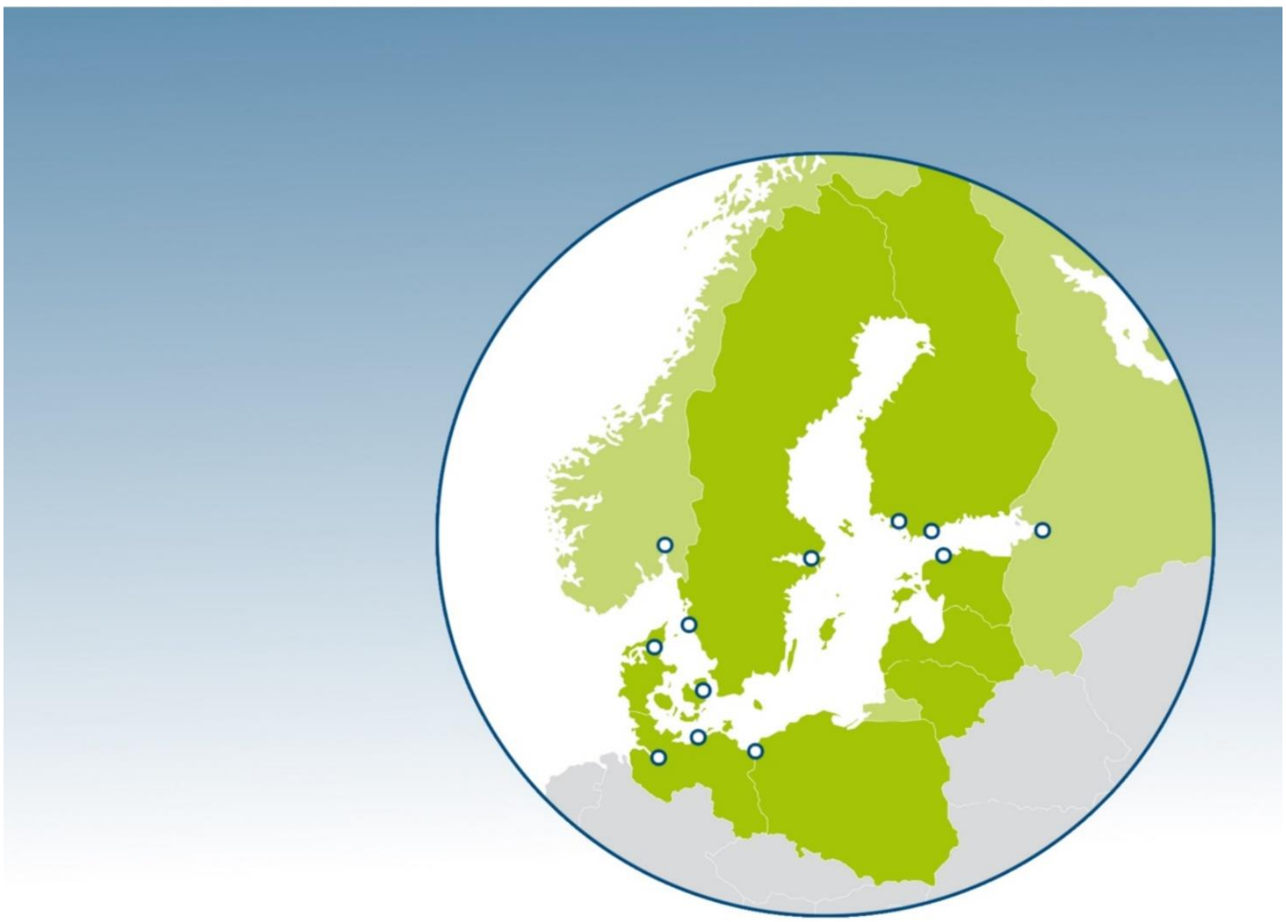
State of play and Future need of Clean Shipping

Final report



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State of Play and Future needs for Clean Shipping

Contents

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Disclaimer

This paper was written in the context of the CSHIPP project platform. The work is based on literature studies, internet research, study visits and experiences as well as the authors' level of knowledge and experiences and gives the current state of scientific-technical developments and the state-of-play on the basis of selected examples. The data used in the study are taken from resources that are publicly available in the English and German literature (e.g. presentations, reports, previous studies, press releases, news, videoclips, etc.). The representation in number and quality and completeness of the listed technologies and projects is given by the provision of information by technology providers, industrial developers, owners and operators, financial supporters or the press. Due to these limitations of available sources, possible inconsistencies and errors, it is noted that the work may not be able to cover all aspects of the subject. The attempt at an outlook is based on estimates as well as current discussions in the professional community. Throughout the study, efforts have been made to avoid duplication of efforts that are difficult to avoid in practice. The authors are aware of the fact that in case of a concrete upcoming development work, a deeper consideration will be necessary, for which further development work will be required. Therefore, the authors do not guarantee the accuracy or suitability of this information for decisions to be made. The work reflects the status as of December 2020.

1 Introduction

1.1 Framework, background and motivation

Maritime transport in the Baltic Sea is an important backbone for trade. At any given time, more than 2000 vessels are operating in the Baltic Sea. Both the number and size of ships have increased in recent years and currently account for up to 15% of global cargo traffic. Shipping is a very effective means of transportation, measured in terms of emissions per ton of cargo. However, shipping can still have negative impacts on the environment, such as emissions to air and sea. Shipping is expected to continue to increase in the coming years.

In addition to shipping, the Baltic Sea is exposed to a variety of sometimes competing uses, such as installations, submarine cables, pipelines and offshore wind farms, which put additional pressure on the Baltic Sea ecosystem. This is all the more significant because the Baltic Sea environment is very fragile due to its shallow, semi-enclosed waters and densely populated shores. In addition to spatial planning and land use strategies, the international nature of shipping means that equally far-reaching regulations and rules are needed. The aim of the work of specialized organizations, such as the International Maritime Organization (IMO), HELCOM are joint proposals and activities aimed at protecting the maritime environment of the Baltic Sea. Further for the protection of the environment, clean shipping must also include the economic and technical side and all factors must harmonize.

1.2 EUSBSR

Given the importance of maritime transport for the Baltic Sea region and the need for protection of the marine environment, the Baltic Sea countries act together to minimize pollution from ships while preserving the positive effects of maritime transport. This goal is pursued in the EU Strategy for the Baltic Sea Region (EUSBSR) and implemented through various policy areas.

The policy area "Ship" (PA Ship) focuses on implementation of clean shipping in the Baltic Sea, complementing the work of the other regional forums, such as the Baltic Marine Environment Protection Commission (HELCOM, which focuses on regulation and policy measures). The strength of the Ship Policy Area with the other regional cooperation forums is the focus on project-based policy dialogue and the ability to align EU funding with agreed policy objectives and in turn develop projects to achieve these objectives.

1.3 Solution approaches

Many new technologies and measures are currently being developed in the region to reduce the negative environmental impacts of maritime transport. In fact, the Baltic Sea region is the home of world champions in shipping and marine equipment manufacturing. Thus, there are great opportunities and significant growth potential for this industry in achieving both environmentally friendly and clean shipping and a strong maritime economy in the Baltic Sea region.

1.4 Projects in CSHIPP

As an activity in the implementation of the EUSBSR and in cooperation with the PA Ship, the project platform CSHIPP bundles different projects dealing with Clean Technology as well as clean shipping issues. Most of the projects focus on tasks, topics and issues of information gathering and information assessment on impacts of shipping on the marine environment and ultimately on human health. Furthermore, projects deal with analyses of the state of play of technological and economic solutions as well as alternatives for the implementation of clean shipping. The objectives are to provide information, to develop tools for decision making and to derive recommendations for policy makers.

The partners of the project platform cover a multidimensional spectrum due to their different professional backgrounds, so that the topic complex Clean Shipping is considered from different aspects.

Table 1 Projects within the CSHIPP

BalticLines	Development and harmonization of a pan-Baltic data and information base for maritime spatial planning.
ECOPRODIGI	Eco-efficiency Digitization Phases of a ship's life cycle Measurement, visualization and optimization Training courses.
EnviSuM	Tools and recommendations for the development of future environmental regulations; technical efficiency and the socio-economic impact; measurement and modeling strategies for assessment ; socio-economic classification.
Go LNG	Alternative fuel and energy sources, business models, LNG business clusters, expertise and technology.
BSR electric	Electromobility on water, electric ferries and electric barges; considerations for expansion to large vessels.
SmartUp Accelerator	CleanTech; knowledge and awareness of cleantech; new business creation.

1.5 Classification and basic possibilities

For the implementation of clean shipping to reduce or avoid the impact of shipping on the environment as well as on the climate, various effective means are available, which can be implemented at the political-social / ecological level, at the economic level as well as at the technical-technological level with varying degrees of effort.

Political level

- Global governance processes affecting world economy and trade,
- Removal of trade barriers
- Regional policy, reduction of administrative barriers,
- Behavior of people as consumers, consumption reduction and renunciation
- Sense of responsibility and environmental knowledge,

Level of the economy

- Driving slowly - driving less often - not driving at all
- Adjustment of logistics chains and schedules

- Adjustment of freight rates, prices, revenues and tonnage
- Reduction of global interdependence
- Less consumption

Technology level

- Clean energy supply systems for propulsion and on-board energy,
- Alternative fuels and energy sources,
- Exploiting physical-technical effects and influences,
- Propulsion systems - hydrodynamics - ship design
- Control systems, digitalization
- Education and training
- Technical operational knowledge, design knowledge, social control knowledge.

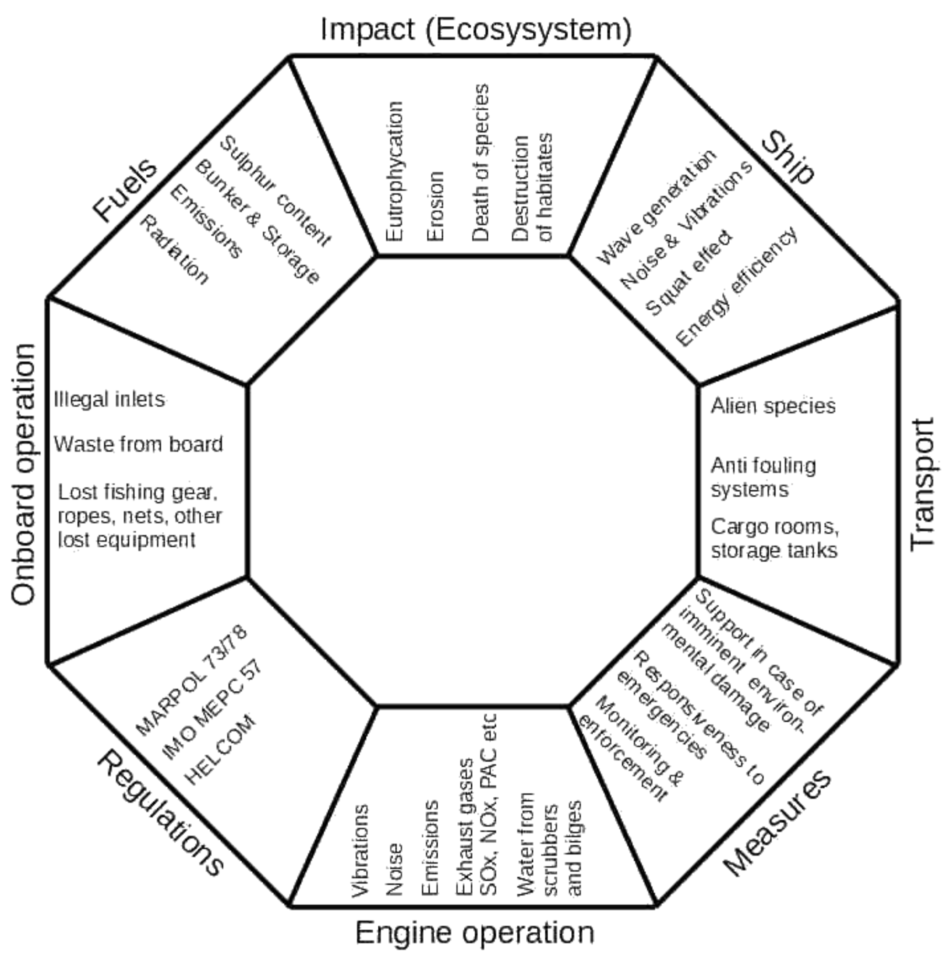

Figure 1 Graphs showing the complexity and interrelationships of the topic.

1.6 Delimitation of the work

„Navigare necesse est"[1].

The interconnectedness of global politics, social control processes is clearly evident in shipping, both from the indicator and with its effects on the shipping economic sector. This became clear most recently during the Corona period.

Influential and well-connected lobby organizations are pushing for the acceleration and facilitation of global trade. e.g. through the creation of a Global Alliance for Trade Facilitation (GATF, 10th WTO Ministerial Conference in Nairobi, December 2015). [1] On the other hand, other groups seem to want to do the opposite and intervene in a controlling way through regulations and restrictions. The Clean Shipping topic complex is located in this area of tension. For own analyses and conclusions, these and the institutions associated with them offer good clues for developments against the background of global social steering processes.

For regional political decisions, it is also advisable to keep the level of global politics in view, because the effects will always have local manifestations.

Due to the multidimensionality (refer also to *Table 2*) and diversity of the problem areas in the subject complex Clean Shipping and due to the specialization of the project partners on concrete partial aspects, the authors of this work limit themselves to three areas:

- Drives and energy supply, alternatives and fuels, e.g. electromobility,
- Alternative modes of operation for Clean Shipping, e.g. slow steaming, opportunities and impacts,
- Impact of education & training of ship officers and operations personnel, human factor, capabilities, simulation.

Adjacent topics as well as additional thoughts are moved to an appendix.

Table 2 Multidimensionality of the topic

Monitoring	Measurement, data collection, data evaluation, research.
Technology	Research, development, construction, optimization.
Operation	Operating modes, operation, crew qualification.
Training	Teaching, training, education, research.
Energy use	Fuels, supply, storage, conversion, methods.
Regulations	Reasonable implementation of compliance of set conditions, Proposals for that.

[1] Gnaeus Pompeius Magnus, roman statesman.

The methodological approach sheds light on the respective subject matter and explains relevant key points about the complex Clean Shipping to the state of the art (state-of-play). The chapter is preceded by a summary, which includes assessments, trends, future requirements and recommendations, as far as possible.

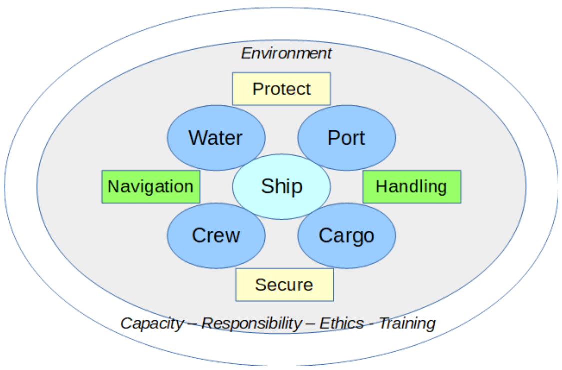

Figure 2 Influencing factors on Shipping.

1.7 Impact of shipping on the environment

Shipping and other activities at sea unfortunately also have a negative impact on the environment. The main environmental impacts are air pollution, illegal and accidental discharge of oil, hazardous substances and other wastes, and the introduction of alien species and organisms via ballast water and the hulls of ships.

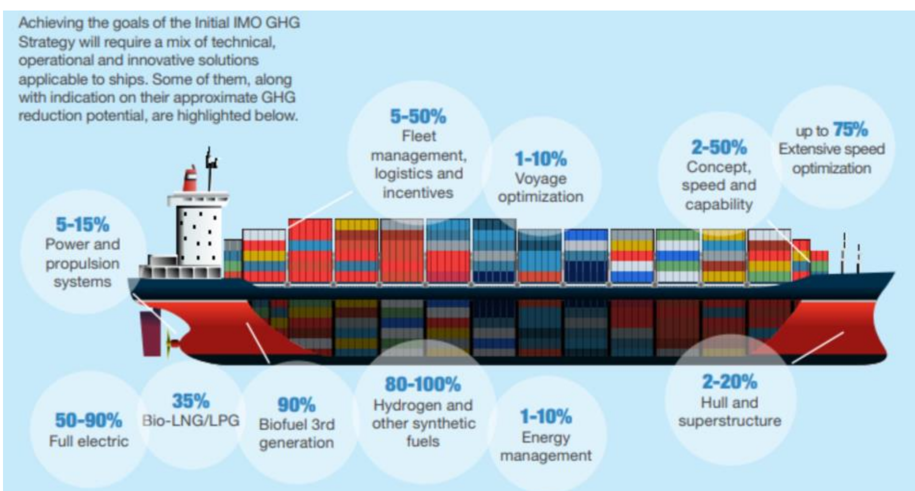

Figure 3 Impacts, influences and emissions [IMO]

The main areas of concern regarding human activities at sea and their potential negative impacts are reflected in the management objectives aimed at maintaining a good ecological status of the environment in the Baltic Sea.

Important in implementing a strategy for the Baltic Sea are:

- Enforcement of international regulations against illegal discharges,
- Safe maritime transport without accidental pollution,
- Efficient emergency response capability,
- Minimal wastewater pollution from ships,
- No introduction of alien species by ships,
- Reduction of air pollution from ships,
- Reduction of environmental threat from offshore installations,
- Optimal interaction between ship and port, crews and landing facilities, and monitoring and enforcement of laws,
- High level of training of stakeholders as well as crews.

1.8 Impact of the pandemic on Clean Shipping

- The pandemic and lockdowns have proven positive and effective for the environment and climate goals: about 10% reduction.
- The transport sector, shipping, made the largest contribution.
- Action by the world's largest emitting countries is not enough.
- A real transformation to a green policy is urgently needed. The pandemic and eventual recovery from it provides a golden opportunity for this transformation.

