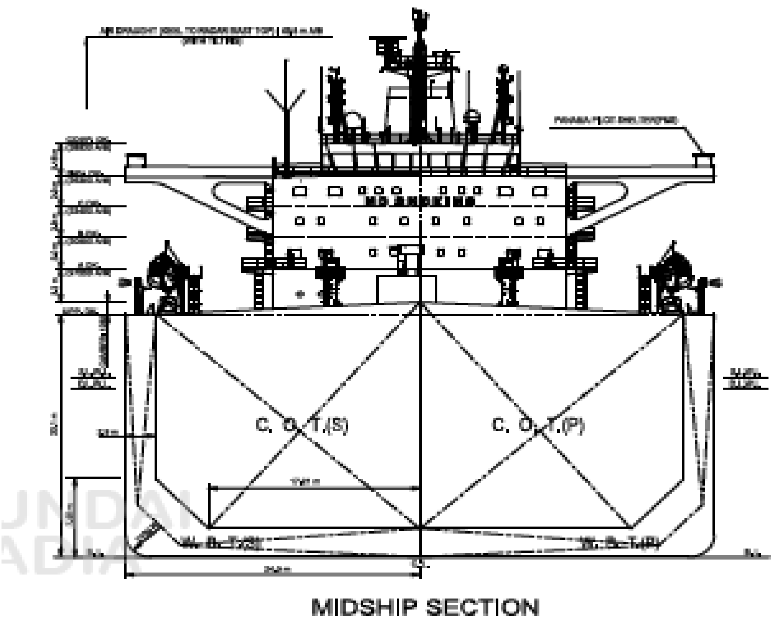


Figure 7-14 Midship section of Aegean Dream – Water Ballast Tanks are symbolized as W.B.T.



[9] Draft or draught of a ship's hull is defined as the vertical distance between the sea waterline and the ship's keel (bottom of the hull).

7.5 Laden

On the contrary, when a vessel is said that it sails Laden, it is implicated that is loaded with cargo. For a crude oil tanker, the cargo is crude oil and the tanks that is stored are named as Crude Oil Tanks (C.O.T.), as seen in Figure 7-13 and Figure 7-14.

In Laden condition the vessel is loaded more resulting in bigger resistance in movement (drag). Thus, for the same speed, in Laden condition the fuel oil consumption of the main engine will be greater than in Ballast condition.

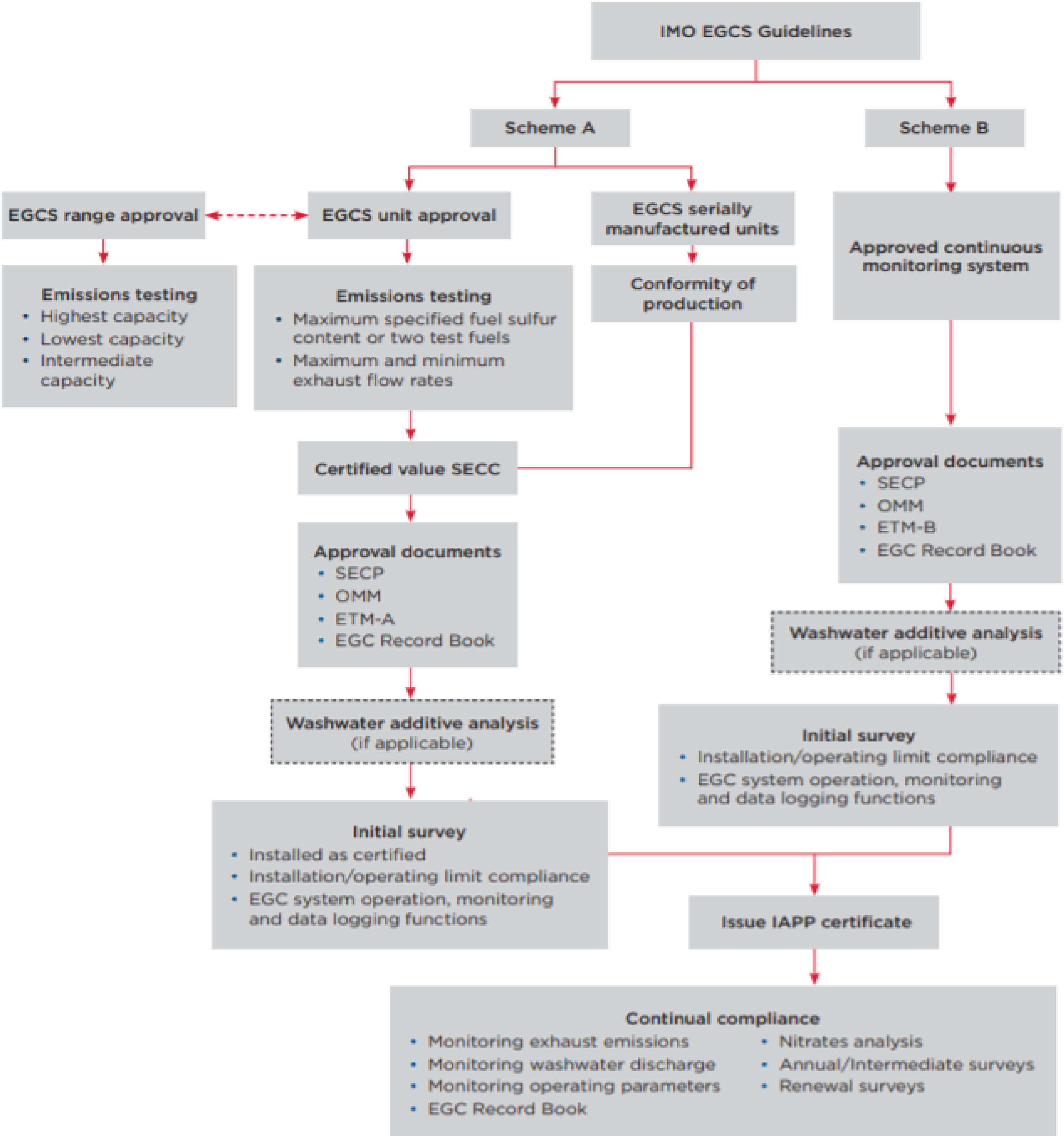
For a suezmax tanker, the Water Ballast Tanks have total capacity approximately 50,000 m^3, while the total cargo capacity is approximately 170,000 m^3.

7.6 Compliance with MARPOL Annex VI Regulation 14

There are two EGCS schemes in order to comply with the new regulation:

- **Scheme A** based on initial emission performance unit certification together with a continuous check of operating parameters and daily exhaust emission monitoring.
- **Scheme B** based on continuous exhaust emission monitoring together with a daily check of operating parameters.

Figure 7-15 Statutory Performance Approval



Source: American Bureau of Shipping (2018). Advisory on exhaust gas scrubber systems.

7.7 Dimensioning procedure

The dimensioning procedure below is entirely based on (MAN Energy Solutions, 2018) and are approximations in order to gather rough estimates for the scrubber.

7.7.1 Scrubber Water Flow

- Open loop: The necessary scrubber water flow is determined by the exhaust gas amount, which depends on the engine power. An estimate of the open loop SW flow is found by the following formula:

$$Flow_{SW} = 50\ m^3/h/MW$$

- Closed loop: The required flow of fresh water for sufficient closed loop scrubbing is significantly smaller than required for sea water in open loop. The relation between the engine power and freshwater flow is estimated as follows:

$$Flow_{FW} = 30\ m^3/h/MW$$

7.7.2 Electric power consumption

- Open loop: The electric power consumption in open loop mode relates to pumping sea water into the scrubber. Accordingly, the power relates to the flow and pressure delivered by the scrubber pumps. The required pressure reflects the injection pressure and the lifting height.
-

The required power can be calculated as follows:

$$P = P_{pump} = P_{ME} \times MCR\ \% \times Flow_{SW}/3{,}600 \times 1.025 \times 9.81 \times (H+IP)/eff_{Pump}$$

where, P_{ME} = Power of main engine (MW)

MCR = Maximum Continuous Rating (%)

$Flow_{SW}$ = Sea water flow (m^3/h)

H = Height between the sea water level and scrubber inlet (m)

Injection pressure (IP) = 10 (m WC)

eff_{Pump} = Sea water pump efficiency

- Closed loop: The power consumption in closed loop mode relates to the power to circulate the fresh water to treat and discharge the bleed-off water. Compared to open loop mode, the required power for closed loop is smaller as the freshwater flow and the water column height is smaller. The power required for closed loop mode is:

$$P = P_{Pump} + P_{Aux} = P_{ME} \times MCR\ \% \times Flow_{FW}/3{,}600 \times 1.000 \times 9.81 \times (h+IP)/eff_{Pump} \times (100\% +10\%)$$

where, $Flow_{FW}$ = Fresh water flow (m^3/h)

h = Height between the circulation pump and the scrubber inlet (m)

Assuming a 10% additional power for covering the WCU and cooler.

7.7.3 NaOH consumption

In closed loop mode, the required additive applied to neutralize the accumulated sulphur in the scrubber water is normally a 50% $NaOH$ solution. The amount of $NaOH$ depends on the engine size, engine load, SFOC and the sulphur content in the fuel.

$$NaOH = P_{ME} \times MCR\% \times SFOC \times S\ \% \times 3.27 \times 10^{-3}$$

where, $NaOH$ = Amount of $NaOH$ (m^3/h)

SFOC = Specific Fuel Oil Consumption (kg/MWh)

7.7.4 Sludge production

The sludge accumulated in closed loop mode in the bleed-off system is removed by the separator. The amount of sludge accumulated depends on the engine size, engine load, SFOC and the sulphur content in the fuel. Furthermore, the water content in the sludge has a significant influence on the sludge amount. A solution of 93% water and 7% sludge is chosen. A lower fraction of water will increase the viscosity and might give problems in handling the sludge. Furthermore, a higher value will rapidly increase the volume needed to store the sludge.

An estimate of the accumulation of sludge in a 93% water solution could be expressed as:

$$Sludge = P_{ME} \times MCR\% \times SFOC \times (S\% \times 3.45+0.022) \times 10^{-3}$$

where, Sludge = Amount of sludge (m^3/h)

7.7.5 Cooling water capacity:

To minimize the freshwater consumption in closed loop mode, the water circuit includes a scrubber water cooler that reduces the evaporation of the scrubber water through the exhaust gas stream. The capacity of the cooler depends on the engine size and could roughly be estimated to 50% of the main engine power.

7.8 Capital Expenditure (CAPEX)

Generally, the CAPEX term is used to describe funds that are utilized by a company to acquire, upgrade, and maintain physical assets. In this study, the acquisition and installation of a scrubber unit is considered as CAPEX.

The CAPEX consists of the scrubber machinery & equipment, the new pipes, electrical installations and modifications, the class approval cost, the preparation & plan approval cost and lastly the off-hire cost.

The type of the scrubber that will be chosen, either that will be an open, closed loop or hybrid will define most of the cost. The open loop system usually is the cheapest due to its simplicity, a closed loop is more expensive since the scrubbing process is more complex, and the hybrid, as it has been mentioned before, combines both the open and closed loop operations hence more machinery and auxiliary equipment, making it the most expensive out of all three.

The tonnage of the vessel defines the scrubber's size and hence its cost and time that will spent on installing it.

7.9 Operational Expenditure (OPEX)

OPEX, short for operational expenditure, is the money a company spends on an ongoing, day-to-day basis in order to run a business or a system. In naval terms, OPEX of a ship is the money that company spends to maintain the ship running, including wages, consumables, bunker fuels, etc.

In this study, OPEX is considered the additional operational cost of the scrubber that will occur after installing it. This includes the increased electrical consumption in order for the new machineries to operate; corresponding to extra fuel consumption in the ship's generator engines, the cost of alkali that are used in the scrubbing process, the sludge disposal cost, maintenance costs and an additional fuel consumption cost due to the backpressure.

7.9.1 Electrical energy consumption

The machinery that usually an open loop scrubber consists of are fans, seawater pumps, and other miscellaneous equipment (separators, dosing units, control processors, sensors and monitoring equipment), which require electric energy to operate. Same thing applies to the closed loop scrubber but with the addition of process pumps (recirculation and water treatment), since the wash water is treated and recirculated. The hybrid scrubber has the combination of the aforementioned equipment. A general rule is that the open loop system will consume more electrical energy than the closed loop, since it requires higher seawater supply and thus the seawater pumps will operate at maximum loads. However, that may not be the case always when alkali is dosed in open loop systems to scrub up to 0.10 % S.

7.9.2 Alkali consumption

An open loop system can operate with only the use of seawater and be depended on its alkalinity. Usually in all the cases, to scrub the exhaust gases to 0.50% S, alkali is not needed, but that does not always apply to 0.10% S, where shipowners and scrubber manufacturers recommend the use of chemicals to make the process more efficient. A closed loop system requires alkali addition in all its functions, since the washwater is circulated and the prevention of it to become saturated is mandatory for its efficiency to not be reduced.

7.9.3 Sludge production

The particulate matter removed from the exhaust gases must in turn be removed from the washwater to prevent it entering the sea. This sludge is stored in a separate tank (sludge tank) and need to be disposed in reception facilities. The amount of sludge not only depends on the amount of particulate but also on the amount of water remaining mixed with it after treatment.

These three factors are the key considerations when it comes to calculate the running cost of the scrubber unit.

Chapter 8. CASE STUDY “M/T AEGEAN DREAM”

8.1 Introduction

The third part of this research is a case study of complying to the Sulphur Cap’s requirements. The study was carried out in collaboration with Arcadia ShipManagement Co. Ltd, a Greek-owned shipping company based in Athens, Greece. Recently, the company received four newbuildings (sister ships), thus expanding its fleet into thirteen oil tankers, which are operated both in spot and time-charter market. Arcadia has decided to enter 2020 by switching the entire fleet to compliant fuels. For the purpose of this research, M/T Aegean Dream was selected as the study object. The said vessel had been scheduled for VLSFO change-over during late-2019, hence low-sulphur fuels were considered as the base case and scrubber installation feasibility was investigated.

Aegean Dream is a suezmax oil tanker delivered in 2016 and is currently being chartered in the spot market. It was built in Hyundai Heavy Industries shipyard, South Korea and is registered in port of Piraeus, under IMO number “9645425”. Below, follows Table 8-1 with the main particulars of the vessel.

In order to compare the cost-effectiveness between using VLSFO or installing a scrubber, various data of Aegean Dream’s operation had to be taken into consideration:

- Operating profile
- Trading pattern
- Time spent inside ECAs
- Annual HFO/MGO consumption

The foregoing data were obtained from the company’s past records. However, the ship is relatively new (delivered in 2016) thus had not many recorded data; since using data of annual only basis was deemed a necessity, it was decided that the study will be based on the ship’s operation between 22/06/2018 and 21/06/2019. In addition to the vessel’s past data, several other possible scenarios were considered in order to gain better insight regarding the financial pros and cons of the two compliance methods. Finally, it has to be highlighted that the present study was based upon a number of requisite assumptions, which are listed below.

8.2 Assumptions

- The precise start or end time of Aegean Dream's data, as quoted above, was not considered a matter of importance, therefore the aforementioned time period (22/06/2018 - 21/06/2019) will be hereafter referred to as the annual operation of the ship.

- Vessel operation was categorized into:

    - Sea time[10]: the sum of time intervals between Departure & Arrival time of each two consecutive ports of call, based on the company's records

        - Time spent in sea was furtherly distinguished as Laden or Ballast, as explained below.
        - Time spent for drifting or maneuvering[11] of the ship was considered as sea time of the respective voyage.

    - Port time: the sum of time intervals between Arrival & Departure time at each port of call, based on the company's records

- Annual fuel consumption:

    - Fuel Consumption was distinguished between Sea consumption and Port consumption.
    - Port consumption was known from the company's records. Sea consumption was not available, so it was estimated as explained below.
    - Fuel consumption during "drifting" was considered as part of Port consumption during the stay at the next port of call.
    - Since the ship's data are referring to pre-2020 era, the tanker consumed HFO for non-ECA operation and MGO inside ECAs.
    - Actual carried cargo and ballast water per voyage were not considered, and voyages were simplified as Laden or Ballast, as follows,

        - Laden voyage
            - Average vessel speed of 11.5 knots
            - Average fuel consumption of 31 tons

        - Ballast voyage
            - Average vessel speed of 13 knots
            - Average fuel consumption of 34 tons
    - Both Laden & Ballast consumptions refer to the total fuel consumption of all consumers that are typically in operation during seagoing mode (1 M/E + 1 G/E) and are detailed in the operating profile's table below.

[10] "Sea time" as defined above, will be used below interchangeably with the term "en route".

[11] Maneuvering is an operation during which a vessel enters or exits coastal waters of a country, crosses several ships on the way, and proceeds towards or departs from a berth or jetty of a port. A ship may need to maneuver not only while arriving or departing a port but also while crossing canals and traffic zones.

- Time spent inside ECAs:
    - ECA time was estimated based on annual MGO consumption during seagoing mode bearing in mind that MGO would only be consumed inside ECA areas.
    - MGO consumption inside ECAs was calculated as the difference between total bunkered MGO and total MGO port consumption during the period considered.
    - ECA/Non-ECA Sea time ratio (see Figure …) was calculated as the fraction of ECA MGO consumption to the total annual estimated fuel consumption during seagoing mode.

- The heating values of MGO, VLSFO and HFO were considered no different, therefore Laden and Ballast average fuel consumptions were assumed steady, both while burning HFO/VLSFO (Non-ECA) or MGO (ECA).

- A hybrid multi-stream inlet scrubber was preselected, in order to utilize the diversity that it offers and to serve all the combustion units (main engine, generators, boilers).

- A sludge tank was chosen only for closed loop operation; hence sludge do not accumulate during open loop operation.

- Space constrains were not taken into consideration for the selection of the scrubber.

- The three generators that the vessel is already equipped with, are enough to provide the necessary power to the scrubber at all conditions (normal seagoing, maneuvering and cargo loading / offloading).

- Scrubber's effect on the vessel's stability was not considered.

- The scrubber weight and the scrubber consumables weight were considered insignificant in a way that neither the vessel's stability, nor the cargo payload weight are affected.

- Ship's lifetime after installation was considered 15 years. A common lifespan range is 18 – 25 years, while Aegean Dream was constructed in 2016.

- Total investment cost was considered to be paid upfront.

- Operational cost was calculated assuming HFO price equal to 350$.

- Since the scrubber manufacturer, Clean Marine, is assuring that CleanSOx Compact has zero backpressure, the extra fuel cost that it would occur was not taken into consideration for the calculation of the system's Operational Expenditure (OPEX).

- Personnel cost was considered zero, since the training cost is included in the EGCS acquisition cost; scrubber operation is included in the ship's crew regular duties.

- Off-hire cost amounts to the total freights that are lost due to due to the unavailability of the vessel. The scrubber installation time was considered to be 3-5 weeks while the special survey will take place simultaneously. The typical time that a vessel spends dry-docked for special survey is 14-16 days, and the resultant off-hire cost is included in the daily break-even cost of the vessel when chartered. Thus, the total off-hire cost that derives from the scrubber installation was calculated for 21 days – 3 weeks.

8.3 The ship's particulars

Table 8-1 Aegean Dream's particulars

M/T "AEGEAN DREAM" MAIN PARTICULARS		
General Information		
Type	Suezmax Tanker	
Classification Society	American Bureau of Shipping	
Flag	Hellenic	
Port of Registry	Piraeus	
IMO No	9645425	
Distances		*Unit*
Length Overall	274.22	m
Breadth Moulded	48.00	m
Deck to Keel	23.14	m
Capacities		*Unit*
Deadweight Tonnage (Summer)	158,888.00	MT
Cargo tanks (98%)	169,735.50	m^3
HFO bunker tanks (98%)	3,447.10	m^3
MGO bunker tanks (98%)	588.20	m^3
Machinery		
Main Engine	MAN B&W 2 STROKE Model: 6G70ME - C 9.2 (NO_x Tier II) MCR:16,590 KW X 77.1 RPM NCR: 11,613 KW X 68.5 RPM	
Main Generators	HYUNDAI 4-STROKE Model: HiMSEN 6H21/32 MCR: 1,200 kW Number: 3 Generators	
Boilers	ALFA LAVAL Aalborg OL 35 Steam Output: 35,000 kg/hr Number: 2 Boilers	
Composite Boiler	ALFA LAVAL OC-TCi Steam Output: 2,150 kg/hr	

8.4 Trading Pattern

Table 8-2 Trading pattern of Aegean Dream for 22/06/2018 to 21/06/2019

Voyage Number	Country of Departure	Port Sulphur Limit[12]	Open Loop Use[13]	PORT OF DEPARTURE	PORT OF ARRIVAL	Voyage Type
1	UK	0,10%		PEMBROKE (22/06/2018)	STURE	Ballast
2	Norway	0,10%		STURE	PHILADELPHIA	Laden
3	U.S.	0,10%		PHILADELPHIA	YUUM KAK NAAB	Ballast
4	Mexico			YUUM KAK NAAB	CARTAGENA	Laden
5	Spain	0,10%	Banned	CARTAGENA	MALTA	Ballast
6	Malta	0,10%		MALTA	SIDI KERIR	Ballast
7	Egypt			SIDI KERIR	CANAPORT	Laden
8	Canada	0,10%		CANAPORT	PUERTO JOSE	Ballast
9	Venezuela			PUERTO JOSE	SW PASS LIGHT. AREA	Laden
	Louisiana	0,10%		SW PASS LIGHT. AREA	CHALMETE	Laden
10	Louisiana	0,10%		CHALMETE	“DRIFTING”	Ballast
	-			“DRIFTING”	DOS BOCAS	Ballast
11	Mexico			DOS BOCAS	BILBAO	Laden
12	Spain	0,10%		BILBAO	LA CORUNA	Laden
13	Spain	0,10%		LA CORUNA	LAS PALMAS	Ballast
14	Spain			LAS PALMAS	KOME KRIBI	Laden
15	Cameroon			KOME KRIBI	GIBRALTAR	Laden
16	UK		Banned	GIBRALTAR	BONGA TERMINAL	Ballast
17	Nigeria			BONGA TERMINAL	GOTHENBURG	Laden
18	Sweden	0,10%		GOTHENBURG	SKAW	Ballast
19	Denmark	0,10%		SKAW	STURE	Ballast
20	Norway	0,10%		STURE	GOTHENBURG	Laden
21	Sweden	0,10%		GOTHENBURG	TALLIN	Ballast
22	Estonia	0,10%		TALLIN	SKAW	Laden
23	Denmark	0,10%		SKAW	SUEZ	Ballast
	-			SUEZ	TANJUNG PELEPAS	Ballast
24	Malaysia			TANJUNG PELEPAS	SINGAPORE	Laden
25	Singapore		Banned	SINGAPORE	BASRAH	Ballast

[12] Empty cells imply a maximum fuel sulphur limit of 0,50% m/m.

[13] Empty cells imply that Open loop scrubber operation is allowed.

26	Iraq			BASRAH	SUEZ	Laden
	-			SUEZ	FOS	Laden
27	France	0,10%		FOS	MALTA	Ballast
28	Malta	0,10%		MALTA	“DRIFTING”	Ballast
	-			“DRIFTING”	SIDI KERIR	Ballast
29	Egypt			SIDI KERIR	CEYHAN	Laden
30	Turkey			CEYHAN (21/06/2019)	MILFORD HAVEN	Laden

Aegean Dream called at a total of thirty (30) ports during the period considered, the eighteen (18) of which are ports with a 0,10% maximum sulphur requirement, primarily due to the introduction of the EU “Sulphur Directive”. In addition, in three (3) out of thirty (30) ports, open loop scrubber operation is prohibited, and compliance to the sulphur can only be succeeded via closed loop operation or use of MGO. Total “sea time” inside ECAs accounted for roughly 12% of the annual sea time, and was spent mainly in the North Sea ECA and the North American ECA (Figure 8-1). In regard to the vessel’s aggregate port time, that accounted for 29% (equal to 105 days) of the total operation time, and sea time (Laden plus Ballast) accounted for the rest 71% or equally around 258 days.

Figure 8-1 Sea Time distribution among ECA and Non – ECA areas

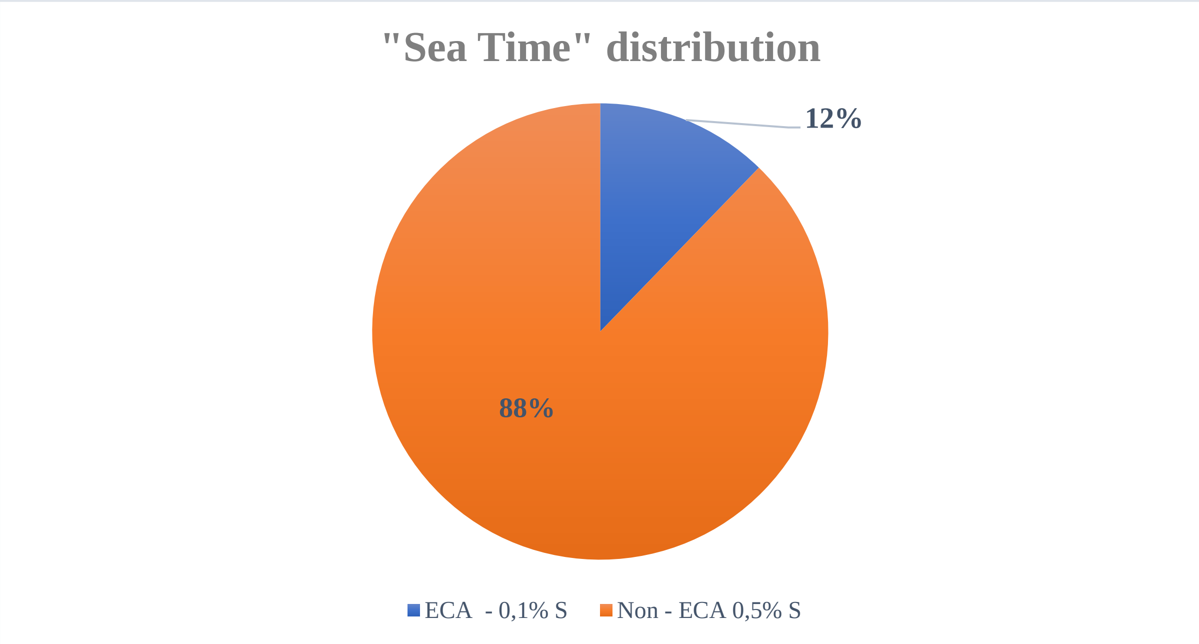
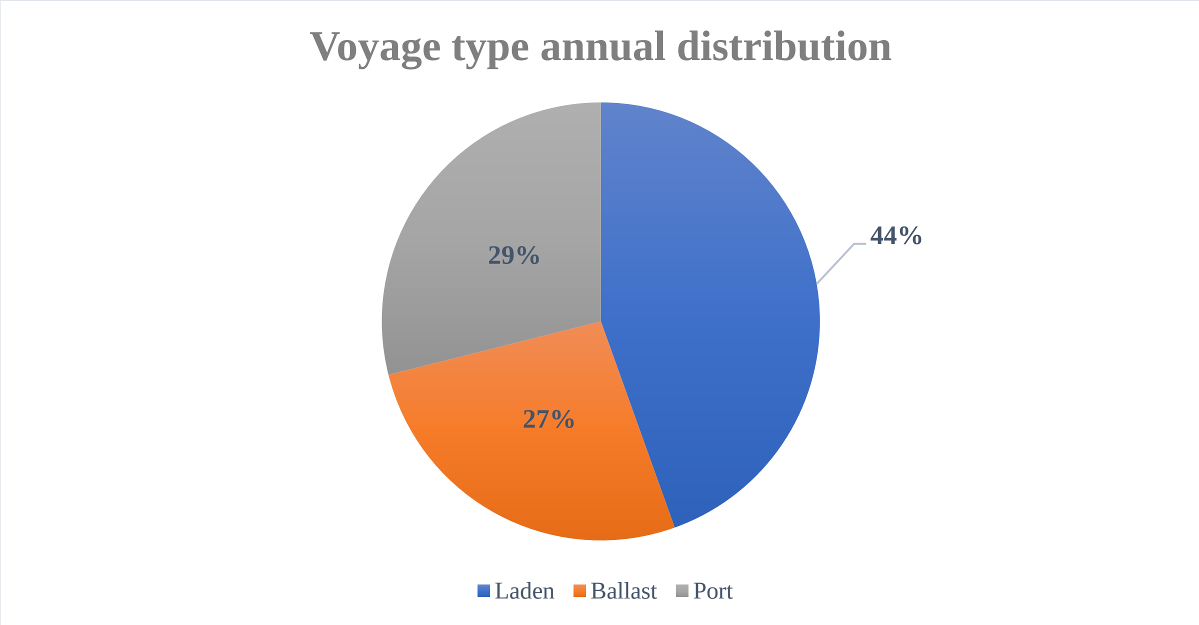


Figure 8-2 Voyage Type Annual Distribution



8.5 Operational profile

The technical department of shipping companies normally designates specific load ranges for the fleet's engines (therefore speed as well) and boilers, depending on the freight levels, fuel prices, but also the charterer's requirements in case of time-chartering. Aegean Dream is chartered in the spot market, thereby its operational profile is designated by Arcadia ShipManagment Co. Ltd itself, as presented in Table 8-3.

This tanker will be normally sailing in a specific speed – both for laden and ballast voyages – as defined in Assumptions. Unpredictable factors though, can alter the vessel's operation. On one hand, bad weather might force a speed reduction, on the other hand high freights can incentivize the company to increase vessel speed so as to perform extra voyages. Nevertheless, such factors were not considered in this study, which was based solely on Arcadia's typical designated parameters. Vessel operation alternates between seagoing mode, maneuvering and port mode. Regarding the latter, the typical loads of the Table 8-3, refer to the normal power needs during cargo unloading/loading. It was assumed that the ship's composite boiler does not operate in oil-fired mode, but in exhaust gas mode only.

	Max Loads (%MCR)	Typical load in seagoing mode (%MCR)	Typical load in manoeuvring mode (%MCR)	Typical load in port mode (%MCR)
M/E	75%	55%	40%	0%
G/E 1	90%	80%	80%	90%
G/E 2	90%	0%	0%	90%
G/E 3	90%	0%	0%	90%
OFB1	90%	0%	0%	90%
OFB2	90%	0%	0%	90%

Table 8-3 Operational profile of Aegean Dream

8.6 Annual fuel consumption

The annual fuel oil consumption of Aegean Dream is presented in Table 8-4 and schematically in Figure 8-3 for sea and port.

Table 8-4 Annual fuel consumption of Aegean Dream

Annual Fuel Consumption (tons)			
	HFO	**MGO**	**Total**
En route	7,280.00	1,021.00	8,301.00
Port	491.00	831.00	1,322.00
Total	**7,771.00**	**1,852.00**	**9,623.00**

The fuel oil consumption is further categorized in open and closed loop operation regarding both the fuel consumption and the time that was spent in sea and ports. To classify whether the operation will be in open or closed loop and 0.50 or 0.10% S scrubbing limit, the ECA areas and zero – discharge ports were considered. Hence, the results are summed in the Table 8-5 & Table 8-6 and overall in Table 8-7.

Figure 8-3 Annual Fuel Consumption distribution divided based on HFO and MGO consumption at Sea and Port

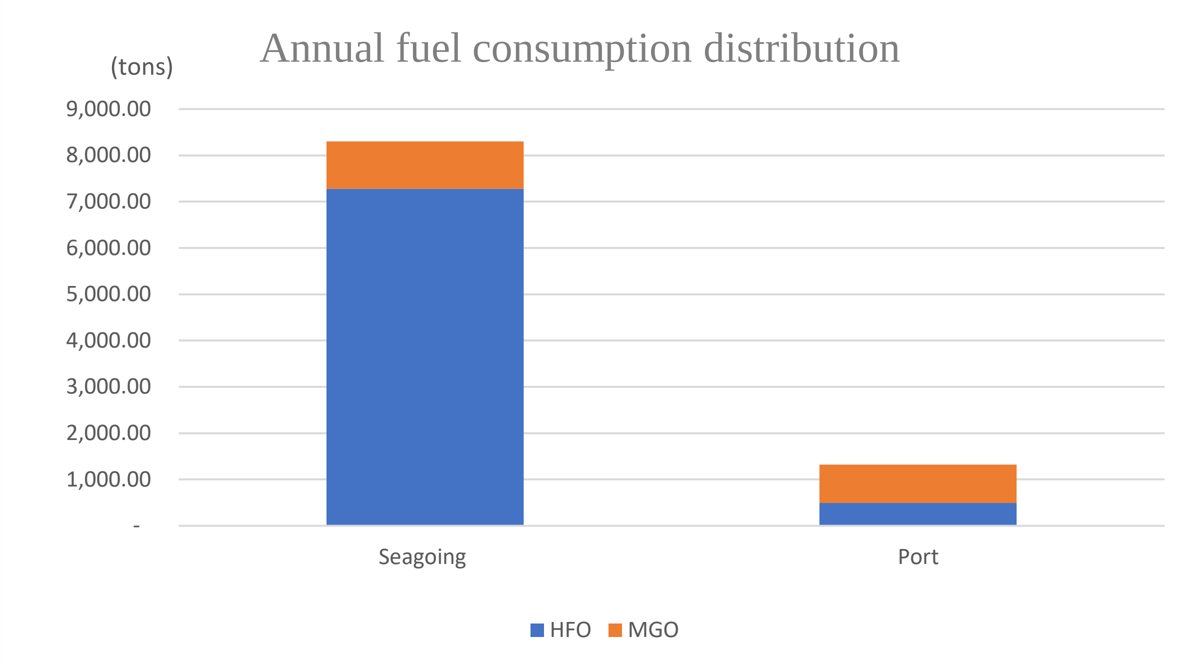


Table 8-5 Scrubber operation in ports

Scrubber Operation (Seagoing)	Sulphur Limit	Percentage	Time (days)	Fuel Consumption (tons)
Open loop	0.50%	88.00%	227.48	7,306.91
	0.10%	12.00%	30.97	994.82
Closed loop	0.50%	0%	0	0
	0.10%	0%	0	0
Total	-	-	**258.45**	**8,301.72**

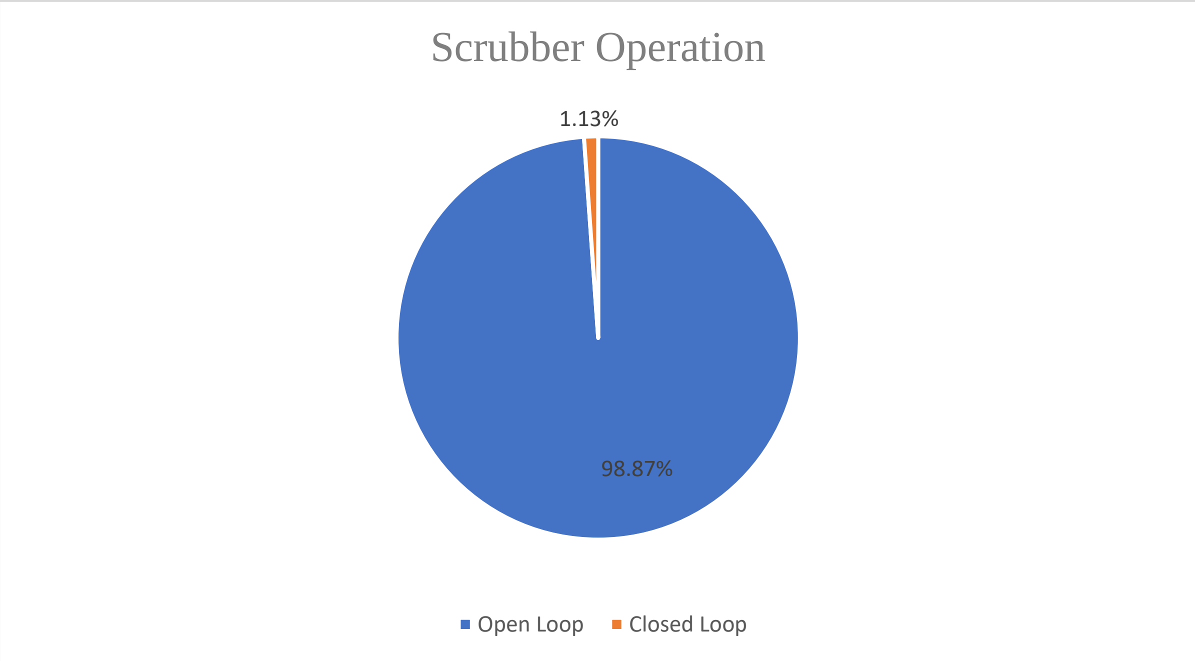
Table 8-6 Scrubber operation in sea

Scrubber Operation (Ports)	Sulphur Limit	Percentage	Time (days)	Fuel Consumption (tons)
Open loop	0.50%	48.80%	51.36	455.41
	0.10%	47.30%	49.70	758.26
Closed loop	0.50%	2.00%	2.10	35.76
	0.10%	1.90%	2.00	73.00
Total	-	-	**105.16**	**1,322.43**

Table 8-7 Overall scrubber operation

Scrubber Operation (Overall)	Sulphur Limit	Percentage	Time (days)	Fuel Consumption (tons)
Open loop	0.50%	76.69%	278.84	7,762.32
	0.10%	22.19%	80.67	1,753.08
Closed loop	0.50%	0.58%	2.10	35.76
	0.10%	0.55%	2.00	73.00
Total	-	-	**363.61**	**9,624.16**

Figure 8-4 Overall scrubber operation chart



8.7 Compliance through low sulphur fuels

As was said before, Sulphur Cap indirectly requires switch-over to low sulphur fuels, but also leaves room for alternative means of compliance such as the use of a scrubber, provided that the ship's exhaust gases are cleaned to a point that is at least equivalent to the emissions produced by max. 0,50% sulphur (or 0,10% inside ECA) fuels. The majority of the global tonnage, including Arcadia ShipManagment Co. Ltd, is expected to enter 2020 having bunkered VLSFO and MGO in fuel tanks, consequently change-over to these fuels was considered the base case.