Global carbon dioxide emissions in the year of the 2020 coronavirus pandemic fell by 7% from 40.1 billion to 37 billion metric tons as a result of action, the largest decline in history since the first industrial revolution. Even before the pandemic, global emissions fell by about 15% to 20%. [2] This was due in part to utilities moving away from coal and toward cheaper, cleaner natural gas and wind and solar power, as well as the retirement of coal-fired power plants. In the U.S., the pandemic-related economic slowdown caused a reduction in greenhouse gas emissions of more than 10 percent. Most of the reductions were in the transportation sector, which remains heavily dependent on fossil fuels. [3]

The pandemic put climate diplomacy behind schedule, with fewer than half of the countries that had committed to higher climate targets by 2020 having done so by the end of last year. [4]

UN Secretary-General António Guterres warned during a virtual event marking the 75th anniversary of the first session of the UN General Assembly, "In the meantime, the global response to the climate emergency has been woefully inadequate." [4]

The annual 2020 Flagship Report (Emissions Gap Report) also notes that the closures have had little impact on emissions. Since 2010 on average, they have increased by 1.4 percent annually and had an even faster increase of 2.6 percent in 2019 due to an increase in wildfires. The projected 7 percent reduction in emissions in 2020 due to the pandemic is equivalent to only a 0.01°C reduction in global warming by 2050. "The fact that a global pandemic and subsequent lockdowns in most of the world's largest emitting countries were not enough to significantly reduce the rate of emissions and bring us closer to closing the gap demonstrates the urgent need for truly transformative green policies. The recovery from the pandemic provides a golden opportunity to do so," stresses Anne Olhoff (co-author of the report, , UNEP DTU Partnership). Inger Andersen, Executive Director of UNEP also emphasizes in this regard that "2020 is on track to be one of the warmest on record, while wildfires, storms and droughts continue to wreak havoc" and calls on governments to focus on green recovery in the next phase of COVID-19 finance and to significantly increase their climate targets for 2021. Compare also Figure 4 and Figure 5. [5]

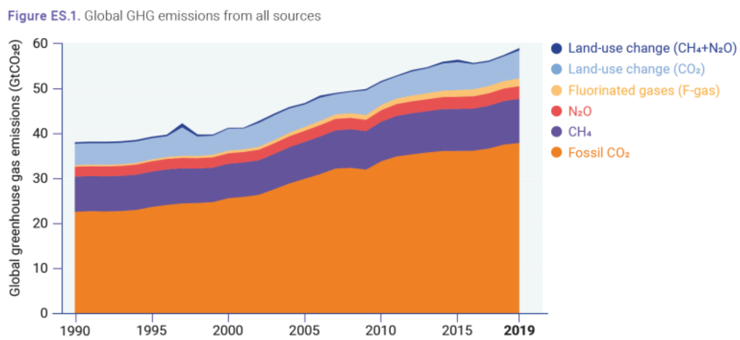

Figure 4 From the Report [5]

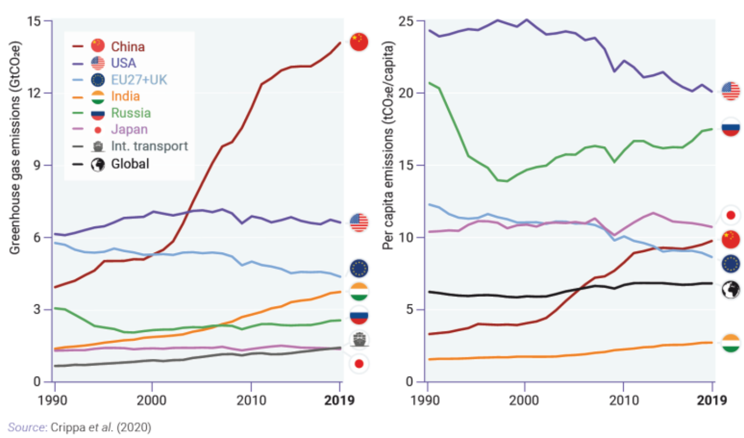

Figure 5 From the report [5]. Absolute GHG emissions of the biggest emitters (exclusive LUC[2]) of international transportation (left) and per capita emissions of the six biggest emitters compared with international average (right).

1.9 Clean Shipping and Zero Emission Ships

Driven by IMO Greenhouse Gas Roadmap (GHG) targets, MEPC 72, Paris Climate Agreement, etc. means that the shipping industry will have to go through some fundamental changes by 2030. The limitation of

[2] Land use change, land use defined by the UN Climate Secretariat as a GHG inventory sector, with a source of emissions and a sink through removals of GHGs resulting from direct human-induced land use change.

sulfur oxides in exhaust gas is regulated by IMO and will be implemented from January 1, 2020. This has resulted in some changes in the market, in the technical equipment of ships, and in operating regimes, such as the petroleum industry and bunkering companies adapting promptly to provide reduced-sulfur fuel.

The changes will require a level of innovation unprecedented in the industry, considering that the introduction of the diesel engine and the development of bunkering infrastructure took decades. The change means adding zero-emission vessels to the fleet, which will make up a significant portion of newbuilds from that point forward. Shipping has been optimized to a fossil fuel "paradigm" for decades and the path to Clean Shipping is not simply to find a substitute for fossil, zero-emission, sustainable energy sources but to change that paradigm." [6] [7]

There is widespread recognition among shipowners of the need for decarbonization as well as Clean Shipping. The introduction of ZEVs as a core part for implementation is welcomed if they are commercially, rentable and technically feasible. In the global economic system, economic viability and competitiveness define the red lines that must guide the implementation of Clean Shipping and ZEV. Certain thresholds apply to shipowners for investments and costs associated with ZEV implementation. Vessel ranges, relative costs, global supply chains, carbon pricing, upstream emissions, and the likelihood of the extent to which ZEV costs can be passed down the supply chain are critical. [8]

The following (Figure 6, Figure 7) illustrates concerns and factors, and the relationships between them, that are important for shipowners from a technical and economic perspective.

- What are the options and which are more appropriate for a ship type?
- How do the options relate to each other and how do they compete?
- What are the additional costs of building and operating ZEVs?
- Can ships be converted?
- What ranges are possible with Clean Shipping technology?
- How do ZEV options compare to the HFO option?

The largest LUC sources, emitters through land conversion (forests to cropland or pasture) are Brazil, Indonesia, and the Democratic Republic of Congo.

The largest LUC sinks, through managed forests, are in China, the Russian Federation, the United States, and Brazil.

In the net balance of LUC emissions, countries with the largest sources are: the Democratic Republic of Congo, Brazil, and Indonesia, and the countries with the largest sinks are China, the Russian Federation, and the United States.

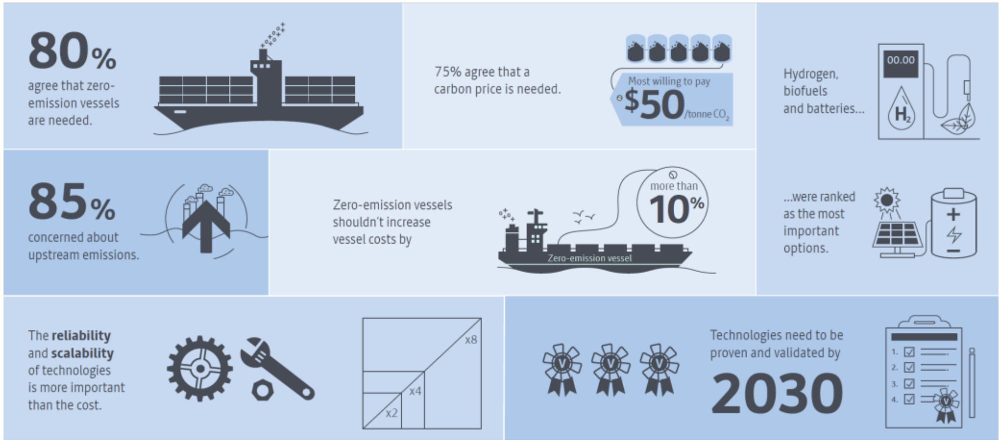

Figure 6 Shipping stakeholder survey responses. Research, by LR Group Ltd and UMAS. [8]

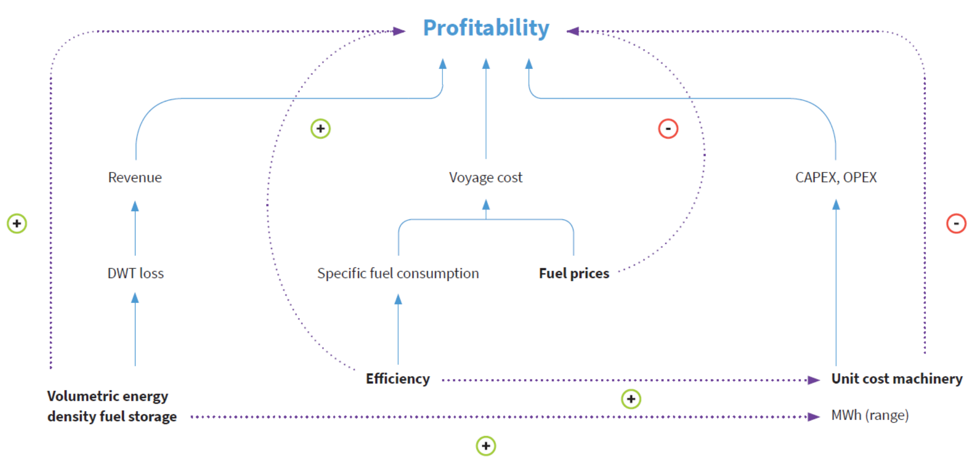

Figure 7 Key drivers of profitability and relationships [8]

2 Control of Emissions from Ships – The State of the Art on Technologies

Tadeusz Borkowski, Przemyslaw Kowalak

2.1 Introduction

Industrialization and growing specialization have created the need for large shipments of goods and materials over substantial distances. Also, economic development increases transport demand, while availability of transport stimulates even more development by allowing trade and accelerating globalization has greatly increased these flows too. In last decades, shipping companies were trying to deliver goods as quickly and reliably as possible. Even higher fuel prices could not stop this trend and resulted costs could be compensated by revenues, following worldwide demand for fast transport. Industrialization and growing specialization have created the need for large shipments of goods and materials over substantial distances. Despite of high volume of transported goods, analysis of the energy consumption and exhaust emissions for ships shows that sea transport, in most cases, is the most environmentally favorable form of transport.

For ships, the energy demand varies very much from one ship to another and even the same ships exhibit great energy demand variations. Energy demand depends mostly on ship size and speed. The most important factor influencing energy consumption is ship's service speed. Economic development and transport are inextricably linked.

Scenarios for future emissions from ships show that effect of greenhouse gas (GHG) from shipping is likely to increase, principally due to an anticipated increase in demand for transport. It is believed that global increase in temperature of 2°C which addresses climate impacts, puts the future emission from shipping in a global context.

Energy efficiency has always been an important factor to minimize ship operational costs, yet it has not always been a focus during design and operation. Since 2011 the energy efficiency regulations are amended to Annex VI of MARPOL and they include the Energy Efficiency Design Index (EEDI), and the Ship Energy Efficiency Management Plan (SEEMP), which come into force in 2013. The EEDI benchmarks the design of a new ship against a reference line giving an allowable EEDI value limit for a given deadweight. The calculation of the EEDI includes parameters that can be used to represent a predicted operational profile of a ship and requires a minimum energy efficiency level (CO_2 emissions) per transport work unit (e.g., ton-mile), for different ship type and capacity. With the level being tightened over time, the EEDI stimulates continues technical development of all the components influencing the energy efficiency of a ship such as; capacity, speed, main and auxiliary engines.

A comparison of the air pollution impacts from shipping with those from land-based sources (e.g., power plants, traffic, farming) has indicated that accumulated harmful emissions of SO_X, NO_X and PM from international shipping are responsible for about 7 % of the total health damage from air pollution in Europe, and the share is prospected to increase. This is due to increase in shipping and decrease of emissions from land-based emission sources. The height, i.e., health-effective layer from shipping is also different causing emission release closer to the surface than stationary power plants, but higher from the ground than vehicles.

At the IMO Marine Air Pollution Committee, more stringent limits for the NO_x and SO_x emissions of marine diesel engines were defined, recently the last stage of SO_X implemented. Combusting marine oils and residuals (MGO, MDO, HFO) all have combined disadvantages in terms of nitrogen oxide (NO_x), particulate matter (PM) and sulphur oxide (SO_x) emissions. Depending on the measures taken to reduce shipping emissions global output will either be enhanced slightly or considerably depending the environmental policy.

Current IMO and EU policies require ship operators to reduce the SO_X emissions on ships operating globally and in a Sulphur Emission Control Areas and there is a need to use of low or ultra-low sulphur fuels or a technology that can reduce emissions to an equivalent level.

As an extension of SECAs, there are areas in which local authority ordinances require a different sulphur limits (equivalent to fuel sulphur content) not exceeding 0.1% or 0.5% -depending on the port. Currently, such areas are found in many Asian and European ports (Hong Kong, Zhejiang, Ningbo, Shenzen, Algeciras). Generally, ships' SO_X emission control means may be divided into methods termed:

- Primary (Pre-treatment) - formation of the pollutant is avoided by means of low or ultra-low sulphur fuel and sulphur free alternative fuels
- Secondary (After-treatment) – pollutant i.e., SO_X, NO_X or PM is formed but removed, prior to discharge to the atmosphere, by means of engine gas cleaning system – EGCS (scrubber, selective catalytic reactor, filter).

An alternative strategy of emissions reduction is to slow down the ship as it is well known, that the fuel consumption and related emissions of cargo vessels is rising exponentially with vessel's speed. Slow steaming is a process of deliberate reduction the speed of cargo ships to cut down fuel consumption and emissions. In many companies a slow steaming procedure were implemented. That was especially effective for fast vessels like container carriers. The slow steaming revolutionized not only economical side of the fleet but technical management as well.

2.2 The SOX emission reduction technologies

The seagoing fleet consumes 7–8% of the world's oil refineries output approximately. Historically, mostly of maritime shipping's global fuel consumption has been residual fuel oil, mainly used by the largest ships. The remaining part of the fuel are consumed by a range of different ships, generally smaller but representing large group of the global fleet. Nearly all these smaller ships use distillates and the only change in 2020 is that the sulphur content in their fuel must be lower than 0.5% globally or 0.1% locally in ECA. It has to be mentioned, that the regulation of sulfur oxides was already enforced earlier, as the Baltic Sea, English Channel and North Sea were defined as SECAs (sulfur emission control area) and the sulphur limit has been 0,1% as of 2015. In 2020, the limit is 0,5% globally and 0.1% in ECAs.

Desulphurisation process of residual fuel oils implies cost and complexity similar to conversion from residual to distillate, while sulphur removal from distillates is common and well proven technology for all refineries. However, both desulphurization methods require substantial capital expenditures. Also, Exhaust Gas Cleaning Systems (EGCS) technology is available to comply with the limits. Presently employed in shipping SO_X abatement technologies are shown in Figure 8.

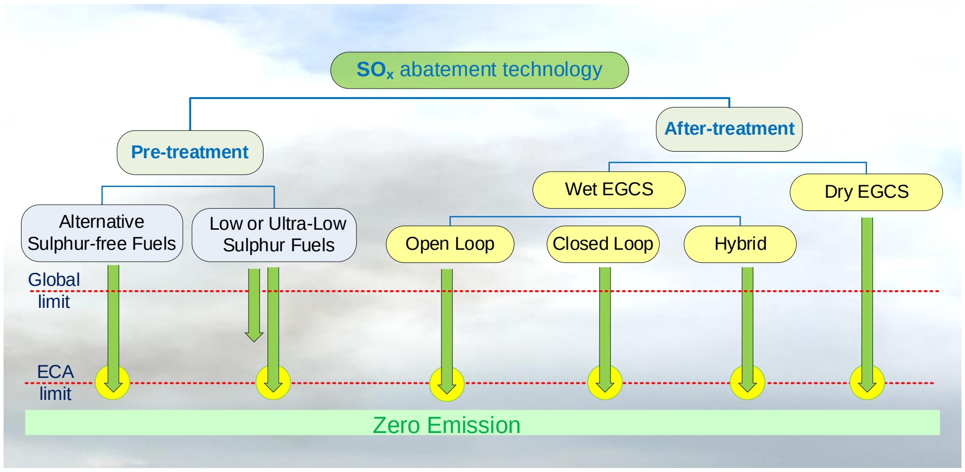

Figure 8 Marine shipping SO_X reduction methods currently in use

EGCS can be used as an alternative to low, ultra-low or sulphur free fuels. The scrubber is a device that is installed in the exhaust gas system of an engine or boiler. It is used to treat the exhaust gas with a variety of substances including sea water, chemically treated fresh water or dry substances so as to remove most of the SOx from the exhaust and reduce PM (Particulate Matter) to some extent. After scrubbing, the cleaned exhaust is emitted into the atmosphere.

In general, there are two types of EGCS systems: wet and dry; with wet systems divided further into open loop, closed loop and hybrid. All types of EGCS - scrubbers achieve the required emission reduction, but create a waste stream containing the residuals of the cleaning process, mainly in form of heavy metal compounds rinsed out from the exhaust gas. There is common concern about the operation of marine EGCS systems in EU ports.

2.3 Wet EGCS method

Scrubbing principally depends on straightforward process in which the exhaust gas passes through a sprayed liquid jet in order to remove the SO_X compounds. The common liquid is seawater, eventually freshwater.

2.3.1 Open Loop EGCS

An open loop EGCS system uses easily available seawater, but such system is effective only if the water alkalinity is sufficient for SO_2 neutralisation. If seawater alkalinity is too low, the sulphur scrubbing process is not adequate to comply with the current SO_X emission regulations. Simplified scheme of EGCS based on open loop principle is shown in Figure 9.

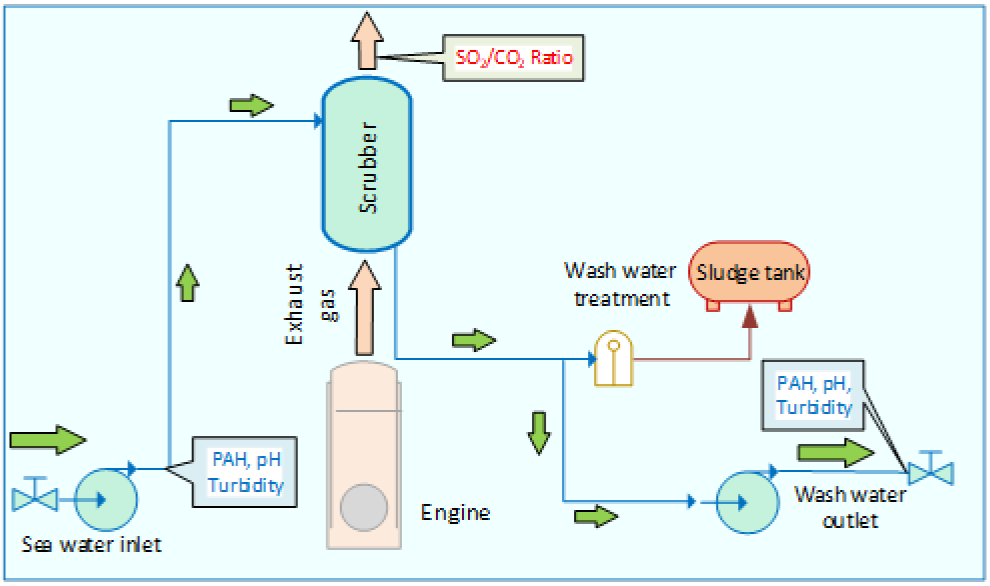

Figure 9 Open Loop EGCS set-up

Seawater is normally supplied by a dedicated pump to a scrubber tower and sprinkled from top against hot exhaust gas stream. Next, the scrubbing water falls to a wet sump at the bottom of the scrubber tower. As SO_X (SO_2 and SO_3) gases are water-soluble, they easily form acid that is neutralized by a natural alkalinity of the seawater, forming soluble sulphate salt, which is found naturally in the ocean. This wash water is removed from the scrubber sump by means of discharge pump overboard. Due to legal limitations, the pH, turbidity and PAH of the wash water discharged must be controlled, therefore the effluent quality is continuously monitored to maintain required criteria.