8.7.1 Preparations

Like all HFO fuelled ships, so shall Aegean Dream get prepared for the fuel transition.

8.7.1.1 Fuel Tanks

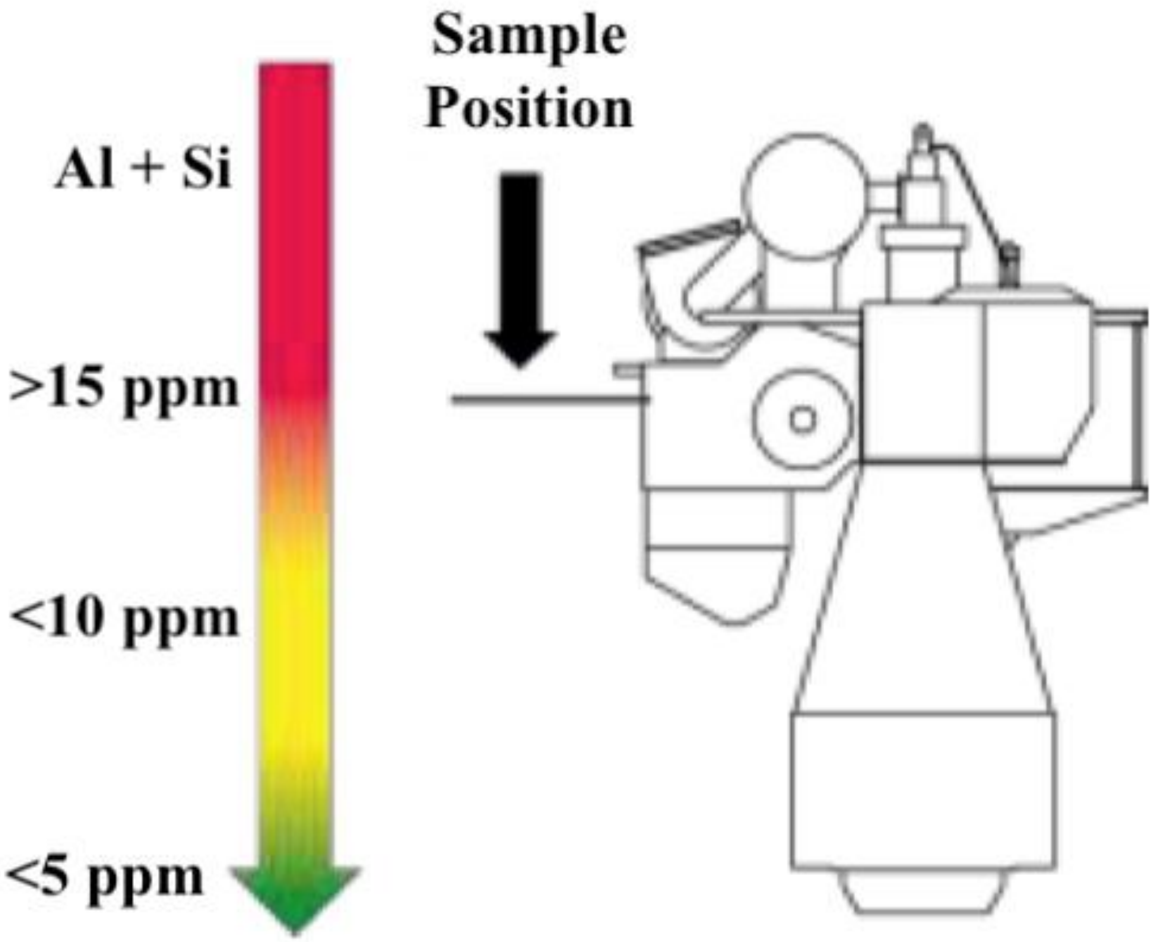
The newbuilt oil tanker has six HFO dedicated tanks (four bunker, one settling, one service) and three for MGO (two bunker and one service tank). Tank arrangement is not 100% flexible, in the way that it was explained in 6.2.1.1.2, however it will be adequate for VLSFO transition. HFO tanks will be used as VLSFO tanks and as for the whole MGO system, this one will remain untouched, for use inside Emission Control Areas.

The ship is relatively new (delivered in 2016) so fuel tanks' surfaces are not expected to be facing serious issues in regard to precipitated HFO residues. The vessel's crew is sufficiently experienced with the cleaning process so it can undertake the whole fuel tank cleaning procedure. Proper project management is a must, both from a time perspective as well as a safety viewpoint, following strictly IMO's guidelines for entrance in confined spaces, as set forth in Appendix C. All of the six HFO tanks have to be cleaned, so the process must be carried out consecutively, commencing from the bunker tanks and finishing with settling and service tanks. Each tank must be emptied from HFO before cleaning and loaded only with VLSFO after cleaning. As regards to settling tank and service tank, flexibility is constrained, and since fuel feeding cannot be interrupted, their cleaning might require a temporary switch-over to MGO. This stage can be done while the ship is sailing inside an ECA, thus avoiding unnecessary consumption of the costly MGO.

8.7.1.2 Fuel treatment system

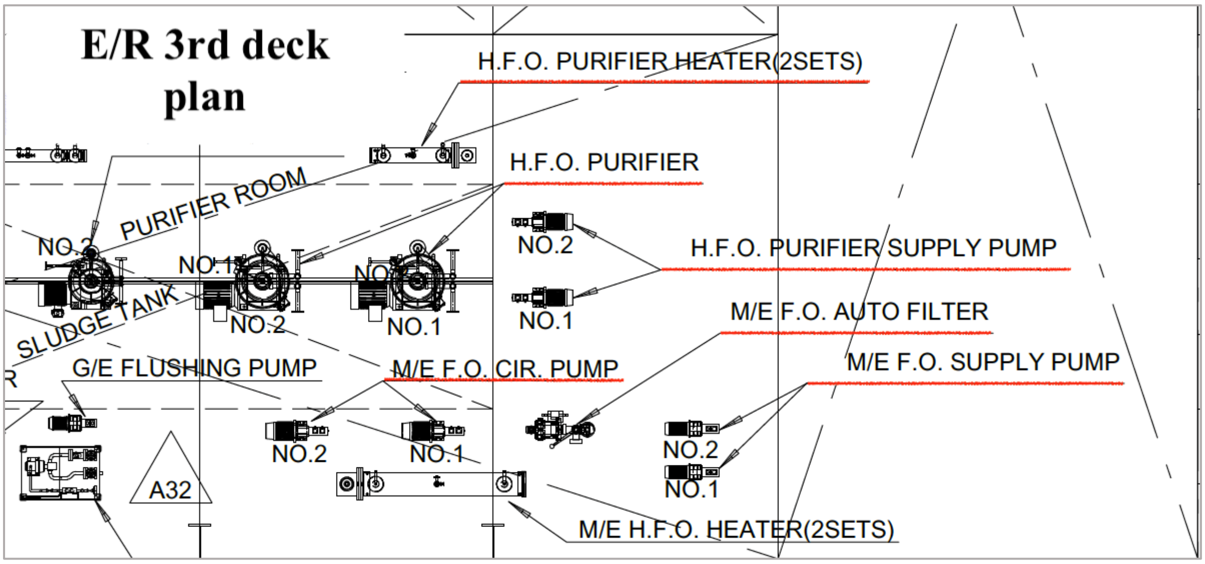
Special attention must be paid on the ship's two centrifugal separators. Should they contain HFO residues, action shall be taken in order to avoid the likelihood of VLSFO contamination. Moreover, the new 0.50% fuel might subsequently dissolve any sediment that had precipitated in fuel pipelines and thus release high amounts of cat-fines. MAN B&W – the tanker's M/E manufacturer – designates a maximum cat-fine content at the main engine's fuel inlet of 15 ppm, although insists that the lower the amount the better for the engine (Figure 8-6). During the first bunkerings of VLSFO, the crew shall pay attention for increased cat-fine content or poor purifier efficiency, a good indication of which two can be the system's auto back-wash filter.

Figure 8-6 Cat-fine limit at M/E fuel inlet



Source: MAN Energy Solutions

Figure 8-5 Aegean Dream E/R 3rd deck top view



Source: Reprinted with kind permission of Arcadia ShipManagement Co. Ltd.

8.7.2 Financial feasibility

The transition procedure, as described above, does not imply a significant cost, in the sense of CAPEX. The tank cleaning may be the most demanding task in terms of resources, however it can be undertaken by the crew and included in the ship's breakeven cost.

In respect to OPEX, the operating cost of fuels is expected to rise considerably. As of February 2020, the global average VLSFO price fluctuates at a 150 $ premium to HFO. MGO consumption will remain the same, depending only from time spent in ECAs. Below, follows an indicative comparison of the annual fuel cost, burning HFO or VLSFO. The fuel consumption figures and ECA time were taken from Aegean Dream's data.

Table 8-8. Fuel cost comparison before and after Sulphur Cap

Annual Fuel Cost ($)			
Before Sulphur Cap			
	Consumption (tons)	Price	**Total Cost**
HFO	7.771,00	$350,00	$2.719.850,00
MGO	1.852,00	$700,00	$1.296.400,00
		Total	**$4.016.250,00**
After Sulphur Cap			
	Consumption (tons)	Price	**Total Cost**
VLSFO	7.771,00	$550,00	$4.274.050,00
MGO	1.852,00	$700,00	$1.296.400,00
		Total	**$5.570.450,00**

Source: Courtesy of Arcadia ShipManagment Co. Ltd

As shown in Table 8-8, VLSFO brings a 38% increase in fuel costs, from approximately 4 million ($) per year to roughly 5.6 million ($) per year. These figures are based on 12% ECA time and average global fuel prices of February, 2020. The said parameters play an important role in the financial feasibility study, thus are going to be examined comprehensively below.

8.8 Compliance through scrubbers

At this stage of the study, it was necessary to contact a scrubber manufacturer in order to provide us with possible EGCS solutions. World-leading EGCS manufacturer Clean Marine, responded positively to our request and offered their help and expertise. The scrubber selection commenced with the dimensioning procedure.

Scrubber design capacity depends primarily on the exhaust gas flow and can be determined in two ways. The first one is targeting to cover all the accumulated installed power through summing the exhaust gases of all combustion units, each one operating at Maximum Continuous Rating (MCR)[14], as described in the second column of Table 8-9. The second one and more realistic method is to design in accordance to the highest accumulated exhaust gas flow that the system will encounter during operation (seagoing, maneuvering or port mode), which probably sums to a smaller flow than the first one, as shown in column No. 3 & 4 of Table 8-9.

In either occasion, there had to be a comparison of the exhaust gases that are produced in each and every operation mode (i.e. seagoing, maneuvering and in port) of the vessel, in order to get the maximum amount and dimension the EGCS accordingly. Calculations were based on Arcadia's designated profile for Aegean Dream and the results are presented below.

Table 8-9 Amount of exhaust gases for different operation modes

Operational profile							
Machinery	**100%MCR kg exh/h**	**Design condition – Seagoing mode**		**Maneuvering**		**In port**	
		Load (%)	**Exhaust gas (kg/h)**	**Load (%)**	**Exhaust gas (kg/h)**	**Load (%)**	**Exhaust gas (kg/h)**
ME1	*114,840*	**75%**	100,800	**40%**	57,600	**0%**	0
AUX1	*7,680*	**90%**	7,020	**80%**	6,432	**90%**	7,020
AUX2	*7,680*	**90%**	7,020	**0%**	0	**90%**	7,020
AUX3	*7,680*	**0%**	-	**0%**	0	**90%**	7,020
Boiler 1	*42,320*	**50%**	21,160	**-**	0	**90%**	37,000
Boiler 2	*42,320*	**0%**	-	**-**	0	**90%**	37,000
SUM	**222,520**	**136,000**		**64,032**		**95,060**	

In order to calculate the flue gas flow that was presented in Table 8-9 the corresponding amounts were derived from the different manufacturers (i.e. MAN for the main engine, Alfa Laval for the generators and Hyundai for the boilers) and are displayed in Table 8-10.

[14] Maximum Continuous Rating (MCR) is the maximum output power that an engine can produce while remaining in the safe limits and conditions that the manufacturer has set.

Table 8-10 Main engine's, generator's and boiler's exhaust gas amounts for different % MCR

Main Engine		Generator	Boiler
% MCR	**Exh. Gas Amount (kg/hr)**	**Exh. Gas Amount (kg/hr)**	**Exh. Gas Amount (kg/hr)**
10%	23,040	-	-
15%	31,680	-	-
20%	37,800	-	-
25%	44,280	2,640	-
30%	50,040	-	12,500
35%	51,120	-	-
40%	57,600	-	-
45%	63,720	-	-
50%	69,480	4,320	21,160
55%	75,240	-	-
60%	80,640	-	-
65%	85,680	-	-
70%	93,240	-	-
75%	100,800	6,120	31,125
80%	105,480	6,432	34,000
85%	106,560	6,732	35,500
90%	106,920	7,020	37,000
95%	110,880	-	39,000
100%	114,840	7,680	42,320

Specific Fuel Oil Consumption (SFOC) and flue gas temperature values were also important for the EGCS dimensioning procedure and are depicted in Table 8-11.

Table 8-11 Additional Aegean Dream's data

Main Engine	Fuel consumption @ 100% MCR (g/kWh)	163
	Exhaust gas temperature (after turbocharger & economizer @ 100% MCR) (˚C)	185
Generators	Fuel consumption @ 100% MCR (g/kWh)	183
	Exhaust gas temperature (after turbocharger & economizer @ 100% MCR) (˚C)	315
Boilers	Exhaust gas temperature (°C)	386

Based on all the abovementioned data, Clean Marine made us two EGCS proposals, one hybrid system and one open loop system.

8.8.1 CleanSOx Compact proposal

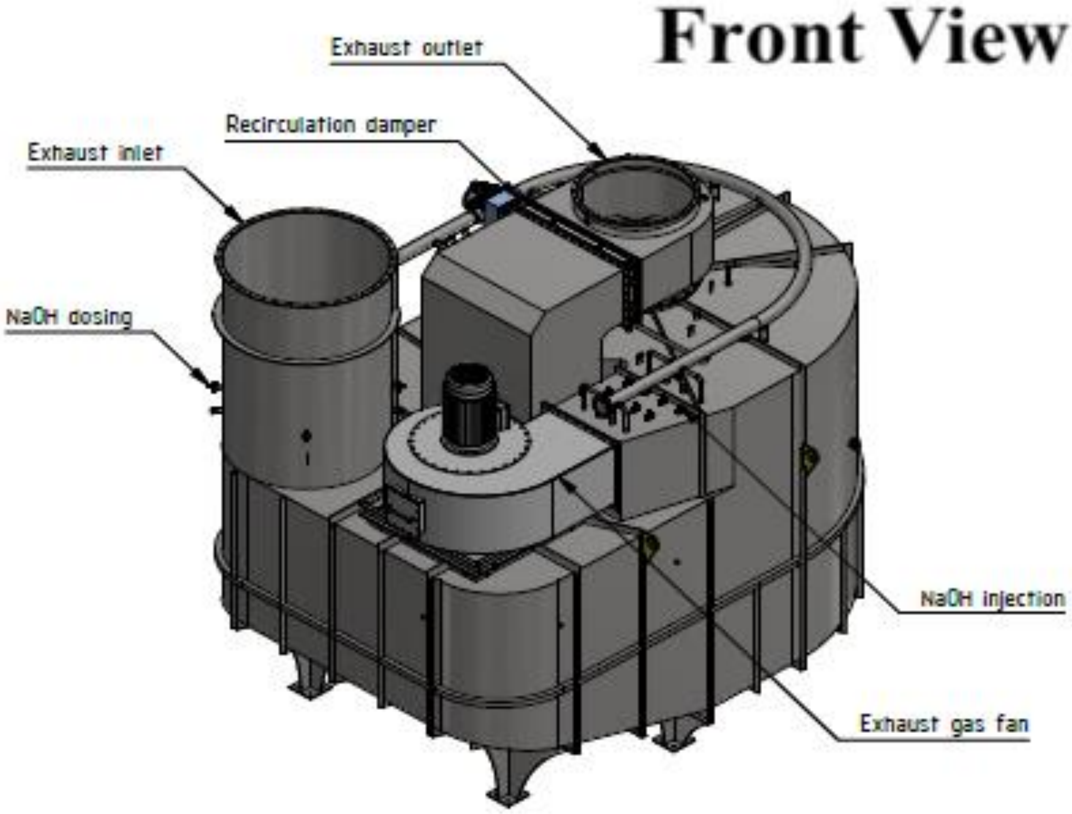
The first solution addresses the CleanSO$_x$ Compact hybrid multi – stream inlet scrubber, a patented system with unique gas recirculation technology and the flagship of Clean Marine. This EGCS is manufactured and certified according to "Scheme B" (EMB-B) as described by MEPC 259 (68) – IMO 2015 Guidelines for Exhaust gas cleaning systems.

8.8.1.1 General

The exhaust gas cleaning unit will serve the M/E, the three G/E and the two auxiliary boilers. The system works with sea water in open loop but also allows addition of NaOH in case of inadequate sea water alkalinity. Closed loop operation is done via sea water plus periodic NaOH injection. The design capacity was calculated as explained in Table 8-9, with a range of 0-136,000 kg/h incoming exhaust gases, and an ability of cleaning the 3.50% sulphur fuel to the equivalent of 0,10% sulphur content. It was checked that the ship's exhaust gases are not going to exceed the scrubber's capacity, namely the latter will be able to treat up to 136,000 kg/h continually and efficiently without any NaOH addition, when sailing in max. 0.50% sulphur areas. An important requirement is a minimum water alkalinity of 2200 μmol. For lower values, addition of NaOH is needed. The scrubber unit is not built for running on dry mode[15], thus it has a built-in bypass for guiding the exhaust gases through the ship's old funnel, in case of deliberate halt or malfunction.

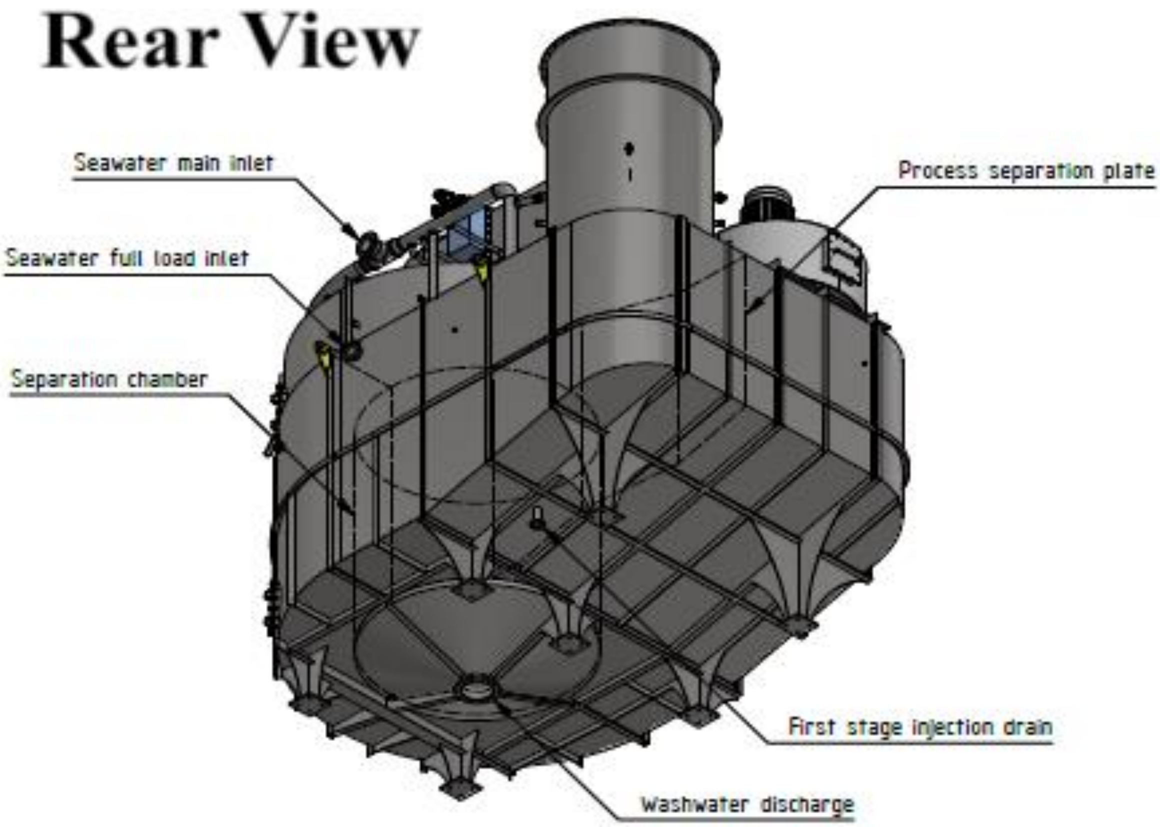
[15] Dry mode is when the scrubber incoming water flow has stopped and the exhaust gases pass through the unit without cooling, with temperatures reaching 350-400°C. If the scrubber is not built with the proper high-temperature resistant materials, the exhaust gases could cause a serious damage to the unit's parts.

Figure 8-8 Top view of CleanSOx Compact



Source: Reprinted with the kind permission of Clean Marine.

Figure 8-7 Rear view of CleanSOx Compact



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8.8.1.2 The Exhaust Gas Cleaning Unit

The accumulated exhaust gases enter the cleaning unit from the exhaust inlet, at a temperature of around 360-380 °C. During entrance, sea water is sprayed into the gas stream cooling it down and neutralizing the sulphur oxides. Received the strong tractive force of the ~2.1 m diameter fan, the increased pressure liquid-gas mixture is led to a cyclone where water and gas separation takes place. The saturated water is led to the wash-water outlet at the bottom of the unit while the treated exhaust gas is headed to the recirculation damper. The latter, either drives a part of the stream back to the unit's exhaust inlet or releases all of it back to the atmosphere at a temperature of 20-50°C. The damper's role in the EGCU is to adjust the exhaust outflow, so as absorb load fluctuations. The fan's rotational speed is automatically controlled by the EGCS control system via VFD, in order to maintain zero backpressure, regardless of load.

SO_2 concentration in exhaust gases will fluctuate between different fuel-to-air ratios, contrary to the carbon - to - sulphur - ratio which remains roughly the same among marine fuels. For this reason, IMO 2015 Guidelines (MEPC 259 (68)) have established the SO_2/CO_2 % v/v (emission ratio), as an equivalent for the sulphur content in emissions in comparison with the fuel's maximum permitted sulphur content. The SO_2/CO_2 ratio is monitored at the EGCU's exhaust outlet by a continuous emission monitoring system (provided by Clean Marine).

The EGCU efficiency is boosted, when necessary, with 50% NaOH solution which is sprayed from several nozzles along the scrubber's surface (either during open or closed loop).

Table 8-12. Fuel sulphur content equivalents

Fuel oil sulphur content (%m/m)	**Emission ratio SO_2/CO_2 (% v/v)**
3.50	151.7
1.50	65.0
1.00	43.3
0.50	**21.7**
0.10	**4.3**

Source: MEPC 259 (68) – IMO 2015 Guidelines for Exhaust gas cleaning systems

Figure 8-9. CleanSOx Compact front side

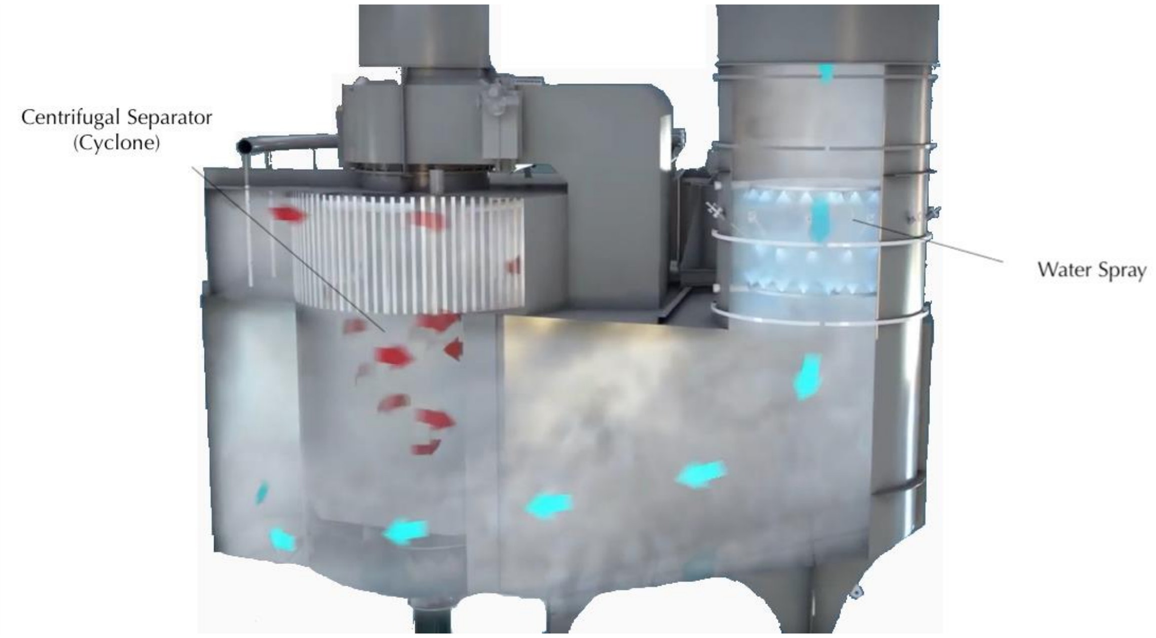

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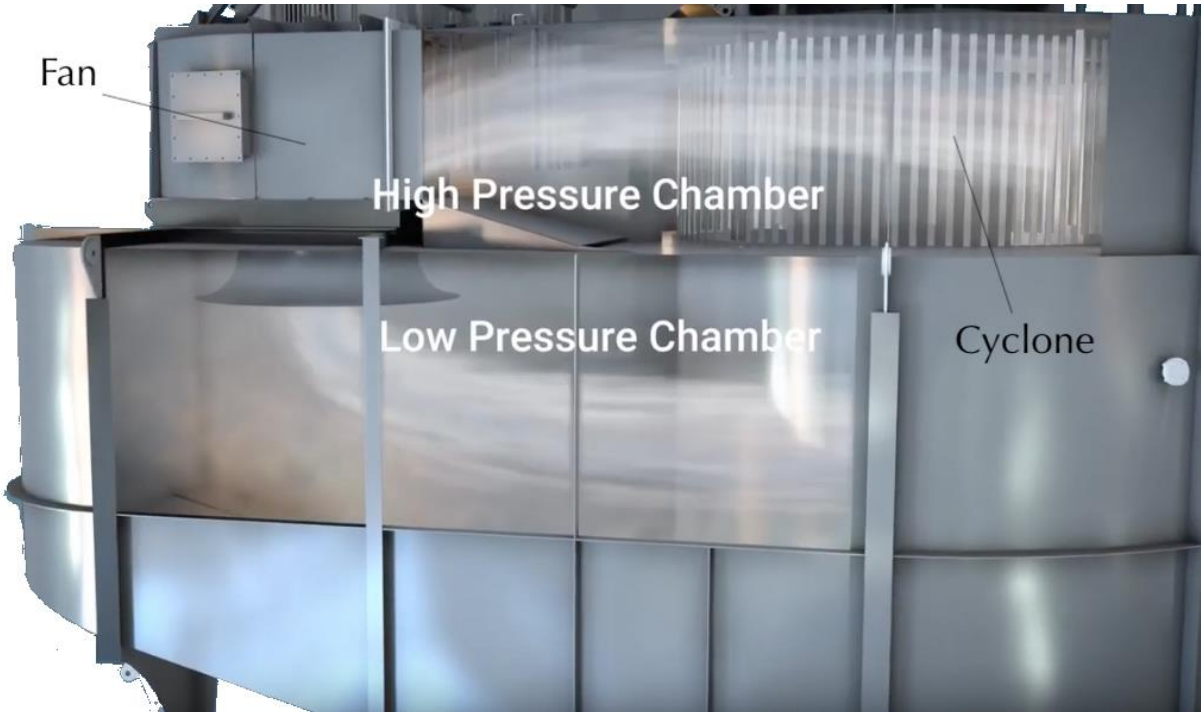
Figure 8-10. CleanSOx Compact rear side



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Additional notes:

- The EGCU's inlet pipe has to be insulated, thus it is delivered with brackets for insulation of inlet section.
- Scrubber weight and distance from deck can affect the vessel's stability, mandating the latter's need to be checked in advance of any installation.
- The EGC unit may come in 1-10 pcs, requiring in situ assembly by the Client, according to Clean Marine's guidance and specifications.
- Sea-chest of the vessel may require modifications thus leading to the need of dry-docking.

Table 8-13 CleanSOx Compact's weight

Weight		Units
Dry weight	26,600	kg
Operational weight (Wet weight)	30,300	kg

Table 8-14 Analytical description of the views

CleanSO$_x$ Compact Nozzle Scheduling	
Mark	**Description**
N01	Exhaust Inlet
N02	Exhaust Outlet
N03	Seawater Inlet
N04	Seawater Inlet
N05	Wash-water Outlet
N06	1st Stage Drain Outlet
N07 A-L	NaOH Inlet
N08 A-F	NaOH Inlet
N09 A-F	NaOH Inlet
M01	Manhole
M02	Manhole
M03	Fan Inspection Hatch

Figure 8-11. CleanSOx Compact isometric view

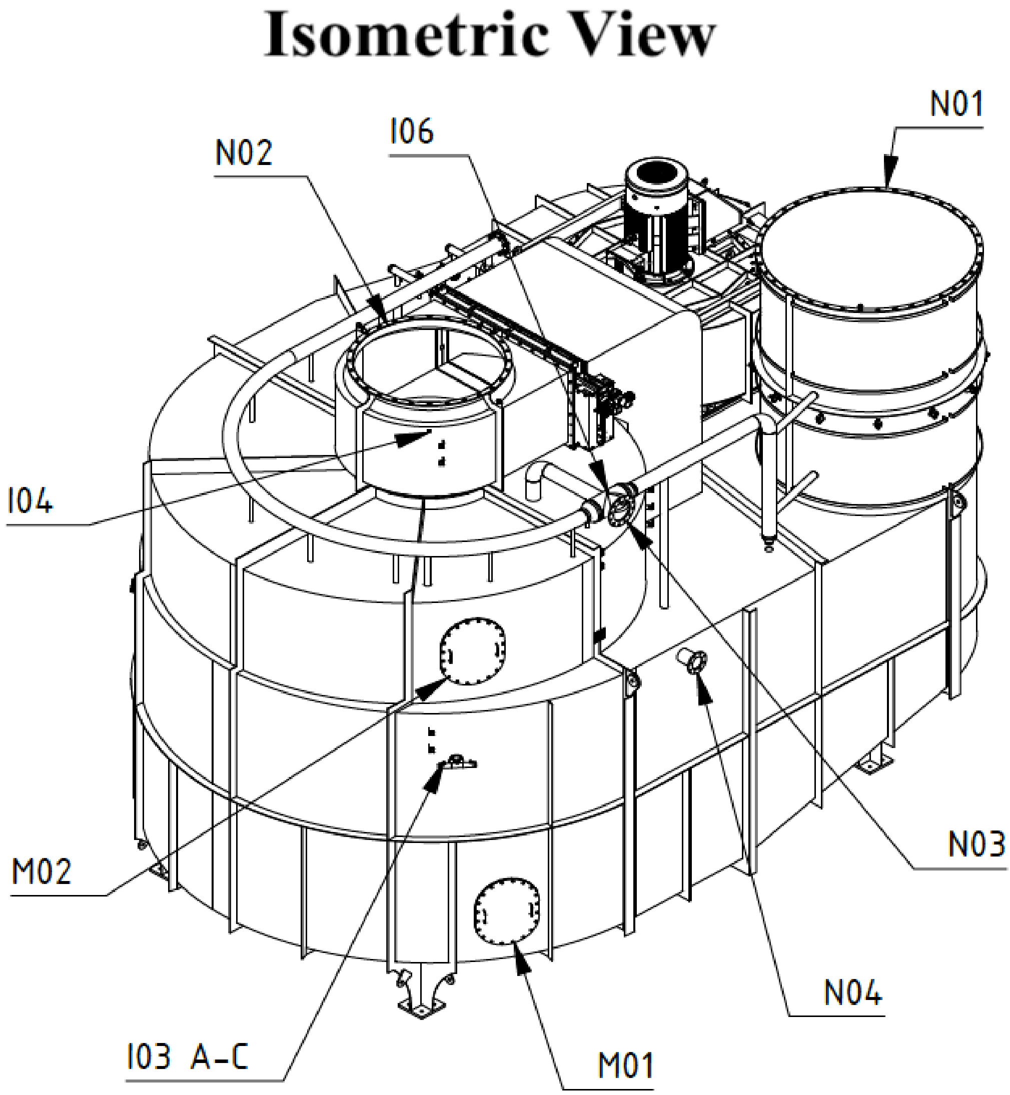

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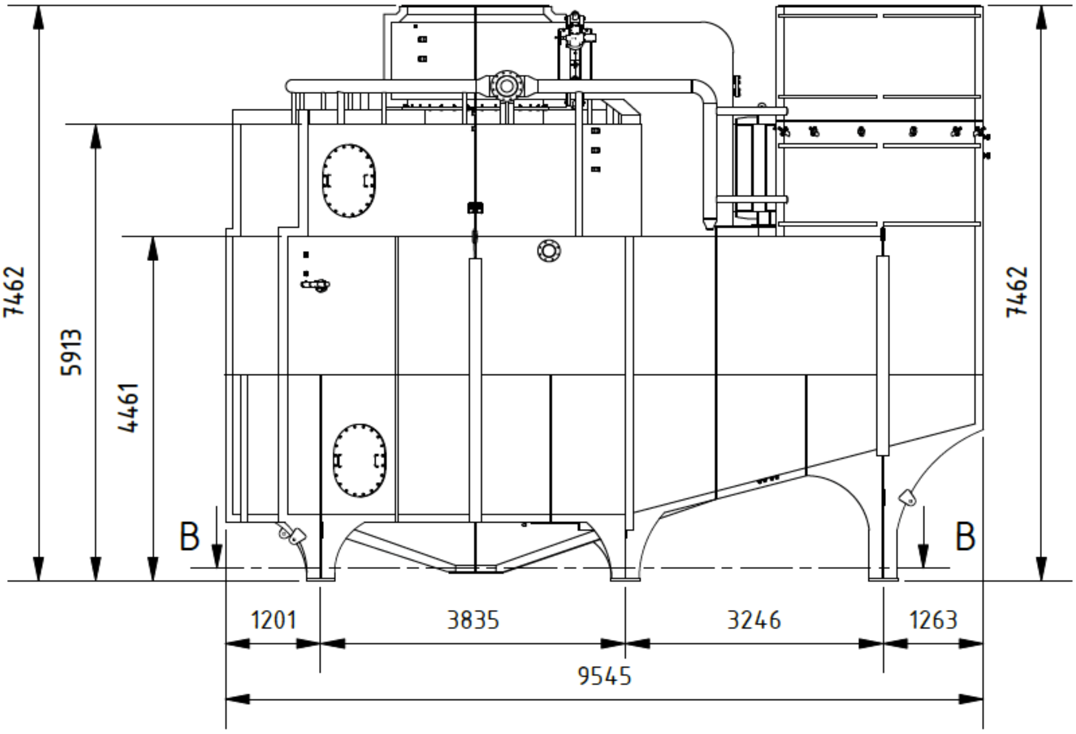
Figure 8-12 CleanSOx Compact front view



Source: Reprinted with the kind permission of Clean Marine.

Figure 8-13. CleanSOx Compact top view

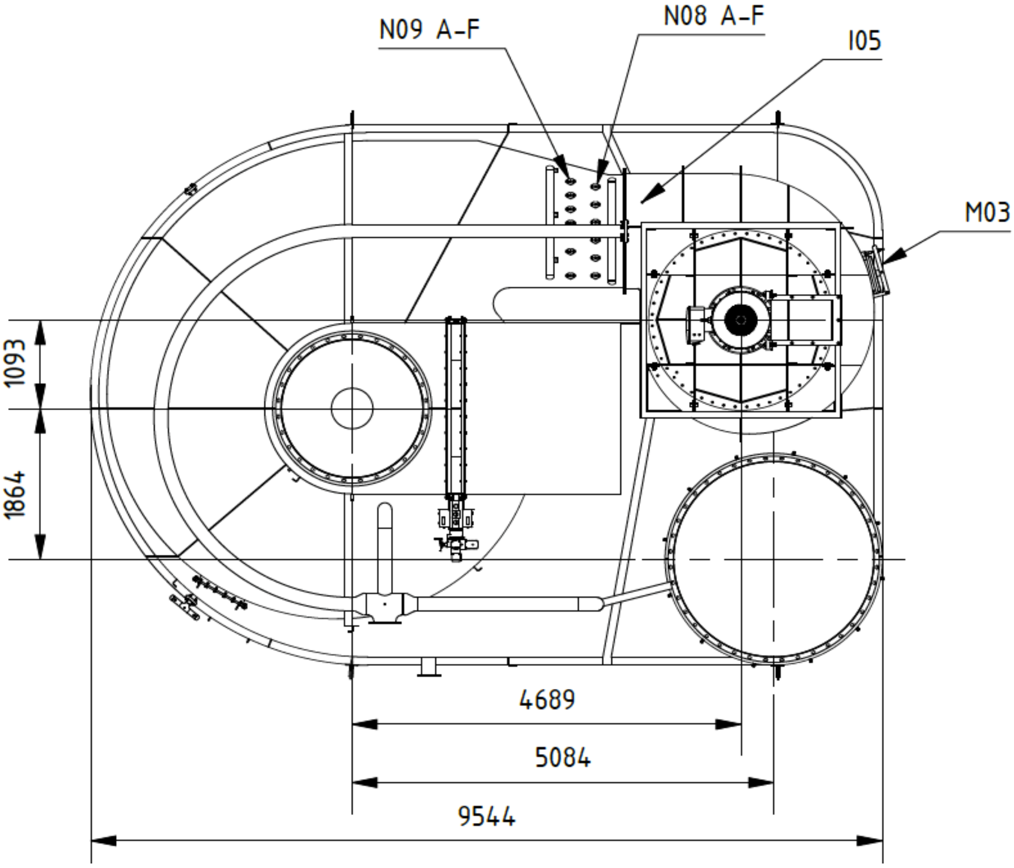


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Figure 8-14 CleanSOx Compact side view

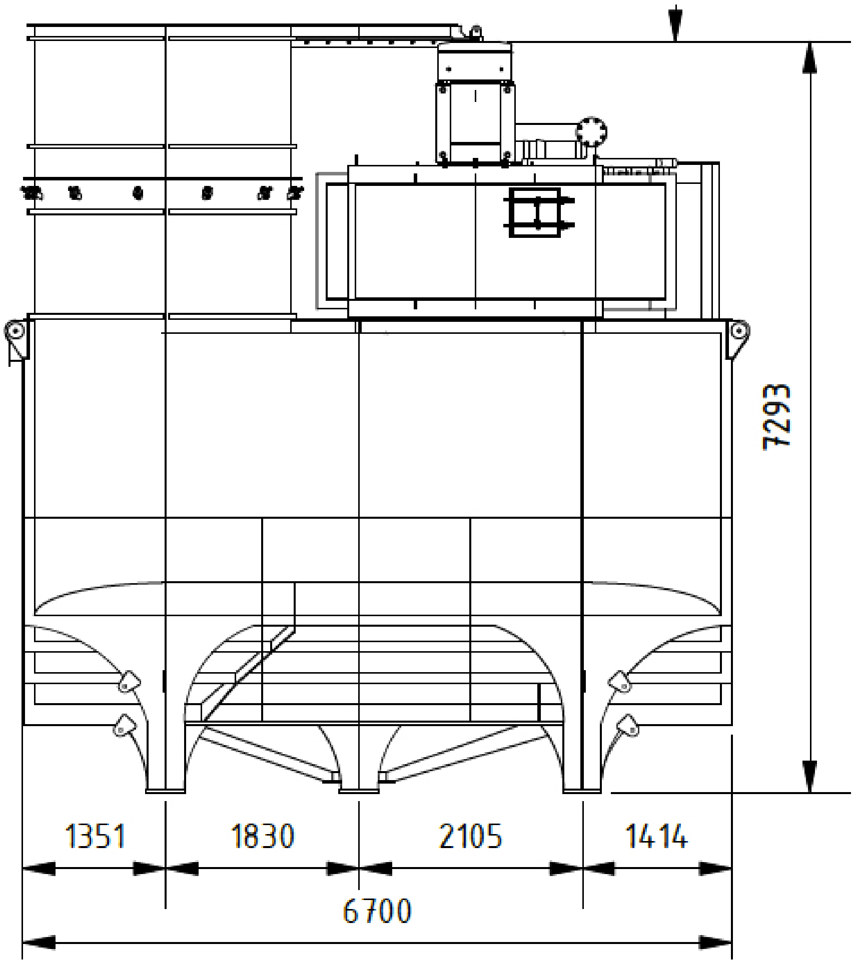

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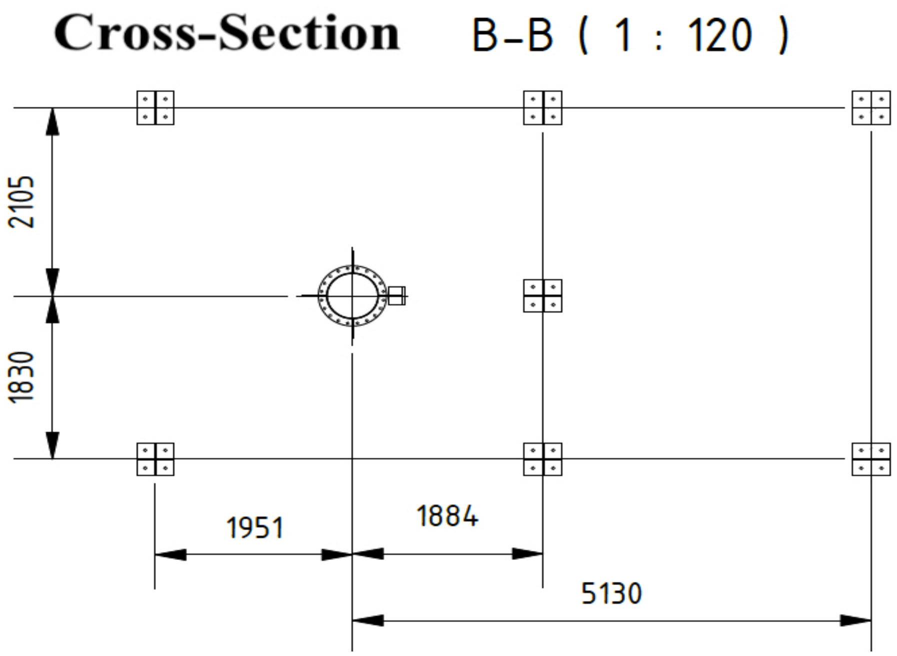
Figure 8-15 CleanSOx Compact base



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8.8.1.3 Placement

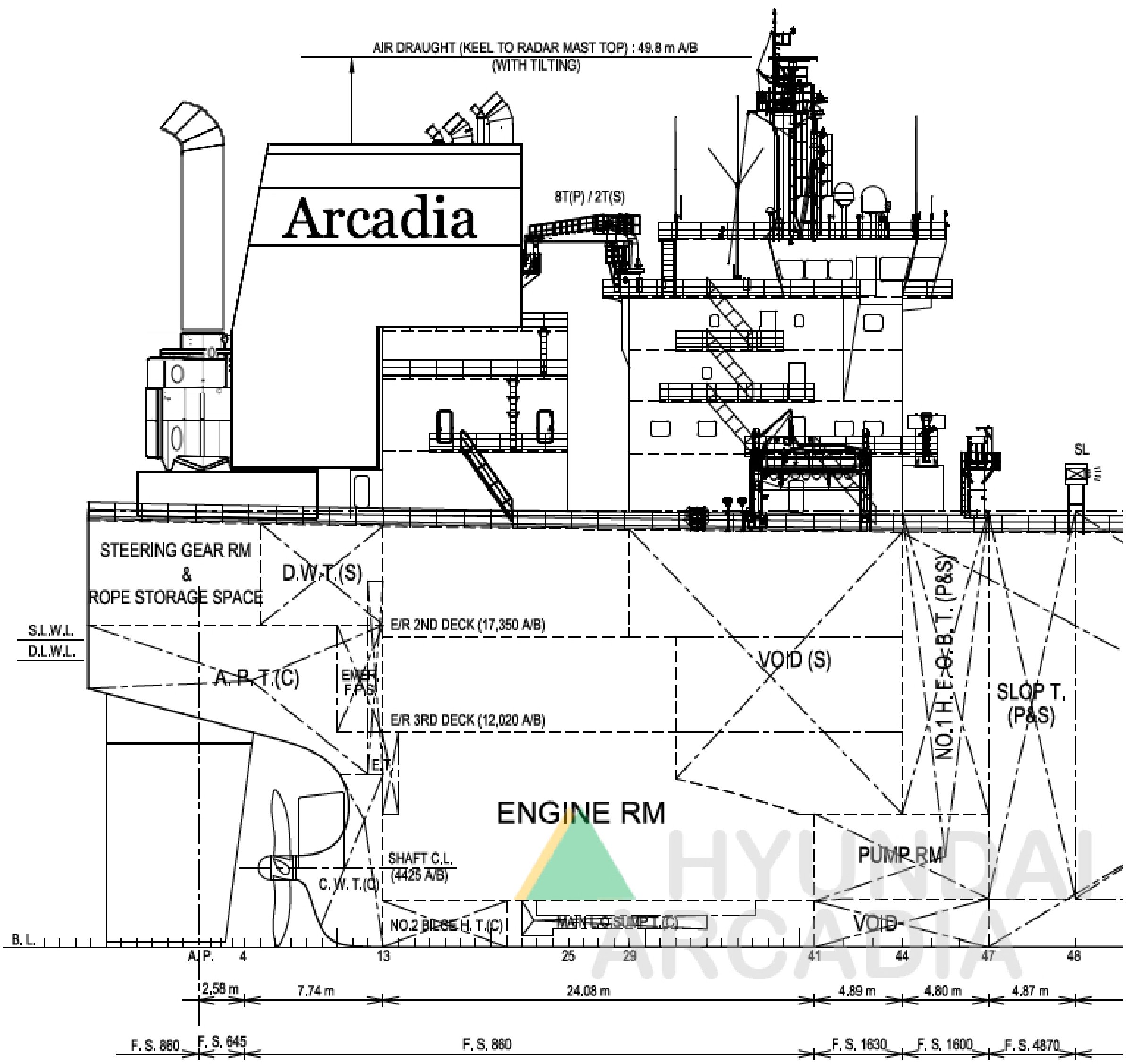
Generally, the EGC unit is placed at some distance behind (towards the aft) the funnel, as appropriate. CleanSO$_x$ scrubber can be placed either exposed to the external environment, or within the funnel enclosure or even only partly enclosed by the funnel (Figure 8-16). A robust structure will likely be needed so as to support the unit and raise it to the desired height.

All exhaust gas funnels (M/E, G/E, aux. boilers) converge to the exhaust gas manifold. The manifold has a built-in damper, by which the crew can control the aggregate gases route, either towards the EGCU or by-pass it to straight to the atmosphere. Concerning the by-pass function, it can be used in cases such as scrubber malfunction, switch-over to MGO etc. and generally when the flue gas shall not pass through the desulfurizing unit.

Additional notes:

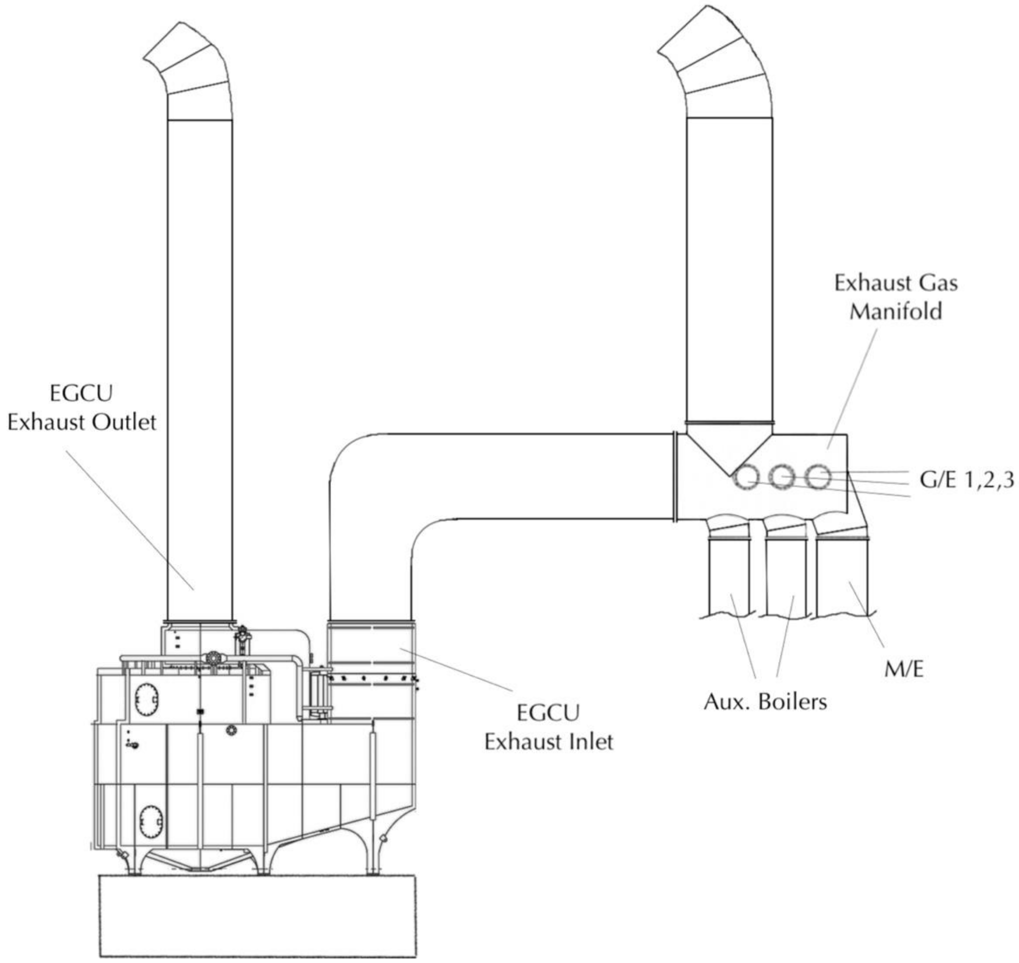
- Extensive funnel and exhaust gas piping modifications may be required.
- Besides the common bypass, one generator is also connected to a separate bypass line, located before the exhaust manifold, allowing for bypass damper inspection.

Figure 8-16. CleanSOx Compact position



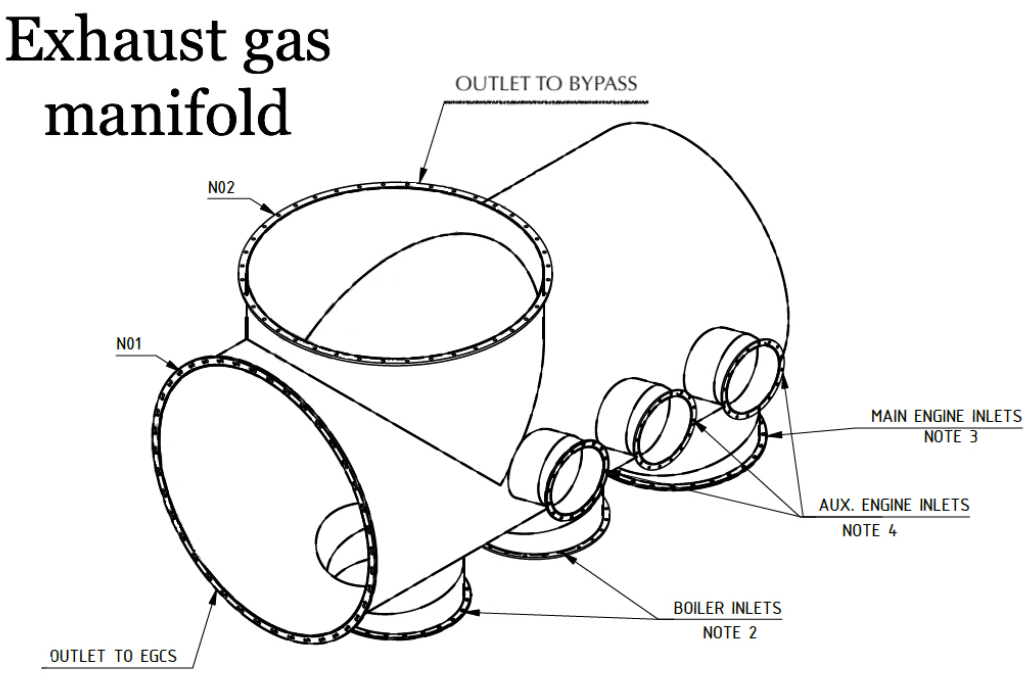
Source: Produced from material that was provided from Arcadia ShipManagment Co. Ltd and Clean Marine.

Figure 8-17. The inside of the funnel enclosure



Source: Produced from material that was provided from Clean Marine.

Figure 8-18. Exhaust gas manifold (by-pass damper)



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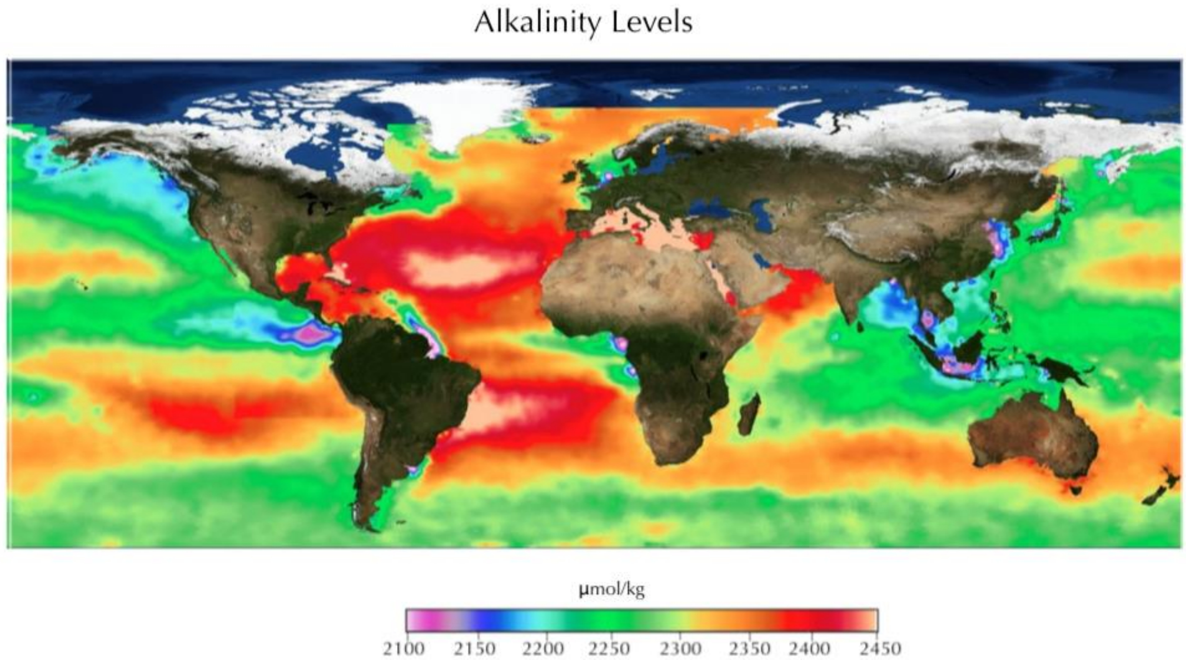
8.8.1.4 Open loop mode

In open loop mode, neutralization of the exhaust gas sulphur oxides is attained by the sea water's natural alkalinity and salinity. Clean Marine guarantees that this custom-made EGCS is able to achieve and maintain its maximum capacity (136,000 kg/h) in 0,50% Sulphur limit waters, provided that the sea water's alkalinity is at least 2200 μmol/kg.

In general, ocean alkalinity exceeds the prerequisite level, as shown in Figure 8-19. In certain areas though, such as the Baltic Sea, parts of the North Sea and the Gulf of Guinea, alkalinity levels drop below 2200 μmol. Moreover, some closed areas such as ports, estuaries, rivers and etc. have brackish waters, namely with lower alkalinity and salinity, comparing to normal sea levels. In this case, the cleaning medium (seawater/brackish water) might not be adequate by itself; instead of increasing the water flow - therefore the pump's power consumption as well - Clean Marine has resulted to a less cost-demanding option, allowing the simultaneous spraying of NaOH solution so as to achieve the desired efficiency levels. As in closed loop, 50% NaOH solution is sprayed to the seawater flow from various nozzles placed along the EGC unit, increasing the pH and neutralization capacity of the liquid medium and thus overcoming local waters' potential restrictions.

Figure 8-19. Alkalinity levels around the world (May 2015)



Source: National Aeronautics and Space Administration (NASA). (2015, October). Ocean alkalinity. Retrieved from https://svs.gsfc.nasa.gov/30697

The seawater is pumped through the vessel's sea chest via a set of two powerful pumps, provided by Clean Marine. Their capacity is selected so that one pump will be enough for operation and the other will be on standby. The seawater pumps are followed by a water analyzing unit for pH, turbidity and temperature. The whole EGC system is designed for ambient water temperature of 0-32°C. Before entering the scrubber, the absorbing medium passes through an automatic back-flush filter that withholds impurities and prevents system clogging. Clean Marine provides also a manual cleaning filter in case of malfunction of the automatic one.

Table 8-15. Seawater pumps

Seawater Pumps		
Seawater pump	Quantity	2 x 100%
	Capacity each (m^3/h)	935

Source: Courtesy of Clean Marine.

Table 8-16. Incoming seawater analysing unit

Water analyzing unit (incoming seawater)		
Seawater analyzing cabinet (Turbidity, pH and temperature)	Dimensions (cm)	80 x 60 x 30
	Weight (kg)	57
Seawater analyzer pressure reduction	Dimensions (cm)	120 x 60 x 30
	Weight (kg)	75

Source: Courtesy of Clean Marine.

Table 8-17. Incoming seawater filters

Filters (incoming seawater)		
Seawater filter (automatic back-flush)	Dimensions [L x W x H] (cm)	TBA
	Capacity (m^3/h)	935
	Weight (kg)	TBA
Seawater filter (manual cleaning – standby for redundancy)	Dimensions [L x W x H] (cm)	TBA
	Capacity (m^3/h)	935
	Weight (kg)	TBA

Source: Courtesy of Clean Marine.

After exiting the wash-water outlet of the EGC unit, the “dirty” water is routed to a wash-water analyzing unit for certifying compliance (or not) to the regulations that IMO mandates before overboard discharge, which are summarized in IMO 2015 Guidelines as follows:

pH: “The discharge washwater should have a pH of no less than 6.5 measured at the ship's overboard discharge with the exception that during maneuvering and transit, the maximum difference between inlet and outlet of 2 pH units is allowed measured at the ship's inlet and overboard discharge. The pH discharge limit, at the overboard monitoring position, is the value that will achieve as a minimum pH 6.5 at 4 m from the overboard discharge point with the ship stationary, and which is to be recorded as the overboard pH discharge limit.”

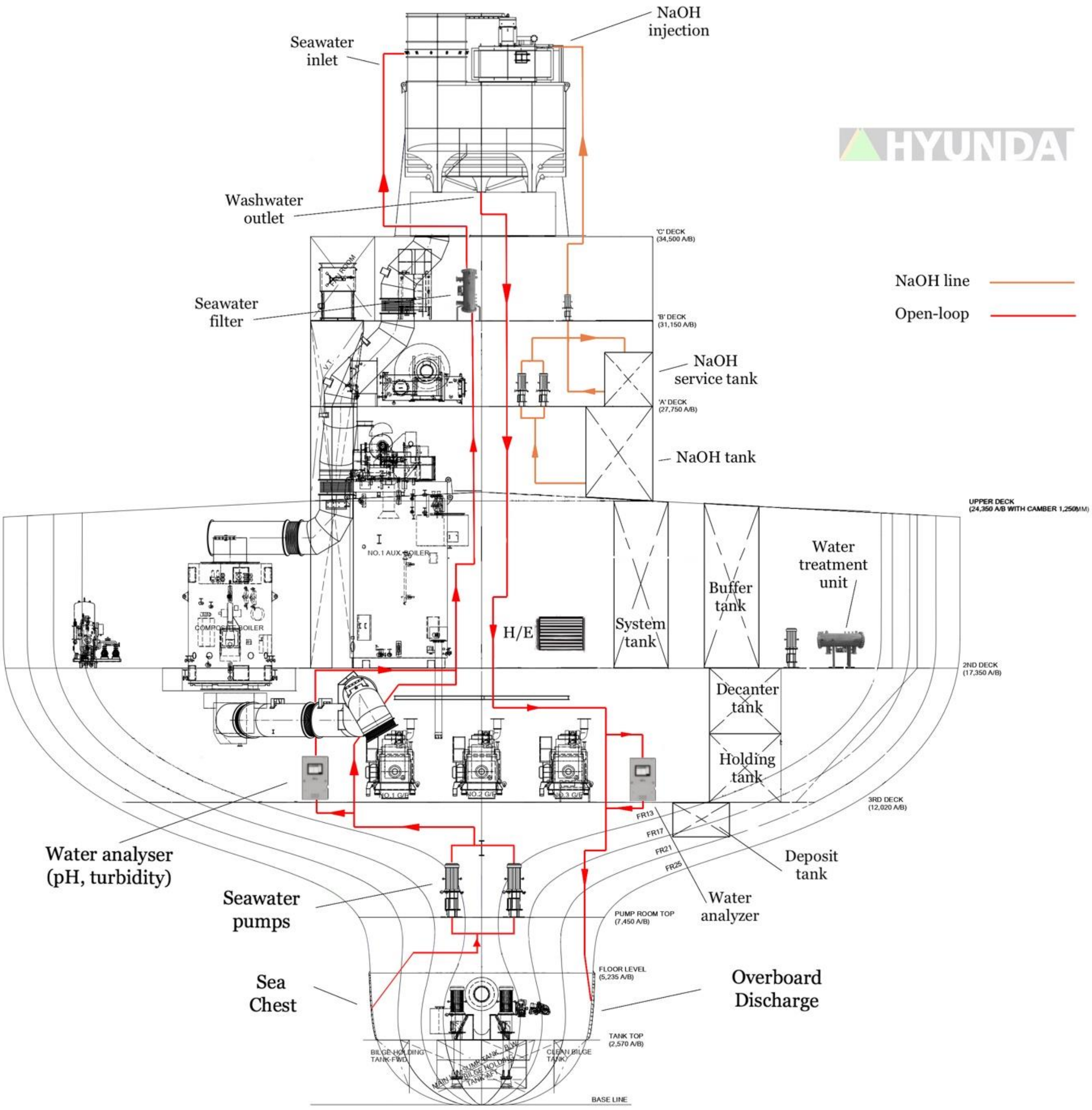
U.S. Coast Guard requites for operation inside US ECA, a minimum pH 6,0 at overboard discharge outlet.

Turbidity: The maximum continuous turbidity in washwater should not be greater than 25 FNU or 25 NTU or equivalent units, above the inlet water turbidity. The wash water’s turbidity should be measured downstream of the water treatment equipment but upstream of washwater dilution (or other reactant dosing) prior to discharge.

Moreover, the regulations specify certain washwater limits for PAH as well as nitrates content.

Below, follows a simplified illustration of the CleanSO$_x$ Compact system in Aegean Dream (Figure 8-20). This scheme was produced only for visual representation of the arrangement and does not represent the actual installation. A lot of the vessel's machinery have been intentionally ignored. Furthermore, it is focused on the open loop operation and the corresponding components.

Figure 8-20. Open loop arrangement of CleanSOx Compact in Aegean Dream



Source: Produced from material provided by Arcadia ShipManagment Co. Ltd and Clean Marine.

8.8.1.5 Closed loop mode

In case that the vessel is approaching an area that has banned open loop operation the crew shall switch the EGCU into closed loop.

For the sake of clarification, this mode is not entirely “closed”, in the strict sense. Most of the absorbing medium is recirculated, although the loop has a small bleed-off outflow which prevents the circuit from saturating. This relatively small outflow is offset by make-up seawater pumped by the seawater pumps. Concurrently, 50% NaOH solution is periodically sprayed from the EGC unit’s nozzles in the recirculated water, increasing its pH and maintain the efficiency of the cleaning process.

Before entering the EGCU, the cleaning water passes though the system’s seawater filter. After neutralizing the exhaust gases’ sulphur oxides inside the EGCU, the liquid medium exits the unit through the wash-water discharge outlet, and enters the system tank, in which make-up seawater is added at the same time. The renewed absorbing medium, is pumped via the recirculation pump to the heat exchanger, where ambient seawater is used to cool it down at the desired temperature. Thence, it is routed back again to the seawater filter and the scrubber.

Table 8-18. Closed loop main tank

System tank	Capacity (m^3)	17
	Recommended material	Epoxy coating

The bleed-off outflow passes firstly through the buffer tank and then is pumped by the water treatment pump to the wash-water filter. The latter cleans the stream at IMO’s required levels. The filter has two outlets, one for the cleaned medium and one for the withheld impurities. As for the first one, after exiting the treatment unit it passes through the decanter tank and ends up in the holding tank. As for the second one, it is routed straight to the deposit tank. Both deposit and holding tank are interconnected with the drain pump, for onshore discharge. Besides that, the holding tank is also connected to the overboard discharge line, in order to be utilized when discharge is allowed.

Table 8-19. Closed loop auxiliary tanks

Tanks		
Buffer tank	Capacity (m^3)	8
	Recommended material	Mild steel, pure epoxy coating. Paint on intact shop primer.
Decanter tank	Capacity (m^3)	17
	Recommended material	Mild steel, pure epoxy coating. Paint on intact shop primer.
Holding tank	Capacity (m^3)	Depending on the deposition frequency
	Recommended material	Mild steel, pure epoxy coating. Paint on intact shop primer.
Deposit tank	Capacity (m^3)	10

	Recommended material	Mild steel, pure epoxy coating. Paint on intact shop primer.

The seawater that is used for cooling purposes, is routed to the wash-water analysing unit and thence for overboard discharge.

Table 8-20. Recirculation cooler

Recirculation cooler	Dimensions [LxWxH] (cm)	TBA
	Capacity (m^3/h)	935/700
	Weight (kg)	TBA

NaOH is used in the form of 50% water-NaOH solution. The chemical solution can be supplied in several bunkering ports and it is delivered onboard either in bulk or in IBC pallets. The hazardous chemical is stored in the NaOH storage tank, which is connected with two pumps, one for regular operation and one in standby for redundancy. Via these pumps, caustic soda is routed to a 1 m^3 NaOH service tank and thence via four small pumps in the corresponding nozzles on the EGC unit. Both tanks are heated to approximately 30°C.

Table 8-21. NaOH tanks

NaOH storage tank	Capacity (m^3)	Depending on the refilling frequency
	Recommended material	Mild steel, Phenolic resin coating (NaOH resistant). Sa 2/12 pretreatment.
NaOH service tank	Capacity (m^3)	1
	Recommended material	Mild steel, Phenolic resin coating (NaOH resistant). Sa 2/12 pretreatment.

Below, are quoted the typical NaOH consumption for 0,10% areas during open and closed loop. Sailing in 0,50% areas and when operating in open loop does not normally requite NaOH addition, as explained before. The precise values of NaOH consumption in respect to vessel's loads can result only after detailed engineering.

Table 8-22. NaOH consumption

Alkali consumption (NaOH) (scrubbing to 0.10% S)	Open loop	12	liters/%S in mt fuel consumed
	Closed loop	25	liters/%S in mt fuel consumed

Table 8-23. Closed loop pumps

Machinery		
Recirculation pump	Quantity	1

	Capacity (m^3/h)	700
Water treatment pump	Quantity	1
	Capacity (m^3/h)	31
Drain pump	Quantity	1
	Capacity (m^3/h)	30

Energy consumption during open loop mode comes mainly from the seawater pump and the exhaust gas fan. During closed loop, it is the sum of the recirculation pump, water treatment pump, seawater pump, the fan and some smaller consumers (e.g. drain pump, wash-water analyzer etc.)

Table 8-24. CleanSOx Compact power consumption

Utilities			**Units**
Electrical consumption	Open loop	360	kW
	Closed loop	410	kW

Table 8-25. Recommended piping material

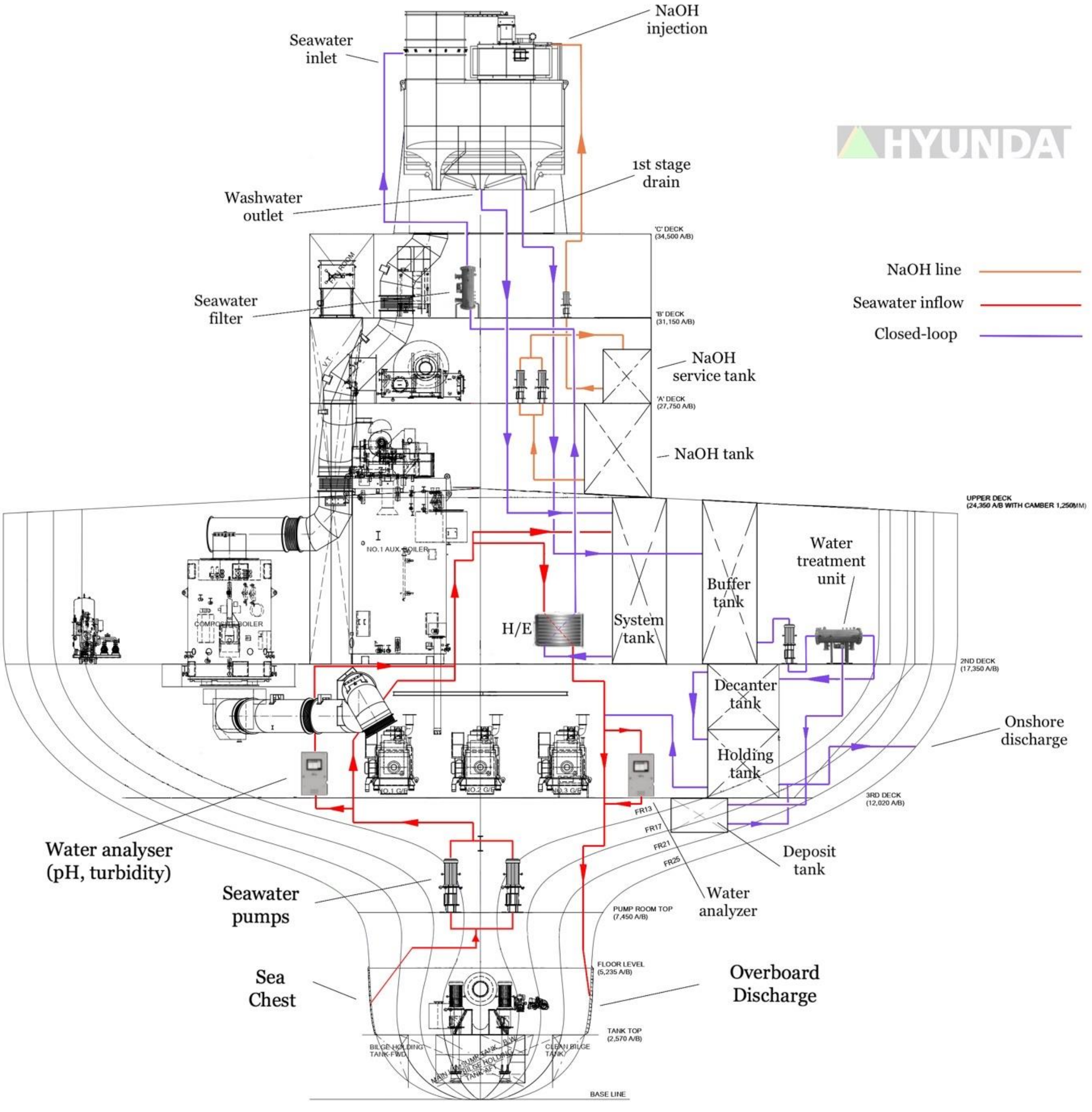
Line	**Recommended structural material**	**Coating/lining**
Seawater supply	Hot dip galv. CS or lined CS	PU/PE/PP lined if CS
Circulation/system lines	GRE	N.A.
Overboard line	GRE	N.A.
NaOH dosage line	Stainless steel 316L	N.A.
Closed loop drain line	GRE	N.A.

Additional notes:

- Some ports prohibit the discharge of any wash-water, namely require zero-discharge mode (e.g. Port of Singapore). The holding tank shall be dimensioned based on the maximum duration that the vessel is expected to spend in zero-discharge mode. The crew may face reasonable problems, in case of underestimated tank capacity.
- All tanks are to be designed by the Client according to applicable Class / Flag rules.
- According to IMO, residues that are produced from the EGC unit (in our case the water-treatment filters) should be delivered ashore to adequate reception facilities. Incineration of overboard discharge of such residues is prohibited. Storage and disposal record keeping of the residues is mandatory.
- NaOH is a hazardous chemical, thus requiring special attention as well as the use of protective equipment from the crew during handling.

Below, follows a simplified illustration of the CleanSO$_x$ Compact system in Aegean Dream (Figure 8-21). This scheme was produced only for visual representation of the arrangement and does not represent the actual installation. A lot of the vessel's machinery have been intentionally ignored. Furthermore, it is focused on the closed loop operation and the corresponding components.