For areas where more stringent wash water discharge requirement is established, the effluent may be treated by means of additional equipment; hydro-cyclone or separator in order to remove residues. The removed residues usually contain PM, ash, and heavy metals, as well as insoluble calcium sulphate and silt from turbid waters, and must be retained on board and held in a dedicated tank. It must be disposed of at suitable reception facilities ashore. Open loop scrubbers have larger water flow rates than closed loop scrubbers because there is less control over water alkalinity and more water is needed to make the scrubbing process effective when lower alkalinity water is used.

2.3.2 Closed Loop EGCS

In an EGCS of a closed loop type, treated water is circulated through the system to keep the scrubbing process independent of the overboard sea water, see Figure 10. Basically, EGCS closed loop internals are similar to those of an open loop version, and the chemical processes of SO_X removal from exhaust gas is similar. The wash water can be fresh or sea water depending on the design. Specifically, closed loop system is equipped with wash water treatment assembly, that circulates wash water, controls the flow and doses alkaline chemical solution to restore its alkalinity prior return to the scrubber tower. As alkaline chemical, usually sodium hydroxide (NaOH) or rarely magnesium oxide (MgO) is used.

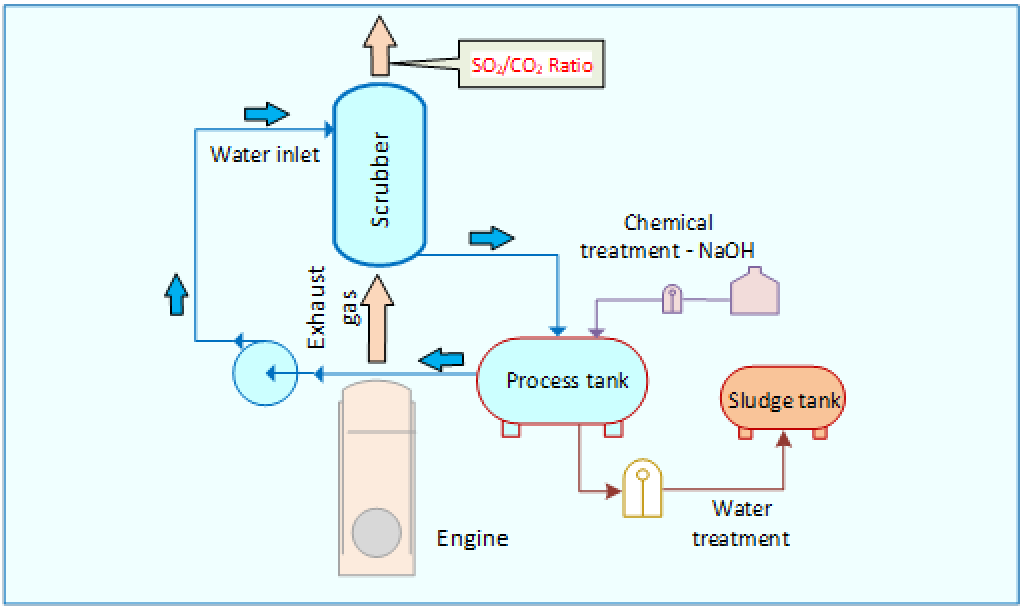

Figure 10 Closed Loop EGCS set-up

In a closed loop system, the used wash water flowing out of the scrubber undergoes reconditioning in a circulating process tank. Make-up water is added to the process tank to replenish the wash water lost in the particulate treatment process, bleed off and evaporation during the scrubbing process. Part of wash water is transferred to a hydro-cyclone or separator, where the residues are removed, or for some systems the extracted water passes through a bleed-off treatment unit. During technological and chemical processes, the cleaned bleed-off water is discharged either overboard or to a holding tank, depending on the ship's location and local regulations. Residual sludge removed from the wash water goes to a residue/sludge tank for further disposal in port.

Consequently, pump circulates the scrubbing water from the process tank back to the scrubber tower. Additionally, water passes through a cooler, before re-injection into the scrubber in order to keep proper temperature. A dosing unit adds caustic soda to the scrubbing water, either in the processing tank or to the water as it leaves the tank, with the amount varied depending on the actual alkalinity of the water. Closed loop system requires about half or less of the wash water flow than an open loop system to achieve the same scrubbing efficiency. Another, not less important difference between the closed and open loop system is that SO_2 does not react with the natural bicarbonate of seawater.

2.3.3 Hybrid EGCS

Both versions of the EGCS presented earlier have important advantages that have been used to realize the most complex EEGS hybrid construction. There are advantages of open loop-type systems, primarily simplicity that gives low investment and running costs. However, closed loop system providing similar efficiency, secure independence of where the vessel is operating and there is little or no water discharge making it best suited for coastal, port and inland waters. In order to utilize both advantages of open and closed loop systems, some manufacturers have designed and built hybrid scrubbing system. Hybrid EGCS can be operated as an open loop system when in the open water – away from coast, and as a closed loop system when in a prohibited area or in a low alkalinity water area. The changeover from open to closed loop is done by changing over the circulating pump suction from seawater to the circulating tank, and by changing the wash water discharge from the overboard discharge to the circulating tank. (see Figure 11)

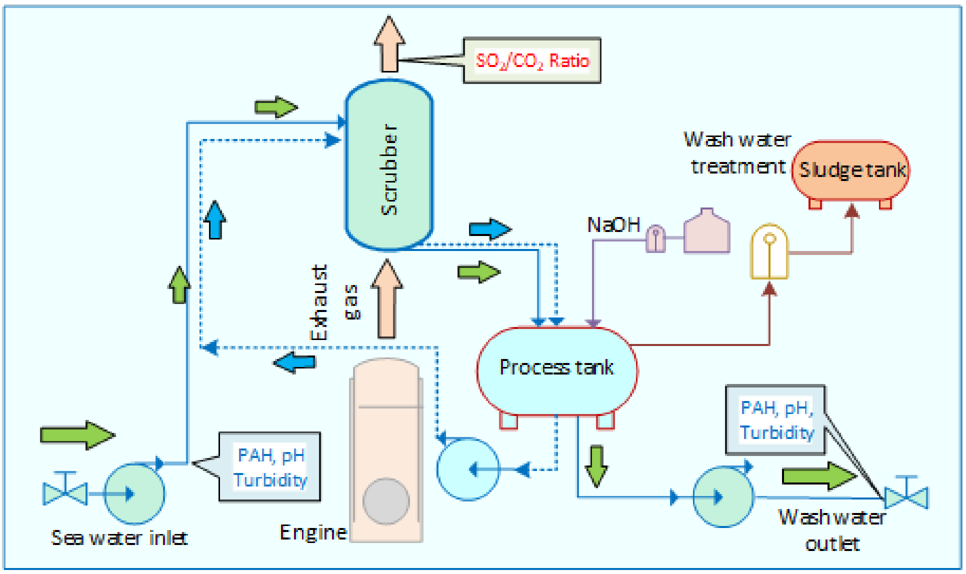

Figure 11 Hybrid EGCS set-up

2.4 Dry EGCS method

A dry EGCS does not use water nor other liquid to carry out the cleaning process. Contrary to wet flue gas cleaning systems, the number of dry system manufacturers is very small, and despite much simpler design, commercial popularity is very low, so far. It may be related to the lack of appropriate operational experience and confirmed operational properties, such as: operational reliability, low operational costs, access to the necessary chemicals and easy waste disposal.

In a dry desulfurization method, the sorbent is mostly of a calcium-type or sodium-type, mainly sodium bicarbonate (NaHCO3). The sorbent is injected directly into a flue gas, where it reacts with the acidic products of the combustion process. A dry EGCS presents attractive and simple mechanical design which does not require bulky housing incorporated in engine exhaust gas installation. The main cleaning process takes place in typical exhaust gas boiler and is assisted with granulated and hydrated lime. The result of chemical reaction with SO_X is calcium sulphate and is accompanying with exothermic effect of heat release. Typically exhaust gas temperature is in the range of 185°C and 380°C, as the reaction is exothermic there is no loss of exhaust gas temperature during the cleaning process.

Due to the prevailing high temperature and properly controlled residence time, the NaHCO3 molecules are activated and are strengthened by the reactive surface of powder. This activation is necessary for the NaHCO3 to react with the sulphur components. Such a process requires a temperature of at least 150 °C. If the temperature of the exhaust gas stream from the engines is higher than 250 °C, a dosing powder is divided and second part is injected after the exhaust boiler. A flow diagram of the dry EGCS facility is shown in Figure 12.

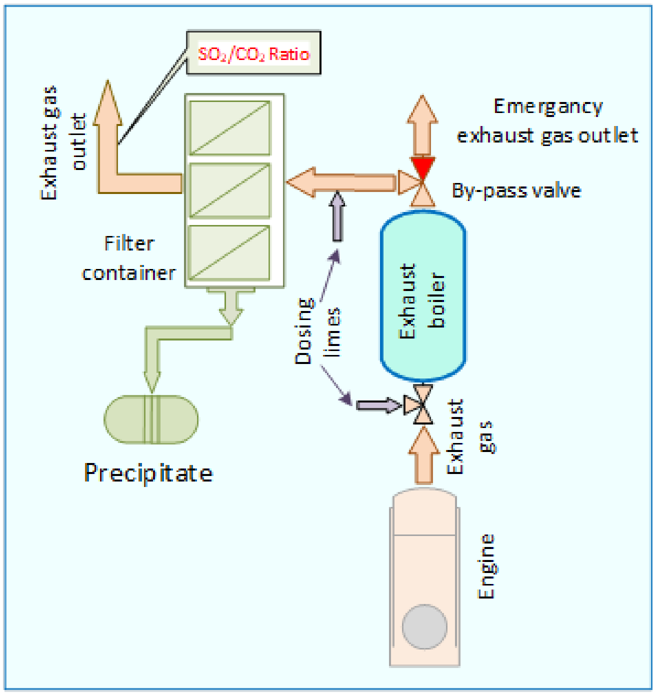

Figure 12 Dry chemically assisted EGCS set-up

Dry EGCS technology would be specifically beneficial if sodium injection systems could be used on exhaust systems equipped with electrostatic precipitators (ESP) to control of particle emissions. Alternatively, mechanical filter system is necessary to achieve high SO_2 removal efficiencies due to the enhanced contact between the exhaust gases and reagent particles that occurs at the filter.

2.5 Emission Monitoring

For EGCS operating on board, exhaust emission compliance with the equivalent fuel oil sulphur content is verified from the measured SO_2/CO_2 concentration ratio.Table 3 shows the required SO_2/CO_2 ratio in a diesel engine's exhaust and the equivalent sulphur concentration in the fuel. If the exhaust from the scrubber has the same or lower ratio value as that tabulated, then the scrubber is considered to be providing equivalent effectiveness.

Table 3 EGCS Sulphur Content Emission Equivalence

Fuel Oil Sulphur Content	Emission Ratio
3.5	151.7
1.5	65.0
1.0	43.3
0.5	21.7
0.1	4.3

Recommended EGCS installation operational parameters which are to be continuously monitored and recorded automatically are chiefly:

- wash water pressure and flow rate at the unit's inlet connection;
- flue gas pressure before the unit;
- flue gas pressure drop across the unit;
- flue engine and/or boiler load(s);
- flue gas temperature before and after the unit;
- flue gas SO_2 concentration (ppm)
- flue gas CO_2 concentration (%);
- wash water pH, PAH and turbidity,
- ship position.

Monitoring system should be capable of preparing reports over specified time periods and the data should be retained for a period of no less than 18 months from the date of recording. The copy of the data and reports should be made available to the flag Administration or Port State Control (PSC) authorities upon request. The emission and discharge measurement details are shown in Table 4.

Table 4 Measurement of emission and discharge details

	Design Requirements	Measurement Method
SO_2/CO_2	CO_2 and SO_2 analyser are to be operating on non-dispersive infrared (NDIR) principle or nondispersive ultraviolet (NDUV) – only SO_2	Sampling probe is to be upstream of the exit of exhaust gas system.
pH	The pH meter is to meet the requirements in BS EN ISO 60746-2:2003 standard or equivalent	The overboard pH discharge limit can be determined by the direct measurement at overboard discharge monitoring position.
PAH	PAH measurement is to use ultraviolet light technology.	To be measured downstream of the water treatment equipment and upstream of

Turbidity	Turbidity monitoring equipment is to meet requirements in ISO 7027:1999 or USEPA 180.1	any wash water dilution or other reactant dosing unit.
Nitrates	Analysis of nitrates is to be based on methods of seawater analysis by Klaus Grasshoff, et al.	

In sea areas where the discharge of EGCS discharge water is prohibited, ships using an EGCS should keep their discharge water on board in dedicated holding tank(s) for discharge into port reception facilities in the next port of call able to accept the discharge water accordingly. However, outside these areas, the stored discharge water could be discharged into the sea in accordance with the discharge criteria given in the Guidelines for Exhaust Gas Cleaning Systems.

Residues from the EGCS wash water are to be collected onboard and delivered ashore at suitable reception facilities that administrations are required to provide under Regulation 17 to MARPOL Annex VI. Discharging these residues at sea or incinerating them onboard is prohibited. It is also mandated by the Guidelines that storage and disposal of such residues are to be recorded in an EGCS log, including the date, time and location of delivery. The EGCS log may form a part of an existing logbook or electronic recording system as approved by the Administration.

The EGCS technology is available in order to comply with the sulphur limits. A scrubber is, indeed, the key component of EGCS but designing the overall system, including all the ancillaries and integrating it into the vessel, is a challenging task. Since distillate fuel is still more expensive than residuals, EGCS have earned moderate attention over the last years and the number of EGCS installed onboard of ships is relatively limited. This can be explained by various factors, such as large investment costs, limited experience with different EGCS types and a variety operational issue. Currently 3,600 ships are equipped with EGCS, see Figure 13 [(see Figure 6)], which is much less than the predicted number. Despite the clearly large increase in the number of ships equipped with EGCS in 2018-2020, which may seem to be a development trend. However, these data should be associated with the dates of the SO_2 emission limitations introduction in the SECA (2015) and globally (2020) and a typical shipbuilding period. Hence, the observed increase in EGCS installed in the recent period may be temporary.

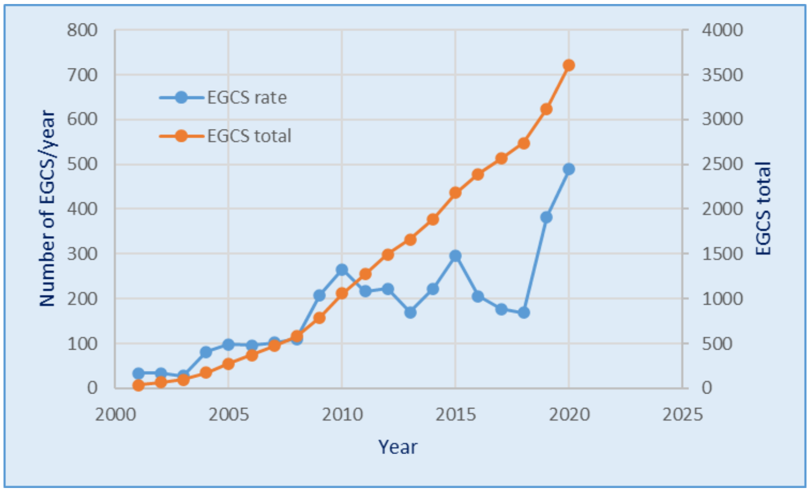

Figure 13 Current EGCS applications on ships

The application profile of EGCS use on different types of ships is also changing quite significantly. In the initial period of SO_2 emission limitation, EGCS was introduced on ships according to individually implemented investment programs, also with the use of state or institutional aid. Hence, retrofitted Ro-Ro and cruise ships were the group of leaders in the EGCS installation quite quickly. Later, when ships built with EGCS became operational, the current - real picture of applications shows the dominant group of ships, which are bulk carriers and tankers, following by container ships, as shown in Figure 14.

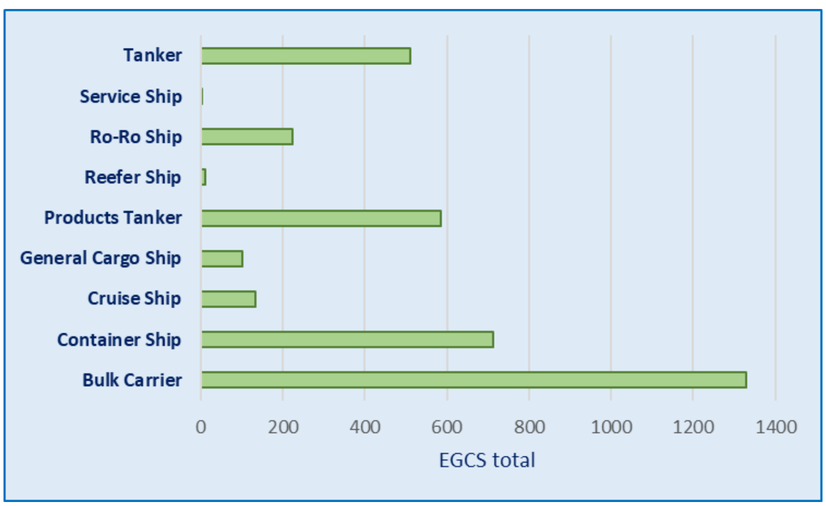

Figure 14 Current EGCS applications on ships

2.6 Air pollution reduction by means of fuel type change over

The introduction of regulations aimed at limiting the emission of sulphur oxides to the atmosphere by sea transport has resulted in many changes, primarily in the way ship fuel systems are operated. The basic means of meeting the emission limits imposed by the IMO has been the combustion of low sulphur fuels, including distillate and hybrid fuels, in designated ship areas. Hybrid fuels have not been widely used in shipping worldwide so far, but their share in the marine fuel market is expected to increase as an alternative to distillate fuels. Trials conducted on ships powered by this type of fuel (hybrid one) have been successful, which encourages the shipowners to use them.

New regulations require from the ship proper maintain of sulphur level in bunkered fuel. Therefore, any contamination of low sulphur fuels with any amount of high sulphur fuel must be avoided. Together with the incompatibility of some grades of fuels, especially hybrid, bunkering, storage and even supply systems are being adopted on new and existing ships. On existing ships retrofit is always expected to reduce the costs of ship operation, however the initial cost are usually high. Such retrofitting carried out on existing ships leads to alterations in operational procedure and frequently alterations in ship stability. That poses additional challenge for the crew – the routines are broken triggering higher risk of incidents. Proper training and familiarization should be provided by the owners especially during starting up.