Figure 8-21. Closed loop arrangement of CleanSOx Compact in Aegean Dream

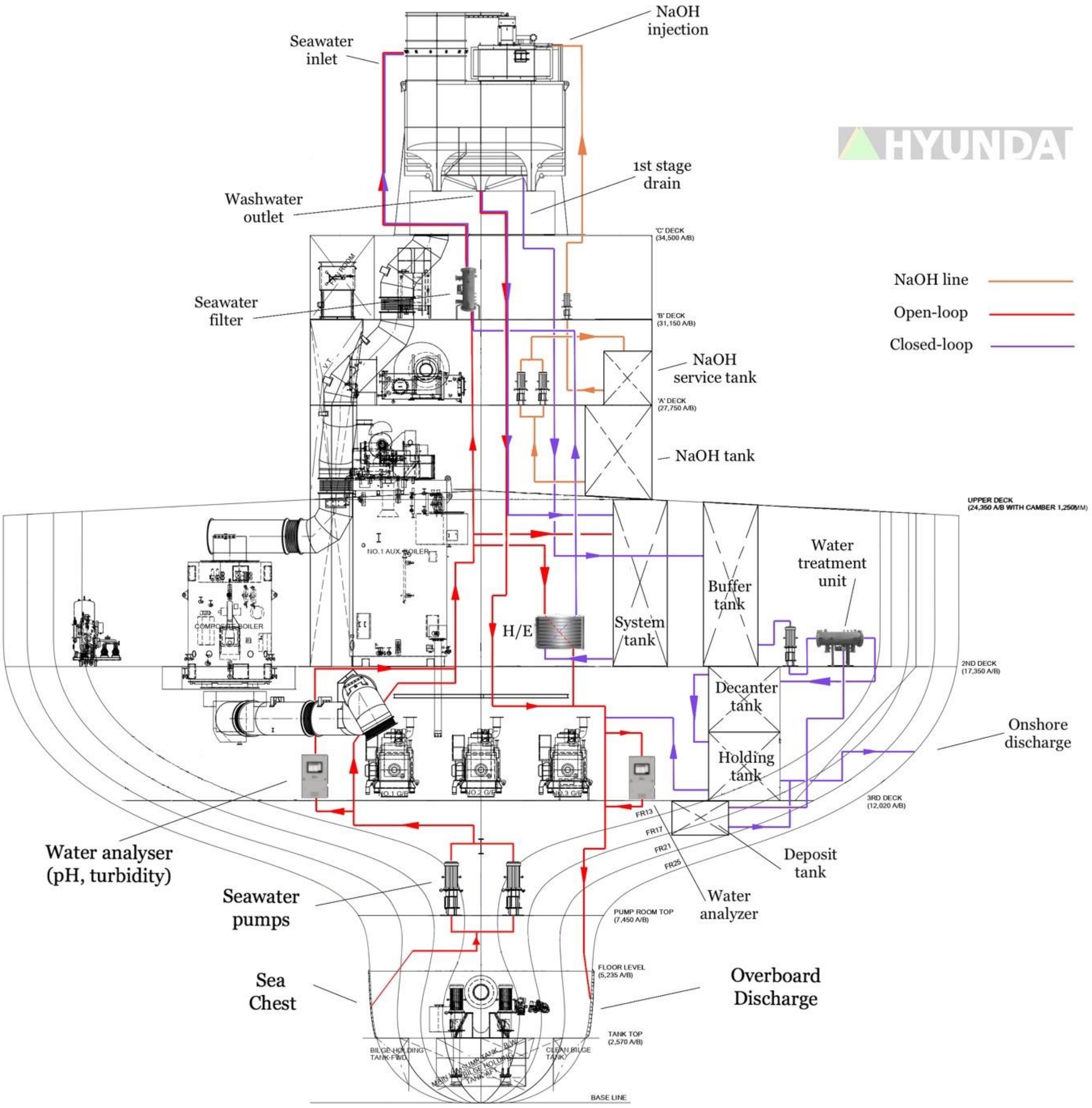


Source: Produced from material provided by Arcadia ShipManagment Co. Ltd and Clean Marine.

8.8.1.6 Hybrid mode

Below follows a simplified illustration of the overall EGC system (Figure 8-22). As was said before, this is only for visualization purposes and by no means represents the actual arrangement. All connections and components though were placed in the right way, thus meaning it can be used as a reliable tool for understanding the general concept of the CleanSOx Compact system's installation on Aegean Dream.

Figure 8-22 Overview of CleanSOx Compact system's installation on Aegean Dream



Source: Produced from material provided by Arcadia ShipManagment Co. Ltd and Clean Marine.

8.8.1.7 Financial feasibility of EGCS1

The main purpose of the assessment is estimating the payback period and Net Present Value (NPV) of the Scrubber investment, including all costs of the retrofit onboard the Aegean Dream. The payback period of the investment was calculated mainly based on the annual fuel oil consumption and the scrubber's capital and operating expenditure.

Annual fuel consumption is estimated for both occasions, using:

- Compliant fuels (VLSFO for 0,50% areas & MGO for ECAs)
- Scrubber and HFO

The most important factor for the results is the price differential between these fuels. For instance, the cost of HFO in Rotterdam is 293 \$/mt, while VLSFO costs 469 \$/mt and MGO 492.5 \$/mt at Wednesday 19 of February 2020. The fuel's price spread affects the payback period and defines whether the investment is profitable.

8.8.1.7.1 Capital Expenditure of CleanSOx Compact ($CAPEX_1$)

As it has been said before the investment's $CAPEX_1$ consists of:

- Scrubber machinery and equipment
- Modifications (including piping, electrical installations, funnel modification, engine room rearrangement, sea-chest modification if needed, etc.)
- Preparation and plan approval
- Classification cost
- Off-hire cost

The abovementioned costs were estimated that add up to **$CAPEX_1$ = 4,268,000 \$**.

8.8.1.7.2 Operational Expenditure of CleanSOx Compact ($OPEX_1$)

8.8.1.7.2.1 Electrical Consumption

It is estimated from Clean Marine that the electrical consumption of the hybrid scrubber is:

Open loop: 360 kW

Closed loop: 410 kW

Assuming an 80% MCR typical load on seagoing mode of Aegean Dream's Hyundai HIMSEN H21/32 generators the available generated power on board is 960 kW which corresponds to 176.64 kg HFO/hr fuel consumption of the generator as it can be seen in Figure 8-23.

Thus, the fuel consumption per generated kilowatt-hour is 0.184 kg HFO/kWh. Assuming an average HFO price of 350 \$/mt, it occurs that the cost per generated kWh on board the ship is 0.0644 \$/kWh.

Figure 8-23 SFOC & Fuel Consumption versus %MCR of Aegean Dream's generator

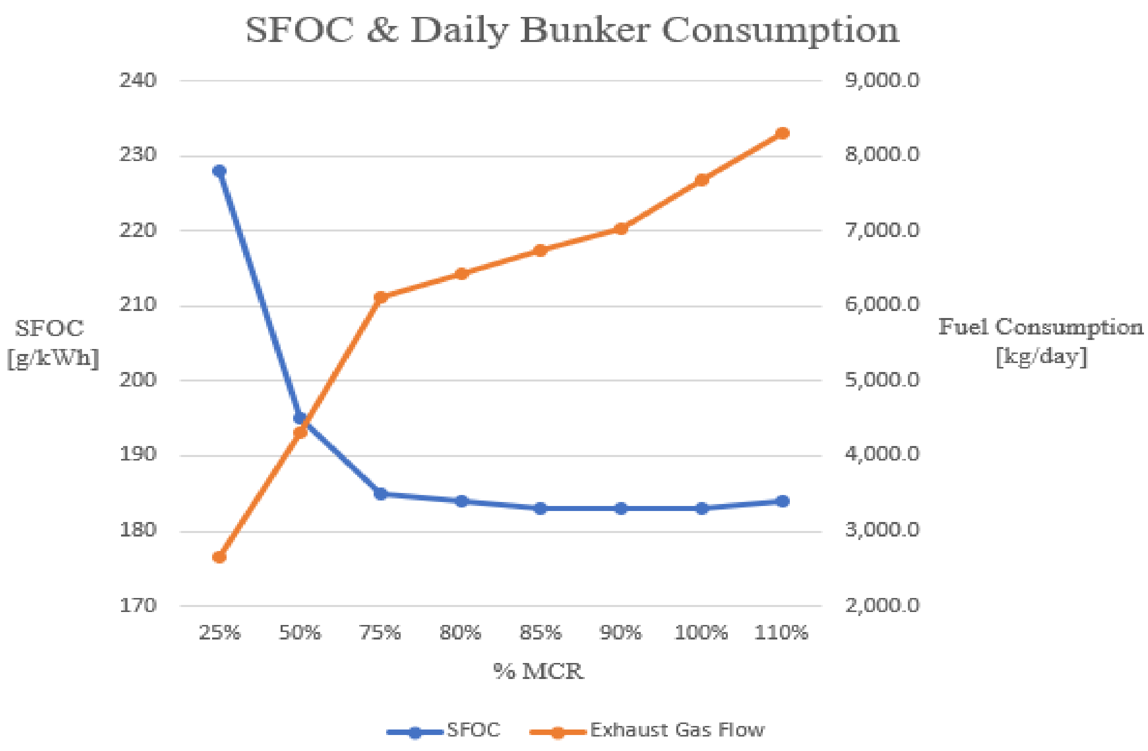


Table 8-26 Additional electrical consumption of EGCS1

	Electrical Consumption (kW)	Annual Trade Pattern	Total Operation (hr/year)	Total Consumption (MWh)	Cost of Electricity ($)
Open loop	360	98.87%	8,661	3,117.96	200,797
Closed loop	410	1.13%	99	40.59	2,614

Thus, the total cost of electricity is **203,411 $/year**.

8.8.1.7.2.2 Alkali consumption

It is estimated that the consumption of NaOH for the open and closed loop operations is

Open loop: 12 liters/%S in fuel/mt consumed of NaOH (50% solution)

Closed loop: 25 liters/%S in fuel/mt consumed of NaOH (50% solution)

The NaOH in the open loop operation is used to scrub the exhaust gases to 0.10% S.

According to the annual trade pattern that the company provided for the fuel consumption and assuming that the sulphur content of the HFO that the vessel will burn is 3.50% S and the price for the NaOH 50% solution, with density 1.5059 kg/l @ 20 °C, is 0.56 $/kg, the alkali cost is displayed on Table 8-27.

Table 8-27 . Alkali cost for EGCS1

Scrubber Operation	Sulphur Limit	Fuel Consumption (mt)	NaOH Consumption (liters)	NaOH Cost ($)
Open loop	0.50%	7,762.32	-	-
	0.10%	1,753.08	73,629.36	62,091.9
Closed loop	0.50%	35.76	3,129	2,628.7
	0.10%	73	6,387.5	5,386.6

Hence, the total cost for the NaOH solution is **70,107.2 $/year**.

8.8.1.7.2.3 Sludge disposal

Since the sludges accumulate only in closed loop operation which accounts for 1.13% of the time the vessel operates in a year (assuming the same trade pattern), sludge disposal was considered approximately zero compared to the other costs.

8.8.1.7.2.4 Maintenance

Maintenance cost was considered **40,412 $/year**, since the scrubber has few moving parts.

8.8.1.7.2.5 Backpressure formation

The CleanSOx Compact does not cause backpressure of the exhaust gases, so there was no extra cost of fuel.

To summarize, the total $OPEX_1$, considering all the assumptions that were stated, is **313,931 $**.

8.8.1.7.3 Payback Period

It must be noted that for reference point it has been chosen the exclusive usage of HFO in order to calculate the additional costs that come up from using more expensive fuels.

For the estimation of payback period, 12 different scenarios were chosen about the price gap between VLSFO and HFO and 5 scenarios regarding price gaps between MGO and HFO price.

Table 8-28 1st part: 12% ECA and MGOprice-HFOprice= 450$

Scenario	**1**	**2**	**3**	**4**	**5**	**6**
VLSFOprice - HFOprice	420	385	350	315	280	245
MGOprice - HFOprice	450	450	450	450	450	450
VLSFO at sea	3.068.317	2.812.624	2.556.931	2.301.238	2.045.545	1.789.852
VLSFO at port	206.291	189.100	171.910	154.719	137.528	120.337
MGO at sea	448.293	448.293	448.293	448.293	448.293	448.293
MGO at port	374.067	374.067	374.067	374.067	374.067	374.067
Additional cost	4.096.968	3.824.084	3.551.200	3.278.316	3.005.432	2.732.548
Savings	3.783.037	3.510.153	3.237.269	2.964.385	2.691.501	2.418.617

Table 8-29 2nd part: 12% ECA and MGOprice-HFOprice= 450$

Scenario	**7**	**8**	**9**	**10**	**11**	**12**
VLSFOprice - HFOprice	210	175	140	105	70	35
MGOprice - HFOprice	450	450	450	450	450	450
VLSFO at sea	1.534.159	1.278.466	1.022.772	767.079	511.386	255.693
VLSFO at port	103.146	85.955	68.764	51.573	34.382	17.191
MGO at sea	448.293	448.293	448.293	448.293	448.293	448.293
MGO at port	374.067	374.067	374.067	374.067	374.067	374.067
Additional cost	2.459.664	2.186.780	1.913.896	1.641.012	1.368.128	1.095.244
Savings	2.145.733	1.872.849	1.599.965	1.327.081	1.054.197	781.313

The meanings of the Table 8-28 and Table 8-29 contents are:

- **VLSFOprice - HFOprice** = price differences between VLSFO and HFO
- **MGOprice - HFOprice** = price differences between MGO and HFO
- **VLSFO in sea** is the additional cost that would apparent from the usage of VLSFO in sea in order to comply with 0.50% S limit, instead of using HFO and the $EGCS_1$.
- **VLSFO in port** is the additional cost that would apparent from the usage of VLSFO in port in order to comply with 0.50% S limit, instead of using HFO and the $EGCS_1$.
- **MGO in sea** is the additional cost that would apparent from the usage of MGO in sea in order to comply with 0.10% S limit, instead of using HFO and the $EGCS_1$.
- **MGO in port** is the additional cost would apparent from the usage of MGO in port in order to comply with 0.10% S limit, instead of using HFO and the $EGCS_1$.
- **Additional cost** includes the summary of the additional cost by using VLSFO and MGO in sea and ports. For example, for the 1st scenario if HFO price was 200$, VLSFO price would be 200 + 420 = 620$ and MGO 200 + 450 = 650$. In case that $EGCS_1$ has been installed, the cost would be 1,924,830$, otherwise, using VLSFO this cost amounted to 4,833,946$. So, the additional cost of not using the $EGCS_1$ in this case is: 6,021,799$ - 1,559,337$ = 4,096,968$.
- **Savings** are calculated as the additional cost by using the expensive fuel minus the scrubber's operational cost (Savings = Additional cost – $OPEX_1$). For example, for the 1st scenario: Savings = 4.096.968,76 $ - 313.931,60 $ = 3.783.037 $.

It is unambiguous that the payback period depends on each fuel's consumption. Thus, the calculation of payback period (PP) is given as:

$$PP = \frac{(VLSFOprice - HFOprice) * Cons1 + (MGOprice - HFOprice) * Cons2 - OPEX}{Investment's\ Cost}$$

where,

Cons1 = Annual consumption at sea.

Cons2 = Annual consumption at ECA areas and ports.

Result is given in years.

8.8.1.7.4 Net Present Value (NPV)

NPV is defined as the difference between the present value of cash inflows and the present value of cash outflows over a period. It is often used in capital budgeting and investment planning to analyze the profitability of a projected investment or project.

A positive net present value (NPV > 0) indicates that the projected earnings generated by a project or investment exceeds the anticipated costs. It is assumed that an investment with a positive NPV will be profitable, and an investment with a negative NPV (NPV < 0) will result in a net loss.

NPV is calculated as:

$$NPV = -4{,}268{,}000 + \sum_{i=1}^{n} \frac{Savings}{(1+r)^i}$$

where,

i = years = 15

r = cost of capital rate = 3%

8.8.1.8 Results

8.8.1.8.1 MGOprice – HFOprice = 225 $

Savings, payback period and NPV are presented in Table 8-30, Table 8-31, Table 8-32, Table 8-33, Table 8-34, Table 8-35 for 12 scenarios regarding VLSFOprice – HFOprice and 7 different scenarios regarding % ECA, while MGOprice – HFOprice = 225 $ = constant.

Table 8-30 1st part: Savings for MGOprice – HFOprice = 225 $

Scenario	**1**	**2**	**3**	**4**	**5**	**6**
VLSFOprice-HFOprice	420	385	350	315	280	245
Savings for 12% in ECAs	3.371.857	3.098.973	2.826.089	2.553.205	2.280.321	2.007.437
Savings for 20% in ECAs	3.242.350	2.992.711	2.743.072	2.493.433	2.243.793	1.994.154
Savings for 30% in ECAs	3.080.467	2.859.883	2.639.300	2.418.717	2.198.134	1.977.551
Savings for 40% in ECAs	2.918.583	2.727.056	2.535.529	2.344.001	2.152.474	1.960.947
Savings for 50% in ECAs	2.756.699	2.594.228	2.431.757	2.269.286	2.106.815	1.944.344
Savings for 60% in ECAs	2.594.816	2.461.401	2.327.986	2.194.570	2.061.155	1.927.740
Savings for 70% in ECAs	2.432.932	2.328.573	2.224.214	2.119.855	2.015.496	1.911.137

Table 8-31 2nd part: Savings for MGOprice – HFOprice = 225 $

Scenario	**7**	**8**	**9**	**10**	**11**	**12**
VLSFOprice-HFOprice	210	175	140	105	70	35
Savings for 12% in ECAs	1.734.553	1.461.669	1.188.785	915.901	643.017	370.133
Savings for 20% in ECAs	1.744.515	1.494.876	1.245.236	995.597$	745.958	496.319
Savings for 30% in ECAs	1.756.967	1.536.384	1.315.801	1.095.218	874.635	654.051
Savings for 40% in ECAs	1.769.420	1.577.893	1.386.366	1.194.839	1.003.311	811.784
Savings for 50% in ECAs	1.781.873	1.619.401	1.456.930	1.294.459	1.131.988	969.517
Savings for 60% in ECAs	1.794.325	1.660.910	1.527.495	1.394.080	1.260.665	1.127.250
Savings for 70% in ECAs	1.806.778	1.702.419	1.598.060	1.493.701	1.389.342	1.284.983

Table 8-32 1st part: Payback period for MGOprice – HFOprice = 225 $

Scenario	**1**	**2**	**3**	**4**	**5**	**6**
VLSFOprice-HFOprice	420	385	350	315	280	245
Payback period for 12% in ECAs	1,266	1,377	1,510	1,672	1,872	2,126
Payback period for 20% in ECAs	1,316	1,426	1,556	1,712	1,902	2,140
Payback period for 30% in ECAs	1,386	1,492	1,617	1,765	1,942	2,158
Payback period for 40% in ECAs	1,462	1,565	1,683	1,821	1,983	2,176
Payback period for 50% in ECAs	1,548	1,645	1,755	1,881	2,026	2,195
Payback period for 60% in ECAs	1,645	1,734	1,833	1,945	2,071	2,214
Payback period for 70% in ECAs	1,754	1,833	1,919	2,013	2,118	2,233

Table 8-33 2nd part: Payback period for MGOprice – HFOprice = 225 $

Scenario	**7**	**8**	**9**	**10**	**11**	**12**
VLSFOprice-HFOprice	210	175	140	105	70	35
Payback period for 12% in ECAs	2,461	2,920	3,590	4,660	6,637	11,531
Payback period for 20% in ECAs	2,447	2,855	3,427	4,287	5,722	8,599
Payback period for 30% in ECAs	2,429	2,778	3,244	3,897	4,880	6,525
Payback period for 40% in ECAs	2,412	2,705	3,079	3,572	4,254	5,258
Payback period for 50% in ECAs	2,395	2,636	2,929	3,297	3,770	4,402
Payback period for 60% in ECAs	2,379	2,570	2,794	3,062	3,386	3,786
Payback period for 70% in ECAs	2,362	2,507	2,671	2,857	3,072	3,321

Table 8-34 1st part: NPV for MGOprice – HFOprice = 225 $

Scenario	**1**	**2**	**3**	**4**	**5**	**6**
VLSFOprice-HFOprice	420	385	350	315	280	245
NPV for 12% in ECAs	34,936,904	31,774,116	28,611,327	25,448,539	22,285,750	19,122,962
NPV for 20% in ECAs	33,435,890	30,542,514	27,649,138	24,755,763	21,862,387	18,969,012
NPV for 30% in ECAs	31,559,621	29,003,012	26,446,402	23,889,793	21,333,183	18,776,574
NPV for 40% in ECAs	29,683,353	27,463,510	25,243,666	23,023,823	20,803,980	18,584,136
NPV for 50% in ECAs	27,807,085	25,924,008	24,040,930	22,157,853	20,274,776	18,391,698
NPV for 60% in ECAs	25,930,817	24,384,506	22,838,194	21,291,883	19,745,572	18,199,261
NPV for 70% in ECAs	24,054,549	22,845,004	21,635,459	20,425,913	19,216,368	18,006,823

Table 8-35 2nd part: NPV for MGOprice – HFOprice = 225 $

Scenario	**7**	**8**	**9**	**10**	**11**	**12**
VLSFOprice-HFOprice	210	175	140	105	70	35
NPV for 12% in ECAs	15,960,173	12,797,385	9,634,596	6,471,808	3,309,019	146,231
NPV for 20% in ECAs	16,075,636	13,182,260	10,288,885	7,395,509	4,502,133	1,608,758
NPV for 30% in ECAs	16,219,964	13,663,355	11,106,745	8,550,136	5,993,526	3,436,917
NPV for 40% in ECAs	16,364,293	14,144,449	11,924,606	9,704,762	7,484,919	5,265,075
NPV for 50% in ECAs	16,508,621	14,625,543	12,742,466	10,859,389	8,976,311	7,093,234
NPV for 60% in ECAs	16,652,949	15,106,638	13,560,327	12,014,015	10,467,704	8,921,393
NPV for 70% in ECAs	16,797,278	15,587,732	14,378,187	13,168,642	11,959,097	10,749,551

Figure 8-25 Payback period for MGOprice – HFOprice = 225 $

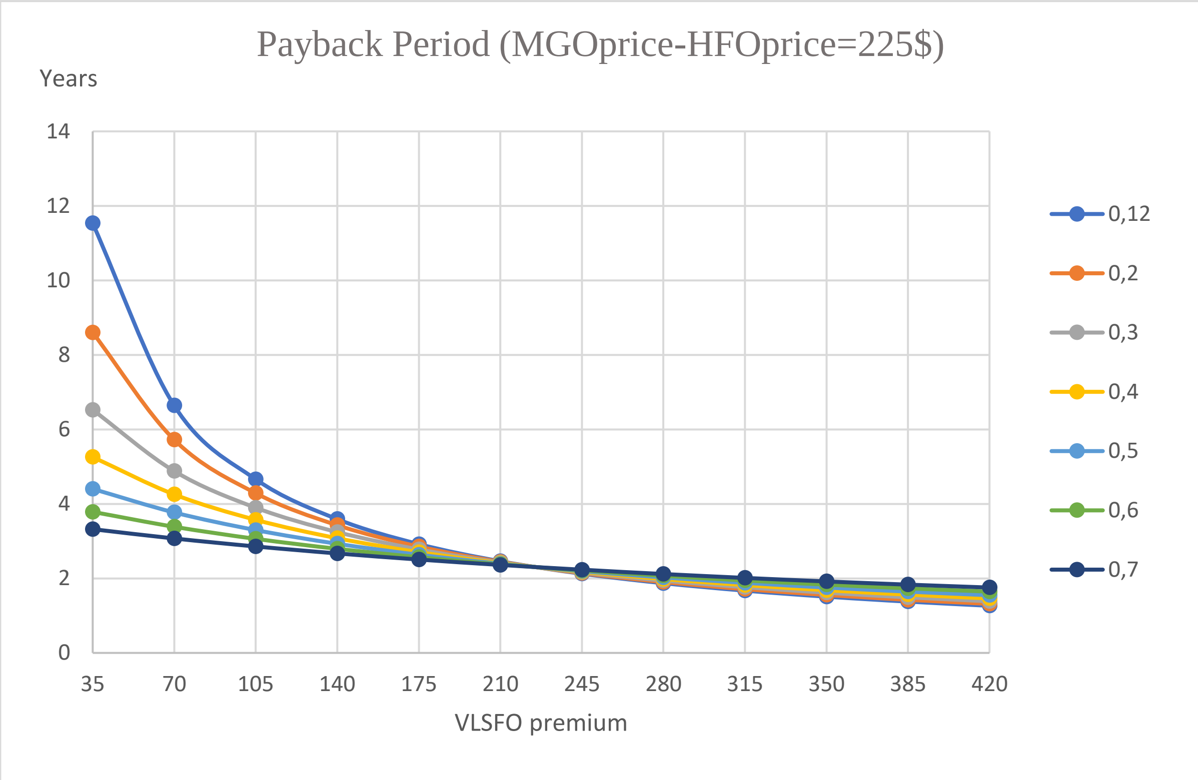
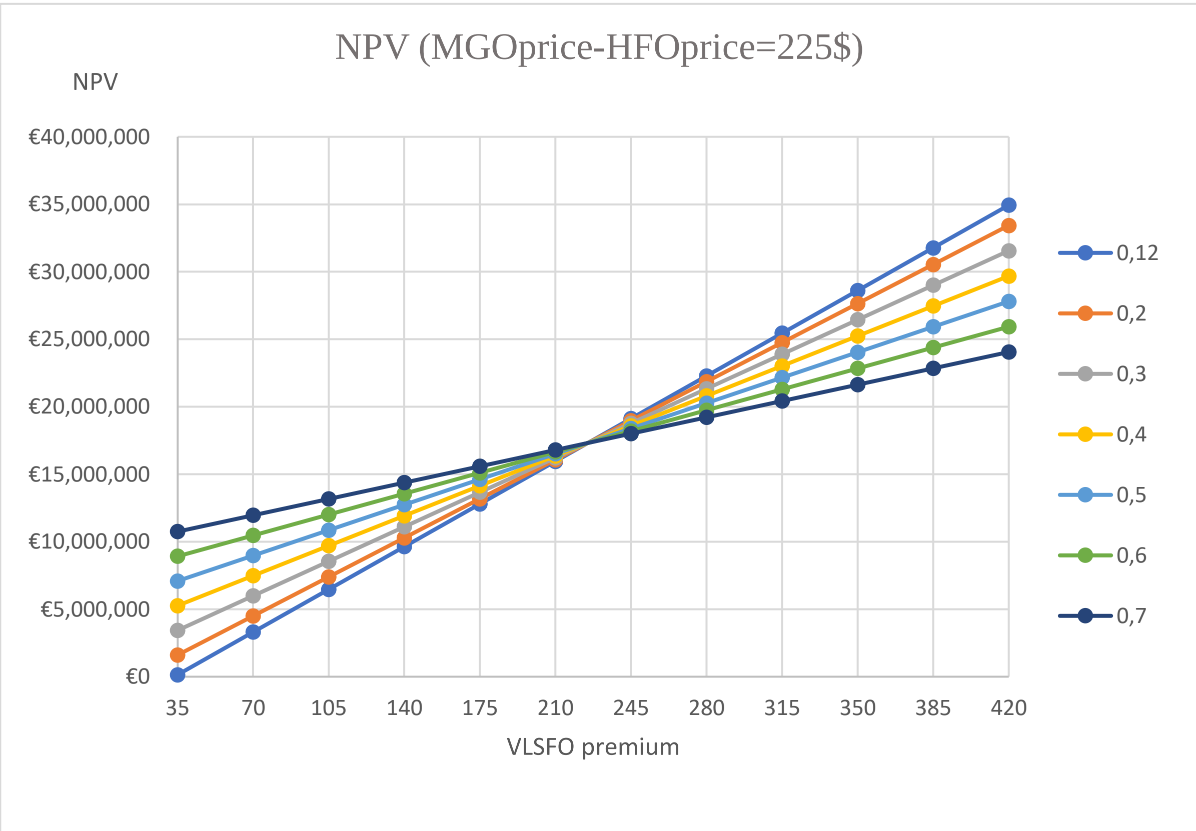


Figure 8-24 NPV for MGOprice – HFOprice = 225 $



8.8.1.8.2 MGOprice – HFOprice = 450 $

Only the payback period is presented in Table 8-36 and Table 8-37 for 12 scenarios regarding VLSFOprice – HFOprice and 7 different scenarios regarding % ECA, while MGOprice – HFOprice = 450 $ = constant.

Table 8-36 1st part: Payback period for MGOprice – HFOprice = 450 $

Scenario	**1**	**2**	**3**	**4**	**5**	**6**
VLSFOprice-HFOprice	420	385	350	315	280	245
Payback period for 12% in ECAs	1,128	1,216	1,318	1,440	1,586	1,765
Payback period for 20% in ECAs	1,122	1,201	1,292	1,397	1,522	1,671
Payback period for 30% in ECAs	1,115	1,183	1,260	1,348	1,449	1,566
Payback period for 40% in ECAs	1,108	1,166	1,230	1,302	1,383	1,474
Payback period for 50% in ECAs	1,101	1,149	1,201	1,259	1,322	1,392
Payback period for 60% in ECAs	1,094	1,132	1,174	1,219	1,267	1,319
Payback period for 70% in ECAs	1,087	1,116	1,148	1,181	1,216	1,253

Table 8-37 2nd part: Payback period for MGOprice – HFOprice = 450 $

Scenario	**7**	**8**	**9**	**10**	**11**	**12**
VLSFOprice-HFOprice	210	175	140	105	70	35
Payback period for 12% in ECAs	1,989	2,279	2,668	3,216	4,049	5,463
Payback period for 20% in ECAs	1,852	2,076	2,363	2,743	3,267	4,038
Payback period for 30% in ECAs	1,704	1,869	2,069	2,316	2,631	3,045
Payback period for 40% in ECAs	1,579	1,699	1,839	2,005	2,203	2,444
Payback period for 50% in ECAs	1,470	1,557	1,656	1,767	1,894	2,042
Payback period for 60% in ECAs	1,376	1,438	1,505	1,580	1,662	1,753
Payback period for 70% in ECAs	1,293	1,335	1,380	1,428	1,480	1,536

Figure 8-27 Payback period for MGOprice – HFOprice = 450 $

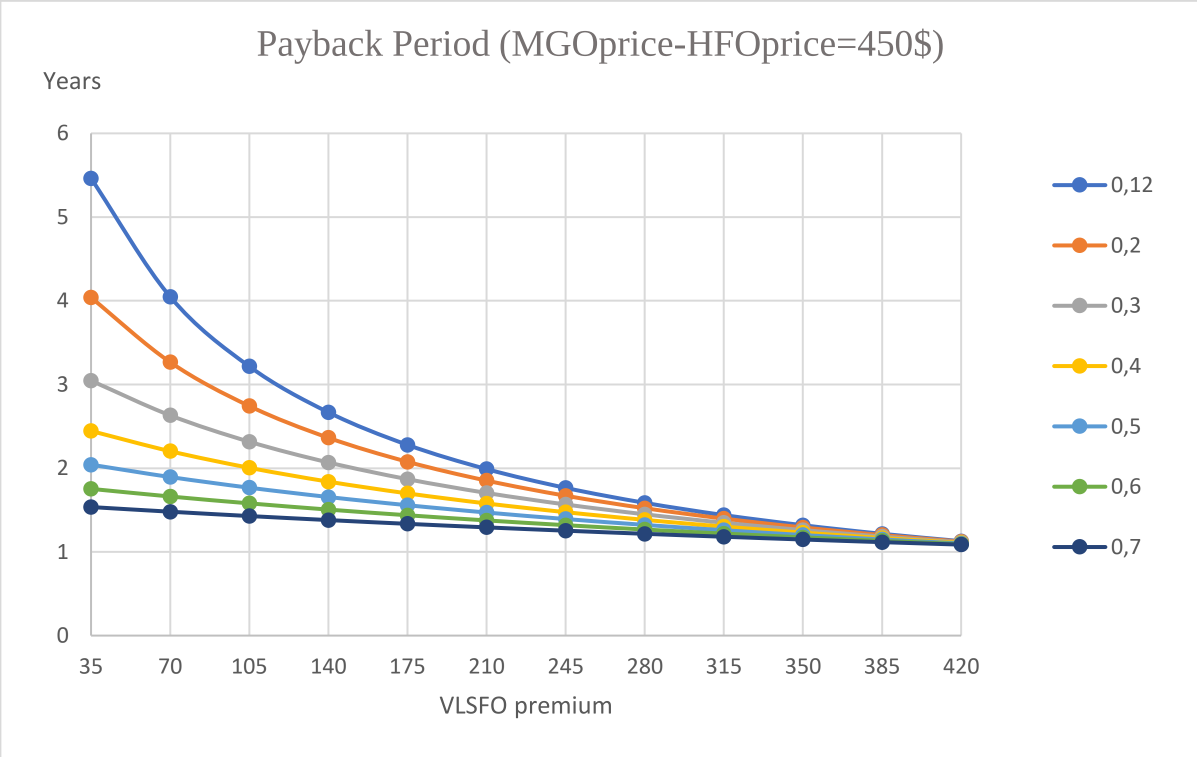
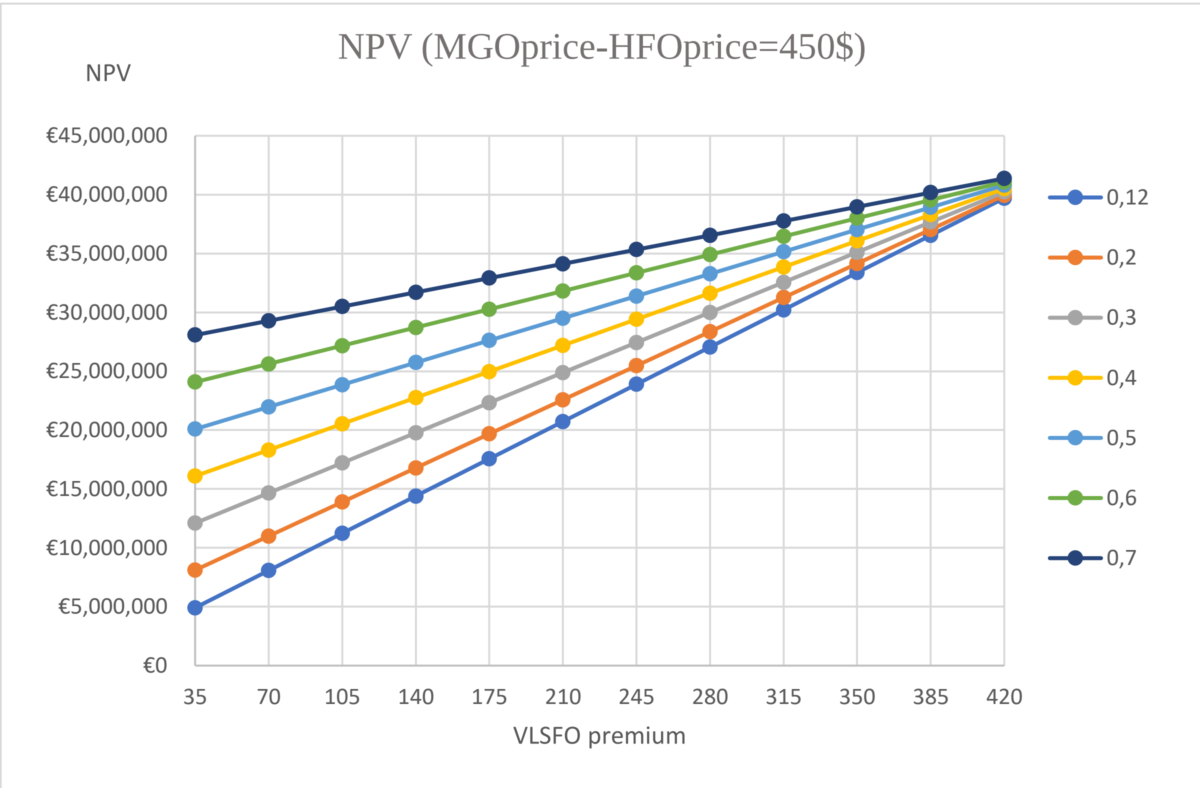


Figure 8-26 NPV for MGOprice – HFOprice = 450 $



8.8.1.8.3 MGOprice – HFOprice = 375 $

Only the payback period is presented in Table 8-38 and Table 8-39 for 12 scenarios regarding VLSFOprice – HFOprice and 7 different scenarios regarding % ECA, while MGOprice – HFOprice = 375 $ = constant.

Table 8-38 1st part: Payback period for MGOprice – HFOprice = 375 $

Scenario	**1**	**2**	**3**	**4**	**5**	**6**
VLSFOprice-HFOprice	420	385	350	315	280	245
Payback period for 12% in ECAs	1,171	1,265	1,377	1,510	1,671	1,871
Payback period for 20% in ECAs	1,180	1,268	1,369	1,489	1,631	1,802
Payback period for 30% in ECAs	1,193	1,271	1,360	1,463	1,583	1,724
Payback period for 40% in ECAs	1,205	1,274	1,351	1,439	1,538	1,652
Payback period for 50% in ECAs	1,218	1,277	1,343	1,415	1,495	1,586
Payback period for 60% in ECAs	1,231	1,280	1,334	1,392	1,455	1,525
Payback period for 70% in ECAs	1,245	1,284	1,325	1,370	1,417	1,468

Table 8-39 2nd part: Payback period for MGOprice – HFOprice = 375 $

Scenario	**7**	**8**	**9**	**10**	**11**	**12**
VLSFOprice-HFOprice	210	175	140	105	70	35
Payback period for 12% in ECAs	2,125	2,459	2,917	3,586	4,654	6,625
Payback period for 20% in ECAs	2,015	2,284	2,636	3,117	3,812	4,905
Payback period for 30% in ECAs	1,892	2,098	2,353	2,678	3,109	3,704
Payback period for 40% in ECAs	1,784	1,939	2,124	2,348	2,625	2,975
Payback period for 50% in ECAs	1,687	1,803	1,936	2,090	2,271	2,486
Payback period for 60% in ECAs	1,601	1,685	1,779	1,884	2,001	2,135
Payback period for 70% in ECAs	1,523	1,581	1,645	1,714	1,789	1,871

Figure 8-29 Payback period for MGOprice – HFOprice = 375 $

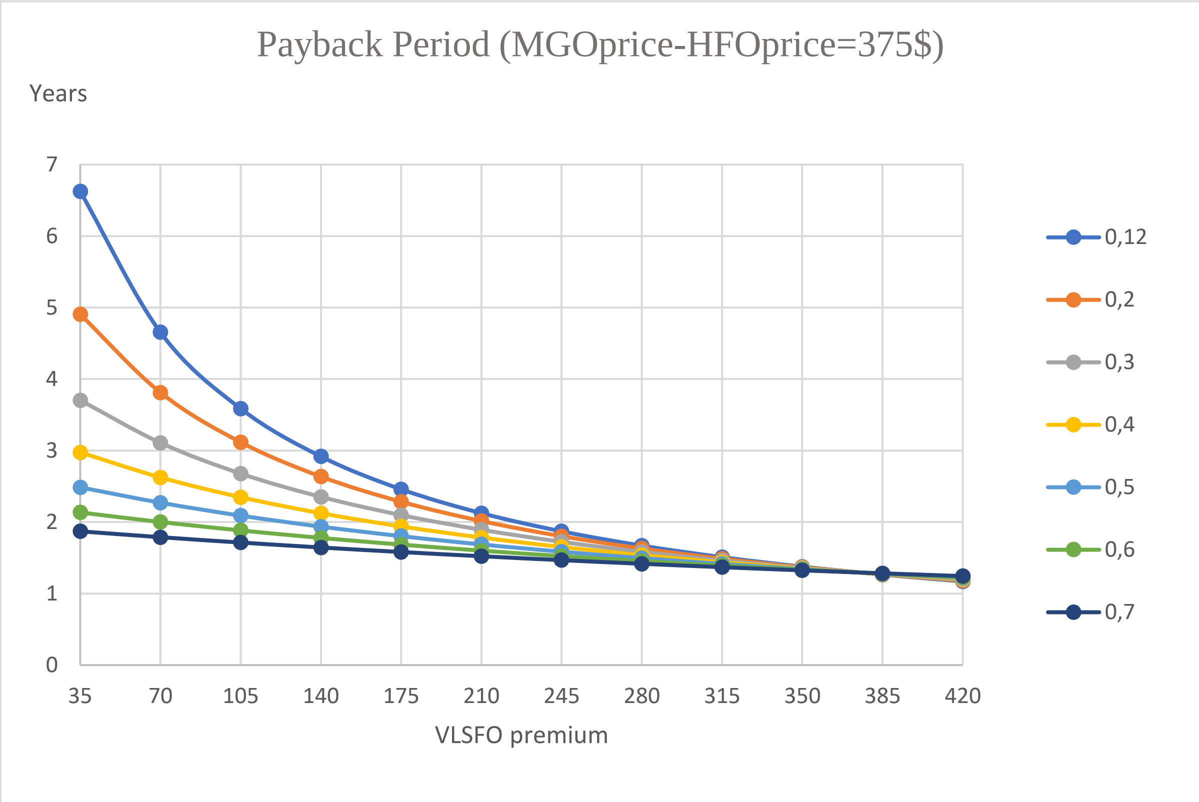
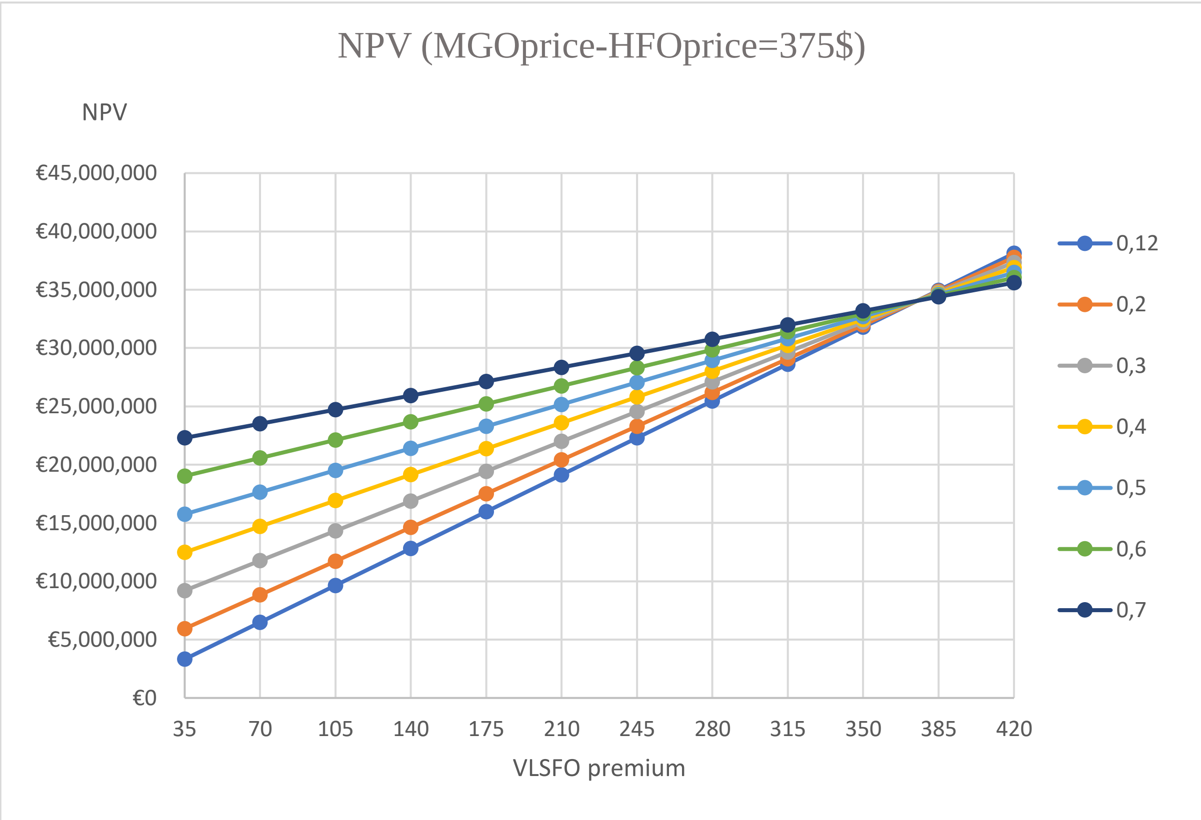


Figure 8-28 NPV for MGOprice – HFOprice = 375 $



8.8.1.8.4 MGOprice – HFOprice = 300 $

Only the payback period is presented in Table 8-40 and Table 8-41 for 12 scenarios regarding VLSFOprice – HFOprice and 7 different scenarios regarding % ECA, while MGOprice – HFOprice = 300 $ = constant.

Table 8-40 1st part: Payback period for MGOprice – HFOprice = 300 $

Scenario	**1**	**2**	**3**	**4**	**5**	**6**
VLSFOprice-HFOprice	420	385	350	315	280	245
Payback period for 12% in ECAs	1,216	1,319	1,440	1,586	1,766	1,990
Payback period for 20% in ECAs	1,245	1,342	1,457	1,592	1,756	1,957
Payback period for 30% in ECAs	1,282	1,373	1,478	1,600	1,744	1,917
Payback period for 40% in ECAs	1,321	1,405	1,499	1,607	1,732	1,878
Payback period for 50% in ECAs	1,363	1,438	1,521	1,615	1,721	1,841
Payback period for 60% in ECAs	1,408	1,473	1,544	1,623	1,709	1,806
Payback period for 70% in ECAs	1,456	1,510	1,568	1,630	1,698	1,771

Table 8-41 2nd part: Payback period for MGOprice – HFOprice = 300 $

Scenario	**7**	**8**	**9**	**10**	**11**	**12**
VLSFOprice-HFOprice	210	175	140	105	70	35
Payback period for 12% in ECAs	2,280	2,670	3,219	4,053	5,471	8,415
Payback period for 20% in ECAs	2,210	2,538	2,980	3,609	4,575	6,247
Payback period for 30% in ECAs	2,128	2,390	2,727	3,175	3,798	4,726
Payback period for 40% in ECAs	2,051	2,259	2,514	2,834	3,246	3,800
Payback period for 50% in ECAs	1,980	2,141	2,331	2,559	2,835	3,178
Payback period for 60% in ECAs	1,914	2,035	2,174	2,332	2,516	2,730
Payback period for 70% in ECAs	1,852	1,939	2,036	2,143	2,261	2,393

Figure 8-31 Payback period for MGOprice – HFOprice = 300 $

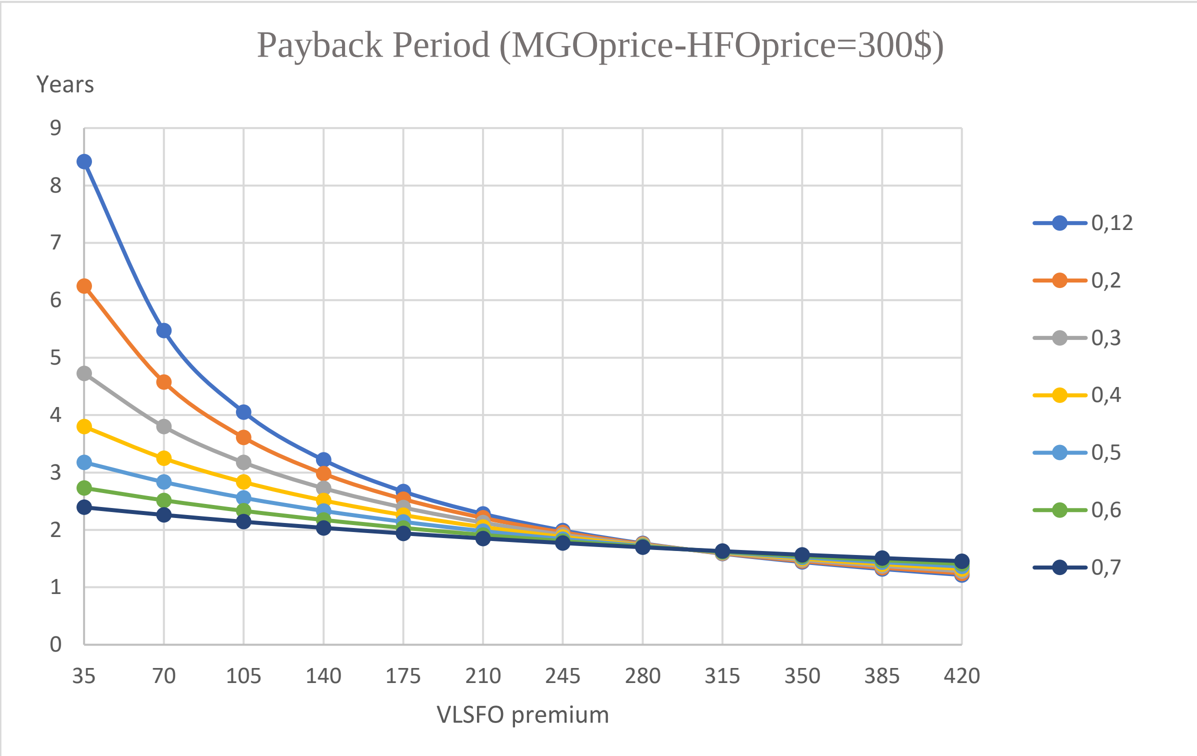
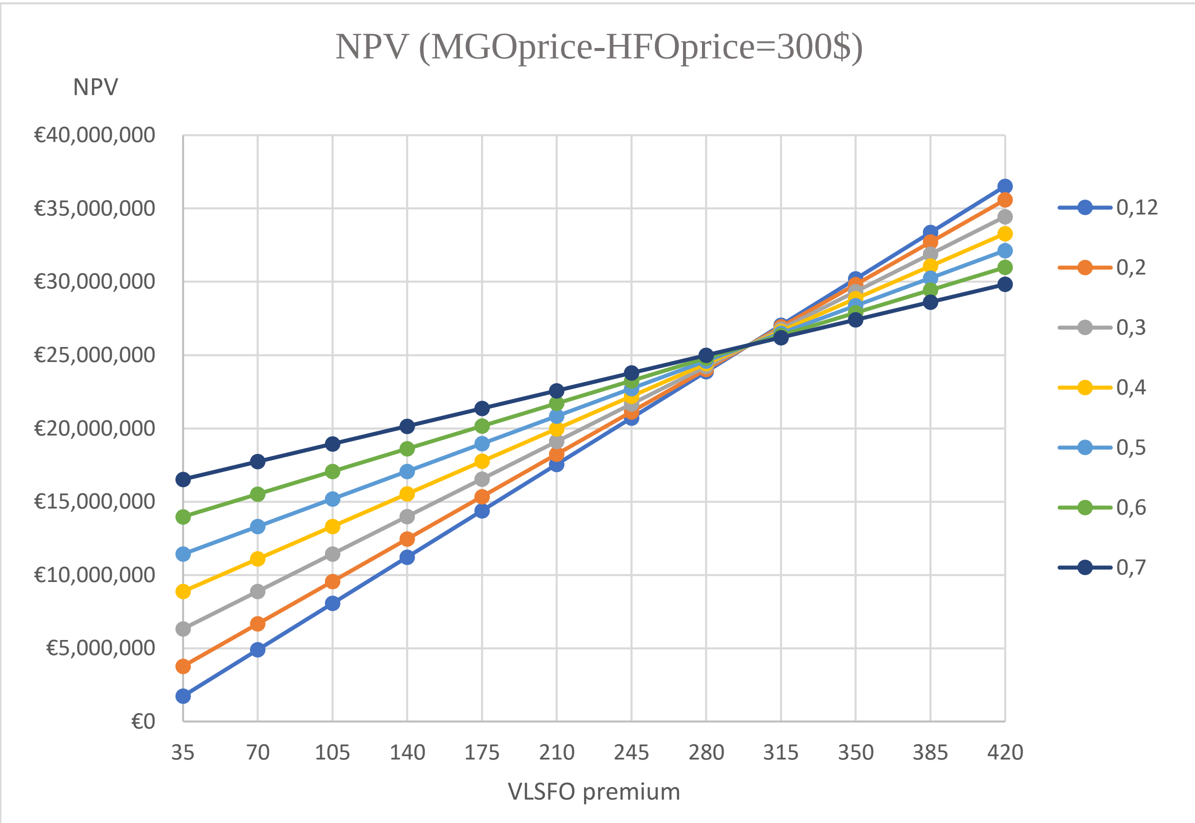


Figure 8-30 NPV for MGOprice – HFOprice = 300 $



8.8.1.8.5 MGOprice – HFOprice = 150 $

Only the payback period is presented in Table 8-42 and Table 8-43 for 12 scenarios regarding VLSFOprice – HFOprice and 7 different scenarios regarding % ECA, while MGOprice – HFOprice = 150 $ = constant.

Table 8-42 1st part: Payback period for MGOprice – HFOprice = 150 $

Scenario	**1**	**2**	**3**	**4**	**5**	**6**
VLSFOprice-HFOprice	420	385	350	315	280	245
Payback period for 12% in ECAs	1,319	1,441	1,587	1,766	1,991	2,282
Payback period for 20% in ECAs	1,397	1,521	1,670	1,850	2,075	2,362
Payback period for 30% in ECAs	1,507	1,635	1,786	1,967	2,190	2,469
Payback period for 40% in ECAs	1,637	1,767	1,919	2,100	2,318	2,587
Payback period for 50% in ECAs	1,791	1,922	2,074	2,251	2,463	2,717
Payback period for 60% in ECAs	1,977	2,107	2,256	2,427	2,626	2,861
Payback period for 70% in ECAs	2,206	2,332	2,473	2,632	2,813	3,021

Table 8-43 2nd part: Payback period for MGOprice – HFOprice = 150 $

Scenario	**7**	**8**	**9**	**10**	**11**	**12**
VLSFOprice-HFOprice	210	175	140	105	70	35
Payback period for 12% in ECAs	2,672	3,222	4,058	5,480	8,436	18,312
Payback period for 20% in ECAs	2,740	3,263	4,033	5,277	7,634	13,792
Payback period for 30% in ECAs	2,831	3,316	4,001	5,044	6,823	10,540
Payback period for 40% in ECAs	2,927	3,370	3,970	4,831	6,168	8,529
Payback period for 50% in ECAs	3,031	3,426	3,940	4,635	5,628	7,163
Payback period for 60% in ECAs	3,142	3,484	3,910	4,454	5,175	6,174
Payback period for 70% in ECAs	3,262	3,544	3,880	4,287	4,789	5,425

Figure 8-33 Payback period for MGOprice – HFOprice = 150 $

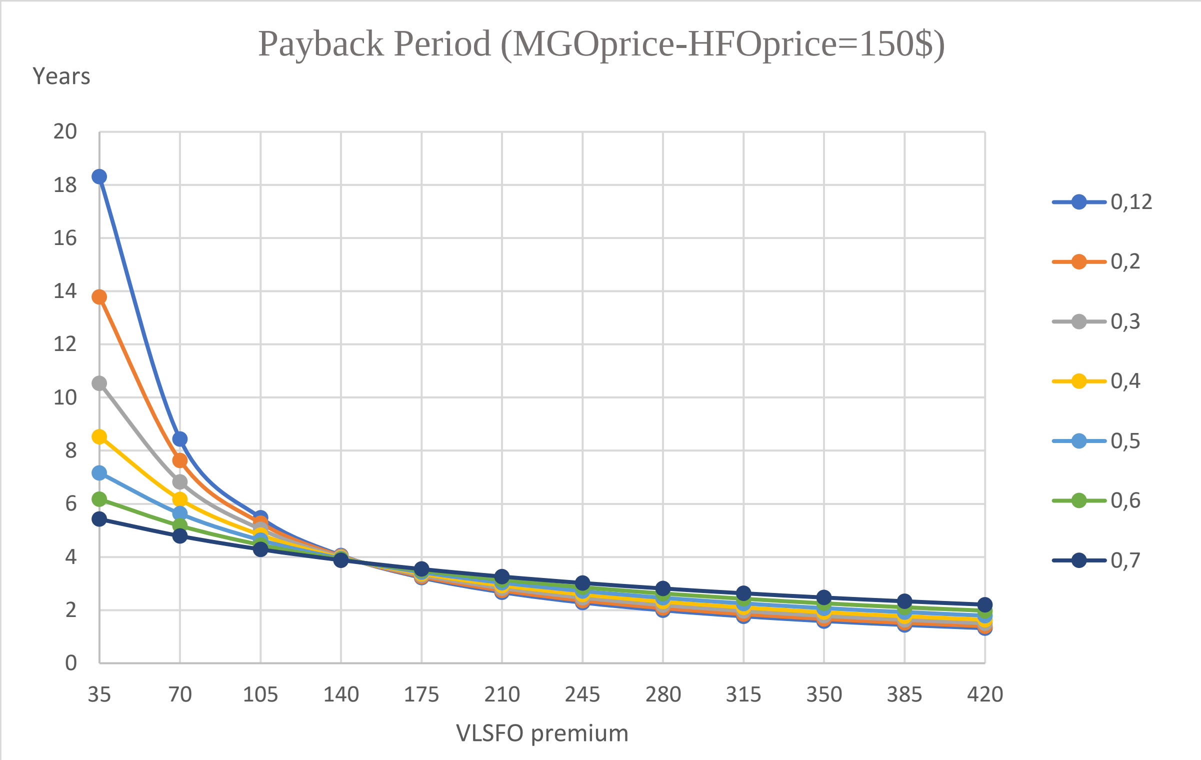
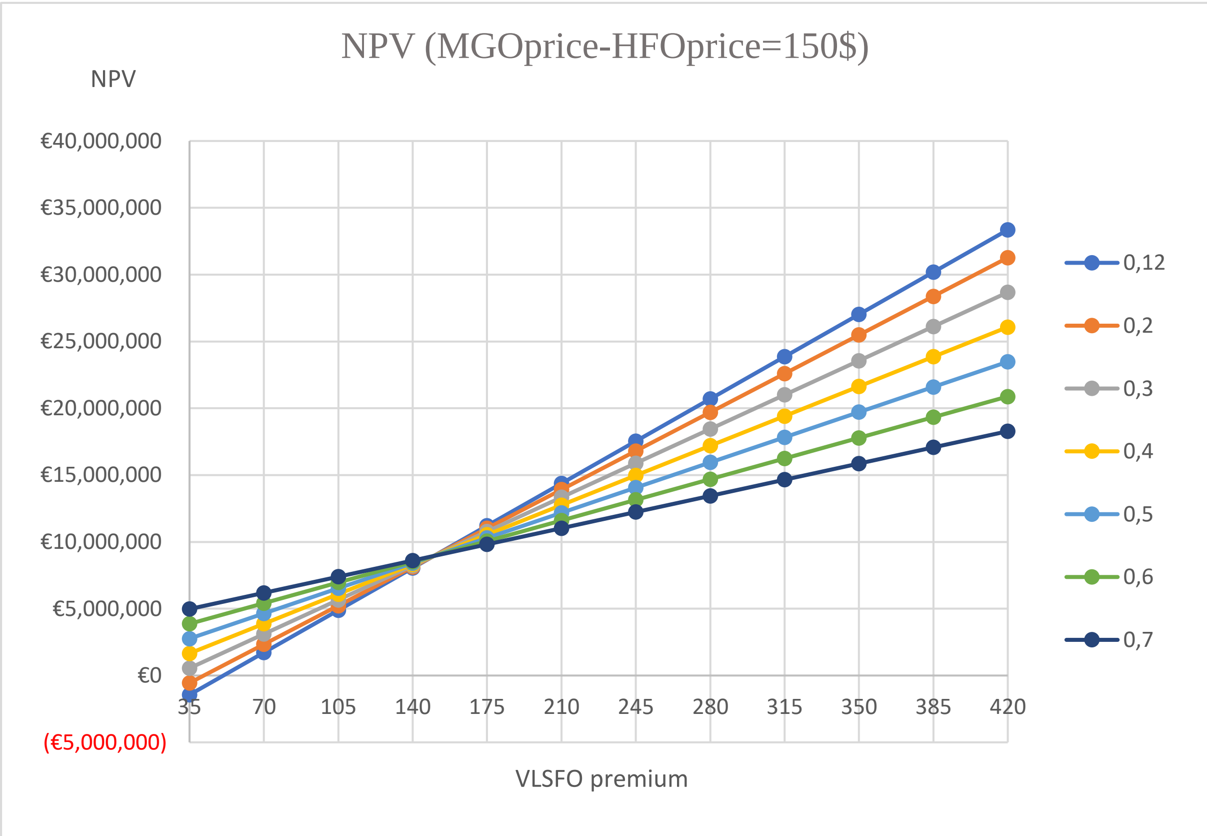


Figure 8-32 NPV for MGOprice – HFOprice = 150 $



As has already been mentioned above, the larger the fuel price gap, more savings occur by using the $EGCS_1$. Hence, as it is about two fuels, savings are being determined the most by the fuel with the larger price difference from HFO.

The aforementioned can be described with 2 cases:

For $\underline{MGOprice - HFOprice > VLSFOprice - HFOprice \Rightarrow MGOprice > VLSFOprice}$: the weighting of savings is given to MGO. So, using more MGO means more savings and shorter payback period. Consequently, when vessel's operation in ECA areas increases, payback period shortens.

For $\underline{VLSFOprice - HFOprice > MGOprice - HFOprice \Rightarrow VLSFOprice > MGOprice}$: the weighting of savings is given to VLSFO. So, more usage of VLSFO means more savings and shorter payback period. Hence, when the ship operates in ECA areas less, the payback period shortens.

In more detail:

- The price spread of MGO – HFO = 450$ is always larger compared to all 12 scenarios for VLSFO – HFO. Hence the more time the vessel operates in ECA areas, the more profitable the investment is proved to be.

- The critical value of MGO – HFO is 420$. For this value and every value below that, there will be a point where VLSFO - HFO > MGO – HFO. From this point and on, the investment will continue to be cost – effective, only if the ECA time is decreased.

8.8.2 Open Loop EGCS Proposal

The second proposal is a U – type open loop multi – stream inlet scrubber. Likewise, the $EGCS_1$ is manufactured for compliance against IMO resolution MEPC 259(68) “Scheme B”. Additionally, it is designed for efficiency corresponding to reduction from fuel of 3.50% Sulphur content to an equivalent of 0.10%.

The system is open loop only, therefore compliant fuel consumption is necessitated inside areas with relevant bans. Given that some of the ports with open loop prohibition have 0.10% Sulphur limit, the compliant fuel shall be MGO. It must be noted also that the system is not equipped with a water treatment unit[16]. For this reason, sailing in sensitive areas with strict requirements regarding wash-water discharge might require switch-over to MGO as well.

Key Features:

- The EGC unit is a U-type scrubber with packed-bed material. The packing consists of a layer of randomly packed objects designed to maximize the surface area of the injected water, which ensures good counterflowing exhaust gas.
- The maximum pressure caused by the EGC unit (excluding piping) is 150 mm WC. Attention must be paid by the engineers so as not to let the engines and boilers’ backpressure limits be exceeded.
- The EGC unit is not designed for running in dry mode. In case of malfunction of the seawater supply or stop of the scrubber’s operation, the exhaust gas has to be bypassed directly to the atmosphere.

1.1.1.1 The EGC unit

At first stage, seawater is sprayed when the incoming exhaust gas enters the quencher, so as to cool it down. The temperature limit is set to 60°C, after the quencher. The main seawater injection is at the top of the scrubber to feed the packed bed. Under the influence of gravity, water is routed down through the packing in a counter current flow with the exhaust gas flowing up through the packing material. The wash-water is drained out of the bottom of the scrubber, while the clean gas continues through the packing bed via the demister unit, before it is released into the atmosphere. The released exhaust gas has a temperature upper limit of 45°C.

Table 8-44 U-Type material

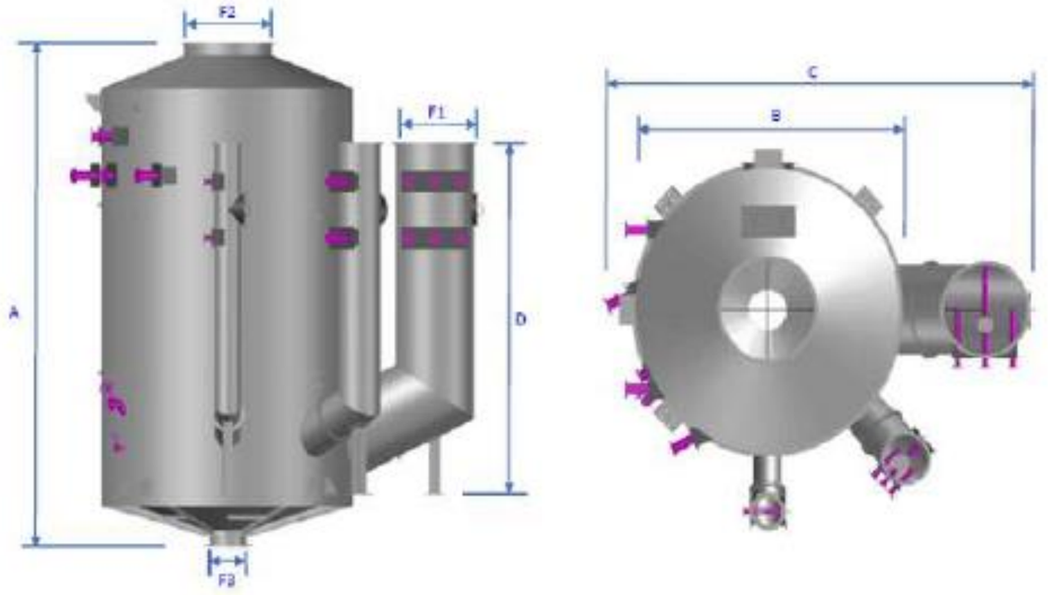
Component	Material
Scrubber body	SMO254 (stainless steel, corrosion resistant)
Quencher	SMO254 (stainless steel, corrosion resistant)

[16] A water treatment unit can be provided by Clean Marine for an extra cost, upon request.

Table 8-45 U – type's weights

Weight		Units
Dry weight	12,485	kg
Operational weight (Wet weight)	16,855	kg

Figure 8-34. U-type front and top view



Source: Reprinted with the kind permission of Clean Marine.

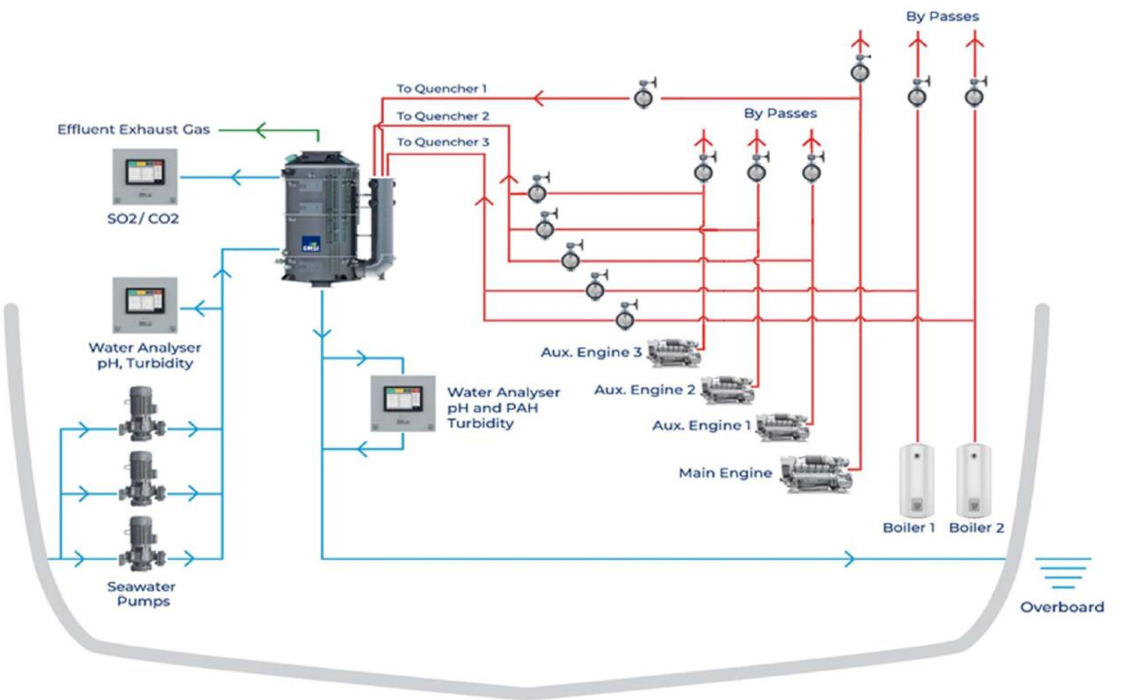
Table 8-46 U – type's dimensions

Scrubber Dimensions		**Units**
Height: A	9.0	m
Diameter: B	4.7	m
Length: C	6.7	m
Quencher Height: D	6.3	m

1.1.1.2 Placement and arrangement

The EGC Unit has to be installed indoors. A possible location would be next to the existing funnel, although with a new bigger enclosure that can contain both the scrubber and the pre-existing funnels. Unlike CleanSOx Compact, in the U-type arrangement there is a dedicated bypass for every exhaust gas line (six in total). Each exhaust line has also a separate damper that can be used to isolate the scrubber in case of malfunctions or switchover to MGO.

Figure 8-35. Simplified overview of the EGCS arrangement



Source: Reprinted with the kind permission of Clean Marine.

1.1.1.3 Auxiliaries

The seawater is pumped through a total of three pumps, of which normally the two are in operation and one is on standby condition. Normal seawater flow rate is 1,511 m^3/h for 0,10% S areas and 1,236 m^3/h for 0.50% S areas.

Table 8-47. U – type's machinery

Seawater pump	
Quantity	3
Capacity each (m^3/h)	700
Pump Type	Vertical Centrifugal
Pump head	55 m

Installed power each (kW)	160
Normal usage each (kW)	145
Specifications	440 V/3phase/60Hz

Like in CleanSOx Compact arrangement, the absorbing medium is measured for pH, turbidity, temperature (and PAH before discharge) both after being pumped and before overboard discharge.

The treated exhaust gas passes through an analyzing unit before being released into the atmosphere. The unit measures the SO_2/CO_2 ratio and examines compliance to IMO's requirements.

The control system is fully automated and can be operated and monitored from Local and ECR. The control system is designed to meet easy and simple operation. The system can be started and stopped with only 1 key press.

Table 8-48. U-type additional auxiliaries' electrical consumption

Electrical consumption		Units
Sealing air fan	25.0	kW
Control system	1.5	kW
Total (including pumps)	316.5	kW

8.8.2.1 Capital expenditure of U – type open loop ($CAPEX_2$)

The $CAPEX_2$ of the U – type open loop consists of the same things as the $CAPEX_1$ for the CleanSOx Compact hybrid but the price itself is lower. The open loop system does not require the addition of new tanks (system tank, holding tank, deposit tank, buffer tank, decanter tank, NaOH storage and service tanks) and thus fewer modifications to the piping system and the engine room.

Hence, it was estimated to **$CAPEX_2$ = 3,300,000 $**.

8.8.2.2 Operational expenditure of U – type open loop ($OPEX_2$)

8.8.2.2.1 Electrical consumption

The electrical consumption of the EGCS was identically calculated as before with cost of 0.0644 $/kWh and is placed in Table 8-49.

Table 8-49 Additional electrical consumption of Aegean Dream for EGCS2

	Electrical Consumption (kW)	**Annual Trade Pattern**	**Total Operation (hr/year)**	**Total Consumption (MWh)**	**Cost of Electricity** ($)
Open loop	316.5	98.87%	8,661	2,741.2	176,533

Thus, the total cost of electricity is **176,533 $/year**.

8.8.2.2.2 Sludge disposal

Since the sludges accumulate only in closed loop operation, for the $EGCS_2$ such cost is zero.

8.8.2.2.3 Maintenance

Maintenance cost was considered **20,000 $/year**.

8.8.2.2.4 MGO usage

The 1.13% of the time that the open loop scrubber is prohibited and cannot be used, MGO usage is mandatory. The MGO price times the fuel consumption of the discussed time period result in extra fuel cost which is added to the fuel cost of HFO for the other 98.87% of the time. The MGO usage cost is not considered as an operational cost.

8.8.2.2.5 Backpressure formation

The $EGCS_2$ causes maximum pressure drop over its assembly, 150 mmWC and the increase in the fuel consumption of the engine was approximated to 2%. The open loop estimated fuel consumption is 9,515.4 mt/year and the HFO price remains as before 350 $/mt, the additional cost is **66,607.8 $/year**.

To summarize, the total $OPEX_2$, taking into consideration all the assumptions that were stated, is **236,140.8 $**.

8.8.3 CleanSOx Compact & U – Type comparison

The similar method as before can be used once again to calculate the savings, payback period and NPV for the same 12 scenarios regarding VLSFO & HFO price spread, and 7 regarding % ECA with the base case being the VLSFO & HFO compliance option. Nevertheless, the results are not analytically presented, but instead a comparison of economic feasibility of the $EGCS_1$ – CleanSOx Compact versus the $EGCS_2$ – U – type.

Closed loop time, ECA time and VLSFO-HFO price spread were selected as the variable parameters.

The fluctuation of closed loop operation is between the range of 3% to 38% of port time which account for 0.72% to 10.85% of total time vessel operation time respectively. However, the closed loop operation is divided in 0.50% and 0.10% S limit. Aegean Dream's ports of call of the previous year had a 2/3 ratio between 0.50% S limit and 0.10% S limit. The closed loop time, as a variable parameter, was therefore assumed to agree with this value.

Regarding the ECA time, only two values were examined, a normal one (12% annually) and a slightly increased one of 25% annually.

The prices of MGO and HFO were also assumed and remained constant throughout the comparison and equal to **575 $** and **350 $** respectively. VLSFO price influence was examined among twelve different values, spread across a range of 30 – 430 $ premium to HFO.

1. The first scenario relates to 12% ECA corresponding to the annual operation of the ship and 15 & 30% of closed loop operation in ports;

2. The second refers to 25% ECA and 15 & 30% of closed loop operation in ports.

Between the two variables, % ECA and % closed loop operation, in each comparison figure, only one is changed at a time with the other remaining constant. Figure 8-36, Figure 8-37, Figure 8-38 and Figure 8-39 depict the payback period in the vertical axis and the VLSFO & HFO price spread in the horizontal.