Entire process of change-over always brings some level of hazard. The exact properties and compatibility of fuels to be used are never fully known on board. The resulting blend properties vary with the change of concentration. There is a number of parameters which has to be observed and controlled at the same time: viscosity, temperature, pressure, engine load. Therefore, even engine makers recommend carrying out the change-over procedure in a safe area, remotely from intense traffic and shore or port vicinity. There are different risks assigned for entering and leaving the SECA. When changing-over to distilled/hybrid fuels a risk of filter blockage, to low viscosity and increased fuel leaks are high. When leaving SECA the highest risk is related to fuel injection components seizing due to thermal expansion.

The clear example is discussion of change-over procedure commencement time. The MARPOL convention requires that the vessel has to use low sulphur fuels in all machinery already when entering SECA. That means, the entire supply system has to be flushed from high sulphur fuels in advance. The flashing time varies and depends on several factors. Some of them, like the fuel supply system volume are constant and specific for every vessel. Other, like actual fuel consumption or fuel sulphation are various and specific for the actual voyage. In Figure 16 the difference in flushing time for various sulphur content of high and low sulphur fuel is presented.

Proper management of fuel on board and selection of fuels with the lowermost sulphur content helps in reduction of flushing time. That reduces the cost of more expensive low sulphur fuels consumption during flushing. The flushing process may take significantly long time in case of relatively large fuel supply system volume and low consumption. An example of such situation may be a container carrier auxiliary engines fuel supply system. If the vessel has high capacity of refrigerated containers carriage, it usually is equipped with three or four even more auxiliary engines. In case the refrigerated containers capacity is not utilized, typically one auxiliary is operating on low partial load, but the fuel supply system remains of high throughput and consequently volume.

In Figure 15 an example of flushing period for container carrier with four auxiliary generators of 4250 kW each and nearly no refrigerated containers on board is presented. Depending on the sulphur contend in fuels used for change-over, the flushing time may take tens of hours. Comparing to the flushing time presented in Figure 16 it is clear that the flushing commencement may differ for various consumers. Finally, the consumer load i.e., the fuel consumption influences the time of flushing significantly too.

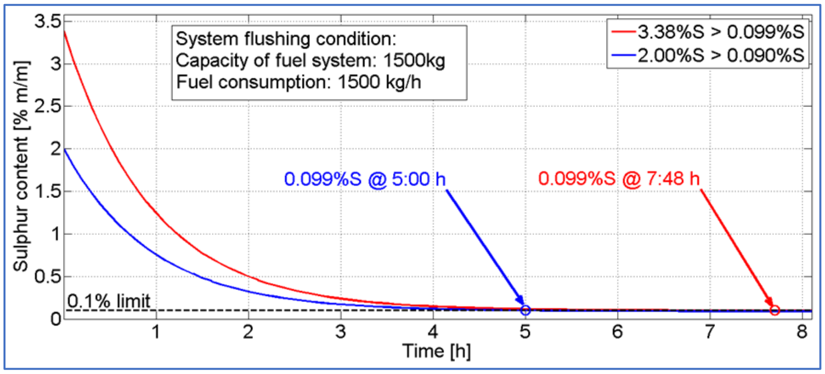

Figure 15 Main engine flushing time comparison for two combination of fuel sulphur content.

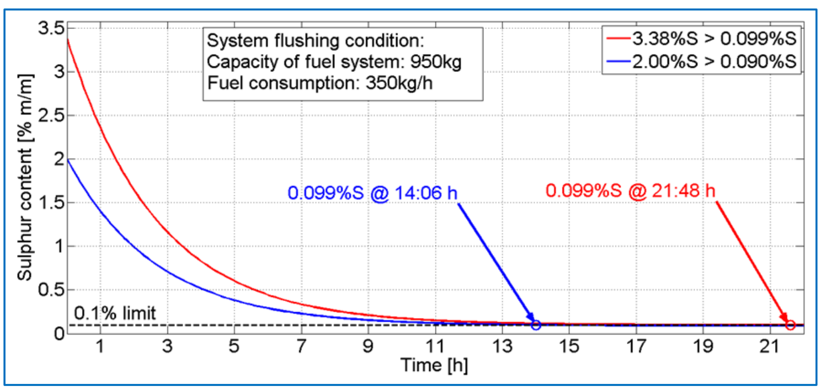

Figure 16 Auxiliary engine flushing time comparison for two combination of fuel sulphur content.

While the main engine load may be relatively easily controlled by adequate vessel speed setting, the load of auxiliaries or boilers depends exclusively on the actual electric or heat load. The crew has very limited means on the load adjustment. The only way is by starting additional unnecessary consumers, what not always is possible. In Figure 17 the flushing time for auxiliary engines in case of two different loads is presented.

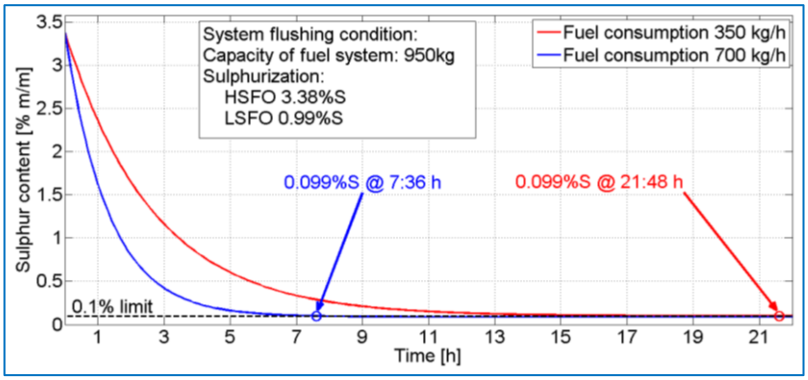

Figure 17 Auxiliary engine flushing time comparison for two for two different loads and fuel consumptions

If the electric load might be increased twice (resulting in approximate fuel consumption from 350 to 700 kg/h), the flushing period would be reduced from nearly 22 to around 7.5 hours. The resulting low sulphur fuel total consumption during flushing period is 5.3 t for high load and 7.6 t for low load condition respectively. Above presented examples prove that the crew may significantly contribute in economic and environmental costs of the process. However, all activities related to fuel management are very time consuming. This is additional burden mainly for engine crew. The time sacrificed for fulfilling SECA regulations has to be derived from other routines as additional crew very seldom was engaged.

In addition to the unequivocally positive aspect of reducing sulphur oxides emissions, there have been many operations related to the use of distillate fuels for the long-term supply of combustion engines in SECAs. The procedures developed by engine manufacturers for changing-over supply from residual to distillate fuel are in many cases only a set of general guidelines, so the responsibility for the correct and safe fuel change-over falls on the ship engine room staff. Due to the properties of distillate and hybrid fuels, it may happen that even though the fuel change-over procedure has been carried out correctly, the engine operation may be disturbed by some equipment, such as filters, centrifuges, heaters, and the engine own components. As a rule of thumb, it is important to follow strictly the recommendations of engine manufacturer and the procedures developed for changing-over the type of fuel used in order to minimize the possibility of failure.

2.7 Marine hybrid fuels

Fossil fuels still dominate the marine fuels market. Ultra-Low Sulphur fuels and LNG are presently most common alternative for conventional residual fuels even if they are still fossil. They are considered as fuels for transition period. The renewable fuels are still at a very early stage of application in shipping, however, several ships were built or retrofitted for different types of biofuels recently. Also, engine builders take a step-in advancement of their technology towards fuels with lower environmental impact. Main reason for slow transition to biofuels is mainly limited availability of biomass and technological issues with compatibility of biofuels properties with presently used materials and technology for engine fuel supply and combustion.

Nevertheless, we are in the down of the revolution in the marine fuels' technology. The conventional fuels derived from crude oil are going to be replaced with renewable fuels of different origin (see Table 5). The transformation period will take some time. Perhaps less than 10 years, perhaps even over 50 years. Because of the large differences in price and in properties, the necessity of switching from one type of fuel to another one arose.

Table 5 Example of substances in use or considered to be marine fuels

	Fossil fuels	Renewable fuels
Gases	LNG	
		Biogas
		Hydrogen
Liquids	Residual fuel oils	
	Distillate fuel oils	
	Hybrid oils (Ultra-Low Sulphur)	
		Bio-ethanol/Bio-methanol
		Plant oils and their derivatives
		Waste cooking oils

The alternative hybrid fuels (Ultra Low sulphur) are produced as a blend of residual fuels and low sulphur distillate fuels to meet the maximum sulphur content of 0.1% required in the SECA. Presently, there are many marine fuels of this grade available on the market. Even though hybrid fuels are produced to meet the IMO SECA limit, they do not always meet the requirements of ISO 8217 standard. Nevertheless, their share of the marine fuel market is expected to increase as an alternative to conventional distillate fuels. Hybrid fuels comply with some of ISO 8217 standard requirements for residual and some for distillate fuels, but there is no standard for this grade available, especially presently.

Therefore, when ordering hybrid fuel from a supplier, the specification should be checked carefully that there are no deviations from the ISO 8217 standard of fuel grade acceptable for the specific engine. In Table 6 some parameters of hybrid fuels were compared with ISO 8217:2017 limits for the two most popular marine fuel grades. While the level of contamination specified by ash and carbon residues meets limits for residual fuels, the viscosity and density of hybrid fuels is closer to limits for distillate fuels. Even more problematic is the range of pour point which is very wide. Differences of hybrid fuels parameters from those conventional makes its storage and preparation for injection very complicated.

Table 6 Comparison of hybrid fuels selected parameters against ISO 8217:2017 limits for two popular grades of fuel

Parameter	Residual fuel RMK700	Distillate fuel DMB	Hybrid fuel oils
Kinematic viscosity at 50 °C [cSt]	700	11 (defined at 40°C)	6 to 65
Density at 15°C [kg/m^3]	max. 1010	max. 900	790 to 915
Sulphur content [mass %]	As defined by purchaser	As defined by purchaser	Max. 0.1
Pour point winter / summer [°C]	30 / 30	0 / 6	-20 to 27 / 9 to 15
Ash [mass %]	0.15	0.01	0.003 to 0.07
Carbon residue (micro method) [mass %]	max. 20	max. 0.30	0.1 to 14
Acid number [mg KOH/g]	max. 2.5	max. 0.5	0.5 to 2.5

2.8 LNG as marine fuel

Natural gas fueled engines are expected as an imperative substitute for diesel engines and the utilization of dual-fuel engines appears particularly promising. Since 2014, the continuous decline in the price of LNG has increased its availability, which, combined with its lower environmental impact and stricter IMO regulations, has sparked growing interest among ship operators seeking to reduce operating costs through dual fuel or even gas technology. International policies and regulations, as listed below, have a key role in the development for the use of LNG as fuel in maritime industry:

1. IMO International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code).
2. IMO Interim Guidelines on Safety for Natural Gas-Fueled Engine Installations in Ships MSC 285(86) (IGF Interim Guidelines)
3. International Association of Classification Societies Unified Requirement M59: Control and Safety Systems for Dual Fuel Diesel Engines.
4. IMO International Code of Safety for Ships using Gases or other Low-flashpoint Fuels – IGF Code.
5. Classification Societies Rules for Gas Fueled Ships.
6. ISO Guidelines for systems and installations for supply of LNG as fuel to ships.
7. ISO Standard Installation and Equipment for Liquefied Natural Gas – Ship to shore interface and Port.

The LNG technology brings substantial changes in ship design, operation, processes and practices that need to be strategically implemented to achieve class requirements compliance regarding safety, reliability, but also operating efficiency, maintenance planning (control and cost), resource allocation and spare parts management in order to achieve specific objective and to address issues as diverse as environmental compliance, class compliance, safety, reliability, operating efficiency, maintenance planning (control and cost), resource allocation and spare parts. Engine room technical issues addresses the following key issues:

- objectives and safety analysis,
- arrangement of hazardous areas and spaces,
- gas-fueled engines and systems,
- gas storage and bunkering arrangements,
- gas piping systems,
- access, airlock and pressurization,
- ventilation systems,
- control systems,
- electrical equipment,
- gas detection systems,
- testing and trials.

The environmental performance of LNG as a marine fuel is analysed using lifecycle approach known as "well-to-wake" (WtW) for ships, see Figure 18. A range of parameters is used to describe the entire lifecycle of a particular type fuel and is usually expressed as CO_2 equivalent emission, per unit of supplied energy (CO_{2eq}/MJ). However, ship operators and engine makers frequently refer to the Tank-to-Wake (TtW) emissions that occur during fuel combustion within the marine engine, and this includes the aspect of engine efficiency only. The TtW approach does not present the whole environmental impact of the specific fuel and in some cases may give a false impression that one fuel is or is not more harmful than others.

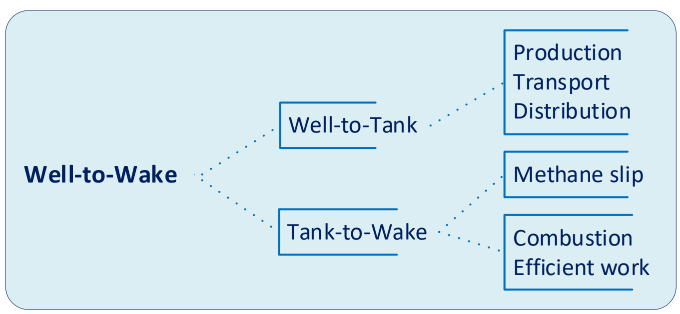

Figure 18 Marine engine LNG lifecycle and related effects analysis structure

Natural gas is a mixture of gases consisting mainly of methane with ethane and propane. Additionally, other components like butane, pentane and nitrogen may be found in various portions depending of the source of origin. In order to facilitate its storage and transport natural gas is liquefied (LNG). This process reduces the volume of the gas by about 600 times. Depending on the gas composition the liquification process under atmospheric pressure takes place at temperatures of about -162°C (111K). Due to the extremely low temperatures this is called a cryogenic process and cryo-liquid. The composition of LNG may vary significantly, what influences the kind storage and combustion properties of the gas. Table 7 shows typical boundary limits of LNG.

Table 7 Typical boundary molar contents of LNG composition

Component	Chemical symbol	Boiling temperature [°C]	Lower limit [%mol]	Upper limit [%mol]
methane	CH_4	-161.5	87 %	99 %
ethane	C_2H_6	-89	< 1 %	10 %
propane	C_3H_8	-42	< 1 %	5 %
n-butane	C_4H_{10}	-0.5	< 1 %	> 1 %
iso-butane	C_4H_{10}	-12	< 1 %	> 1 %
pentane	C_5H_{12}	36.1	< 0.1 %	< 1 %
nitrogen	N_2	-195.8	< 0.1 %	1 %

Presently there is no standard available for a natural gas and LNG as a marine fuel. Physical properties of LNG are shown in Table 8. Under typical storage conditions LNG is unstable and has a high sensitivity to temperature changes. Some fractions of lower boiling temperature tend to evaporate earlier causing an increased pressure in the storage tank. To avoid this over-pressurization vapors have to be released to consumption or to the atmosphere or for reliquification. Releasing to the atmosphere is environmentally harmful, the reliquification consumes energy and is therefore not economical. Using LNG as fuel for combustion engines after regasification is the same as of using natural gas.

Because of the lack of a standard for LNG as a marine fuel, one of the most important properties to describe LNGs suitability as fuel for combustion engines, the methane number (MN) is used. This is a comparative meaningful parameter, similarly to the octane number used for evaluation and comparison of fuels for spark ignition engines. The MN is used to indicate the tendency of the gas fuel to knocking combustion.

Methane is a gas of good resistance to knocking combustion and it was given an index value of 100. Unlikely, hydrogen tends to burn very rapidly, and it was assigned an index value of 0. Any fuel gas (natural, biogas or other) which tends to knock similarly to a mixture of 80% of methane with 20% of hydrogen is given an MN index of 80. Most engine makers indicate the lowest MN of the gas fuel, their engines may safely accept. Typically, it is about 80, however some engine makers accept much lower MN index values (Mitsubishi -60, Yanmar-65, Rolls-Royce-70).

Table 8 Typical physical properties of LNG as a fuel

Physical parameter	**Value**
Density [kg/m3]	410 – 500
Specific calorific value [MJ/kg]	42 – 58
Toxicity	Nontoxic
Typical storage pressure	Close to atmospheric
Typical storage temperature [°C]	-162

There are two main advantages of a natural gas used as fuel alternatively to conventional liquid fuel. The first is that the gas is practically free of any sulphur compounds, and therefore engines fueled with gas do not require any additional pre or after processing to fulfil IMO sulphur requirements. There are also no particulate matter (PM) emissions. The second advantage is related to the natural gas chemical composition. Because it consists of a short-chain hydrocarbon the carbon content is significantly lower compared to conventional liquid fuels. According to studies carried out by the consulting group Think step for Society for Gas as a Marine Fuel Limited (SGMF), it is estimated, that resulting greenhouse gases (GHG) emissions may be reduced by approximately 5 to22 % compared to liquid fuels. The differences result from the type of engine, fuel supply and ignition technology and liquid fuel type used for comparison.

2.9 Marine LNG fueled engines

Currently LNG fueled engines are offered for the full range of demand in terms of propulsion power and speed. There are four-stroke medium speed and two-stroke, slow speed and large bore engines. In contrast to classic diesel principle of operation, a variety of gas engines types are available. In maritime transport, two different engine concepts for the application of LNG are currently available: gas fueled engines, exclusively powered by LNG and dual-fuel engines that switch between MDO or HFO and LNG.

Furthermore, dual-fuel operation can be maintained with low and high-pressure gas admission systems (see Figure 179). Dual-fuel engines with combined high-pressure gas injection and diesel pilot flame represent a particularly efficient utilization of LNG. Due to the different combustion characteristics of natural gas compared to MDO fuel, a dual-fuel engine cannot safely achieve complete diesel fuel replacement rates at low or high rated loads and still achieve satisfactory performance at the same time.

The exhaust emission of a gas engine is affected mainly by design and operational adjustment of gas injection assembly, compression ratio and scavenge uniformity. The combustion process is specifically identified by quantitative values (indicated mean effective pressure, maximum pressure, etc.). Therefore, by optimizing the engine combustion and gas admission, these extremes can be fine-tuned to achieve the expected performance. Specifically, dual-fuel and gas engines can comply with Marpol Tier III limit if the lean-burn operation is achieved, which will reduce significantly NO_X emissions.