Figure 8-37 Payback period versus VLSFO & HFO price difference for 12% ECA time and 15% closed loop operation in ports

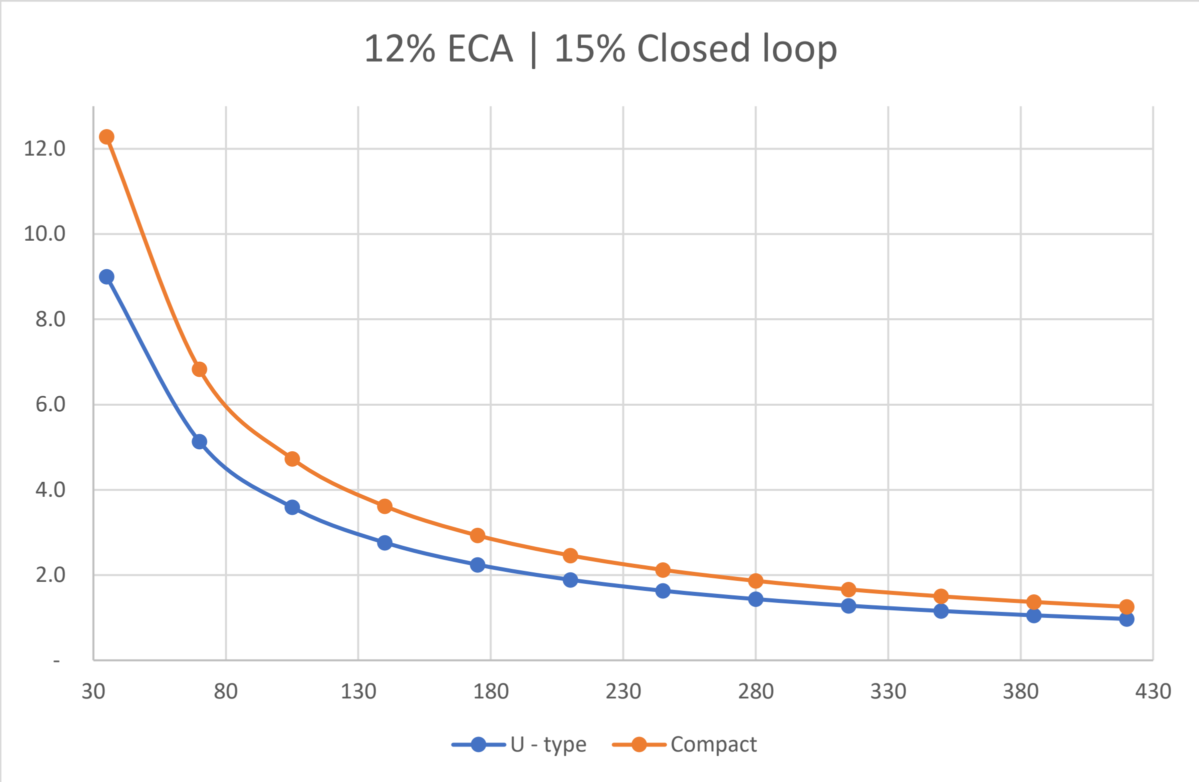


Figure 8-36 Payback period versus VLSFO & HFO price difference for 12% ECA time and 30% closed loop operation in ports

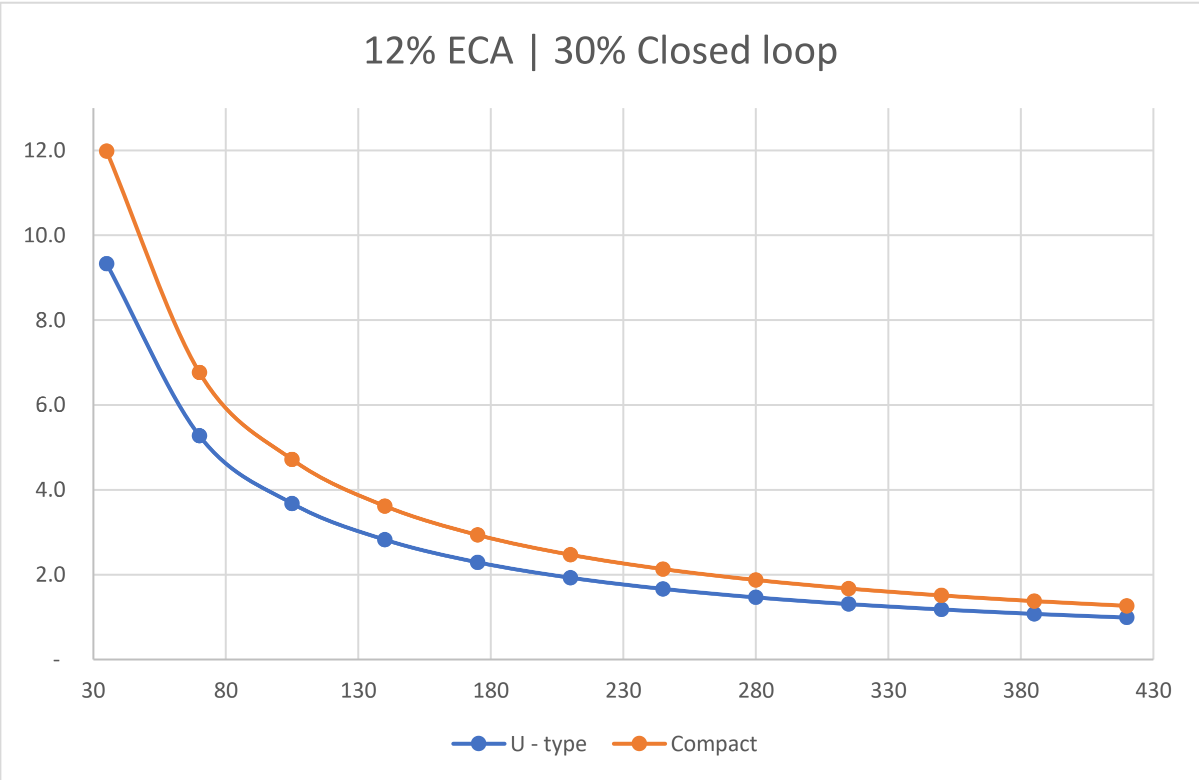


Figure 8-39 Payback period versus VLSFO & HFO price difference for 25% ECA time and 15% closed loop operation in ports

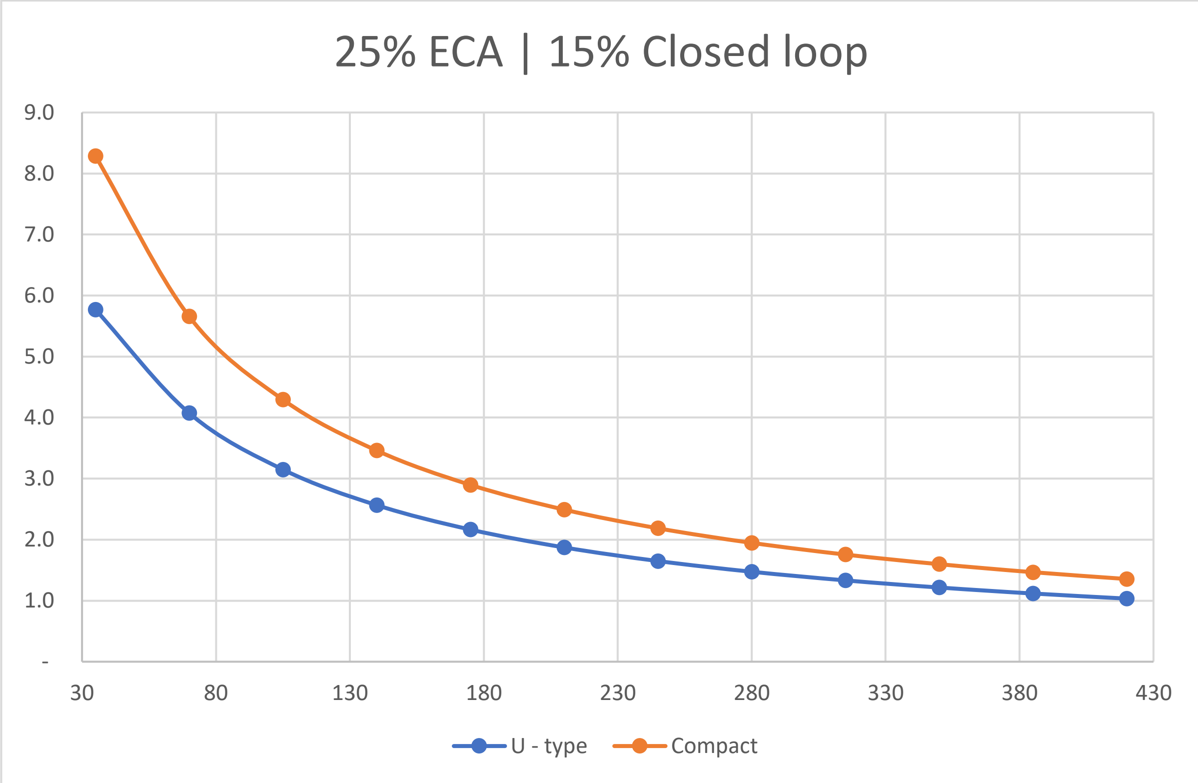
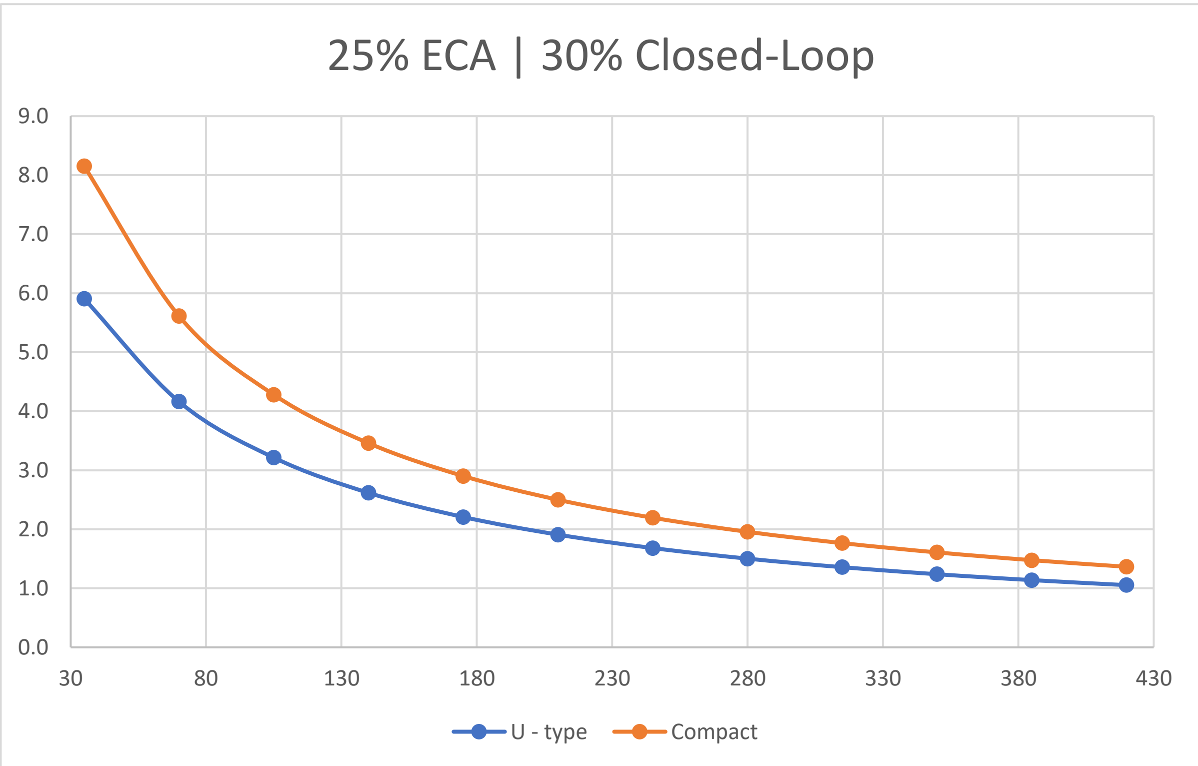


Figure 8-38 Payback period versus VLSFO & HFO price difference for 25% ECA time and 30% closed loop operation in ports



It is unambiguous that the $EGCS_2$ – U – type proves to be more **profitable** choice in all the price differences with the assumptions that were stated before in the two cases, than the $EGCS_1$ - CleanSOx Compact. That is not an absurd obervation, since the $CAPEX_2 < CAPEX_1$ and the $OPEX_1$ and $OPEX_2$ are relatively close and are not hugely affecting the payback period.

Chapter 9. Conclusions

9.1 Scrubber

The scrubber will be installed in recently constructed ships (2016), hence there is enough operation time for amortization of the investment.

The most crucial factor that will determine if the amortization will happen in half a year, or fifteen years, or even at all, is the future prices of VLSFO, MGO and HFO.

According to the calculations and assumptions that were made, this investment is profitable with a satisfactory payback period. The relatively high fuel price differences and the size of the vessel (Suezmax with 158,888 deadweight tonnage) which has considerably greater fuel consumption compared to smaller ships, are factors that lead to these results.

The abovementioned is apparent also from the NPV figures (Figure 8-24, Figure 8-26, Figure 8-28, Figure 8-30 and Figure 8-32). Specifically, the investment is considered non - profitable only in cases where the price gap of VLSFO - HFO and MGO - HFO are both extremely low. Considering the fuels' present prices of February 2020, it is safe to say that the shipping company will turn a profit with a short payback period, given that for the next few months the price spreads will not differentiate much from the current.

Although, the possible threats and risks as have been discussed in the whole study regarding the scrubber retrofit, must be considered. Thus, the EGCS installation is not a one – dimensional problem that someone should consider only its payback period and profit.

9.2 Open Loop versus Hybrid scrubber

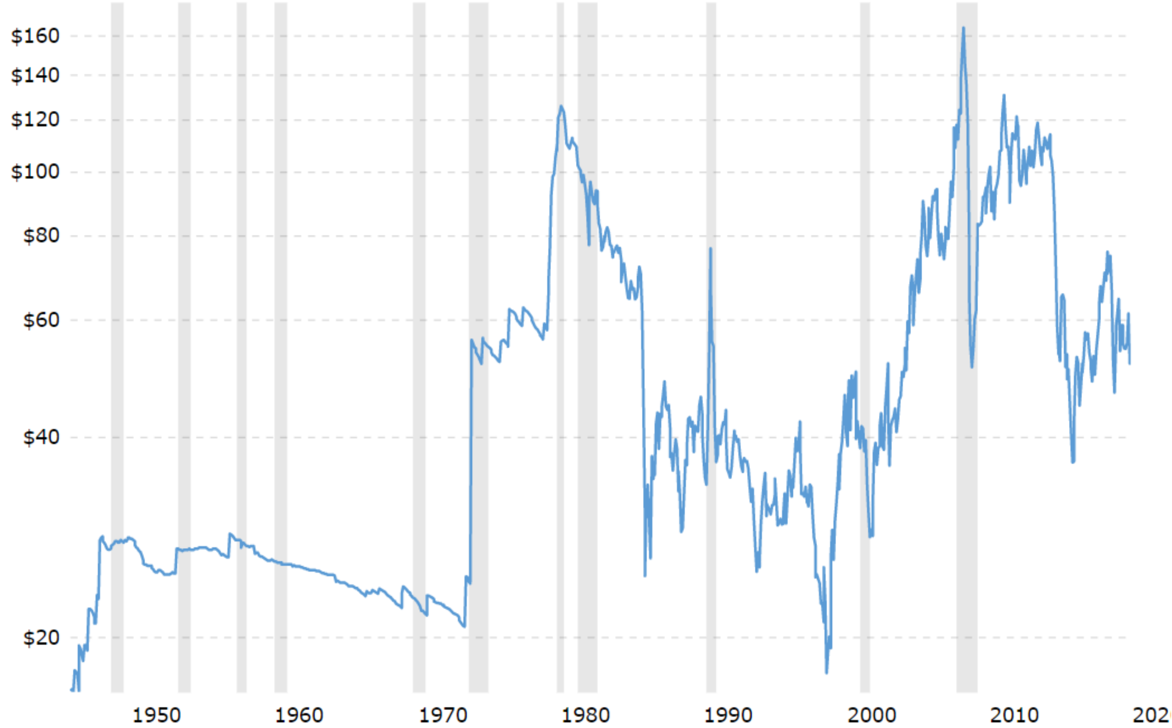
Given that the company will proceed with the scrubber installation, due to the profitability as mentioned before, a decisive issue is the selection of the most proper type. Considering the two options of $EGCS_1$ and $EGCS_2$, that Clean Marine recommended, given the fact that all the assumptions that were made will not change (i.e. percentage of closed loop operation), the $EGCS_2$ – Open Loop is the most cost-effective (see also CleanSOx Compact & U – Type comparison) and thus we recommend that the company shall install it.

In the case that the CAPEXs of an Open Loop and a Hybrid system, do not have a significant price difference, we recommend that the Hybrid system shall be installed since it can cope with open loop prohibitions.

Chapter 10. Factors of Uncertainty

The shipping industry is proved to be one of the most vulnerable industries. It is governed mostly from the oil prices, which in their turn are prone to geopolitical events, international sanctions, and generally are affected from several variables. Also, other events such as pandemics and naturals disasters can damage the industry, if they strike important areas (e.g. China).

Figure 10-1 West Texas Intermediate (WTI) crude oil price evolution per barrel from 1946 to 2020



Source: Macrotrends. Crude oil prices – 70-year historical data. Received from: https://www.macrotrends.net/1369/crude-oil-price-history-chart

As it can be seen from the Figure 10-1, there are price spikes and downturns throughout the years.

Specifically, the most critical moments that affected the most the crude oil prices are:

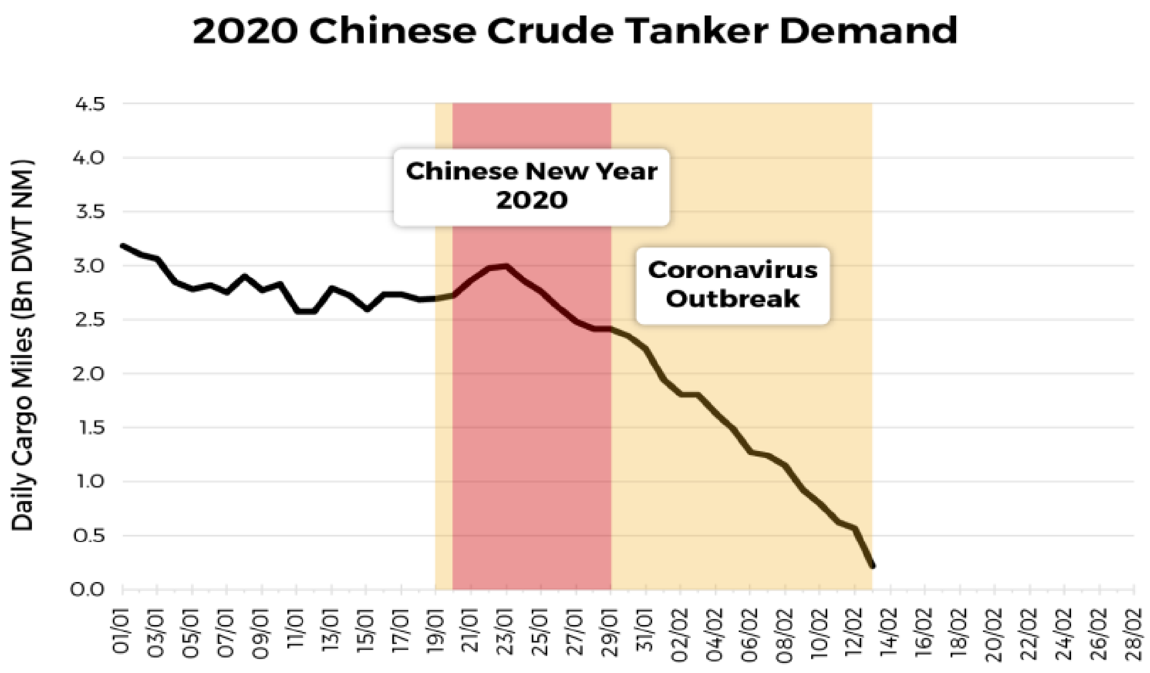
- 1973: OPEC members proclaimed oil embargo
- 1980s oil glut: Caused by the 1970s energy crisis
- 1990 oil price shock: Due to Iraqi invasion of Kuwait
- 2000s energy crisis: From 2000, up to 2009

Hence, every investment in the shipping industry is a potential threat to the company, since it is governed by factors of uncertainty which at any time can alter a safe and profitable investment into an uncertain one.

The latest event that affected the industry is the Coronavirus disease (COVID – 19) that was first reported from Wuhan, China, on 31 December 2019. China is well-established in the shipbuilding sector and in general constitutes one of the most important countries when it comes to shipping.

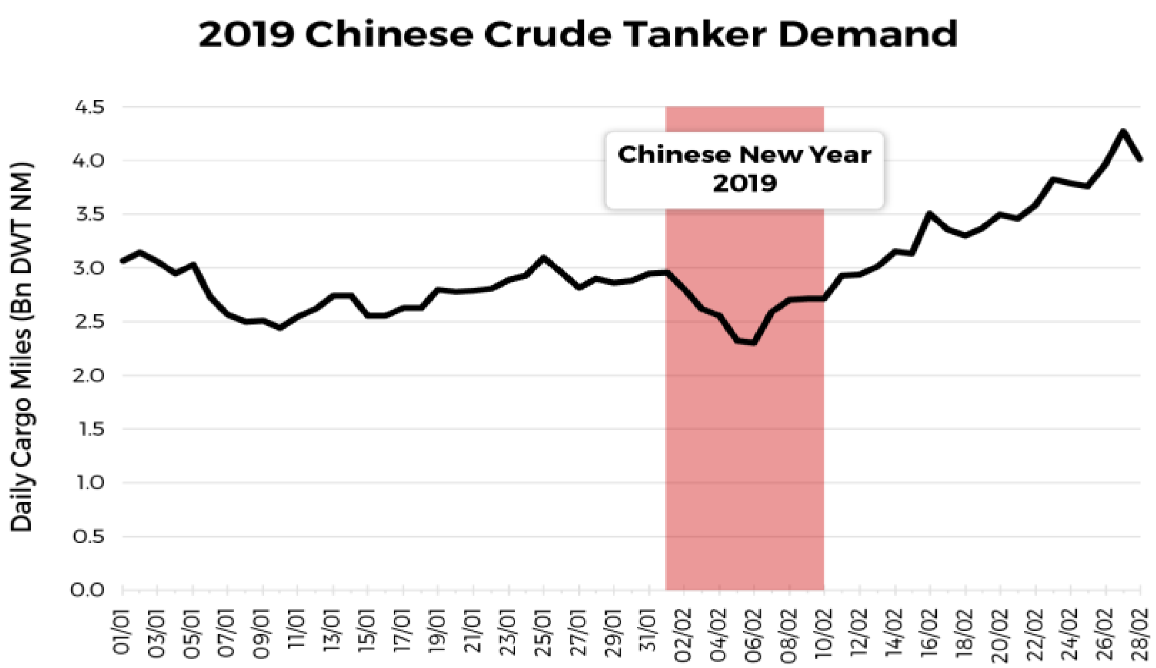
According to VesselsValue the billion ton miles[17] that are transferred in every Chinese New Year are slightly lower, but in 2020 due to the Coronavirus, it have fallen close to zero from 3.42 billion ton miles per day.

Figure 10-2 Daily cargo miles before and after the Coronavirus outbreak



Source: VesselsValue, February 2020

Figure 10-3 Daily cargo miles in Chinese New Year 2019



Source: VesselsValue, February 2020

[17] Ton mile is a ton of cargo that has travelled one nautical mile by sea.

Across wider shipping markets, there have seen delays since the Chinese shipyards are not adequately staffed and resourced in order to complete the newbuildings, repairs and scrubber retrofits.

Chapter 11. The Next Day

During the last years the environmental pollution has skyrocketed and, in an attempt, to prevent its complete destruction, several countries and organizations establish and adopt new measures. In short-term these measures aim to keep the emissions constant despite the increase in the usage of fossil fuels and long-term to reduce and even zero them, not only for the environment but also for the adverse effects in human health.

The European Council adopted a climate & energy framework in October 2014 for the period from 2021 to 2030 with 3 key targets [24]:

- At least 40% cuts in greenhouse gas emissions (from 1990 levels).
- At least 32% share for renewable energy.
- At least 32.5% improvement in energy efficiency.

Under the Paris Agreement, which **sets out a global framework to avoid dangerous climate change by limiting global warming to well below 2°C and pursuing efforts to limit it to 1.5°C**, the EU will have to be a climate – neutral economy meaning an economy with net – zero greenhouse gas emissions by 2050 [110]. So, the first milestone is set for 2030 with at least 40% reduction in greenhouse gases (GHG) from 1990 levels.

To achieve the target:

- EU emissions trading system (ETS) sectors will have to cut emissions by 43% (compared to 2005) – to this end, the ETS has been revised for the period after 2020 [24].
- non-ETS sectors will need to cut emissions by 30% (compared to 2005) – this has been translated into individual binding targets for Member States [24].

For this goal to be accomplished, in the shipping industry, new reliable technologies regarding the oil – based marine fuels have to be developed. The commonly discussed today are Liquefied Natural Gas (LNG), Biodiesel and Methanol. Others that could play a role in future are Liquefied Petroleum Gas (LPG), Ethanol, Dimethyl Ether (DME), Biogas, Synthetic Fuels, Hydrogen – in fuel cells and lastly Nuclear fuel. All the aforementioned alternatives to the conventional fuels are sulphur free and thus their usage has a direct impact on the vessel's emissions, including GHG, NO_x and SO_x [30].

References

[1] Abu Dhabi National Oil Company (ADNOC) (n.d.). Product Specifications: Crude and Condensates. Retrieved from https://www.adnoc.ae/en/doing-business-with-us/product-specifications#F0EE107F71DE4FA5AB31CEACB2CA5864

[2] Alfa Laval. (n.d.). Fuel handling in emission controlled areas [PDF file]. Retrieved from https://www.alfalaval.com/globalassets/documents/products/process-solutions/fuel-conditioning-solutions/fuel-handling-in-emission-controlled-areas.pdf

[3] American Bureau of Shipping (ABS). (2018, July). ABS advisory on exhaust gas scrubber systems: July 2018 [PDF file]. Retrieved from https://ww2.eagle.org/content/dam/eagle/advisories-and-debriefs/exhaust-gas-scrubber-systems-advisory.pdf

[4] American Bureau of Shipping (2019, December). Practical considerations for the installation and operation of exhaust gas cleaning systems. Retrieved from https://www.standard-club.com/media/3229390/abs_scrubber-guidance.pdf

[5] American Bureau of Shipping (ABS). (2019, December). Marine fuel oil advisory: December 2019 [PDF file]. Retrieved from https://ww2.eagle.org/content/dam/eagle/advisories-and-debriefs/marine-fuel-oil-advisory.pdf

[6] Annika K. J., Andreas B., Jennie Barthel S., Ing-Marie G.(n.d.). Science of the total environment. Elsevier. https://doi.org/10.1016/j.scitotenv.2019.133637

[7] Arezki, R., Blanchard, O. (2015, January 13). The 2014 oil price slump: Seven key questions. Retreived from https://voxeu.org/article/2014-oil-price-slump-seven-key-questions

[8] Assays available for download. (n.d.). Retrieved from https://corporate.exxonmobil.com/Crude-oils/Crude-trading/Assays-available-for-download

[9] Barsamian, A., Curcio, L. (2019). IMO 2020 Stability and Compatibility Headaches. Retrieved from https://www.maritime-executive.com/blog/imo-2020-stability-and-compatibility-headaches

[10] BBC News. (2019, December 9). Six charts that show how hard US sanctions have hit Iran. Middle East. Retrieved from https://www.bbc.com/news/world-middle-east-48119109

[11] Beattie, A. (2019, August 8). Shale Oil vs. Conventional Oil: What's the Difference?. Retrieved from https://www.investopedia.com/articles/active-trading/051215/cost-shale-oil-versus-conventional-oil.asp

[12] Biofuel Engine Research Facility. (n.d.). Shipping emissions and their impacts on air quality. Retrieved from https://research.qut.edu.au/berf/projects/shipping-emissions-and-their-impacts-on-air-quality/

[13] Bluebird Marine Systems Ltd. (n.d.). MARPOL- International maritime pollution 1973-1978. Retrieved from https://www.bluebird-electric.net/MARPOL_International_Convention_Marine_Pollution_1978.htm

[14] Camphuysen, C. J., Leeuw, J. et al. (Eds). (2011, November). Monitoring Chemical Pollution in Europe's Seas Programmes, Practices and Priorities for Research. Oslo, Norway: European Marine Board.

[15] Centrifuge oil cleaning on board ships. (n.d.). Retrieved from https://www.brighthubengineering.com/marine-engines-machinery/32006-how-does-a-centrifuge-work/

[16] Čampara, L., Hasanspahić, N., Vujičić, S. (2018). Overview of MARPOL ANNEX VI regulations for prevention of air pollution from marine diesel engines [Paper presentation]. Global Maritime Conference (GLOBMAR 2018): Sustainable Shipping. DOI: 10.1051/shsconf/20185801004

[17] Cojen, A. (2019, November 26). Making History: U.S. Exports more petroleum than it imports in September and October. Retrieved from https://www.forbes.com/sites/arielcohen/2019/11/26/making-history-us-exports-more-petroleum-than-it-imports-in-september-and-october/#25e65f9f5f3b

[18] Corbett, J.J., Winebrake, J.J., Green, E.H., Kasibhatla, P., Eyring, V., Lauer, A. (2007) Mortality from ship emissions: A global assessment, Environmental Science and Technology. doi:10.1021/es071686z

[19] Crude Assays. (n.d.). Retrieved from https://www.totsa.com/pub/crude/index2.php?expand=1&iback=1&rub=11&image=africa

[20] Crude Grades. (n.d.). Retrieved from https://www.mckinseyenergyinsights.com/resources/refinery-reference-desk/crude-grades/

[21] Crude oil assays. (n.d.). Retrieved from https://www.equinor.com/en/what-we-do/crude-oil-and-condensate-assays.html

[22] Crude Oil Prices - 70 Year Historical Chart. Retrieved from https://www.macrotrends.net/1369/crude-oil-price-history-chart

[23] Donev J.M.K.C. et al. (2019). Energy Education - Conventional vs unconventional resource. Retrieved February 20, 2020 from: https://energyeducation.ca/encyclopedia/Conventional_vs_unconventional_resource#cite_note-RE1-1

[24] European Commission (2014). A policy framework for climate and energy in the period from 2020 to 2030. Retrieved from https://ec.europa.eu/clima/policies/strategies/2030_en

[25] Environmental impact of shipping. (2019, December 19). In *Wikipedia.* Retrieved February 21, 2020, from https://en.wikipedia.org/wiki/Environmental_impact_of_shipping#Bilge_water

[26] European Environment Agency. (2013a). Air quality in Europe — 2013 report (report No. 9/2013). Retrieved from https://www.eea.europa.eu/publications/air-quality-in-europe-2013

[27] European Environment Agency. (2013b). The impact of international shipping on European air quality and climate forcing (report No 4/2013). Retrieved from https://www.eea.europa.eu/publications/the-impact-of-international-shipping

[28] European Environment Agency. (2019a). Air quality in Europe — 2019 report (report No. 10/2019). Retrieved from https://www.eea.europa.eu//publications/air-quality-in-europe-2019

[29] European Environment Agency. (2019b). National emission ceilings directive emissions data viewer 1990-2017. Retrieved from https://www.eea.europa.eu/data-and-maps/dashboards/necd-directive-data-viewer-2#tab-based-on-data

[30] European Maritime Safety Agency. Alternative fuels. Retrieved from http://www.emsa.europa.eu/main/air-pollution/alternative-fuels.html

[31] European Union, European Parliament and the Council. (2016, May). Directive (EU) 2016/802 of the European Parliament and of the Council of 11 May 2016 relating to a reduction in the sulphur content of certain liquid fuels (codification). (Directive 2016/802/EU). Retrieved from https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:327:0001:0013:en:PDF%20

[32] Exhaust Gas Cleaning Systems Association. (n.d.). What are the effects of sulphur oxides on human health and ecosystems? – EGCSA. Retrieved from: https://www.egcsa.com/technical-reference/what-are-the-effects-of-sulphur-oxides-on-human-health-and-ecosystems/

[33] Fattouh, B. (2011, January). An anatomy of the crude oil pricing system. Oxford, UK: Oxford Institute for Energy Studies.

[34] Ford, M. C. (2012, February). A master’s guide to: Using fuel oil onboard ship [PDF file]. Retrieved from https://www.standard-club.com/media/24163/AMastersGuidetoUsingFuelOilOnboardships.pdf

[35] Frozee, J. (2013, May 2). Centrifugal purifiers basic principle and working on ships. Retrieved from https://marineengineeringonline.com/centrifugal-purifiers/

[36] Fuel oil. (n.d.). Retrieved from https://www.mckinseyenergyinsights.com/resources/refinery-reference-desk/fuel-oil/

[37] Fuel Oil. (n.d.). Retrieved from https://www.pei.org/wiki/fuel-oil

[38] Fuel oil system. (n.d.). Retrieved from https://www.wartsila.com/encyclopedia/term/fuel-oil-system

[39] Fuel preparation: From settling tank to final conditioning. (2019, September 5). Retrieved from https://shipinsight.com/guides/fuel-preparation-from-settling-tank-to-final-conditioning

[40] Gamal, Tan and Mukherjee (2018, October). UAE's ADNOC starts producing new Umm Lulu crude oil stream. Reuters. Money News. Retrieved from https://in.reuters.com/article/emirates-oil/uaes-adnoc-starts-producing-new-umm-lulu-crude-oil-stream-idINKCN1MS0VB?rpc=401&

[41] Hamilton, M. (2019, December). U.S. petroleum exports exceed imports in September. Retrieved from https://www.eia.gov/todayinenergy/detail.php?id=42176

[42] Heather H. (2015, July 29). Scientists find a natural way to clean up oil spills, with a plant-based molecule. Smithsonian magazine. Retrieved from https://www.smithsonianmag.com/innovation/scientists-find-natural-way-to-clean-up-oil-spills-with-plant-based-molecule-180955815/

[43] Hocking, M.B. (2005). 18 - Petroleum Refining. In M. B. Hocking (Ed.). Handbook of Chemical Technology and Pollution Control (3rd ed., pp. 593-636). New York, NY: Academic Press. ISBN 9780120887965

[44] InterContinental Exchange. (n.d.). Trading and Clearing the Argus Sour Crude Index ("ASCI") with ICE, p. 1. Retrieved from https://www.theice.com/publicdocs/ICE_ASCI_Product_Guide.pdf

[45] International Maritime Organization. (2018, July). List of special areas, emission control areas and particularly sensitive sea areas (MEPC.1/Circ.778/Rev.3). Retrieved from http://www.gard.no/Content/26411326/IMO%20MEPC1-Circ778-Rev3_Special%20Areas%2C%20ECAs%20and%20PSSAs%20under%20MARPOL.pdf

[46] International Maritime Organization (IMO). (n. d.). International Convention for the Prevention of Pollution from Ships (MARPOL). Retrieved from http://www.imo.org/en/About/Conventions/StatusOfConventions/Documents/StatusOfTreaties.pdf

[47] International Maritime Organization. (n.d.). In Wikipedia. Retrieved December 02, 2020, from https://en.wikipedia.org/wiki/International_Maritime_Organization#cite_note-about-1

[48] International Maritime Organization (IMO). (2020, February). Status of treaties [PDF file]. Retrieved from http://www.imo.org/en/About/Conventions/StatusOfConventions/Documents/StatusOfTreaties.pdf

[49] International Maritime Organization. (n.d.). Ballast Water Management. Retrieved from http://www.imo.org/en/OurWork/Environment/BallastWaterManagement/Pages/Default.aspx

[50] International Maritime Organization. (n.d.). MARPOL Annex I – prevention of pollution by oil. Retrieved from

[51] International Maritime Organization. (n.d.). Nitrogen Oxides (NOx) – Regulation 13. Retrieved from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Nitrogen-oxides-(NOx)-%E2%80%93-Regulation-13.aspx

[52] International Maritime Organization. (n.d.). Prevention of pollution by garbage from ships. Retrieved from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/Garbage/Pages/Default.aspx

[53] International Maritime Organization. (n.d.). Prevention of pollution by sewage from ships. Retrieved from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/Sewage/Pages/Default.aspx

[54] International Maritime Organization. (2014). Reduction of GHG emissions from ships. Third IMO GHG study 2014 – final report. Retrieved from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/MEPC%2067-6%20-%20Third%20IMO%20GHG%20Study%202014%20-%20Executive%20Summary%20(Secretariat).pdf

[55] International Maritime Organization (IMO). (n. d.). Sulphur oxides (SOx) and Particulate Matter (PM) – Regulation 14. Retrieved from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Sulphur-oxides-(SOx)-–-Regulation-14.aspx

[56] International Maritime Organization. (n.d.). The Protocol of 1997 (MARPOL Annex VI). Retrieved from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/The-Protocol-of-1997-(MARPOL-Annex-VI).aspx

[57] International Monetary Fund. (2018, June). Algeria: 2018 Article IV Consultation – Press Release; Staff Report: and Statement by the Executive Director for Algeria (IMF Country Report No. 18/168). Washington, D.C: International Monetary Fund.

[58] International Monetary Fund. (2019, January). United Arab Emirates: 2018 Article IV Consultation – Press Release; Staff Report: and Statement by the Executive Director for the UAE (IMF Country Report No. 19/35). Washington, D.C. : International Monetary Fund.

[59] International Monetary Fund. (2019, April). Kuwait: 2019 Article IV Consultation—Press Release; Staff Report; and Statement by the Executive Director for Kuwait (IMF Country Report No. 19/95). Washington, D.C. : International Monetary Fund.

[60] International Organization for Standardization. (2017). Petroleum Products – Fuel (class F) – Specifications of Marine Fuels (ISO 8217:2017). Retrieved from https://www.iso.org/standard/64247.html

[61] International whaling commission. (n.d.). Ship Strikes: collisions between whales and vessels. Retrieved from https://iwc.int/ship-strikes

[62] Kent, J. A. (1983). Riegel's Handbook of Industrial Chemistry (8th ed.), pp.492-493. New York: NY. Van Nostrand Reinhold Company ISBN 0-442-20164-8

[63] Komar, I., & Lalić, B. (2015). Sea Transport Air Pollution. doi:10.5772/59720

[64] Kurt, D. (2020, January). Benchmark Oils: Brent Crude, WTI and Dubai. Retrieved from https://www.investopedia.com/articles/investing/102314/understanding-benchmark-oils-brent-blend-wti-and-dubai.asp

[65] Kuwait Institute for Scientific Research. (2019). Kuwait Energy Outlook 2019: Sustaining Prosperity Through Strategic Energy Management. p. 27. Retrieved from https://www.undp.org/content/dam/rbas/doc/Energy%20and%20Environment/KEO_report_English.pdf

[66] Lloyd's Register. (2012, June). Understanding exhaust gas treatment systems: Guidance for shipowners and operators [PDF file]. Retrieved from https://www.rtu.lv/writable/public_files/RTU_understanding_exhaust_gas_treatment_systems.pdf

[67] Main engine fuel oil diesel oil transfer and service system. (2018, September 14). Retrieved from https://themarinewhales.blogspot.com/2018/09/main-engine-fuel-oil-diesel-oil.html

[68] MAN Diesel & Turbo. (2017). Cat Fines: Impact on engine wear and how to reduce the wear [PDF file]. Retrieved from https://marine.man-es.com/docs/librariesprovider6/marketing-publications/catfines-paper/catfines-paper-5510-0207-00-web.pdf?sfvrsn=1c10fda2_4

[69] MAN Energy Solutions (2018). MAN B&W two-stroke marine engines: emission project guide for MARPOL Annex VI regulations. Retrieved from https://marine.man-es.com/applications/projectguides/2stroke/content/special_pg/7020-0145-09_uk.pdf

[70] MAN Energy Solutions. (2019). 0,50% S fuel operation [PDF file]. Retrieved from https://marine.man-es.com/docs/librariesprovider6/test/0-50-s-fuel-operation.pdf

[71] MAN Energy Solutions. (2019, July). Fuel tank cleaning (Service Letter SL2019-674/JAP). Retrieved from https://marine.man-es.com/docs/librariesprovider6/service-letters/sl2019-674.pdf?sfvrsn=c7bcc3a2_4

[72] Marine fuels. (2020, February). Retrieved from www.shipandbunker.com

[73] Marine gasoil (MGO). (2015, December). Retrieved from https://www.marquard-bahls.com/en/news-info/glossary/detail/term/marine-gasoil-mgo.html

[74] Metacentric height. (n.d.). In Wikipedia. Retrieved February 14, 2020 from https://en.wikipedia.org/wiki/Metacentric_height#Metacentre

[75] Mills, Robin M. (2008). The myth of the oil crisis: Overcoming the Challenges of Depletion, Geopolitics, and Global Warming. Greenwood Publishing Group. pp. 158–159. ISBN 978-0-313-36498-3.

[76] Mohammad, J.J., Majid, H.B., Ahmad, R.Y., Yadoolah, M., Rooholah, G., Marzieh, K. (2012). The role of packing media in a scrubber performance removing sulfur acid mists.

[77] National Iranian Oil Company (NIOC). (n.d.). Crude Oil Specifications. Retrieved from https://www.nioc-intl.com/EN/CrudeSpec.aspx

[78] Nigerian Light Crude Oil. (n.d.). Retrieved from http://www.americahopepetroleum.com/professionals-nigerian-light-crude-oil

[79] North P&I Club. (2019). Preparing for the Big Switch: Compliant VLSFO Products [PDF file]. Retrieved from https://www.nepia.com/preparing-for-the-big-switch/

[80] Norwegian Petroleum Directorate. (2020, January 17). Production figures December 2019. Retrieved from https://www.npd.no/en/facts/news/Production-figures/2020/production-figures-december-2019/

[81] No scrubs: More ports declare ban on EGCS discharges (2020, January 22). Retrieved from https://www.nepia.com/industry-news/no-scrubs-more-ports-declare-ban-on-egcs-discharges-update/

[82] Nunez, C. (2019, February 28). Acid Rain. Nationalgeographic. Retrieved from https://www.nationalgeographic.com/environment/global-warming/acid-rain/

[83] Office of the Auditor General of Canada. (2012). Retrieved from https://pubs.ciphi.ca/doi/pdf/10.5864/d2016-013.

[84] Oil & Gas Authority. (2019, March 11). UK oil and gas production rises to 1.7 million barrels per day in 2018. Retrieved from https://www.ogauthority.co.uk/news-publications/news/2019/uk-oil-and-gas-production-rises-to-17-million-barrels-per-day-in-2018/

[85] OPEC Says Iran's Oil Production Down By 1.65 Million bpd Since US Sanctions. (2019, November). Retrieved from https://en.radiofarda.com/a/opec-says-iran-s-oil-production-down-by-1-65-million-bpd-since-us-sanctions/30272297.html

[86] Operational information: Centrifugal separators. (n.d.). Retrieved from http://www.marinediesels.info/2_stroke_engine_parts/Other_info/purifiers.htm

[87] Organization of the Petroleum Exporting Countries. (2018, September). OPEC Monthly Oil Market Report – September 2018 Table 5-8. Retrieved from https://www.opec.org/opec_web/static_files_project/media/downloads/publications/MOMR%20September%202018.pdf

[88] Organization of the Petroleum Exporting Countries. (2019). OPEC Annual Statistical Bulletin 2019. Vienna, Austria: Organization of the Petroleum Exporting Countries

[89] Organization of the Petroleum Exporting Countries. (2019). OPEC Annual Statistical Bulletin 2019, Table1.1. Vienna, Austria: Organization of the Petroleum Exporting Countries

[90] Organization of the Petroleum Exporting Countries. (2019, December). OPEC Monthly Oil Market Report – December 2019. Table 5-9. Retrieved from https://www.opec.org/opec_web/static_files_project/images/content/publications/OPEC_MOMR_December_2019.pdf

[91] Packed bed scrubber. Retrieved from https://www.nedermanmikropul.com/en-gb/products/wet-scrubbers/packed-bed-scrubber

[92] Panasiuk, I., Lebedevas, S., Česnauskis, M. (2015). Selection of Exhaust Scrubber: Concept for Optimal Solution. Environmental Research, Engineering and Management. doi: 70. 10.5755/j01.erem.70.4.7490.

[93] Perry, R. H., Chilton, C. H., Kirkpatrick, S. D. (Eds). (1963). Perry's Chemical Engineers' Handbook (4th ed.). United States, US: McGraw Hill. ISBN 0-07-049841-5

[94] Petroleum. (n.d.). In Wikipedia. Retrieved January 22, 2020, from https://en.wikipedia.org/wiki/Petroleum#Unconventional_oil

[95] Petroleum reservoir. (n.d.). In Wikipedia. Retrieved January 20, 2020, from https://en.wikipedia.org/wiki/Petroleum_reservoir

[96] Qatar Petroleum Company. (n.d.). Crude Oil. Retrieved from https://qp.com.qa/en/marketing/Pages/RP_CrudeOil.aspx

[97] Rakonczai, János. (2018). Global and Geopolitical Environmental Challenges. Retrieved from https://www.researchgate.net/profile/Janos_Rakonczai/publication/331398136/

[98] Ritchie, H., & Roser, M. (2019). Outdoor Air Pollution. Retrieved from https://ourworldindata.org/outdoor-air-pollution

[99] Ritchie, H., and Roser, M. (2020). Fossil Fuels. Retrieved from: https://ourworldindata.org/fossil-fuels

[100] Sanderson et al. (2019, October 23). Deciphering the performance puzzle in shales: Moving the US shale revolution forward. Retrieved from https://www2.deloitte.com/us/en/insights/industry/oil-and-gas/us-shale-revolution-playbook/introduction-shale-performance-productivity.html#endnote-sup-2

[101] Settling tank. (n.d.). Retrieved from https://www.wartsila.com/encyclopedia/term/settling-tank

[102] Ship stability – understanding intact stability of ships. (2019, December). Retrieved from https://www.marineinsight.com/naval-architecture/intact-stability-of-surface-ships/

[103] Sofiev, M., Winebrake, J.J., Johansson, L. (2018). Cleaner fuels for ships provide public health benefits with climate tradeoffs. https://doi.org/10.1038/s41467-017-02774-9

[104] South Australia health. (n.d.). Polycyclic Aromatic Hydrocarbons (PAHs). Retrieved from

https://www.sahealth.sa.gov.au/wps/wcm/connect/public+content/sa+health+internet/health+topics/health+conditions+prevention+and+treatment/chemicals+and+contaminants/polycyclic+aromatic+hydrocarbons+pahs#Top

[105] The story of Acropolis. (2017). The Greek observer. Retrieved from https://thegreekobserver.com/greece/culture/article/29100/story-acropolis/

[106] Transportenvironment. (2019). T&E annual report 2018. Ships. Retrieved from https://www.transportenvironment.org/annual-report-2018/campaigns/ships.html#first

[107] Tran, Tien Anh. (2017). Research of the Scrubber Systems to Clean Marine Diesel Engine Exhaust Gases on Ships. Journal of Marine Science Research and Development. DOI: 10.4172/2155-9910.1000243

[108] Turgeon, A. Morse, E. (2018, October 5). Petroleum: Petroleum, or crude oil, is a fossil fuel and non-renewable source of energy. Retrieved from https://www.nationalgeographic.org/encyclopedia/petroleum/

[109] Uhler, A.D. et al. (2016). 13 - Chemical character of marine heavy fuel oils and lubricants. In S. A. Stout., Z. Wang (Ed.). Standard Handbook Oil Spill Environmental Forensics (2nd ed., pp. 641-683). New York, NY: Academic Press. ISBN 9780128038321

[110] United Nations Climate Change (2015). Paris Agreement. Retrieved from https://ec.europa.eu/clima/policies/international/negotiations/paris_en

[111] United Nations. IMO profile. Retrieved from https://business.un.org/en/entities/13

[112] U.S. Energy Information Administration (2012, July). Crude oil distillation and the definition of refinery capacity. Retrieved from https://www.eia.gov/todayinenergy/detail.php?id=6970

[113] U.S. Energy Information Administration. (2013, August). U.S. crude oil and natural gas proved reserves, 2011 [PDF file]. Retrieved from https://www.eia.gov/naturalgas/crudeoilreserves/archive/2011/pdf/uscrudeoil.pdf

[114] U.S. Energy Information Administration (2015, October). Qatar: International energy data and analysis Report. Retrieved from https://www.eia.gov/international/content/analysis/countries_long/Qatar/qatar.pdf

[115] U.S. Energy Information Administration. (2015, November). Short-Term Energy Outlook.

[116] U.S. Energy Information Administration. (2016, May). Country Analysis Brief: Nigeria. Retrieved from https://www.eia.gov/international/content/analysis/countries_long/Nigeria/nigeria.pdf

[117] U.S. Energy Information Administration. (2017, October). Country Analysis Brief: Russia. Retrieved from https://www.eia.gov/international/content/analysis/countries_long/Russia/russia.pdf

[118] U.S. Energy Information Administration. (2017, October). Country Analysis Brief: Saudi Arabia. Retrieved from https://www.eia.gov/international/content/analysis/countries_long/Saudi_Arabia/saudi_arabia.pdf

[119] U.S. Energy Information Administration. (2019). Annual Energy Outlook 2019. Washington, DC: U.S. Department of Energy. Retrieved from https://www.eia.gov/outlooks/aeo/pdf/AEO2020%20Full%20Report.pdf

[120] U.S. Energy Information Administration. (2019, January). Background Reference: Iraq. Retrieved from https://www.eia.gov/international/analysis/country/IRQ/background

[121] U.S. Energy Information Administration. (2019, January). Background Reference: Iran. Retrieved from https://www.eia.gov/international/content/analysis/countries_long/Iran/pdf/iran_bkgd.pdf

[122] U.S. Energy Information Administration. (2019, March). A Background's Reference: Algeria. [PDF file]. Retrieved from https://www.eia.gov/international/content/analysis/countries_long/Algeria/Algeria_background.pdf

[123] U.S. Energy Information Administration. (2019, June). Background Reference: Angola. [PDF file]. Retrieved from https://www.eia.gov/international/analysis/country/AGO/background

[124] U.S. Energy Information Administration. (2019, July). Drilling productivity report for key tight oil and shale gas regions [PDF file]. Retrieved from https://www.eia.gov/petroleum/drilling/archive/2019/07/pdf/dpr-full.pdf

[125] U.S. Energy Information Administration. (2019, November). Crude oil and petroleum products explained: Where our oil comes from. Retrieved from https://www.eia.gov/energyexplained/oil-and-petroleum-products/where-our-oil-comes-from-in-depth.php

[126] U.S. Energy Information Administration. (2019, November). Short-term energy outlook (STEO) [PDF file]. Retrieved from https://www.eia.gov/outlooks/steo/archives/nov19.pdf

[127] U.S. Energy Information Administration. (2019, November). What is the difference between crude oil, petroleum products, and petroleum? Retrieved from https://www.eia.gov/tools/faqs/faq.php?id=40&t=6

[128] U.S. Energy Information Administration. (2019, December). Annual report of domestic oil and gas reserves, year-end 2018 [PDF file]. Retrieved from https://www.eia.gov/naturalgas/crudeoilreserves/pdf/usreserves.pdf

[129] U.S. Energy Information Administration. (2019, December 16). Drilling productivity report for key tight oil and shale gas regions [PDF file]. Retrieved from https://www.eia.gov/petroleum/drilling/archive/2019/12/pdf/dpr-full.pdf

[130] U.S. Energy Information Administration. (2020, January 31). Monthly Crude Oil and Natural Gas Production Data (Form EIA-914). Retrieved from https://www.eia.gov/petroleum/production/

[131] U.S. Energy Information Administration. (2020, February). Short-term energy outlook (STEO) [PDF file]. Retrieved from https://www.eia.gov/petroleum/drilling/archive/2019/12/pdf/dpr-full.pdf

[132] Venezuela Crude oil specifications. (n.d.). Retrieved from https://blacklion-trading.com/venezuela-crude-oil-2/

[133] Ward-Geiger, L.I., Silber, G.K., Baumstark, R.D., Pulfer, T.L. (2005). Characterization of ship traffic in right whale critical habitat. Coastal Management. doi:10.1080/08920750590951965.

[134] Ward, H., Eykelbosh, A., Nicol, A.M. (2016, June 13). Addressing uncertainty in public health risks due to hydraulic fracturing. Vancouver, Canada: National Collaborating Centre for Environmental Health. doi: 10.5864/d2016-013

[135] What is center of buoyancy of a ship?. Retrieved from http://marinegyaan.com/what-is-centre-of-buoyancy-of-a-ship/

[136] What is Crude Oil? A Detailed Explanation on this Essential Fossil Fuel. (2009, July 24). Retrieved from https://oilprice.com/Energy/Crude-Oil/What-Is-Crude-Oil-A-Detailed-Explanation-On-This-Essential-Fossil-Fuel.html

[137] World Health Organization. (2006) Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide. Global update 2005, World Health Organization, Regional Office for Europe, Copenhagen, Denmark. Retrieved from: https://apps.who.int/iris/bitstream/handle/10665/69477/WHO_SDE_PHE_OEH_06.02_eng.pdf?sequence=1

[138] World Health Organization. (n.d.). Air pollution. Retrieved from https://www.who.int/health-topics/air-pollution#tab=tab_2

[139] World's Air Pollution: Real-time air quality index. Retrieved from https://waqi.info/#/c/10.339/24.148/3.2z

APPENDIX A – IMO Guidelines for 0.50% Sulphur Fuels Operation

RESOLUTION MEPC.320(74)

2019 GUIDELINES FOR CONSISTENT IMPLEMENTATION OF THE 0.50% SULPHUR LIMIT UNDER MARPOL ANNEX VI

THE MARINE ENVIRONMENT PROTECTION COMMITTEE,

RECALLING Article 38(a) of the Convention on the International Maritime Organization concerning the functions of the Marine Environment Protection Committee (the Committee) conferred upon it by international conventions for the prevention and control of marine pollution from ships,

RECALLING ALSO that, at its fifty-eighth session, the Committee adopted, by resolution MEPC.176(58), a revised MARPOL Annex VI which significantly strengthens the emission limits for sulphur oxides (SO_X),

RECALLING FURTHER that, at its seventieth session, the Committee adopted, resolution MEPC.280(70), *Effective date of implementation of the fuel oil standard in regulation 14.1.3 of MARPOL Annex VI*, confirming "1 January 2020" as the effective date of implementation for ships to comply with global 0.50% m/m sulphur content of fuel oil requirement,

NOTING ALSO that, at its seventy-third session, the Committee approved circular MEPC.1/Circ.878 on the *Guidance on the development of a ship implementation plan for the consistent implementation of the 0.50% sulphur limit under MARPOL Annex VI*,

HAVING CONSIDERED, at its seventy-fourth session, draft 2019 Guidelines for consistent implementation of the 0.50% sulphur limit under MARPOL Annex VI, prepared by the Sub-Committee on Pollution Prevention and Response, at its sixth session,

1 ADOPTS the *2019 Guidelines for consistent implementation of the 0.50% sulphur limit under MARPOL Annex VI*, as set out in the annex to the present resolution;

2 REQUESTS Parties to MARPOL Annex VI and other Member Governments to bring these Guidelines to the attention of shipowners, ship operators, fuel oil suppliers and any other interested groups;

3 AGREES to keep these Guidelines under review in the light of experience gained with their application.

ANNEX

2019 GUIDELINES FOR CONSISTENT IMPLEMENTATION OF THE 0.50% SULPHUR LIMIT UNDER MARPOL ANNEX VI

1 Introduction

1.1 Objective

1.1.1 The purpose of these Guidelines is to ensure consistent implementation of the 0.50% sulphur limit under MARPOL Annex VI. These Guidelines are intended for use by Administrations, port States, shipowners, shipbuilders and fuel oil suppliers, as appropriate.

1.2 Definitions

1.2.1 For the purpose of these Guidelines, the definitions in MARPOL Annex VI apply.

1.2.2 The following definitions of fuel oils are used, as applicable:

.1 Distillate marine fuels (DM) are as specified in ISO 8217:2017[1] (e.g. DMA, DMB, DMX, DMZ);

.2 Residual marine fuels (RM) are as specified in ISO 8217:2017[1] (e.g. RMD 80, RMG 380);

.3 Ultra-low sulphur fuel oil (ULSFO) are as specified in ISO 8217:2017[1] (e.g. maximum 0.10% S ULSFO-DM, maximum 0.10% S ULSFO-RM);

.4 Very low sulphur fuel oil (VLSFO) (e.g. maximum 0.50% S VLSFO-DM, maximum 0.50% S VLSFO-RM); and

.5 High sulphur heavy fuel oil (HSHFO) exceeding 0.50% S.

2 Ship implementation planning for 2020

2.1 MEPC 70 agreed to "1 January 2020" as the effective date of implementation for ships to comply with the 0.50% m/m fuel oil sulphur content limit requirement and adopted resolution MEPC.280(70) on the *Effective date of implementation of the fuel oil standard in regulation 14.1.3 of MARPOL Annex VI*[2].

2.2 In this context, MEPC 73 agreed that Administrations should encourage ships flying their flag to develop implementation plans, outlining how the ship may prepare in order to comply with the required sulphur content limit of 0.50% by 1 January 2020. The plan should be complemented with a record of actions taken by the ships in order to be compliant by the applicable date.

2.3 MEPC 73, recognizing the need for guidance to support the consistent implementation of the 0.50% sulphur limit under MARPOL Annex VI, approved MEPC.1/Circ.878 on the *Guidance on the development of a ship implementation plan for the consistent implementation of the 0.50% sulphur limit under MARPOL Annex VI.*

3 Impact on fuel and machinery systems

3.0.1 The experiences and lessons learned from the transition to the 0.10% m/m SO_X-ECA limit indicated that current ship machinery operations should be sufficiently capable of addressing the concerns regarding combustion of the new 0.50% m/m limit fuel oils.

3.0.2 Currently most of the marine diesel engines and boilers on ships operating outside Emission Control Areas (ECAs) are optimized to operate on heavy fuel oil. From 2020 ships are required to use fuel oils with a sulphur content of 0.50% m/m or lower, unless fitted with an approved equivalent means of compliance.

3.1 Distillate fuels

3.1.1 A major challenge with distillate fuels is low viscosity. Low viscosity may cause internal leakages in diesel engines, boilers and pumps. Internal leakages in fuel injection system may result in reduced fuel pressure to the engine, which may have consequences for the engine performance (e.g. starting of the engine). Equipment makers recommendations should be taken into account, and adequate testing, maintenance and possible installation of coolers, etc., may be performed.

3.1.2 Cold Filter Plugging Points (CFPP) and Cloud Points (CP) as well as the Pour Point (PP) for distillate fuels need to be considered in light of the ship's intended operating area and ambient temperatures.

3.1.3 These issues are critical concerns as they can result in the formation and accumulation of wax sediment, which can cause costly and avoidable maintenance. In the worst-case scenario, sediment can cause engine fuel starvation and power loss.

3.1.4 ISO 8217:2017[3] limits the cold flow properties of a fuel through setting a limit on the PP. However, given that wax crystals form at temperatures above the PP, fuels that meet the specification in terms of PP can still be challenging to operations in colder operating regions, as the wax particles can rapidly block filters, potentially plugging them completely. For cold weather, additional cold flow properties, CFPP and CP, should be reported by the supplier when the receiving ship has ordered distillate fuel for cold weather operations, a requirement that is specified in ISO 8217:2017[3].

3.1.5 Since the residual fuels are usually heated and distillate fuels are not heated, particular attention needs to be given to the cold flow properties of distillates. Cold flow property challenges can be managed by heating the fuel. CIMAC has issued "01 2015 CIMAC Guideline Cold flow properties of marine fuel oils"[4].

3.1.6 Fuel temperature should be kept approximately 10°C above the PP in order to avoid any risk of solidification, however this may not reduce the risk of filter blocking in case of high CFPP and CP.

3.1.7 It is good practice to review the possibilities of heating arrangements for distillate fuels on board. This is usually very limited, as it is not standard practice to have heating arrangements in distillate storage, settling or service tanks. Transfer arrngements may be adapted to pass through a residual fuel oil heat exchanger should the need arise.

3.1.8 Knowing the fuel properties before bunkering will assist in taking the necessary precautions where and when necessary. If the ship is heading towards colder climates and the cold flow properties are inferior, the fuel may be:

.1 either used before entering cold regions, or

.2 used with suitable heating arrangement, as mentioned above.

3.1.9 If the approach of applying heat is being followed it should be ensured that the fuel is not overheated resulting in the viscosity dropping below the minimum recommendation of 2 cSt at any point in the fuel system, including the engine inlet. In order to reduce this risk, heating should be limited to max 40°C.

3.2 Distillate fuel with FAME content

3.2.1 Increased demand for Distillate fuels may result in more land based products making their way into the marine supply pool, some of these fuels (e.g. biodiesel) may contain Fatty Acid Methyl Ester (FAME).

3.2.2 There are various technical challenges associated with use of fuel having FAME content, e.g. potential oxidation of biodiesel, its biodegradable nature etc. with adverse implications, limitations in storage life etc. It also needs to be tested for stability.

3.2.3 The ISO 8217:2017[3] standard includes a maximum FAME content of 7.0% by volume for DFA/DFZ/DFB fuel oil grades since some ports may offer automotive diesel fuel as the only fuel available, which contains FAME and could violate the fuel flashpoint requirements addressed in SOLAS chapter II-2. The maximum 7.0% (v/v) has been chosen as this aligns with the concentrations allowed in some of the countries applying environmental regulations.

3.2.4 Manufacturers of engines and equipment like oily water separators, overboard discharge monitors, filters, coalescers etc. need to be consulted to confirm the ability of engines and equipment to handle biodiesel blends of up to B7 (i.e. 7.0% v/v).

3.2.5 It is recommended to avoid using such biodiesel blend fuels for lifeboat engines, emergency generators, fire pumps, etc. where it is stored in isolated individual unit fuel tanks and subjected to conditions for accelerated degradation.

3.2.6 CIMAC has provided a Guideline for Shipowners and Operators on Managing Distillate Fuels up to 7.0% v/v Fame (Biodiesel).[5]

3.3 Residual fuels

3.3.1 Stability and compatibility

3.3.1.1 It is essential to distinguish between "Fuel stability" within a single batch of fuel and "Fuel compatibility" between different fuel batches.

3.3.1.2 Regarding stability: the fuel shall be stable and homogeneous at delivery and it is the responsibility of the fuel oil blenders and suppliers to ensure this.

3.3.1.3 A wide range of blends of refined products will be used to make the new 0.50% sulphur fuels, and the stability and compatibility of the blends will be an important concern for shipowners/operators. Unstable fuels can separate on their own and incompatible ones can do so when mixed in a single bunker tank, forming sludge that can block filters and ultimately cause engine failures.

3.3.1.4 It is recommended that ships have a commingling procedure. The procedure should primarily aim to ensure new bunkers are loaded into empty tanks to the extent possible. In the event that a ship finds itself possibly having to commingle a new bunker with bunkers already on board, then it is important that the ship determines the compatibility between the two said bunkers before comingling.

3.3.1.5 The reference test method shall be the total potential sediment test in accordance with ISO 10307-2:2009.

3.3.2 Catalytic fines (cat fines)

Cat fines are a by-product of refining and consist of small particles of metal that are deliberately introduced as catalysts to "crack" the fuel oil. Unless reduced by purification, cat fines will become embedded in engine parts and cause serious and rapid engine damage. Reference should be made to engine manufacturer's guidance with respect to managing cat fines.

3.4 Key technical considerations for shipowners and operators

3.4.1 Ship tank configuration and fuel system – the viscosity of most of these blended residual fuels is such that they cannot be used in distillate fuel-only systems and machinery, as they require heating for cleaning and combustion. A fully segregated fuel system for both distillate fuels and these new fuels is recommended.

3.4.2 Tank cleaning is recommended when using a residual fuel tank for storing these new fuels. This is to prevent sludge that has built up in these tanks from entering the fuel system. Further information on tank cleaning is set out in appendix 3 of MEPC.1/Circ.878 on *Guidance on the development of a ship implementation plan for the consistent implementation of the 0.50% sulphur limit under MARPOL Annex VI*.

3.4.3 Heating requirements – due to the cold flow properties of most of these new fuels, permanent heating of the fuel may be necessary to minimize the risk of wax formation, also in storage. This is especially important in colder regions.

3.4.4 Fuel treatment system – Some of these new fuels may contain cat fines and/or sediments and therefore need on board cleaning. Separator temperature and settings should be adjusted to the fuels' viscosity and density. Please refer to recommendations from OEM and fuel supplier.

3.4.5 Considering that many of these new fuels have lower viscosities compared to conventional residual fuels, care should be taken to ensure no overheating occurs.

3.5 ISO Standard for residual fuels

3.5.1 The bunker market uses ISO 8217:2017[6] specifications to ensure that the properties of the fuels it delivers conform to a standard that mean they comply with MARPOL Annex VI.

3.5.2 The existing ISO 8217:2017[6] specification for marine fuels takes into consideration the diverse nature of marine fuels and incorporates a number of categories of distillate or residual fuels, even though not all categories may be available in every supply location it covers all marine petroleum fuel oils used today as well as the 0.50% Sulphur fuels of 2020. The General requirements, in the ISO 8217:2017[6] specification for marine fuels and characteristics, included in table 1 and 2 of ISO 8217:2017[6] identified safety, performance and environmental concerns and further takes into consideration the on board handling requirements, including.

storage, cleaning and combustion aspects of all fuel oils used today and the anticipated fuel blends of 2020, irrespective of the sulphur content of the fuel oils.

3.5.3 It is important that any new standards address and do not preclude the use of renewable and alternative non-fossil crude derived products, so long as they comply with the chemical properties specified for these fuel oils.

3.6 Cylinder lubrication

3.6.1 The choice of cylinder lubricating oils will often follow the fuel type in use. So, when changing to VLSFO operation from RM operation the choice of appropriate cylinder lubricating oil should be considered in accordance with the recommendations of the engine manufacturer.

4 Verification issues and control mechanism and actions

4.1 Survey and certification by Administrations

4.1.1 When undertaking a survey in accordance with regulation 5 of MARPOL Annex VI, the Administration should conduct a survey of a ship to verify that the ship complies with the provisions to implement the 0.50% sulphur limit. In particular, the Administration should check whether the ship carries compliant fuel oils for use, based on the Bunker Delivery Note (BDN) on board, any other document or fuel oil samples as appropriate consistent with the provisions of regulation 18 of MARPOL Annex VI. If carriage of HSHFO for use is identified, the Administration should check whether regulation 3.2, regulation 4 of MARPOL Annex VI are applied to the ship, or if the ship encountered a fuel availability problem and is operating pursuant to regulation 18.2 of MARPOL Annex VI.

4.1.2 When an Administration decides to analyze a fuel oil sample to determine compliance with the sulphur limits in regulation 14.1 or 14.4, the final analysis should be carried out in accordance with ISO 8754:2003 by a laboratory that is accredited for the purpose of conducting the test in accordance with ISO/IEC 17025 or an equivalent standard. The test results should be in accordance with ISO 8754 reporting protocol, meaning a tested value at or above 0.10% sulphur should be reported with no more than two decimal places.

4.1.3 According to regulation 11.4 of MARPOL Annex VI, the Administration shall investigate any report of an alleged violation and thereafter promptly inform the Party which made the report, as well as the Organization, of the action taken. When informing the Organization, the MARPOL Annex VI GISIS module should be used.

4.2 Control measures by port States

4.2.1 Port States should take appropriate measures to ensure compliance with the 0.50% of sulphur limit under MARPOL Annex VI, in line with the regulation 10 of MARPOL Annex VI and the *2019 Guidelines for port State control under MARPOL Annex VI* (resolution MEPC.321(74)) (2019 PSC Guidelines). Specifically, the port State should conduct initial inspections based on documents and other possible materials, including remote sensing and portable devices. Given "clear grounds" to conduct a more detailed inspection, the port State may conduct sample analysis and other detailed inspections to verify compliance to the regulation, as appropriate.

4.2.2 Regulation 18.2.3 of MARPOL Annex VI requires a Party to take into account all relevant circumstances and the evidence presented to determine the action to take, including not taking control measures. Administrations and port State control authorities may take into account the implementation plan when verifying compliance with the 0.50% sulphur limit requirement.

4.2.3 Inspections based on documents and other possible targeting measurements

During the port State control and other enforcement activities, the port State should investigate whether a ship carries either compliant fuel oils or HSHFOs for use, based on the documents listed in paragraph 2.1.2 of the 2019 PSC Guidelines additionally records required to demonstrate compliance should also then be viewed. Results from remote sensing could be used to trigger inspections and portable devices could be used during the initial inspections, as appropriate. Remote sensing and portable devices are, however, of indicative nature and should not be regarded as the evidence of non-compliance, but may be considered clear grounds for expanding the inspection.

Port state should determine if regulations 3.2, 4 or 18.2.3 apply together with retained bunker delivery notes and IAPP Certificate when considering the status of any HSHFO being carried for use on board.

4.2.4 Fuel oil sample analysis

4.2.4.1 When the port State identifies clear grounds of suspected non-compliance of a ship based on initial inspections, the port State may require samples of fuel oils to be analysed. The samples to be analysed may be either the representative samples provided with BDN in accordance with regulation 18.8.2, MARPOL delivered samples or samples from designated sampling points in accordance with the *2019 Guidelines for on board sampling for the verification of the sulphur content of the fuel oil used on board ships* (MEPC.1/Circ.864/Rev.1) (in-use fuel oil samples) or other samples obtained by the port State.

4.2.4.2 Where the MARPOL delivered sample is taken from the ship a receipt should be provided to the ship. The outcome of the analysis undertaken with appendix VI of MARPOL Annex VI should be advised to the ship for its records.

4.2.4.3 In detecting suspected non-compliance, the sample analysis should be conducted in a uniform and reliable manner as described in paragraph 4.1.2. The verification procedure for MARPOL delivered samples should be in accordance with appendix VI[7] of MARPOL Annex VI. For other samples taken on board the ship, the in-use and onboard sample, the sample should be deemed to meet the requirements provided the test result from the laboratory does not exceed the specification limit +0.59R (where R is the reproducibility of the test method) and no further testing is necessary.

4.2.4.4 Notwithstanding the above process, all possible efforts should be made to avoid a ship being unduly detained or delayed. In particular, sample analysis of fuel oils should not unduly delay the operation, movement or departure of the ship.

4.2.4.5 If a non-compliance is established, consistent with regulation 18.2.3 the port State may prevent the ship from sailing until the ship takes any suitable measures to achieve compliance which may include de-bunkering all non-compliant fuel oil. In addition, the port State should report the information of the ship using or carrying for use non-compliant fuel oil to the Administration of the ship and inform the Party or non-Party under whose jurisdiction a bunker delivery note was issued of cases of delivery of non-compliant fuel oil, giving all relevant information. Upon receiving the information, the Party detecting the deficiency should report the information to the MARPOL Annex VI GISIS module in accordance with paragraph 3.4 of these Guidelines.

4.2.4.6 The Parties (the port and flag States), however, may permit, with the agreement of the destination port authority, a single voyage for bunkering of compliant fuel oil for the ship, in accordance with regulation 18.2.4 of MARPOL Annex VI. The single voyage should be one

[7]Amendments to MARPOL VI, Appendix VI, *Verification procedures for a MARPOL Annex VI fuel oil sample (regulation 18.8.2 or regulation 14.8)*, expected to be adopted in Spring 2020 and set out in annex 11 to document MEPC 74/18.

way and minimum for bunkering, and the ship proceeds directly to the nearest bunkering facility appropriate to the ship. In the case that the parties permit a single voyage of a ship, the port State should confirm that the Administration of the ship has advised the authority at the destination port of the approval for a single voyage including information on the ship granted with the approval and the certified record of analysis of the sample as the evidence. Once confirmation has been provided the port State should permit the ship to sail as agreed.

4.2.4.7 If the port State is made aware that a ship is carrying non-compliant fuel oil, which is not for use through an equivalent method under regulation 4 or a permit under regulation 3.2 of MARPOL Annex VI, the port State should take action to confirm the fuel is not being used. Action to confirm should include, but is not limited to the examination of the oil record book and the record of tank soundings. Where necessary the port State may require tank soundings to be undertaken during the inspection. Where it is determined that the fuel has been used the control action in paragraph 4.2.4.5 should be applied.

4.2.5 Other open-sea compliance monitoring tools:

.1 fuel oil changeover calculator;

.2 data collection system for fuel oil consumption of ships (resolution MEPC.278(70)); and

.3 continuous SO_X monitoring.

4.3 Control on fuel oil suppliers

4.3.1 Designated authorities should, if deemed necessary, take a sample and test fuel oils from bunker barges or shore bunker terminals. Sampling of fuel oils in bunker barges or shore bunker terminals can be taken and tested in the same manner that the MARPOL delivered fuel oils are tested by the PSC. All possible efforts should be made to avoid a ship being unduly detained or delayed. If a sample is analysed, sample analysis of fuel oils should not unduly delay the operation, movement or departure of the ship.

4.3.2 If non-compliance, such as issuance of an incorrect BDN or a BDN without measurement of sulphur content, was found, the designated authorities should take appropriate corrective measures against the non-compliant supplier. In such case, the designated authorities should inform the Organization for transmission to the Member States of the non-compliant supplier, in accordance with the regulation 18.9.6 of MARPOL Annex VI and paragraph 4.4 of these Guidelines.

4.4 Information sharing related to non-compliances under MARPOL Annex VI

4.4.1 When a Party finds a non-compliance of a ship or a fuel oil supplier, the information of the non-compliance should be reported to the MARPOL Annex VI GISIS module (regulation 11.4).

4.4.2 Publication of information on non-compliant ships/fuel oil suppliers or a reporting scheme to IMO to be registered on centralized information platforms are proposed as elements of an effective enforcement strategy. Various PSC regimes have successfully used the publishing of information related to substandard ships/fuel suppliers as a deterrent to non-compliance. Port States also need to report detentions of ships to IMO which may affect the future PSC targeting of the ship. The IMO GISIS database already makes available certain information related to non-compliances with the MARPOL Annex VI regulations.

5 Fuel oil non-availability

5.1 Guidance and information sharing on fuel oil non-availability

5.1.1 Regulation 18.2.1 of MARPOL Annex VI provides that in the event compliant fuel oil cannot be obtained, a Party to MARPOL Annex VI can request evidence outlining the attempts made to obtain the compliant fuel oil, including attempts made to local alternative sources. Regulations 18.2.4 and 18.2.5 then require that the ship notifies its Administration and the competent authority of the port of destination on the inability to obtain compliant fuel oil, with the Party to notify IMO of the non-availability. This notification is commonly referred to as a Fuel Oil Non-Availability Report (FONAR).

5.1.2 Guidance on consistent evidence

5.1.3 Regulation 18.2.1.2 of MARPOL Annex VI requires that evidence be provided to support a claim that all efforts were made to obtain compliant fuel oil. In this regard, a Party may develop more detailed guidance for the consistent use and acceptance of these reports, including what evidence is needed to accompany a report to ensure that port States are applying the provisions under regulation 18.2.3, consistently.

5.1.4 Should a ship, despite its best effort to obtain compliant fuel oil, be unable to do so, the master/company must:

.1 present a record of actions taken to attempt to bunker correct fuel oil and provide evidence of an attempt to purchase compliant fuel oil in accordance with its voyage plan and, if it was not made available where planned, that attempts were made to locate alternative sources for such fuel oil and that despite best efforts to obtain compliant fuel oil, no such fuel oil was made available for purchase; and

.2 best efforts to procure compliant fuel oil include, but are not limited to, investigating alternate sources of fuel oil prior to commencing the voyage. If, despite best efforts, it was not possible to procure compliant fuel oil, the master/Company must immediately notify the port State Administration in the port of arrival and the flag Administration (regulation 18.2.4 of MARPOL Annex VI).