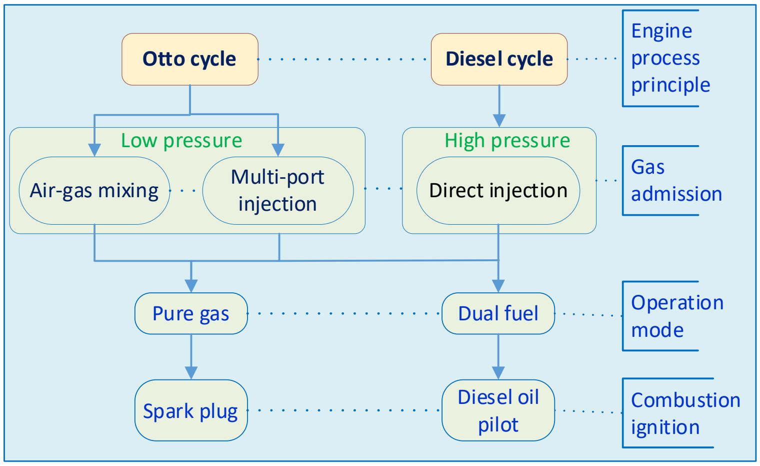

Figure 19 Engine concepts for LNG fueled ships

The efficiency of gas fueled engine is comparable to a diesel engine and due to the LNG lower ratio of carbon per energy content, gas combustion is associated with lower CO_2 emissions. Moreover, the LNG is fundamentally cleaner than conventional fuels with respect to PM emissions. LNG engines have, however, a side-effect – namely methane slip which is associated to emission of unburnt gas, mostly methane. Methane slip from gas engines can be divided into two categories:

- operational emissions;
- engine emissions.

Operational emissions occur under certain operating conditions when methane is released into the atmosphere. Understandably, the release may take place not only in the engine but also in the supply chain from the terminal all the way to the engine supply system. Emissions may be caused by accidental gas leaks in pipe connections, couplings, etc. during refuelling operations, as well as during storage on land and ship. There may also be minor methane releases caused by safety valves, when the storage or transfer system is over pressurized, or caused by safety venting system, like gas leaks detection. The engine emission is related directly to the engine specific construction and principle of operation. One of the main engine methane slip sources is considered flame quenching inside dead volumes of a combustion chamber or inside the boundary layer near a cylinder wall. Crevices in the engine combustion chamber, cold cylinder liner wall, and scavenging process have a big impact on methane slip.

Methane slip is a subject of increasing attention and is currently a major challenge for low-pressure, dual-fuel engines. The global warming potential of methane is much higher than that of CO_2, so methane slip in LNG engines may reduce their GHGs benefits. The problem is partially solved in high-pressure dual-fuel engines where due to the principle of gas admission; methane slip may be considered negligible comparing to low pressure gas admission engines, but still the operational slip over the entire LNG supply chain exists.

However, the most popular contemporary LNG engines with premixed lean-burn combustion process have two major flaws, one being methane slip and the other being abnormal combustion, called knocking. Knock combustion, also known as detonation combustion, is defined as combustion which runs in an uncontrolled manner and causes a rapid pressure increase in the combustion chamber. It results in a strong shock wave, which is transmitted in the form of vibrations to the engine body and shaft line bearings. Several design and operational factors may lead to knocking, but crucial influence is dedicated to air-fuel (gas) ratio that has to be controlled within a narrow range. Engine knocking is a destructive phenomenon, which creates both mechanical and thermal loads to main components of the engine. Prolonged exposure to knocking combustion may cause a serious damage to the engine.

One of the objectives of the Envisum project was to assess the energy and environmental performance of LNG-powered ships. To this end, an analysis has been carried out to identify the number of vessels and the type of engines fueled by LNG. The total number of gas fueled ships in service, given by IHS database at the end of 2020, is 565 and more than half of them, i.e., 298 are LNG or combination LNG/LPG tankers. However, most of these ships are equipped with a multi-engine main propulsion, thus the number of main engines (excluding auxiliaries) on these ships is 988 out of total 1650 units, see Figure 20.

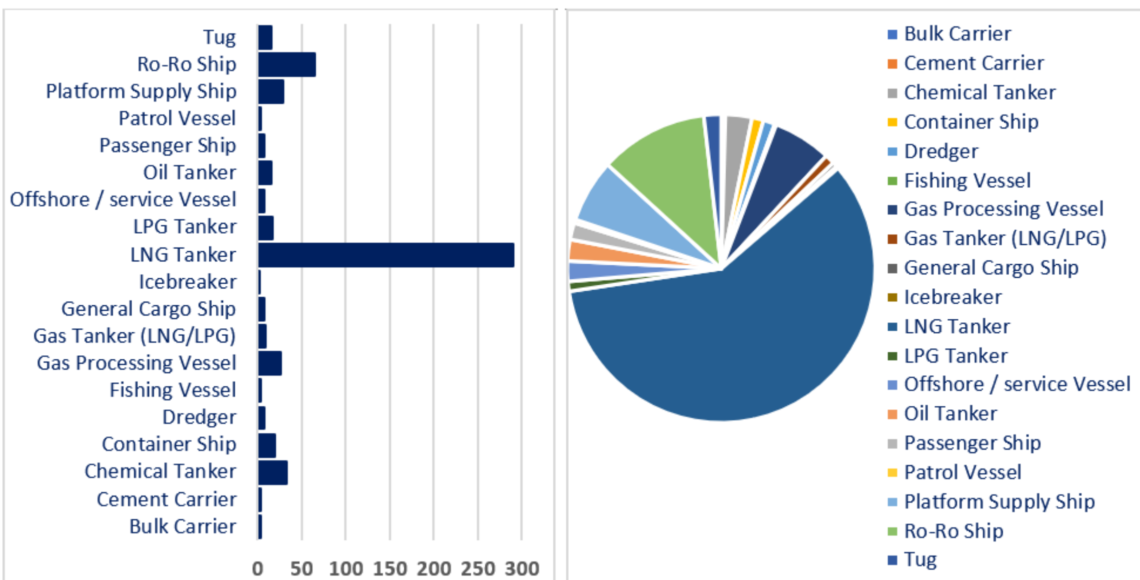

Figure 20 Number of LNG fueled ships and relevant ship type distribution

Similarly, Ro-Ro ships are equipped with multi-engine main propulsion systems and they use usually 4-stroke, medium-speed engines. Noticeable increase in the number of ships with multi-engine Diesel-Electric (D-E) propulsion systems is due to its advantages, mainly:

- Lower fuel consumption and emissions, compared to conventional indirect propulsion system with controllable pitch propeller (CPP) and separated auxiliary engines. The gensets in operation can run on high loads with high engine efficiency. This applies specially to ships with a large variation in power demand.
- Better hydrodynamic efficiency of the propeller. Usually D-E propulsion plants operate a fixed pitch propeller (FPP) via a variable speed drive.
- High reliability and multiple engine redundancy, which brings unique ship manoeuvrability.

- Efficient performance resulting from high electric motor torques at low speed.

It can be anticipated that further structural development in the area of electric power and dual fuel engines will be applied for a large segment of ships.

So far, the use of 4-stroke, medium-speed, gas and dual-fuel engines has been predominant - 1349 out of 1650 units (see Figure 21). In this engine category, due to the method of combustion initiation, there are two types of engines - spark ignited and liquid fuel pilot injection. In this type of marine engines, the global production tycoon engine maker is Wärtsilä, which provided 980 units, based on a confirmed family of engines, as shown in Figure 11. It was, therefore, natural to choose 12V50DF engine for the research (Envisum program) as the most representative of the entire dual-fuel engine population as currently installed on LNG fueled ships.

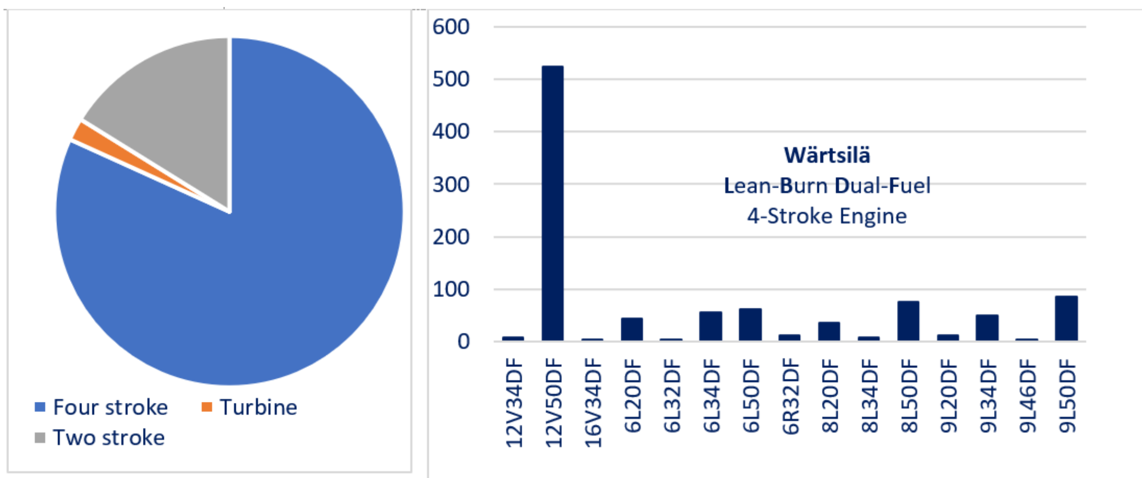

Figure 21 Quantitative relations of different types of LNG engines (left graph) and popular Wärtsilä dual-fuel engine family (right graph)

Sea service tests were conducted on a ship with a Diesel-Electric propulsion system consisting of four Wärtsilä 12V50DF engines. One of the most important aims of the research was to determine the energy efficiency of the ship main propulsion gas consumption. As an example, Figure 22 presents a comparison of actual (Service) indicator - specific natural gas consumption (SNGC), standardized to ISO conditions (including fuel LHV of 42 700 kJ kg), with the new ship performance (after completion of construction and sea trial).

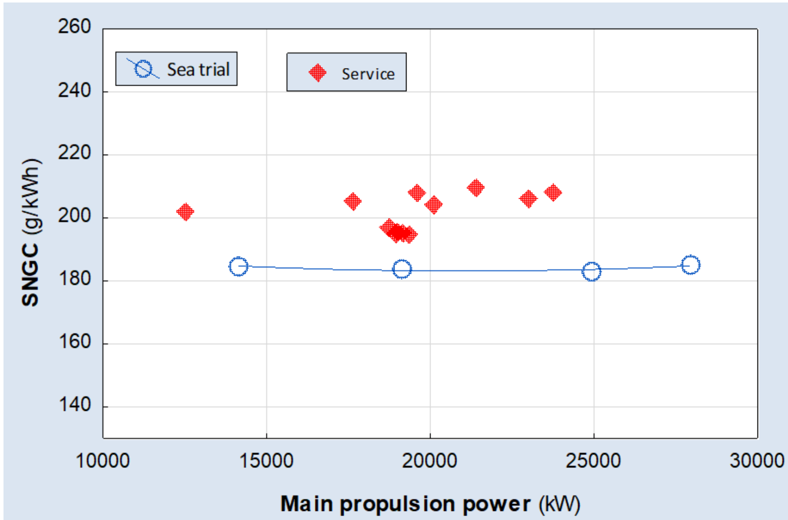

Figure 22 The comparison of SNGC for LNG fueled ship

There are currently no requirements regarding methane slip from gas engines and measurements of methane slip are not included in the Classification Societies regulations and certification processes. For natural gas fueled engines, the methane slip from the incomplete combustion process should be included evaluation of a gas-fueled ships total GHG emission. To obtain methane emission data from gas engines in real operation, measurement tests were carried out on a testbed engine at manufacturer's premises and another on an engine utilized in an industrial co-generation plant. Methane-specific emission factors are determined based on measurements and calculations of fuel and emission data in accordance with ISO 8178 (see Figure 23).

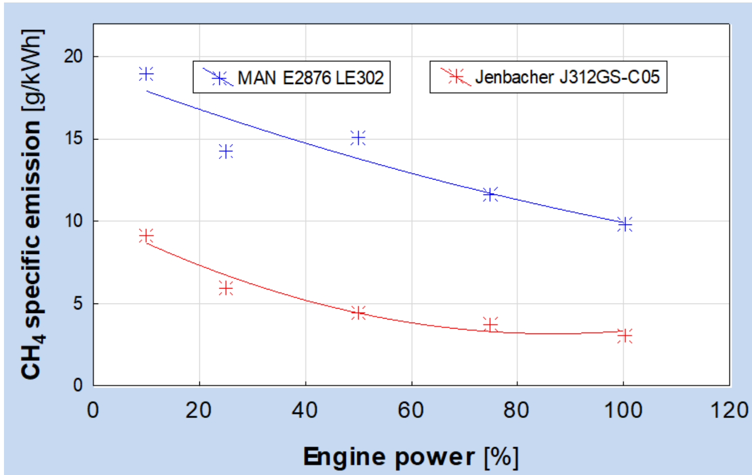

Figure 23 Methane specific emissions from spark ignited gas engines

2.10 Ship's slow steaming an ultimate solution of emission limits

The scenarios for future emission from ships show that the emission of greenhouse gas (GHG) from shipping is likely to increase, principally due to an anticipated increase in demand for transport. It is believed that a global increase in temperature of 2°C which is related to climate impact places the future emission from shipping in a global context. Already in 1997, the MARPOL Conference adopted a resolution on "CO_2 emissions from ships", inviting the IMO to undertake a study on the quantity of GHG emissions from ships and to consider " feasible GHG emission reduction strategies". The MEPC adopted a resolution and provided indexes of greenhouse gases emissions from ships as well as possibilities for the reduction of these emissions through different technical, operational and market-based approaches.

These instruments capture the largest amount of emissions under the scope and allow both technical and operational measures in the shipping sector to be used. A mandatory limit on the Energy Efficiency Design Index for new ships is a cost-effective solution that can provide an incentive to improve the design efficiency of new ships. However, its environmental effect is limited because it only applies to new ships and only incentivizes design improvements, while operation is unaffected. One of the obvious operational measures that is contemplated to reduce emissions is ship speed reduction. This is particularly true for high-speed ships: container ships, RoPax, ferries and other ships that go faster than the average. Also, a reduction in speed may have undesirable side-effects and may include the need for more ships in the fleet.

Slow steaming is a process of deliberate reduction of the speed of cargo ships aimed at cutting down fuel consumption and carbon emissions.

In many companies a slow steaming procedure was implemented, which was especially effective for fast vessels like container carriers. Slow steaming revolutionized not only the economic aspect of the fleet but technical management as well. In many cases the ship owner, the ship technical operator and the charterer are not the same companies. In such a situation, conflicts of interests can be observed frequently. The charterer's fuel cost reduction policy leads to increased wear down of selected parts of machinery and frequently reduces time between overhauls.

With slow steaming, a container ship travels at a speed of around 12-19 knots instead of the usual 20-24 knots. This results in the reduction of necessary engine power and consequently fuel consumption. Slow steaming has successfully helped ship owners in reducing the amount of fuel needed to run ships, which in turn has led to a significant decrease in carbon emissions. Slow steaming has been adopted by the majority of companies and ship owners in order to survive in the tough times of rising fuel prices and financial recession. The pressure to reduce carbon emissions and improve ship efficiency has also pushed shipping companies to implement slow steaming on their ships.

Slow steaming has been a strategy much employed in difficult trading conditions, where fuel prices have steeply increased and freight rates have remained low. Slow steaming may also be seen as an answer to merchant fleet overcapacity. In parallel and given that time at sea increases with slow steaming, there is an increased interest to investigate possible ways to decrease time in port. One possible way to minimize disruption and maximize efficiency is the prompt berthing of vessels upon arrival. By reducing speed and arriving at port in a given time window instead of arriving early and waiting for cargo operation, a ship operator may reduce operating cost and simultaneously reduce emissions by a substantial amount.

However, it should be noted that the reduction of port time may not be possible, as this depends on a variety of factors that may concern either the ship, or the port itself, or both. On the other hand, especially container ports are more advanced in terms of structures and procedures than other ports and most operations are performed in very efficient manners; thus, there is only little room for improvement. But if time in port can be reduced at all, it can be a crucial factor to reduce ship total emissions. Furthermore, even in the case where there is no waiting time, speed reduction can be beneficial for the shipper when bunker prices are high and market rates are low.

Since its initial introduction, the slow steaming concept has increasingly been adopted by the world's shipping. There were also signs of a trend among shipping companies to use the financial gains from slow steaming as a competition parameter. However, mostly propulsion engines are designed to run constantly at full load, a situation that is typically not the optimal operational, while slow steaming. This accordingly sets challenges for operators in terms of how to maximize performance and competitiveness under these operating conditions. Apart from running at part-load, there is a number of other ways to further increase the financial return from slow steaming. Actually, operation of the main propulsion engines of ships allows for the categorization of ship sailing at different lower speeds, as shown in Figure 24.

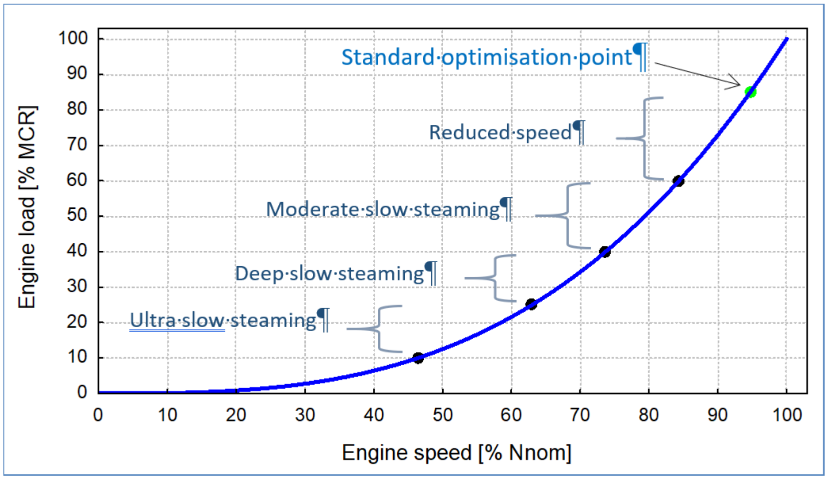

Figure 24 Different modes of ship slow steaming

However, it generates many difficulties for ship technical operators and the crew. It should be underlined and made very clear that the pros and cons balance should be prepared for each individual vessel in order to avoid economic loss and the technical deterioration of the ship.

Energy efficiency has always been an important factor to minimize ship operating costs, yet it has not always been a focus during design and operation. Since 2011 the energy efficiency regulations have been amended to Annex VI of MARPOL and they include the EEDI, and the Ship Energy Efficiency Management Plan (SEEMP), which come into force in 2013. The EEDI benchmarks the design of a new ship against a reference line giving an allowable EEDI value limit for a given deadweight. The calculation of the EEDI includes parameters that can be used to represent a predicted operational profile of a ship. The EEDI requires a minimum energy efficiency level (CO_2 emissions) per transport work unit (e.g., ton-mile) for different ship types and size sectors. With the level being tightened over time, the EEDI will stimulate continuous technical development of all the components influencing the energy efficiency of a ship such as: capacity, speed, main engine and auxiliary power requirements. There are also correction factors for weather conditions and ship types.

The SEEMP is a management plan that should be constructed specifically for a ship, detailing the suitable operational measures that can be implemented, and the personnel responsible for the implementation. In general, the performance of a ship in service is different from that obtained on shipyard sea trial. Apart from any differences due to loading conditions, and for which due correction should be made, these differences arise principally from the weather condition as well as fouling and surface deterioration of the hull and the propeller. The influence of the weather, both in terms of wind and sea conditions, is an extremely important factor in ship performance analysis. Consequently, the weather effects need to be taken into account if a realistic evaluation is to be made. The primary role of the ship service analysis is a standard of performance data under varying operational and environmental conditions. The resulting information derived from this data becomes the basis for an operational and chartering decision. In addition, the role of the data records is to enable the analysis of trends of either the hull or the machinery, from which the identification of potential failure scenarios and maintenance decisions can be derived.

Historically, slow steaming is not a new phenomenon and it has been widely adopted in response to the high bunker fuel cost or the slump in demand and oversupply of ships. Speed restriction in the road and rail sectors is commonplace - mainly for safety and environmental reasons. Generally, global and strong speed restriction in the shipping sector is not appropriate as it limits flexibility and will have negative safety, logistics and cost implications and will also result in a poor economic outcome due to the need to build and operate additional ships.

Currently, environmental aspects without any doubt demand significant attention, in particular when considering the IMO regulations and the international pressure for environmentally- friendly shipping. When looking at these container market issues, a slow steaming consideration can be approached from various sides. We assume that slow steaming represents a fairly wide speed reduction. However, even within service, the ship speed does not remain constant throughout the year. At the same time, a diversity of technical elements should be considered e.g., the main propulsion of container ships is built to sail at optimum speeds of 18-28 knots and with load factors of 70-90%. When considering a support for the decision in the case of the container shipping industry, there is an issue of energy efficiency of the ship propulsion, especially when combining this with environmental issues.

The basic marine engines performance assessment methodology exhibits the necessity of careful considerations, combining fuel consumption savings and emissions. The manufacturers have equipped some versions of ship engines with control systems, allowing for a reliable and predictable choice of the operation mode, taking into account such requirements; this example is shown in Figure 25.

Unfortunately, the knowledge of NO_X emission indicator is not sufficient to perform the applied calculations of changes in fuel consumption, in these two modes of operation and for low engine loads, occurring during ship slow steaming. It is only the use of information contained in the engine documentation (the Technical File), which is an attachment to the EIAPP Certificate, that allows for a reliable and correct assessment, presented in Table 9.

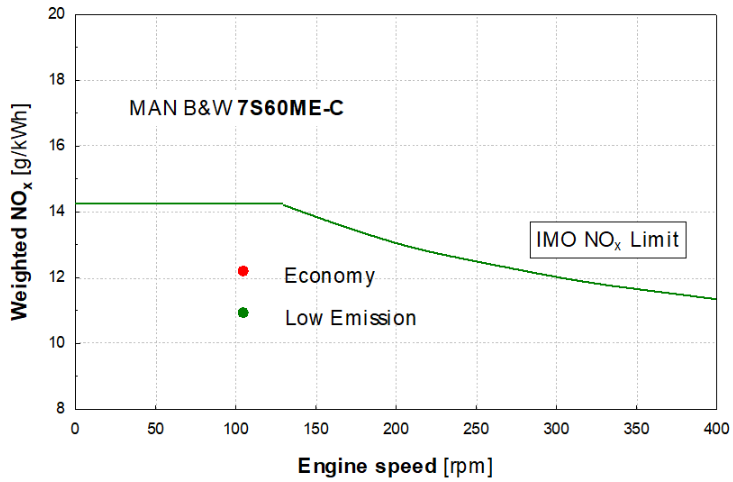

Figure 25 The comparison of the IMO NOX emission factor for a typical main propulsion engine in two operating modes

Such an individual estimation of fuel consumption and environmental impact assessment for a single ship propulsion will be formally correct, but it may turn out to be very difficult when the procedure will have to be applied to more ships and all ship propulsion engines together with auxiliary engines. Also, if one has to take into account weather effects, this could dramatically change the estimation from a static long-term perspective to a dynamic, day by day calculations.

Table 9 The comparison of SFOC and emission main propulsion engine in two operating modes

FOC and Emission	Unit	Engine effective power %				Operation mode
		100	75	50	25	
SFOC	g/kWh	180.1	173.3	172.5	180.8	Economic
NO_X	g/kWh	11.5	12.9	11.3	10.1	
SFOC	g/kWh	180.8	178.5	177.4	193.8	Low emission
NO_X	g/kWh	11.2	11.2	9.53	8.7	

An important component of calculation procedures should also be engine control characteristics, associated with the engine optimization of NO_X emissions. The devices that are responsible for this function in the engine combustion is tuned by the requirements of regulated NO_X emission. As shown in Table 9, [Table 7] this applies both to fuel consumption and strongly changes heat release and NO_X emission rates, depending on the engine load.

The most important question regarding slow steaming is aimed at its sustainability and energy efficiency. There are already a few proven calculation models that enable the estimation of ship performance in terms of fuel consumption and exhaust emissions, taking into account the basic design features of the ship, its main and auxiliary propulsion systems, sailing conditions and the draft resulting from a cargo load.

Assuming a complete access to ship technical documentation, a new model was proposed (Envisum). Basically, the main task of model calculations is to correctly estimate the effective power developed by the main propulsion engine. In the case of a standard selection of ship propulsion engines, the actual engine operational area and relative engine loads are placed between the ballast and the nominal propulsion characteristics (loaded ship, heavy weather conditions), as exemplified in Figure 26.

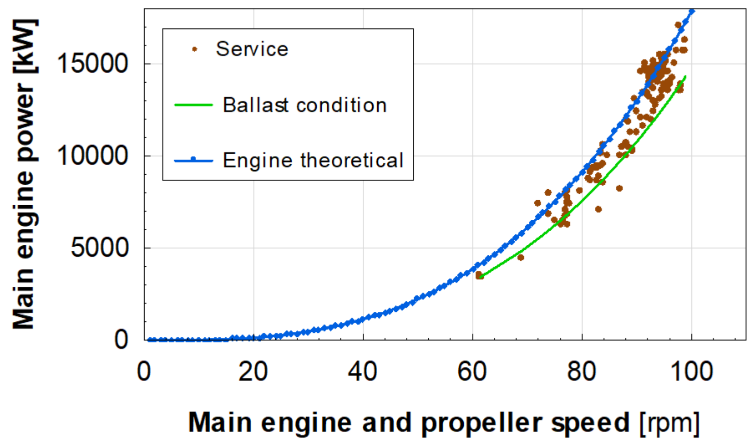

Figure 26 The comparison of model and service main engine effective power

Such a standard relation between the theoretical propulsion characteristics of the ship and its real performance enables accurate estimation of ship performance in various weather conditions. However, modern marine engines allow for the increase of the effective load and, as a result, the operation area shifts significantly, moving the actual loads close to the nominal characteristics. Then, the relevance and correctness of engine power estimation is provided, if rotational engine speed is considered, as shown in Figure 27.

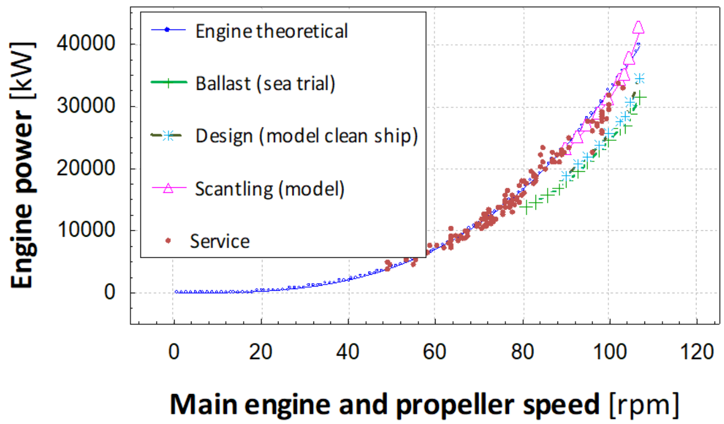

Figure 27 The comparison of model and service main engine effective power in different sailing conditions

At the same time, when considering the main propulsion power estimation, based on the vessel sailing speed, operational area is usually located above the nominal propulsion characteristics and a much larger dispersion can be observed. It becomes particularly important when slow steaming speed is analyzed. An example illustrating this case is shown in Figure 28. The -mentioned example shows how complex the problem of correct estimation of the main propulsion engine power becomes, especially when considering the ship's sailing various conditions like weather conditions cargo load, in particular with slow steaming. Some of the common challenges with today's vessel performance monitoring depends on instrumentation, measuring equipment and practices followed onboard.

There is a significant increase in the attention given to sustainable energy-efficient technologies as mostly emissions increase in parallel with fuel consumption. The driving force behind this development is the implementation of several legislative actions taken by the IMO and EU. It turns out that ships' speed reduction can stimulate effectively energy savings in the design stage, in order to improve EEDI and during the ship's operation for EEOI decrease.

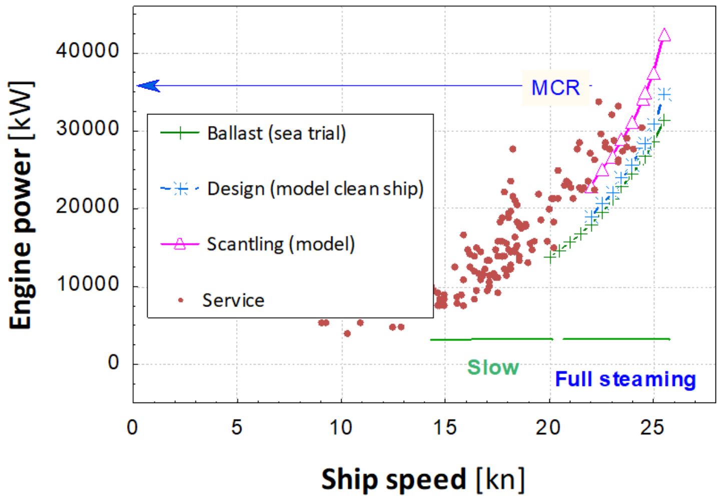

Figure 28 The comparison of model and main engine power based on ship speed

Another fundamental aspect of decision support for the container shipping industry is an issue of economy, especially when combining this with fleet deployment matters. For example, a decision support should reflect the main influencing technical and economic factors, such as vessel characteristics, freight rates, emissions, weather conditions, trim, and objectives, such as cost of emission minimization in parallel with profit maximization. Traditionally, maritime transport services have been divided into three major modes: liner shipping, tramp shipping and industrial shipping. Each mode of operation represents different contract practices and specific key performance indicators for assessing economic efficiency. A convenient starting point for discussing ship's speed reduction measure is division of technical energy efficiency including emissions and structural market instruments

It is important to emphasize that the performance of the propulsion engine should be highlighted as the basic condition for the ship slow steaming speed selection and based solely on energetic and environmental criteria. If the main propulsion unit is equipped with the FPP Fixed Pitch Propeller), the best speed signal is to designate the main engine rotational speed instead of the vessel speed due to the many factors that impact the absolute ship speed (e.g. speed over ground or speed through the water). When such selection is carried out, it is then possible to set the slow steaming speed when typical weather conditions and ship loading cargo are assumed. An example of such a procedure is shown in Figure 29.

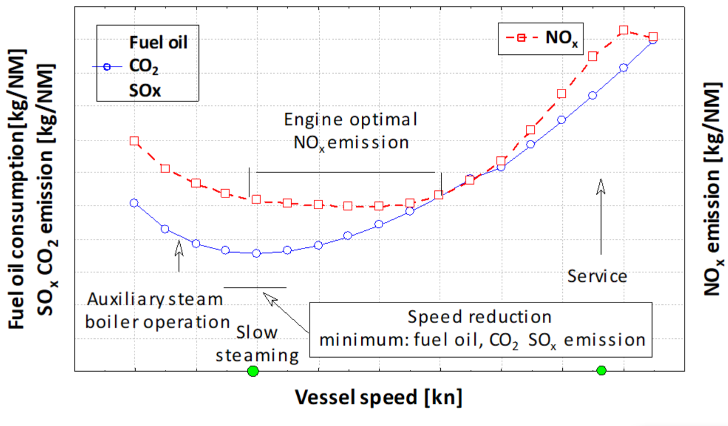

Figure 29 Slow steaming speed selection for FPP propulsion

This also circumvents the issue of sea states and the concern over increasing main engine power when trying to maintain a designated speed in higher sea states (always considering safety and arrival time requirements). Assuming the need to reduce the speed of the ship to an extent lower than the optimum value e.g., the lowest one, it is also possible to determine changes in fuel consumption corresponding to lower sailing speeds, and such an example is shown in Figure 30. It is worth noting that the relative reduction in fuel consumption refers to the distance travelled by the ship.

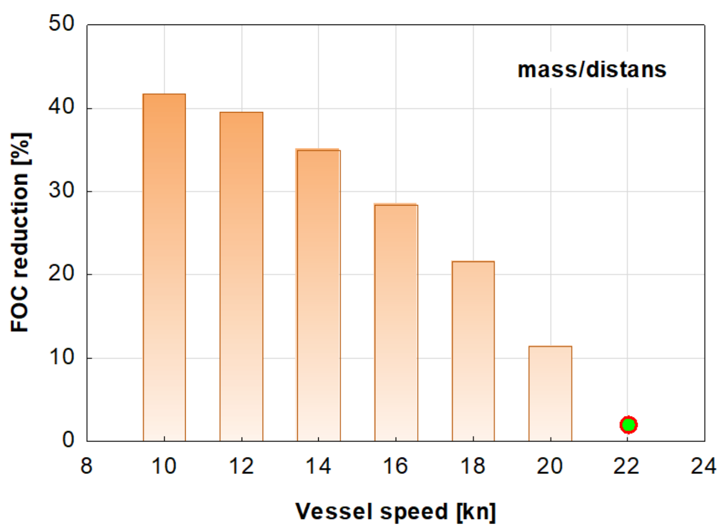

Figure 30 Fuel oil consumption reduction while slow steaming

In this case, it is necessary to estimate the changes in NO_X emissions that will accompany the reduction of ship sailing speed. However, depending on the engine version, NO_X emission changes will be different. If the engine has been optimized for two modes of operation: the economy one and the low-emission one, then the NO_X emission reduction rate in the first mode – the economic mode will only occur in the range of 30% of the service sailing speed.

However, further reduction of the ship speed will not bring relative reduction in NO_X emissions. In the second mode of operation – the low-emission one, the reduction of the ship sailing speed will be accompanied by a constant relative reduction of NO_X emissions up to the maximum level of approx. 70%, even when the ship is sailing at 40% of the service value. The described changes in NO_X emissions are expressed as a mass flow rate to the distance travelled and are shown in Figure 31.

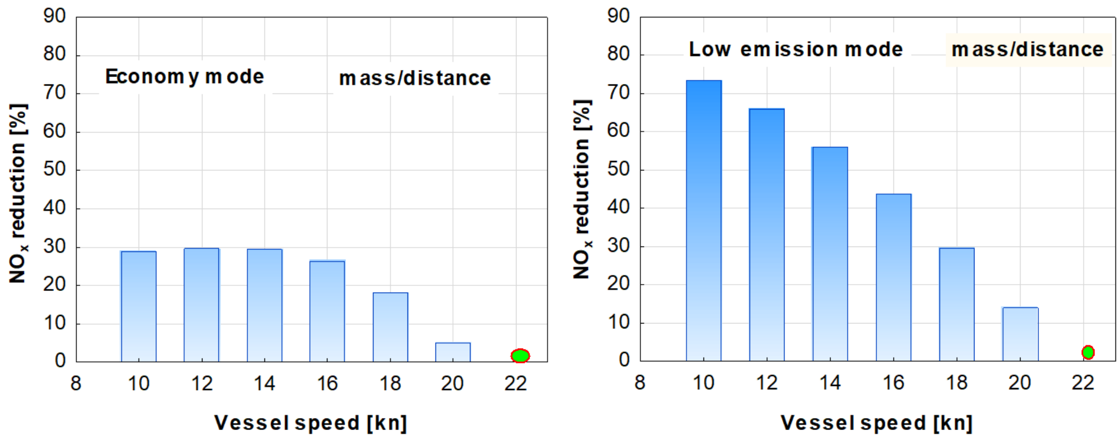

Figure 31 NO_X emission reduction at slow steaming in two modes of operation

To sum up the assessment of ship direct propulsion systems performance at different ship sailing speeds, the following short conclusions can be formulated:

- slow steaming of a ship should be analysed individually, taking into account the main propulsion engine design and operational conditions,
- slow steaming results in lower fuel consumption, while NO_X emissions reduction is dependent on specific engine family adjustments and operational mode, if such arrangements have been provided,
- ultra and deep slow steaming result in minor NO_X emission reduction if the engine is optimized for attractive SFOC.

In the case when the ship indirect propulsion system is considered, the vessel speed control is carried out by means of CPP (Controllable Pitch Propeller) settings. Then the relation of CPP settings to the main propulsion engine and the ship speed can be shown, for example, as in Figure 32.

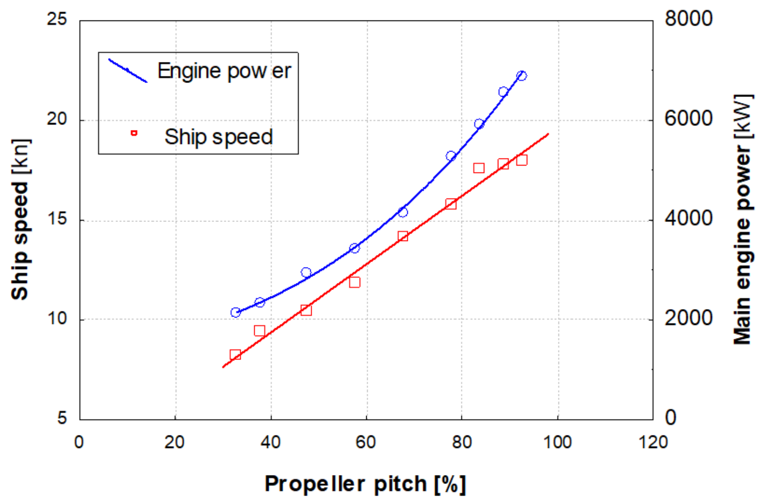

Figure 32 CPP control and main ship performance

Very often shaft generators are used in such propulsion systems to provide better energy efficiency, which enables effective adaptation to different sailing conditions. The measurements made in actual different weather conditions and at different ship cargo loads confirm this important advantage of CPP propulsion systems, as shown in Figure 33.