5.1.5 In order to minimize disruption to commerce and avoid delays, the master/company should submit a FONAR as soon as it is determined or becomes aware that it will not be able to procure and use compliant fuel oil.

5.1.6 Investigating non-availability

5.1.7 A Party should investigate the reports of non-availability. This process is important to ensure a consistent supply of compliant fuel to industry, as well as prevent incentives for ships to use ports where it is known that compliant fuel is not available on an ongoing basis. Critical to this process will be the sharing of information between Member States on reported compliant fuel oil supply issues.

5.1.8 Regulation 18.2.5 of MARPOL Annex VI provides that a Party to MARPOL Annex VI notify the Organization when a ship has presented evidence of the non-availability of compliant fuel oil in a port or at their terminal. For this purpose, MARPOL Annex VI GISIS module provides the platform for Parties to upload such notifications.

5.1.9 Regulation 18.1 of MARPOL Annex VI provides that each Party take all reasonable steps to promote the availability of above compliant fuel oil and inform the Organization through MARPOL Annex VI GISIS module of the availability of compliant fuel oils in its ports and terminals.

5.1.10 Port State control authority may contact the submitter (and/or shipowner or operator), including in the event of an incomplete submission, and request additional information, or to pursue an enforcement action such as a Notice of Violation.

5.2 Standard format for reporting fuel oil non-availability

5.2.1 For ships which are unable to purchase fuel oil meeting the requirements of regulations 14.1 or 14.4 of MARPOL Annex VI, the standard format for reporting fuel oil non-availability is set out in appendix 1 to this document, pursuant to regulation 18.2.4 of MARPOL Annex VI.

6 Possible safety implications relating to fuel oils meeting the 0.50% m/m sulphur limit

6.1 MEPC 73 (October 2018) approved MEPC.1/Circ.878 on *Guidance on the development of a ship implementation plan for the consistent implementation of the 0.50% sulphur limit under MARPOL Annex VI* (hereafter the "Ship Implementation Plan Guidance") addresses some safety issues identified with regard to 0.50% maximum sulphur fuel oil, in particular through the section on risk assessment (section 1 of the Ship Implementation Plan Guidance) and additional guidance provided on impact on machinery systems and tank cleaning (appendix 2 and appendix 3 of the Ship Implementation Plan Guidance, respectively).

6.2 Identified potential safety implications include, but are not limited to, the following:

.1 stability of blended fuel oil;

.2 compatibility, including new tests and metrics appropriate for future fuels;

.3 cold flow properties;

.4 acid number;

.5 flash point;

.6 ignition and combustion quality;

.7 cat fines;

.8 low viscosity; and

.9 unusual components.

6.3 Additional technical information and a review, displayed in tabular format, of the possible potential safety implications is set out in appendix 2.

6.4 Reference should also be made to general industry guidance on potential safety and operational issues related to the supply and use of 0.50% maximum sulphur fuels[8].

8 ICS, ASA and ECSA Guidance to shipping companies and crews on preparing for compliance with

APPENDIX 1

FUEL OIL NON-AVAILABILITY REPORT (FONAR)

Note:

1 This report is to be sent to the flag Administration and to the competent authorities in the relevant port(s) of destination in accordance with regulation 18.2.4 of MARPOL Annex VI. The report shall be sent as soon as it is determined that the ship/operator will be unable to procure compliant fuel oil and preferably before the ship leaves the port/terminal where compliant fuel cannot be obtained. A copy of the FONAR should be kept on board for inspection for at least 36 months.

2 This report should be used to provide evidence if a ship is unable to obtain fuel oil compliant with the provisions stipulated in regulations 14.1 or 14.4 of MARPOL Annex VI.

3 Before filing a FONAR, the following should be observed by the ship/operator:

3.1 A fuel oil non-availability report is not an exemption. According to regulation 18.2 of MARPOL Annex VI, it is the responsibility of the Party of the destination port, through its competent authority, to scrutinize the information provided and take action, as appropriate.

3.2 In the case of insufficiently supported and/or repeated claims of non-availability, the Party may require additional documentation and substantiation of fuel oil non-availability claims. The ship/operator may also be subject to more extensive inspections or examinations while in port.

3.3 Ships/operators are expected to take into account logistical conditions and/or terminal/port policies when planning bunkering, including but not limited to having to change berth or anchor within a port or terminal in order to obtain compliant fuel.

3.4 Ships/operators are expected to prepare as far as reasonably practicable to be able to operate on compliant fuel oils. This could include, but is not limited to, fuel oils with different viscosity and different sulphur content not exceeding regulatory requirements (requiring different lube oils) as well as requiring heating and/or other treatment on board.

1. Particulars of ship

1.1 Name of ship: ______________________________

1.2 IMO number: ______________________________

1.3 Flag: ______________________________

1.4 (if other relevant registration number is available, enter here): ______________________________

2. Description of ship's voyage plan

2.1. Provide a description of the ship's voyage plan in place at the time of entry into "country X" waters (and ECA, if applicable) (Attach copy of plan if available):

____

____

____

2.3. Details of voyage:

1 – Last port of departure

---

2 – First port of arrival in "country X":

---

3 – Date of departure from last port (dd-mm-yyyy):

---

4 – Date of arrival at first "country X" (dd-mm-yyyy):

---

5 – Date ship first received notice that it would be transiting in "country X" waters (and ECA, if applicable) (dd-mm-yyyy):

---

6 – Ship's location at the time of notice:

---

7 – Date ship operator expects to enter "country X" waters (and ECA, if applicable) (dd-mm-yyyy):

---

8 – Time ship operator expects to enter "country X" waters (and ECA, if applicable) (hh:mm UTC):

---

9 – Date ship operator expects to exit "country X" waters (and ECA, if applicable) (dd-mm-yyyy):

---

10 – Time ship operator expects to exit "country X" waters (and ECA, if applicable) (hh:mm UTC):

---

11 – Projected days ship's main propulsion engines will be in operation within "country X" waters (and ECA, if applicable):

---

12 – Sulphur content of fuel oil in use when entering and operating in "country X" waters (and ECA, if applicable):

---

3. Evidence of attempts to purchase compliant fuel oil

6.5 Provide a description of actions taken to attempt to achieve compliance prior to entering "country X" waters (and ECA, if applicable), including a description of all attempts that were made to locate alternative sources of compliant fuel oil, and a description of the reason why compliant fuel oil was not available:

____
____
____

6.6 Name and email address of suppliers contacted, address and phone number and date of contact (dd-mm-yyyy):

____
____
____
____
____

Please attach copies of communication with suppliers (e.g. emails to and from suppliers)

4. In case of fuel oil supply disruption only

4.1. Name of port at which ship was scheduled to receive compliant fuel oil:

____
____
____
____
____

6.7 Name, email address, and phone number of the fuel oil supplier that was scheduled to deliver (and now reporting the non-availability): ________________________

5. Operation constraints, if applicable

5.1 If non-compliant fuel has been bunkered due to concerns that the quality of the compliant fuel available would cause operational or safety problems on board the ships, the concerns should be thoroughly documented.

5.2 Describe any operational constraints that prevented use of compliant fuel oil available at port:

____

5.3 Specify steps taken, or to be taken, to resolve these operational constraints that will enable compliant fuel use:

____

6. Plans to obtain compliant fuel oil

6.1 Describe availability of compliant fuel oil at the first port-of-call in "country X", and plans to obtain it:

____

~~6.2 If compliant fuel oil is not available at the first port-of-call in "country X", list the lowest~~ sulphur content of available fuel oil(s) or the lowest sulphur content of available fuel oil at the next port-of-call:

7. Previous Fuel Oil Non-Availability Reports

7.1 If shipowner/operator has submitted a Fuel Oil Non-Availability Report to "country X" in the previous 12 months, list the number of Fuel Oil Non-Availability Reports previously submitted and provide details on the dates and ports visited while using non-compliant fuel oil, as set out below:

Report:____
Date (dd-mm-yyyy): __________________________________
Port:____
Type of fuel: ______________________________________
Comments: _______________________________________

8. Master/Company information

Master name: ______________________________________
Local agent in "country X": ________________________________
Ship operator name: ___________________________________
Shipowner name: ____________________________________
Name and position of official: ______________________________
Email address: _____________________________________
Address (street, city, country, postal/zip code): ____________________
Telephone number: ___________________________________

Signature of Master: ___________________________________

Print name: _______________________________________
Date (DD/MM/YYYY): __________________________________

APPENDIX 2

TECHNICAL REVIEW OF IDENTIFIED POTENTIAL SAFETY IMPLICATIONS ASSOCIATED WITH THE USE OF 2020 COMPLIANT FUELS

Fuel Property	Potential Challenges	Remarks
Stability	The consequences of a ship receiving an unstable fuel, or one that becomes unstable during storage or handling, can be serious. Sludge may build up in the storage tanks, piping systems or centrifuges and filters can become totally blocked by voluminous amounts of sludge.	The challenge for the fuel producer is to blend a fuel which is not only stable but also has a degree of reserve stability such that it will remain stable during periods of storage and treatment at elevated temperatures. More paraffinic blend components are expected for Very Low Sulphur Fuel Oil (VLSFO) compared to existing fuels. Whereas aromatic components have a stabilizing effect on asphaltenes, paraffins do not. Fuel suppliers are responsible for ensuring that the supplied fuel is stable.
Compatibility issues	Challenges are the same as with stability (above).	An incompatible mix may be harmful to ship's operation. VLSFOs are expected to be paraffinic based in some regions and aromatic based in other regions. There is a risk of experiencing incompatibility when mixing an aromatic fuel with a paraffinic fuel. The same risk exists today, but with the wide range of products which may exist post 2020, it is important to segregate fuels as far as possible and to be cautious of how to manage/handle incompatible fuels on board.

Cold flow properties and Pour Point	ISO 8217:2017 limits the cold flow properties of a fuel through setting a limit on the pour point (PP). However, given that wax crystals form at temperatures above the PP, fuels that meet the specification in terms of PP can still be challenging when operating in colder regions. Wax particles can rapidly block filters, potentially plugging them completely. The paraffin's may crystallize and/or deposit in the storage tanks leading to blockages at the filters and reduced fuel flow to the machinery plants. If fuels are held at temperatures below the pour point, wax will begin to precipitate. This wax may cause blocking of filters and can deposit on heat exchangers. In severe	VLSFO products are expected to be more paraffinic compared to existing fuels. As such, it is important to know the cold flow properties of the bunkered fuel in order to ensure proper temperature management on board. It is important to note that for additives to be effective, they have to be applied before crystallization has occurred in the fuel. Reference 1.

Fuel Property	Potential Challenges	Remarks
	cases the wax will build up in storage tank bottoms and on heating coils, which can restrict the coils from heating the fuel (fuel will become unpumpable from the bunker tanks).	
Acid number	The fuel shall be free from strong, inorganic acids. Fuels with high acid number test results arising from acidic compounds cause accelerated damage to marine diesel engines. Such damage is found primarily within the fuel injection equipment.	There is currently no recognized correlation between an acid number test result and the corrosive activity of the fuel. ISO 8217:2017, appendix E covers the topic.
Flashpoint	Flashpoint is considered to be a useful indicator of the fire hazard associated with the storage of marine fuels. Even if fuels are stored at temperatures below the determined flash point, flammable vapours may still develop in the tank headspace.	SOLAS requirement.

Ignition and combustion quality	Fuels with poor ignition & combustion properties can, in extreme cases, result in serious operational problems, engine damage and even total breakdown. Poor combustion performance is normally characterized by an extended combustion period and/or poor rates of pressure increase and low "p max" resulting in incomplete combustion of the fuel. The resulting effects are increased levels of unburned fuel and soot that may be deposited in the combustion chamber, on the exhaust valves and in the turbocharger system, exhaust after treatment devices, waste heat recovery units and other exhaust system components. Extended combustion periods may also result in exposure of the cylinder liner to high temperatures which may disrupt the lubricating oil film, leading to increased wear rates and scuffing. Unburnt fuel droplets may also carry over impinging on the liner surfaces causing further risk of damage to the liner.	High and medium-speed engines are more prone to experience operational difficulties due to poor ignition and combustion properties than low speed two stroke types. With four stroke engines, poor ignition can result in excessive exhaust gas system deposits, black smoke, engine knocking and difficulties operating at low load. If the ignition process is delayed for too long a period by virtue of some chemical quality of the fuel, too large a quantity of fuel will be injected into the engine cylinders and will ignite at once, producing a rapid pressure and heat rise and causing associated damage to the piston rings and cylinder liners of the engine. Reference 2.

Fuel Property	Potential Challenges	Remarks
Cat fines	Cat fines will cause abrasive wear of cylinder liners, piston rings and fuel injection equipment if not reduced sufficiently by the fuel treatment system. High wear in the combustion chamber can result.	Major engine manufacturers recommend that the fuel's cat fines content does not exceed 10 mg/kg (ppm) at engine inlet.
Low viscosity	Low-viscosity fuels (less than 2 cSt at engine inlet) challenge the function of the fuel pump in the following ways: .1 breakdown of the oil film, which could result in seizures; .2 insufficient injection pressure, which results in difficulties during start-up and low-load operation; and .3 insufficient fuel index margin, which limits acceleration.	Low fuel viscosity does not only affect the engine fuel pumps. Most pumps in the external fuel oil system (supply pumps, circulating pumps, transfer pumps and feed pumps for the centrifuge) also need viscosities above 2 cSt to function properly. Viscosity is highly temperature dependent and the crew must take proper care of fuel oil temperature management to avoid viscosity related issues. Reference 3.

Unusual components	The below components and group of components can be linked to the risk of encountering the following problems: Polymers (e.g. polystyrene, polyethylene, polypropylene) Associated with filter blocking Polymethacrylates Associated with fuel pump sticking Phenols Occasionally Associated with filter blocking/fuel oil pump sticking Tall oils Associated with filter blocking Chlorinated hydrocarbons Associated with fuel pump seizures Estonian shale oil Associated in the past with excessive separator sludging Organic acids Associated with corrosion as well as fuel pump sticking	Only for few components, there exists a clear cause and effect between component and associated operational problems. There is no statistical study performed of which components are typically found in marine fuels and in which concentration. As per ISO 8217:2017, annex B: The marine industry continues to build on its understanding of the impact of specific chemical species and the respective critical concentrations at which detrimental effects are observed on the operational characteristics of marine fuels in use. Only in some of the past cases the origin of the unusual components found in bunkers were revealed and were due to various reasons such as: .1 Russia/Baltic states 1997, cross contamination in storage/piping (polypropylene); .2 Singapore 2001, 4 bunker barges received material from road

Fuel Property	Potential Challenges	Remarks
		tankers which, in addition to transporting fuel, also collected/transported waste oil from shipyards and motor shops (esters); .3 Ventspils 2007, Estonian shale oil to convert HSHFOs to LSFOS; and .4 Houston 2010/11, bunker barges that were not cleaned between cargoes (polyacrylates) Reference 4.

References

1 CIMAC WG7 Fuels Guideline 01/2015: "Cold flow properties of marine fuel oils"
2 CIMAC WG7 Fuels 2011: "Fuel Quality Guide: Ignition and Combustion"
3 MAN Service Letter SL2014-593/DOJA
4 Bureau Veritas Verifuel, Investigative analysis of marine fuel oils: Pros & Cons

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APPENDIX B – IMO Ship Implementation Plan

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MEPC.1/Circ.878
9 November 2018

GUIDANCE ON THE DEVELOPMENT OF A SHIP IMPLEMENTATION PLAN FOR THE CONSISTENT IMPLEMENTATION OF THE 0.50% SULPHUR LIMIT UNDER MARPOL ANNEX VI

1 The Marine Environment Protection Committee, at its seventy-third session (22 to 26 October 2018), approved the *Guidance on the development of a ship implementation plan for the consistent implementation of the 0.50% sulphur limit under MARPOL Annex VI*, as set out in the annex.

2 Member Governments are invited to bring the annexed Guidance to the attention of their Administration, industry, relevant shipping organizations, shipping companies and other stakeholders concerned.

***

ANNEX

GUIDANCE ON THE DEVELOPMENT OF A SHIP IMPLEMENTATION PLAN FOR THE CONSISTENT IMPLEMENTATION OF THE 0.50% SULPHUR LIMIT UNDER MARPOL ANNEX VI

Introduction

1 MEPC 70 agreed to "1 January 2020" as the effective date of implementation for ships to comply with global 0.50% m/m sulphur content of fuel oil requirement and adopted resolution MEPC.280(70) on the *Effective date of implementation of the fuel oil standard in regulation 14.1.3 of MARPOL Annex VI.*

2 In this context, MEPC 73 agreed that Administrations should encourage ships flying their flag to develop implementation plans, outlining how the ship may prepare in order to comply with the required sulphur content limit of 0.50% by 1 January 2020. The plan could be complemented with a record of actions taken by the ship in order to be compliant by the applicable date.

3 Regulation 18.2.3 of MARPOL Annex VI requires a Party to take into account all relevant circumstances and the evidence presented to determine the action to take, including not taking control measures. Administrations and port State control authorities may take into account the implementation plan when verifying compliance with the 0.50% sulphur limit requirement.

4 A ship implementation plan is not a mandatory requirement. A lack of a ship implementation plan or an incomplete ship implementation plan should not be considered as "clear grounds" for a more detailed inspection.

Ship implementation plan for the consistent implementation of 0.50% sulphur limit under MARPOL Annex VI

5 The ship implementation plan for 2020 could cover various items relevant for the specific ship, including, as appropriate, but not limited to:

.1 risk assessment and mitigation plan (impact of new fuels);

.2 fuel oil system modifications and tank cleaning (if needed);

.3 fuel oil capacity and segregation capability;

.4 procurement of compliant fuel;

.5 fuel oil changeover plan (conventional residual fuel oils to 0.50% sulphur compliant fuel oil); and

.6 documentation and reporting.

[1] Amendments to regulation 14.1.3 of MARPOL Annex VI were adopted by MEPC 73 (October 2018).

Issues relating to use of sulphur compliant fuel oil

6 All fuel oil supplied to a ship shall comply with regulation 18.3 of MARPOL Annex VI and chapter II/2 of SOLAS. Furthermore, ship operators could consider ordering fuel oil specified in accordance with the ISO 8217 marine fuel standard. The following potential fuel-related issues may need to be assessed and addressed by ships in preparation for and implementation of the 0.50% sulphur limit requirement:

.1 technical capability of ships to handle different types of fuel (e.g. suitability of fuel pumps to handle both higher and lower viscosity fuels, restrictions on fuels suitable for use in a ship's boilers, particularly the use of distillate fuels in large marine boilers);

.2 compatibility of different types of fuels e.g. when paraffinic and aromatic fuels containing asphaltenes are commingled in bunkering or fuel oil changeover;

.3 handling sulphur non-compliant fuels in the event of non-availability of sulphur compliant fuels; and

.4 crew preparedness including possible training with changeover procedures during fuel switching from residual fuel oil to 0.50% compliant fuel oils.

7 The ship implementation plan could be used as the appropriate tool to identify any specific safety risks related to sulphur compliant fuel oil, as may be relevant to the ship, and to develop an appropriate action plan for the Company to address and mitigate the concerns identified. Examples should include:

.1 procedures to segregate different types of fuel and fuels from different sources;

.2 detailed procedures for compatibility testing and segregating fuels from different sources until compatibility can be confirmed;

.3 procedures to changeover from one type of fuel to another or a fuel oil that is known to be incompatible with another fuel oil;

.4 plans to address any mechanical constraints with respect to handling specific fuels, including ensuring that minimum/maximum characteristics of fuel oil as identified in ISO 8217 can be safely handled on board the ship; and

.5 procedures to verify machinery performance on fuel oil with characteristics with which the ship does not have prior experience.

8 A ship implementation plan for the consistent implementation of the 0.50% sulphur limit under MARPOL Annex VI is recommended to be developed based on the indicative example as set out in appendix 1.

9 The plan could take into account the issues identified in:

.1 appendix 2: additional guidance on development of ship implementation plan (impact on machinery systems); and

.2 appendix 3: additional guidance on development of ship implementation plan (tank cleaning).

APPENDIX 1

INDICATIVE EXAMPLE FOR SHIP IMPLEMENTATION PLAN FOR ACHIEVING COMPLIANCE WITH THE 0.50% SULPHUR LIMIT ENTERING INTO FORCE ON 1 JANUARY 2020 USING COMPLIANT FUEL OIL ONLY

Particulars of ship

1. Name of ship:
2. Distinctive number or letters:
3. IMO Number:

Planning and preparation (before 1 January 2020)

1. Risk assessment and mitigation plan

1.1 Risk assessment (impact of new fuels): YES/NO
1.2 Linked to onboard SMS YES/NO

2. Fuel oil system modifications and tank cleaning (if needed)

2.1 Schedule for meeting with manufacturers and/or classification societies:

2.2 Structural Modifications (installation of fuel oil systems/tankage) required: YES/NO/NOT APPLICABLE

If YES, then:

2.2.1 Fuel oil storage system
Description of modification:

Details of yard booking (as applicable), time schedules etc.:

Estimated date of completion of modification:

2.2.2 Fuel transfer, filtration and delivery systems:

Description of modification:

Details of yard booking (as applicable), time schedules etc.:

Estimated date of completion of modification:

2.2.3 Combustion equipment:

Description of modification:

Details of yard booking (as applicable), time schedules etc.:

Estimated date of completion of modification:

2.3 Tank cleaning required: YES/NO/NOT APPLICABLE

If YES, then:

Details of cleaning schedule (including, yard booking, time schedules etc., if applicable):

Estimated date of completion of cleaning:

3 Fuel oil capacity and segregation capability:

Following any required modifications as per Section 2:

3.1 Expected number of bunker tanks designated to store 0.50% sulphur compliant fuel oil:

3.2 Expected total storage capacity (m^3) for 0.50% sulphur compliant fuel oil:

3.3 Expected number of bunker tanks designated to store 0.10% sulphur compliant fuel oil:

3.4 Expected total storage capacity (m^3) for 0.10% sulphur compliant fuel oil:

3.5 Approximate total fuel oil content (m^3) in the fuel oil transfer, purification and delivery systems:

4 Procurement of compliant fuel oil

4.1 Details of fuel purchasing procedure to source compliant fuels, including procedures in cases where compliant fuel oil is not readily available:

4.2 Estimated date for bunkering compliant fuel oil, not later than 24:00hrs 31 December 2019:

4.3 If fuel arranged by charterer, is there an intention to accept charter party contracts that do not have a specified obligation to provide compliant fuel oil after 1 June 2019 or other date to be identified: YES/N

If YES, then:

Details of alternate steps taken to ensure that the charter party provides timely delivery of compliant fuel:

4.4 Is there confirmation from bunker supplier(s) to provide compliant fuel oil on the specified date: YES/NO

If NO, then:
Details of alternate steps taken to ensure timely availability of compliant fuel oil:

4.5 Details of arrangements (if any planned) to dispose of any remaining non-compliant fuel oil:

5 Fuel oil changeover plan

5.1 Consider whether a ship-specific fuel changeover plan is to be made available. The plan should include measures to offload or consume any remaining non-compliant fuel oil. The plan should also demonstrate how the ship intends to ensure that all its combustion units will be using compliant fuel oil no later than 1 January 2020.

5.2 As per the ship-specific fuel changeover plan, the maximum time period required to changeover the ship's fuel oil system to use compliant fuel oil at all combustion units:

5.3 Expected date and approximate time of completion of the above-mentioned changeover procedure:

5.4 Consider availability of adequately trained officers and crew familiar with the ship's fuel system and fuel changeover procedures to carry out the fuel oil changeover procedure. If this cannot be confirmed, then consider whether there is a sufficient amount of time dedicated for ship-specific familiarization and training of new officers and crew.

6 Documentation and reporting

6.1 If there are modifications planned as per section 2, related documents including the shipboard fuel oil tank management plans and stability and trim booklets should be consequently updated.

6.2 The implementation plan could be kept on board and updated as applicable.

6.3 If when following the implementation plan the ship has to bunker and use non-compliant fuel oil due to unavailability of compliant fuel oil safe for use on board the ship, steps to limit the impact of using non-compliant fuel oil could be:

6.4 The ship should have a procedure for Fuel Oil Non-Availability Reporting (FONAR). The master and chief engineer should be conversant about when and how FONAR should be used and who it should be reported to.

APPENDIX 2

ADDITIONAL GUIDANCE FOR DEVELOPMENT OF THE SHIP IMPLEMENTATION PLAN (IMPACT ON MACHINERY SYSTEMS)

1 Ships are advised to assess potential impact on machinery systems with the use of distillates and fuel oil blends and prepare ships in consultation with chief engineers, equipment manufacturers and suppliers.

2 The ship tank configuration and fuel system may require adjustments. A fully segregated fuel system for distillate fuels and blended fuels is recommended because they may require special attention. Ship tank configuration and segregated fuel system will also allow for better management of potentially incompatible fuels.

Distillates

3 If distillates have been chosen as the option for compliance the following may be considered:

.1 a decrease in fuel oil viscosity may cause an increase in fuel oil leakage between the fuel pump plunger and barrel of diesel engines. Internal leakages in the fuel injection system may result in reduced fuel pressure to the engine, which may have consequences for the engine performance (e.g. starting of the engine). Equipment makers' recommendations should be consulted, and adequate testing, maintenance and possible installation of coolers etc. may be performed;

.2 shipowners may also consider installing fuel pumps and injection nozzles, suitable to fuel oil with low viscosity. Fuel oil with too low viscosity may lead to increased wear or seizure of fuel oil pumps. Engine and boilermakers should be consulted to ensure its safe and efficient operation. Implications for validity of NO_X certification (EIAPP Certificate) should be considered;

.3 while some compliant fuels may not require heating, others, including some distillates, will require heating. It would therefore be prudent to review heating arrangements for distillate fuels on board and, where appropriate, maintain the existing heating arrangements; and

.4 in some locations, bunker suppliers may only be able to offer automotive diesel fuel containing biodiesel (FAME) in accordance with the ISO 8217-2017 Standard which provides a marine biodiesel specification (DFA/DFB) with up to 7.0% by volume of FAME. CIMAC has provided a "Guideline for Ship Owners and Operators on Managing Distillate Fuels up to 7.0 % v/v Fame (Biodiesel)".[2]

4 In view of paragraph 3.3 manufacturers of engines and equipment such as oily water separators, overboard discharge monitors, filters and coalescers, etc. need to be consulted to confirm ability to handle biodiesel blends up to 7% v/v.

Also, some parts of the fuel oil supply system, i.e. fuel pumps, pipefittings and gaskets may need to be overhauled to ensure integrity.

Blended residual fuels

6 New blended 0.50% sulphur fuel oil as and when offered could provide an alternative to conventional distillate fuel such as Marine Distillate Fuel.

7 When using such new blended sulphur fuel oils, the technical specification of such fuels are (a) either within the limits specified by ISO 8217 or are (b) issued with formal documentation indicating no objection to its use by the engine/boiler makers.

8 Before purchasing a new fuel oil product, operators should carefully consider the specific technical and operational challenges that this type of fuel oil may have and, where necessary, contact the fuel oil supplier or Original Equipment Manufacturer (OEM) for the considerations to be made to ensure safe operation.

9 Densities of these fuel oils are in general lower than conventional residual fuel oils. This may require adjustment of centrifuges to ensure adequate cleaning of the fuel oil.

Cold flow

10 Since most distillate fuels do not require heating (in fact, typically, heating is not recommended due to the low viscosity of these products), the fuel's cold flow properties become a potential handling/storage challenge, especially when operating in colder regions.

11 It is however possible to successfully manage cold flow properties through good fuel management, from procurement to technical operation, by considering the following:

.1 where the ship will be operating;

.2 where the risk is higher of getting fuels with poor cold flow properties;

.3 can the required cold flow properties be specified in the fuel contract;

.4 what is the actual low-temperature flow properties of the bunkered fuel; and

.5 which actions have to be taken in order to safely consume the bunkered fuel (e.g. tank and filter heating).

APPENDIX 3

ADDITIONAL GUIDANCE FOR DEVELOPMENT OF THE SHIP IMPLEMENTATION PLAN (TANK CLEANING)

Introduction

1 Most ships will have been using high viscosity high sulphur fuel oil (HSFO) based primarily on residual fuel oils. Such fuels tend to adhere to the inside of fuel tanks forming layers of semi-solid substances containing sediments and asphaltenic sludge; such residues will also typically have solidified and settled in various parts of the fuel oil service system including pipelines, settling and service tanks.

2 The ship operator may choose to clean the fuel oil tanks of these residues before loading compliant fuel prior to 1 January 2020 based on the following considerations.

3 Some of the fuels complying with the 0.50% sulphur limit are expected to be very paraffinic due to crude sources of blending components and also a high content of distillate components. If such fuels are loaded into HSFO fuel tanks that have not been cleaned, there is a possibility that they could dissolve and dislodge sediments and asphaltenic sludge in storage tanks, settling tanks and pipelines, potentially leading to purifier and filter operational issues and in extreme cases fuel starvation resulting in loss of power.

4 Alternatively, ships have been using ship specific changeover procedures to effectively and safely load on top of existing fuel oil and gradually flushing through the fuel system until the sulphur content in the fuel oil is at a compliant level.

5 Should the ship operator determine it is appropriate to clean the ship's fuel oil tanks and system, the following considerations may need to be taken into account when making arrangements for tank cleaning.

Options for tank cleaning, approximate timelines and considerations

6 Fuel oil tanks are normally cleaned on a regular basis on ships to remove built-up sediments and sludge, usually during dry docking and whenever inspections of the fuel tanks are due. However, leading up to 1 January 2020, it would not be practicable for the majority of the global fleet that has been running on HSFO and decided to opt for tank cleaning to undergo dry docking during a very short period. Hence, other options for cleaning tanks and fuel oil systems during service may need to be considered.

7 The time and work involved in cleaning HSFO tanks cannot be defined precisely, as it will vary depending on how long it has been since the last time the tanks were cleaned, the condition of the tank coating and the effectiveness of the cleaning process itself. The estimates in this document may err on the side of caution as it is almost impossible to pinpoint at what stage the ship's fuel oil system is sufficiently clean to guarantee compliance.

Manual cleaning during dry docking

8 Time required varies; it can be done in 2 to 4 days per tank. In addition to cleaning tanks, all of the pipework in the fuel oil service system needs to be flushed through. Overall,

it may take 1 to 2 weeks.

9 A ship that has had all its fuel oil tanks and fuel system cleaned can start loading compliant fuels and expect to be fully compliant right away.

10 However, if only the tanks have been cleaned in dry dock, it could take 2 to 5 days to flush through the pipework in the fuel oil service system to ensure full compliance with the 0.50% sulphur limit.

Manual cleaning during service

11 If tanks are to be cleaned manually during service, risk assessment and safety measures are paramount; refer to IMO resolution A.1050(27) on *Revised recommendations for entering enclosed spaces aboard ships*.

12 Time required will vary depending on tank size and the number of tanks, how long it has been since the last tank cleaning and the number of crew available to perform safe and complete tank cleaning operations. Tank cleaning can be performed by the ship's crew and/or by employing a riding crew for this purpose. It is always good practice to inspect the tank once cleaned to check its condition and to inspect heating coils, conduct pressure tests and undertake repairs as necessary.

13 If the cleaning is done by the ship's existing crew, it would likely take a minimum of 4 days per tank. For an average tank, a week should be allowed. If employing a riding crew to clean the tanks, if working in shifts, it would likely take a minimum of 2 days to clean a tank, but 4 days per tank should be allowed.

14 Tanks need to be empty before they can be cleaned, hence the time needed to drain tanks needs to be taken into account when estimating the overall time required.

15 In addition to cleaning tanks, all of the pipework in the fuel oil service system needs to be flushed. Flushing the remaining pipework and fuel oil service system after all tanks have been cleaned could take another 1 to 2 days.

16 The residues from tank cleaning should be retained on board until they can be disposed of correctly or disposed to shore reception facilities.

Cleaning tanks in service with specialized additives

17 As an alternative to manual cleaning, consideration can be given to gradually cleaning the sediments and asphaltenic sludge from HSFO tanks and fuel systems by dosing additives. There are successful examples of this approach for ships that needed to reallocate HSFO tanks to fuels complying with the 0.10% sulphur limit that took effect in ECAs in 2015.

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APPENDIX C – IMO Guidelines for entering enclosed spaces

Precautions before entering the fuel tanks

According to IMO Resolution A.1050 (27) "Revised Recommendations for Entering Enclosed Spaces on Board Ships", an enclosed space means a space which has any of the following characteristics:

a) Limited opening for entry and exit;
b) Inadequate ventilation; and
c) Is not designed for continuous worker occupancy,

and includes, among others, cargo spaces, ballast tanks and fuel tanks. Enclosed space activities such as fuel tank entry are recognized as a high risk activity. Obstructed access and the confined nature of the space, likelihood of slipping due to oil coated surfaces, limited visibility, toxic and flammable atmosphere due to fuel vaporization make the tank cleaning a very dangerous activity and necessitate precautionary measures.

Recognizing the need for guidance, IMO has adopted the guidelines appended in the foregoing Resolution A.1050 (27), in which the key points of the procedure to entering an enclosed space is outlined verbatim as follows:

1) Risk Assessment

In order to ensure safety, a competent person[18] should always make a preliminary risk assessment of any potential hazards in the space to be entered, taking into account previous cargo carried, ventilation of the space, coating of the space and other relevant factors. The assessment should determine the presence or not of an oxygen-deficient, oxygen enriched, flammable or toxic atmosphere.

2) Authorization of Entry

i. No person should open or enter an enclosed space unless authorized by the master or the nominated responsible person and unless the appropriate safety procedures laid down for the particular ship have been followed.

[18] Competent person means a person with sufficient theoretical knowledge and practical experience to make an informed assessment of the likelihood of a dangerous atmosphere being present or subsequently arising in the space (e.g. ship's 1st or 2nd engineer).

ii. Entry into enclosed spaces should be planned and the use of an entry permit system, which may include the use of a checklist, is recommended. An Enclosed Space Entry Permit should be issued by the master or the nominated responsible person, and completed by the personnel who enter the space prior to entry.

3) General Precautions

The master or the responsible person[19] should determine that it is safe to enter an enclosed space by ensuring that:

i. potential hazards have been identified in the assessment and as far as possible isolated or made safe;
ii. the space has been thoroughly ventilated by natural or mechanical means to remove any toxic or flammable gases and to ensure an adequate level of oxygen throughout the space;
iii. the atmosphere of the space has been tested as appropriate with properly calibrated instruments to ascertain acceptable levels of oxygen and acceptable levels of flammable or toxic vapours;
iv. the space has been secured for entry and properly illuminated;
v. a suitable system of communication between all parties for use during entry has been agreed and tested;
vi. an attendant has been instructed to remain at the entrance to the space whilst it is occupied;
vii. rescue and resuscitation equipment has been positioned ready for use at the entrance to the space and rescue arrangements have been agreed;
viii. personnel are properly clothed and equipped for the entry and subsequent tasks; and
ix. a permit has been issued, authorizing entry

4) Testing the Atmosphere

Appropriate testing of the atmosphere of a space should be carried out with properly calibrated equipment[20] by persons trained in the use of the equipment. Testing of the space should be carried out before any person enters the space and at regular intervals thereafter until all work is completed.

For entry purposes, steady readings of all of the following should be obtained:

i. 20.8% (±0.2%) oxygen by volume by oxygen content meter;

[19] Responsible person means a person authorized to permit entry into an enclosed space and having sufficient knowledge of the procedures to be established and complied with on board, in order to ensure that the space is safe for entry (e.g. ship's engineers).

[20] According to SOLAS Chapter XI-1, Regulation 7 (MSC.1/Circ.1477), every ship to which chapter I applies shall carry an appropriate portable atmosphere testing instrument or instruments. As a minimum, these shall be capable of measuring concentrations of oxygen, flammable gases or vapours, hydrogen sulphide and carbon monoxide prior to entry into enclosed spaces. Instruments carried under other requirements may satisfy this regulation. Suitable means shall be provided for the calibration of all such instruments.

ii. not more than 1% of lower flammable limit (LFL) on a suitably sensitive combustible gas indicator, where the preliminary assessment has determined that there is potential for flammable gases or vapours; and
iii. not more than 50% of the occupational exposure limit (OEL) of any toxic vapours and gases.
iv. If these conditions cannot be met, additional ventilation should be applied to the space and re-testing should be conducted after a suitable interval.

5) Precautions during entry

i. The atmosphere should be tested frequently whilst the space is occupied and persons should be instructed to leave the space should there be a deterioration in the conditions.
ii. Persons entering enclosed spaces should be provided with calibrated and tested multi-gas detectors that monitor the levels of oxygen, carbon monoxide and other gases as appropriate.
iii. Ventilation should continue during the period that the space is occupied and during temporary breaks. Before re-entry after a break, the atmosphere should be re-tested. In the event of failure of the ventilation system, any persons in the space should leave immediately.
iv. In the event of an emergency, under no circumstances should the attending crew member enter the space before help has arrived and the situation has been evaluated to ensure the safety of those entering the space to undertake rescue operations. Only properly trained and equipped personnel should perform rescue operations in enclosed spaces.
v. Appropriate protective clothing should be worn, particularly where there is any risk of toxic substances or chemicals coming into contact with the skin or eyes of those entering the space.