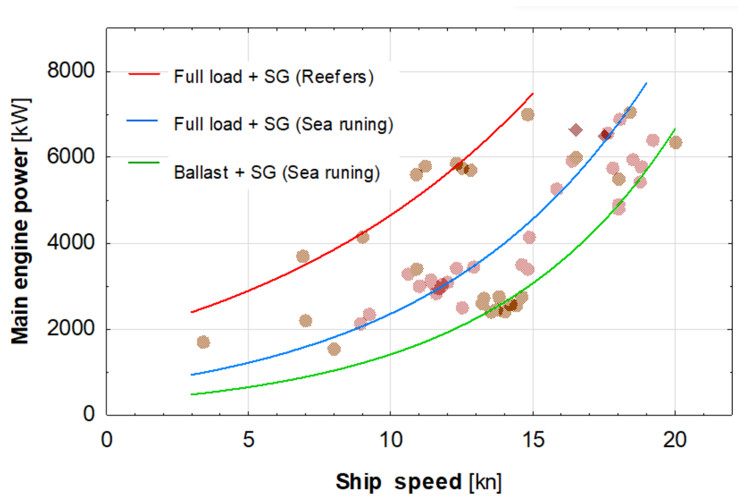

Figure 33 CPP control and main ship performance in different sailing conditions

Finally, for each vessel with an indirect propulsion system and CPP it is possible to develop a matrix of functions, where fuel consumption is determined considering the load of the shaft generator as shown, for example, in Figure 34, where the modelled functions were compared with the actual measured performance of the propulsion system. In order to supplement the propulsion system performance analysis, it is also necessary to assess the fuel consumption and NO_X emission affected by the weather conditions.

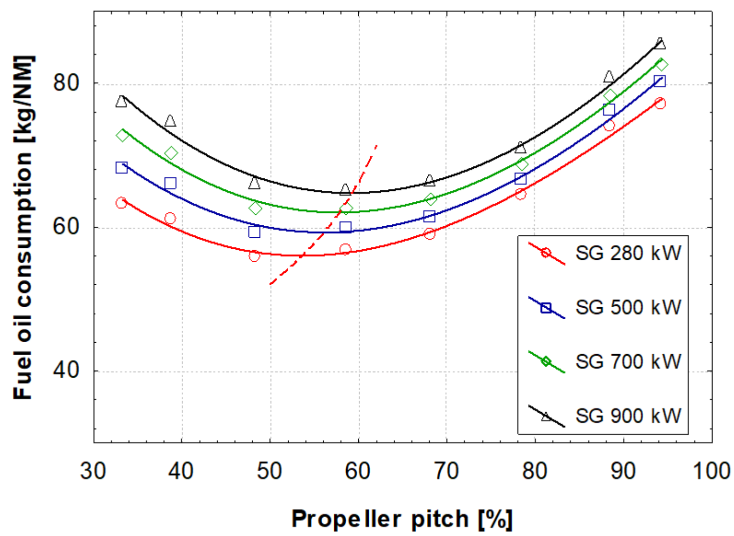

Figure 34 Fuel oil consumption for CPP propulsion unit with SG

Taking into account the vessel's speed reduction, the beneficial decrease of fuel consumption is accompanied by a proportionally high decrease in NO_X emissions as shown in Figure 35 and Figure 36. Deterioration of weather conditions and additionally a shaft generator load increase results in higher fuel consumption decrease and NO_X emissions as well, when the vessel's sailing speed decreases.

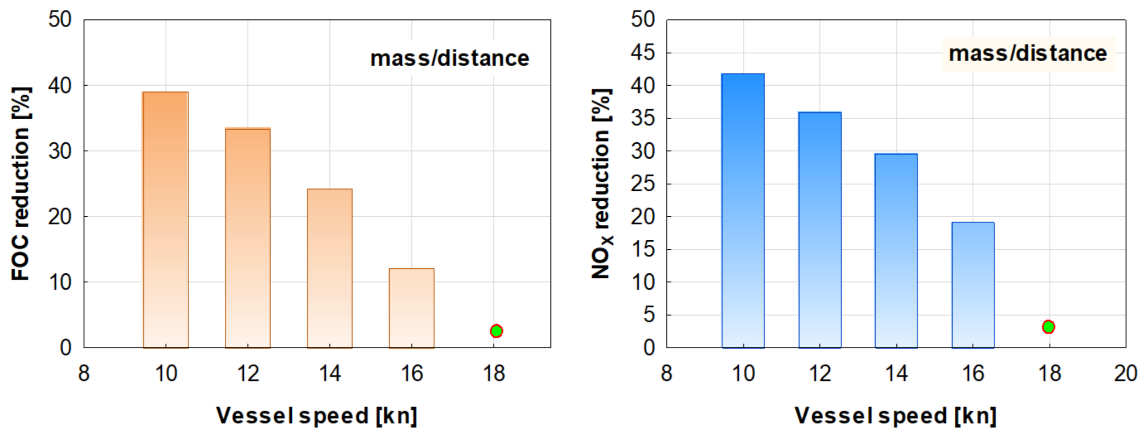

Figure 35 Fuel oil consumption and NO_X emission for a ship operated in moderate weather

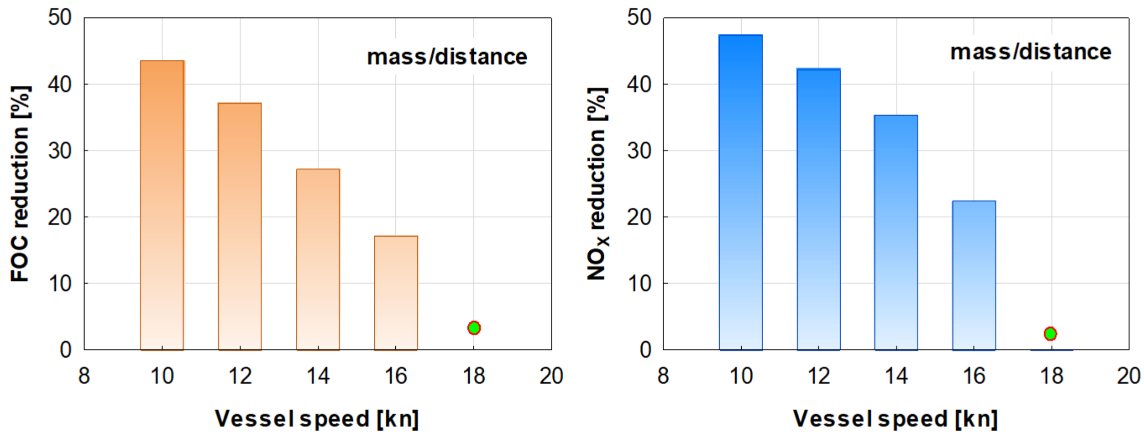

Figure 36 Fuel oil consumption and NO_X emission for a ship operated in heavy weather and high shaft generator load

Considerations regarding slow steaming as a permanent form of marine transport inevitably leads to the need of navigational safety analysis. This aspect is discussed and the results of experimental tests that were carried out onboard during the ship operation (Envisum). Similarly, to the analysis of ship energy performance, validation of modelling results with real manoeuvering parameters, which are documented in the sea trial reports was evaluated and it was concluded that the models satisfactorily reflected the real behaviour of ships. Following the required procedures, the simulations of the most important manoeuvers, determining the ship safety were carried out, such as:

- turning circles and zigzag manoeuvers,
- anti-collision manoeuvers,
- behaviour on the straight section in different external conditions.

The results of model tests exposed a strong need to carry out such an assessment, because of the existing real threat to the ship safety when slow steaming is maintained, which applies mainly to bad weather conditions e.g., it was noticed that vessels had not been able to keep the desired course while proceeding at low speed. The term "low speed" means the individual limit (different for each ship), at which such navigational risk becomes real. Also, other typical ship manoeuvers are affected by slow steaming and due to this the earlier starting of all manoeuvers should be considered.

Finally, there are more technical issues related to slow steaming most of them are well known from the standard ship operation. The slow steaming may cause faster or more intensive development of some of them. The machinery manufacturers, especially engine builders, have been continuously working on solutions and the adequate preparation of their products to a new exploitation model. However, time is needed until such solutions are be found and applied. The slow steaming has been successfully introduced on many vessels of a global fleet in recent years. It has proved to be a very effective way to reduce both the fuel consumption and the exhaust gas emissions. Nowadays it seems to be the most effective way to reduce CO_2 emission and one of the most efficient way to reduce NO_X emission. Because it does not require any additional equipment nor investment, it seems to be one of the cheapest ways as well.

However, all those benefits are not for free. It can be expected that the cost of the vessel technical operation in terms of maintenance and servicing will increase. The vessel management has to investigate carefully how deep slow steaming can be applied and calculate the increased cost accordingly. Many factors like the trading area, customer's requirements, and the type of cargo have to be taken into account. It is of utmost importance that all parties involved: the owner, the charterer, the technical operator, the cargo manager and the crew are well informed of the consequences of prolonged speed reduction and accept the costs. The key to success seems to be distribution of both the benefits and the costs between all the participants. In response to the global demand for slow steaming, manufacturers offer either new engines which are factory optimized for lower load condition or retrofit kits to allow safer operation of older structures at the low load.

3 Technical Energy Transformation Systems for Ship Operation

Alexander John

The environmental impact of shipping is predominantly attributed to the exhaust gases from the internal combustion engines on board ships. The amount, type and composition as well as the resulting impact depend on the fuel used, the technology of the machinery and its mode of operation. This represents the current state of the art / state of play.

Usually, the type of propulsion, e.g. diesel propulsion, is derived from the type of main engine used. Strictly speaking, this is not quite correct. The purpose of engines is primarily energy conversion, e.g. for propulsion, for on-board operation, for auxiliary processes on board, etc.

To systematize the state of the art (state-of-play), we consider energy conversion as a sequence of pairs consisting of energy form (E_i) and conversion principle P_i). the concrete engineering implementations exploit the respective principles of energy conversion, which represents the current state of the art. Through this abstraction, the energy systems known in the shipping industry and alternative variants can be represented for the analysis and classification.

E-in	E_1	P_1	E_2	P_2	E_3	P_3	E_4	Med	P_4	E_out
H		int	R-Gas	F-Cell						
H-C; C	chem	ext	C-Gas	T-Eng	mech	E-Gen	elec	Accu-B	E-Mot	mech
		int		P-Eng						
		ext	Steam	T-Eng						
		ext		P-Eng						
R-Core	nukl	int		T-Eng						
		int		P-Eng						
Wind	mech	ext	Drag	Sail						
Rad	elec	ext	E-Field	TrCvr						
E-Grid	elec	ext	E-Curr	E-Storage						

Figure 37 Abstraction for analysis. For a legend see the Appendix.

The scheme shows the sequence of pairs of energy form (E_i) and conversion principle P_i) with the fuels used, the types of energy, the types of machines for conversion. The colour bars in the scheme mark different variants of systems. For example:

- Yellow: diesel engine. It is known that the redox reaction in a heat engine produces the energy of the reactants (chem) fuel and ambient air a hot working gas (C-gas), which is discharged as exhaust gas after the released (thermal) energy.
  The mechanical energy for the drive can already be decoupled at E_3. For the operation to generate energy for the electrical on-board network, the bar still includes the stages of electrical energy generation (E_out).

- Red: Nuclear drive. The energy conversion process essentially takes place in a closed system that emits no exhaust gases, exhaust air, etc. during operation.
- Green: All-electric drive. The bar is continuous, but certain stages are technologically bridged.

3.1 Analysis

With the chosen system we want to present the state of the art of energy forms, fuels, conversion principles and machine types relevant for shipping. From this, possibilities relevant to Clean Shipping, present and future, can be shown.

- Forms of energy: chemical, electrical and nuclear,
- Principles of energy conversion: ICE, electrical solutions, nuclear solutions,
- Energy machines: Heat engines, reciprocating / turbines, internal / external combustion ,
- Electrical machines: generators and motors,
- Compatibility with fuels,
- Fuels and alternatives: availability, costs, energy densities,
- Power outputs and efficiencies,
- Energy storage: vessels, tanks, electrical energy storage, accumulators, batteries.

From the technical side, the search for solutions for Clean Shipping solutions starts with these factors. Essentially, this is "state-of-play" and strategies for research and development are derived from this.

Fields of action for implementation can be: the improved understanding and better exploitation of principles, the optimization of influencing factors and their interaction with components, the use of alternative energy sources (fuels) and their development and production, as well as optimizations by saving, omitting, shifting energy conversion stages, because the overall efficiency results from the multiplication of the efficiencies of converter stages. As well as alternative technologies.

3.2 Consideration of energy converters as fuel – engine units

Energy converters and (alternative) fuels form a unit and must be compatible. For technological reasons, modifications by changing fuels or operating modes can only be implemented within certain narrow limits. For example, the use of biogenic fuels (biodiesel, vegetable oil, bioethanol) or synthetic fuels (e-fuels, electrolysates, catalysates) or even alternative fossil fuels (LNG, oil blends) as an alternative to the intended fuel requires modifications with more or less effort.

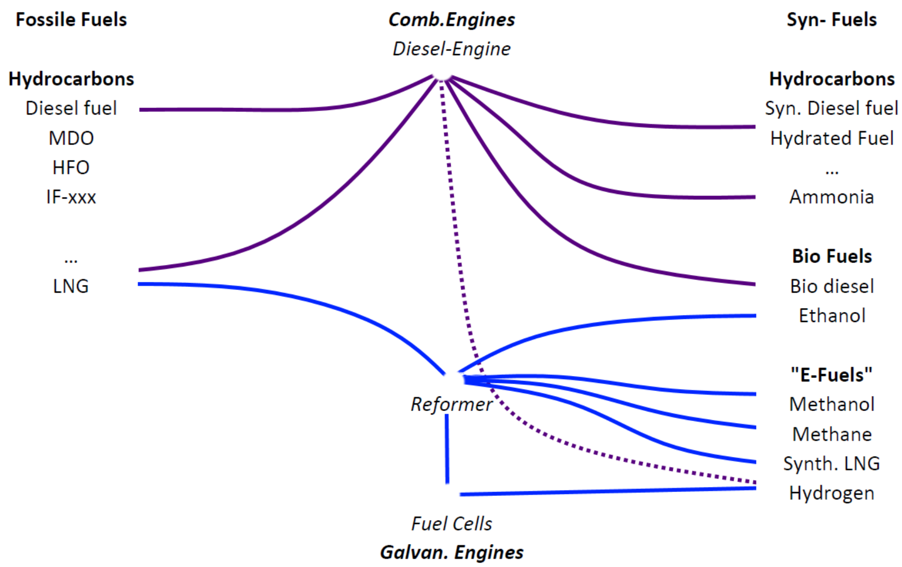

Figure 38 Pictorial representation of the Engine-Fuel context.

3.3 Engines and Fuels

Due to the very close interdependence between fuel and engine, the consideration of energy conversion systems can be approached from two sides, from the fuel side and from the engine side. We thus consider the fuel-machine pairings. The terms energy source and fuel and machine and engine are sometimes used interchangeably.

3.3.1 Engines and fuels

The state of play in large-scale shipping, as opposed to other energy conversion application areas, is faced with challenges such as

- large power outputs for main propulsion and for on-board systems of several megawatts,
- long operating times due to long voyages of several days,
- large demand for energy conversion in general,
- great need for energy carriers (fuel) with the highest possible energy density,
- large need for storage of energy as fuel,
- high efficiency of energy conversion.

With the given physical-technical status, performances in the required range are possible and good efficiencies are achievable. The combustion of hydrocarbons as fuel in heat engines require, on the one hand, corresponding amounts of fuel (e.g. 80 tons IFO/day; HC) and generate corresponding amounts of reaction gases (about 2.7 times the HC amount of CO2 plus other compounds).

The installed state of the art of the plants offer little technological and operational flexibility in terms of energy sources and modes of operation.

The operationally generated exhaust gases can be influenced by

- driving slower,
- driving less, (most radical solution: "no more driving", practiced in the Corona era),
- scrubbing exhaust gases (scrubber),
- driving with other fuels.

The usual daily petroleum consumption of the current predominant fuel and energy source of shipping, before the pandemic, was about 80 million barrels 12.8 million m^3 (159 L / barrel). The supply of petroleum is fundamentally linked to geopolitical considerations.

- reservoirs are controlled by centralized supply structures,
- are linked with global political issues, which include,
- concern security of supply, security policy.
- In the long run, the global political control causes a behavior of economy and consumers towards a reduction of hydrocarbons (decarbonization[3]) and a turn towards alternative energy sources.
- Petroleum companies are responding to this megatrend and are becoming increasingly involved in alternative fuels and energy-saving measures.

[3] The earlier forecasts and warnings about the "peak oil forecast", forest dieback, ozone hole etc. have faded into the background. However, a change is urgent insofar as since the publication of "Limits to Growth" [17] the changes to a sustainable economy were and are not sufficient. But the realization that energy policies are not sustainable is slowly gaining ground.

However, whether the reduction of the energy flow density, as a measure of the development of a civilization, a reduction of human activity against the background of a growing world population is the way to global sustainability, remains to be seen.

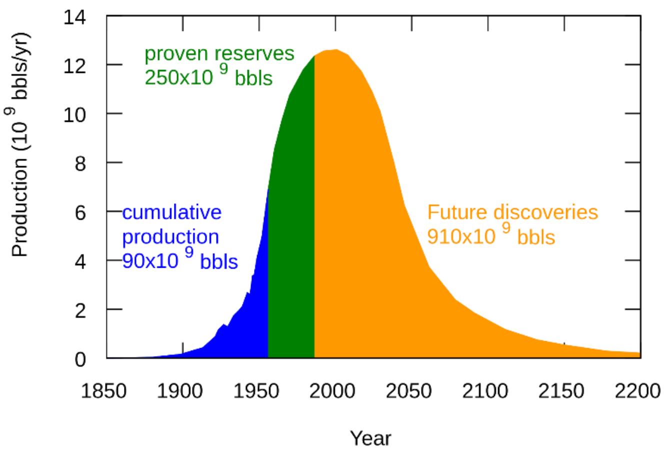

Figure 39 The world oil production distribution, historical data and future production, proposed by M. King Hubbert in 1956. It had a peak of 12.5 billion barrels per year in about the year 2000. As of 2016, the world's oil production was 29.4 billion barrels per year (80.6 Mbbl/day) [9]

3.3.2 Fossil fuels

Fossil fuels as an energy source have a relatively high energy density, they are inexpensive, they can be stored, handled and transported comparatively easily. Currently, these fuels are of great importance to society in general and to shipping in particular. Shipping has been optimized for the fossil "paradigm" for decades. Current technology is further based on the metaphor that only what is physically, materially available can be converted. Since ultimately operation requires an "energy flow" that is produced on board, this metaphor ties technology development to storage, tanks, etc., as well as "carried" potential energy. Even the overcoming of the diesel paradigm, towards alternative fuels does not leave the metaphor of the "material, visible, existing". Overcoming this metaphor is a challenge for the future.

3.3.3 Marine Diesel, HFO, State of Play and Future Needs

By far the most common type of marine fuel used today is HFO (heavy fuel oil). The average sulfur content of today's heavy fuel oil bunkers is 2.7%. Regulations by the IMO that a cap of 0.50% sulfur will apply to marine fuel from 2020 onwards stipulate that only ships equipped with exhaust gas cleaning systems (EGCS, gas scrubbers) can continue to burn the conventional bunker.

Only about one-fifth of shipowners have made appropriate arrangements. All others must use a compliant bunker fuel. The question shipowners must answer is the economics of what impact low sulfur fuel prices will have on the use of gas scrubbers. The vast majority of ships are expected to switch to MGO. This is the easiest path to compliance, as owners will have to make almost zero upfront investment. However, this means higher bunker bills.

A small but growing number of vessels will use liquefied natural gas (LNG) and other compliant, specially designed or modified bunkers. This presents opportunities to manufacture and supply new products.

The reduction of the sulfur cap from 3.5% (IFO380 - Intermediate Fuel Oil) to 0.5% (VLSFO - Very Low Sulphur Fuel Oil) is expected to reduce sulfur oxide emissions. VLSFO meets the IMO requirements. In the ECAs (Emission Control Areas), the 2015 standard remains at 0.1 % sulfur content. This is achieved by ULSFO (Ultra Low Sulfur Fuel Oil).

3.3.4 CSHIPP working group

CSHIPP (Clean Shipping Project Platform) organized a policy workshop with the HELCOM Secretariat in Gothenburg, Sweden on 4 September 2019. Development of shore power in ports as well as discharge of scrubber wash waters in the marine environment were identified as priority policy options. With the implementation of the IMO guidelines, global reduced limits for sulfur have been applied from 2020 onward.

Also by CSHIPP a workshop [11] in Lisbon, Portugal on September 23-26, 2019 was proceeded on antifouling as well as emissions from exhaust gases.

Several approaches are currently being taken to implement the IMO guidelines on exhaust emissions. Low-sulfur but more expensive fuels are being used, or gas scrubber systems are being deployed.

Regarding the mentioned sub-area, the results of the workshop as well as the results of the projects of the CSHIPP platform can be summarized as the current state of affairs as well as for future requirements for clean shipping.

- Only relatively few ships in the Baltic Sea region use gas scrubber systems and an even smaller part uses closed scrubber systems.
- Closed systems shift the wastewater problem to downstream disposal. A hazardous material is created.
- There is still a lack of knowledge about environmental and marine life impacts of discharged scrubber water from open systems, as well as a lack of scientific knowledge about the composition of gas scrubber effluent.
- For the use of low-sulfur fuels, there is not yet sufficient knowledge of the economic impacts. How is the petroleum refining industry adjusting? How are prices and surcharges for clean fuels evolving? Where is a break-even between low-sulfur fuel and use of gas scrubbers.
- There are not yet economic incentives to implement clean shipping policies at a sufficient scale.
- There is a lack of ideas for "waste-2-product" approaches, the use of waste materials to create products.

The diversity of vessel types and variety of transport profiles of the fleet operating in the Baltic Sea makes it difficult to formulate general guidelines for all vessels for the Baltic Sea region or even larger. One way could be to group vessel types and comparable traffic profiles into clusters to enable applicability of guidelines. At the same time, it was assessed that the problems should be implemented locally at the port level and with local regulations. There is more motivation for local solutions and more focus on local sensitive protected areas. Thus, solutions could be implemented more easily, directly and quickly.

According to the assessment of the working group, it is currently difficult to estimate which of the measures (low sulfur fuel, use of scrubbers, alternative fuels) to implement the sulfur limits will be preferred by the shipping industry, compare Table 10.

Table 10 Advantages and disadvantages of various clean shipping measures.

Measure	Disadvantages	Advantages
Low sulfur fuel	Higher fuel costs, may require higher loans,	No capital investment, use of machinery as is,
Use of scrubbers	Investment required, operating costs,	Energy costs Savings Higher fuel costs
Alternative fuels	Higher fuel costs, additional technical retrofitting (investment)	Saving of fuel for tankers (use of exhaust steam from LNG)
"Slow-steaming"	Longer travel times, possibly no scheduled service	Energy savings
Other (electric propulsion)	Expensive energy storage, low energy density	Simpler engine system, environmental benefits

3.3.5 Fuel consumption - fuel costs and prices

In reality, ships with the same engine power can consume very different amounts of fuel. For information regarding vessel operating costs, it should be noted that the fuel costs included have generally been calculated with reference to the engine power of the vessel's main engine.

Table 2.1. Average fuel and operating costs for container vessels

Vessel type	Fuel costs € per travel day	Vessel costs € per travel day	Fuel costs €/TEU per travel day	Vessel costs €/TEU per travel day
Container vessels	24,199	35,983	15.63	23.24
Container feeder vessels	15,081	23,184	12.73	19.56

Table 2.2. Average fuel and operating costs for vessel types

Vessel type	Fuel costs € per travel day	Vessel costs € per travel day	Fuel costs €/t per travel day	Vessel costs €/t per travel day
Conventional dry cargo vessels	6,425	12,320	0.67	1.29
Dry bulk vessels	10,357	19,033	0.29	0.53
Tankers	10,093	21,615	0.40	0.86
Ro-ro vessels	14,587	29,255	1.70	3.41
Car and passenger ferries	41,166	95,407		

Figure 40 The calculations base on a period of time (2006-2008) with 370 USD/mt = 271 €/mt, (exchange rate as of 2009 USD = 0,732 €.), taken from [10].

Vessel speeds have an immense effect on fuel consumption, and therefore on costs, as well as on the emissions generated. One measure to reduce fuel consumption and associated emissions is "slow-steaming," or lowering the ship's speed. However, ships in liner traffic cannot reduce their speed at will without affecting the viability of the entire transport chain. The following tables (shown in Figure 40) are taken from “A study on the impacts of the new IMO regulations and transportation costs” [10] and give a good overview of the daily fuel costs of examples of different ship types. Inspired by and based on this overview, the daily consumptions (mt) were determined and converted to today's fuel costs for comparison, in order to then determine the difference to the low-sulfur grades (Table 11).

Table 11 Daily consumptions and costs (price status 13.05.2020, Rotterdam)

	271 EUR/mt		133 EUR/mt	
	2008		2020	Diff.
Vessel type	**EUR/day**	**mt / day**	**EUR/day**	**EUR/day**
Container	24.199	89,3	11.876	-12.323
Container feeder	15.081	55,65	7.401	-7.680
Dry cargo	6.425	23,71	3.153	-3.272
Dry bulk	10.357	38,22	5.083	-5.274
Tankers	10.093	37,24	4.953	-5.140
Ro-Ro	14.587	53,83	7.159	-7.428
Passenger/ Ferry	41.166	151,9	20.203	-20.963

It is interesting to compare the prices of fuels with different sulfur contents. The following **Fehler! Verweisquelle konnte nicht gefunden werden.** gives an overview and compares the prices from 2009 [10] with today's prices.

Table 12 Comparison: fuel costs 2008 and 2020 for different ship type examples and differences to 2008 [11].

	271 EUR/mt		133 EUR/mt	
	2008		2020	
Vessel type	**EUR/day**	**mt / day**	**EUR/day**	**EUR/day**
Container	24.199	89,3	11.876	-12.323
Container feeder	15.081	55,65	7.401	-7.680
Dry cargo	6.425	23,71	3.153	-3.272
Dry bulk	10.357	38,22	5.083	-5.274
Tankers	10.093	37,24	4.953	-5.140
Ro-Ro	14.587	53,83	7.159	-7.428
Passenger/ Ferry	41.166	151,9	20.203	-20.963

The price differential to ULSFO ultra-low sulfur fuel has narrowed considerably on today's price basis compared to 2008. Obviously, the refineries have adjusted to the demand and furthermore, the sharp drop in prices has had a positive effect on the overall price level. The extraordinary drop in the price of oil has reduced daily consumption costs by a good half. How long these effects will last remains to be seen.

Figure 41 Price charts for marine fuels by Nov.27 2020 [11]

3.3.6 Marine diesel fuels for diesel engines

The most commonly used fuel for large diesel engines for marine propulsion is heavy fuel oil. With the conversion of shipping from steam propulsion and coal as energy sources to diesel engines and petroleum as an energy base, this "paradigm" began and the shipping industry has adapted to it over the decades.

Heavy oil / diesel fuel has a relatively high energy density of 43MJ/kg (12 kWh/kg). It is inexpensive, available in required quantities, and a market and supply infrastructure exists.

Engine technology for using diesel fuel for large ships is mature. Engines can run on heavy fuel oil as well as other fuel variants. Essentially, marine diesel fuels are hydrocarbon mixtures (with some impurities). In ship operation, the residual energy (heat) of the exhaust gas is used in exhaust gas boiler plants for power generation (turbine) and heat supply as well as for charging the fresh air (turbocharger). Modern engine plants achieve overall efficiencies of over 50 %.

The combustion of marine fuels mainly produces carbon dioxide and water vapor. The gas volume generated by combustion and the thermodynamics are used for propulsion in the internal combustion engine. In the generated gas volume there are in distributed form the ingredients contained in the fuel, on one kilogram this is 10 grams (1%) of sulfur and other contained substances. The quantities produced from one kilogram of heavy oil by combustion are shown in the table below. For the estimation, we assumed for simplicity that heavy oil is a long-chain alkane. In reality, it is a mixture of hydrocarbons, such as alkanes, alkenes, aromatics and others.

1 kg Alkane produces:	**Volume (m^3)**		**Weight (kg)**	
CO_2	1,59	m3/kg	3,13	kg/m3
H_2O	1,65	m3/kg	1,33	kg/m3
Total	**3,24**	**m3/kg**	**4,45**	**kg/m3**

Using the example of a container ship (daily consumption 89,300 kg), it can be shown that a scrubber has to cope with a gas volume of 289 520 m^3 (= 89 300 kg x 3,24 m^3/kg). Of this, 142 128 m^3 or 279 tons of CO_2.

Table 13 Estimation of the volume of combustion gases from alkanes

Formula	**Cn H(2n+2)**	**m O2**	**---->**	**n CO2**	**(n+1) H2O**
	C27 H56	41 O2	---->	27 CO2	28 H2O
Mol.lMass (g/mol)	***380***			***44***	*18*
Volume (L) per Gram of a molecule				*0,51*	*1,24*
Volume (L) of the molecule from 1 Gram of an alkane				***1,59***	***1,65***

The amount and composition of particles in the exhaust gas of marine diesel engines depend on the combustion process and the type of fuel used. The composition can be subdivided (MEPC 56 / INF.5 / Annex 1 2007):

- Metal oxides and metal sulfates originate mainly from the fuel used. There may be some input of these substances into the wastewater due to lubricating oil or wear of the engine and gas scrubber unit itself. In the case of seawater scrubbers, the scrubbing water itself may contain harmful substances. This is not additional pollution, and is generally not expected to be a problem. Background levels must be considered when monitoring effluent concentrations.
- Carbon (soot) is generally considered to be a stable compound. The smaller particles (<2.5 µm) are thought to pose a higher respiratory hazard when released into the air. Studies [12] show that carbonaceous soot occurs mainly in medium and larger particles. The size distribution of particles trapped in wet scrubbers needs further investigation. If necessary, results from studies are already available.
- Other organic compounds, typically PAHs and PAH derivatives, aldehydes, alkanes and alkenes, and some unburned fuels or non-combustible elements in the fuel.

Many PAHs and PAH derivatives, especially nitro-PAHs, have been found to be potent mutagens and carcinogens. Therefore, there is a requirement to monitor PAHs in scrubber effluents.

In principle, heavy oil consists of a mixture of long-chain hydrocarbons, such as alkanes, alkenes, aromatics and others. Heavy oil is produced as residual oil during petroleum distillation and the quality depends on the crude oil used. The different specifications and quality levels of marine fuels are achieved by blending the residual oils with lighter fuels, such as marine gasoil or marine diesel. The lighter distillates also lower the sulfur content. The blends are called intermediate fuel oils (IFO) or marine diesel. The most commonly used grades are IFO180 and IFO380 with viscosities of 180 mm^2/s and 380 mm^2/s, respectively. These fuels must be heated to at least 40°C in the ship's tanks to be or remain pumpable. [13]

Marine diesel fuels come in different varieties. They range from heavy residual oils from petroleum distillation to blends, such as marine diesel oil, which is blended from various components, such as kerosene, light gas oil, heavy gas oil, light and possibly heavy cycle oil, vacuum gas oil and others.

For further explanations and terminology on the subject of marine fuels, please refer to the appendix (section 5.3).

3.3.7 Reduction of diesel engine emissions by means of scrubbers (EGCS)

The main purpose of "gas scrubbing systems" is to remove sulfur oxides from exhaust gas streams. A positive, additional effect is the trapping of particles in the exhaust gas, thus reducing the air-side emissions of heavy metals, soot, PAHs and also sulfur, which are bound to the particles. Basically, there are open-loop, closed-loop and hybrid systems. "Gas scrubbing systems" can be broadly divided into two types wet scrubbers and dry scrubbers. Wet scrubber systems use seawater or freshwater in combination with chemical additives such as NaOH. Wet scrubbers dominate for marine applications. (Only one supplier is known to commercially offer dry scrubbers. Scrubbers may be able to operate in both modes.

EGCS technology is state of the art and offers benefits including:

- Removal of sulfur (SOx) from engine exhaust emissions, elimination of airborne sulfur to prevent acid rain,
- Removal of a high percentage of particulate matter (PM) with good efficacy against particles 10 to 2.5 microns in size and ultrafine particles that pose the greatest health risks,
- EGCS can be used to burn HFO and easily meet the IMO MARPOL SOx emission requirements that have been in effect since January 2020,
- An EGCS is relatively easy to retrofit and operate.
- Scrubbers used to remove SOx and particulates from marine engine exhaust,
- EGR (exhaust gas recirculation) scrubbers to remove SOx and particulates from the recirculated exhaust gas to prevent fouling and corrosion of engine components. EGR itself aims to reduce NOX from engine exhaust,
- Inert gas scrubbers (flue gas scrubbers), which remove SOx and particulates from the gas used as an inert substitute in tanks and piping on board ships.

For further details, please refer to section " Control of Emissions from Ships – The State of the Art on Technologies" and especially "The SOX emission reduction technologies".

3.3.8 Scrubber Chemistry and a Policy Recommendation

The primary purpose of "gas scrubber" systems is to remove sulfur oxides from exhaust streams. For all wet scrubbers, the basic chemistry is similar and can be described according to the following principles:

$SO_2 + H2O\ H_2SO_3$ *(sulfurous acid)*

$SO_3 + H_2O\ H_2SO_4$ *(sulfuric acid)*

The sulfurous acid ionizes in water with normal acid and produces bisulfite and sulfite ions. In oxygenated seawater, the sulfite readily oxidizes to sulfate. The SO_3 off-gas fraction reacts similarly to produce sulfate and excess acid. The acid resulting from these reactions in the washing process is mainly neutralized by the natural buffer capacity in seawater, provided sufficient water is available. The buffer capacity in seawater is mainly caused by the content of natural bicarbonate. The purification efficiency depends on the flow rate of the water in the wet scrubber and reaches efficiencies of 65% to 94%.

The situation is similar for the large-scale recovery of sulfur from coal. Here, too, the contents of sulfur in the feedstock are around 3%. This initial consideration led to the suggestion whether a production of sulfurous acid or sulfuric acid can be made from an exhaust gas cleaning process. So, can environmental compliance be transformed into a business model?

Based on the idea, a policy recommendation (see appendix, section 5.4) was formulated and forwarded to the partners in the network.

3.4 Alternative fuels

3.4.1 Problem shifting and hidden emissions with alternative fuels

For many zero-emission options, the way fuels are produced results in high CO_2 emissions. If the hydrogen for ammonia production is produced from fossil fuels, steam reforming releases CO_2 into the environment. An alternative is electricity from renewable sources (see section 3.4.2 “E-Fuels).

Changes in land use are another factor that translates into hidden emissions, e.g., elimination or reduced CO_2 sequestration through conversion of forest to cropland.

In the case of cleaning exhaust gases to reduce emissions, e.g. scrubbing, the situation is from the other side. Shipowners understandably do not want emissions from the shipping industry to be shifted upstream or downstream. Therefore, the overall system and the entire life cycle should always be evaluated when deciding on a possible conversion.

3.4.2 E-fuels

E-fuels are electricity-based synthetic fuels produced from water and carbon dioxide using electrical energy. They are , the production of methane and further as "liquefaction of electrical energy" to methanol. The stages are electrolysis , methanization (catalytic) or synthesis (Fischer-Tropsch, catalytic).

In terms of energy balance, e-fuels must be viewed critically, since their production is energy-intensive, especially if the required carbon dioxide is extracted from the atmosphere. Energetically more favorable is the use of CO_2 from biogas plants.

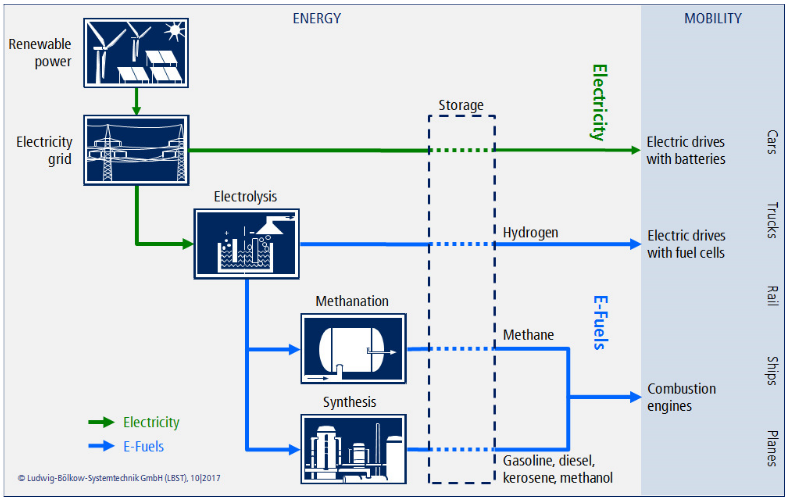

Figure 42 E-Fuels - Schematic overview [14]

Since they are hydrocarbons, the energy densities of E-Fuels are comparable to those of fossil equivalents. The same applies to storage, transport over long distances and the associated costs. For distribution, the entire gasoline/diesel/kerosene infrastructure with pipelines, refueling stations, etc., as well as the natural gas infrastructure can be used.

Thus, e-fuels are also suitable for shipping. As with other hydrocarbons (HC), nitrogen oxides are also produced during combustion in diesel engines. The engine technology is comparable to the diesel engines used for conventional fuel.

E-fuels are currently in the development and pre-market phase. The use of e-fuels is considered necessary to achieve EU climate protection targets for the transport sector. To meet the long-term demand for e-fuels for maritime shipping and aviation, the potential of renewable electricity production would have to be significantly expanded.

Today's EU electricity production would have to be increased by a factor of 1.7 to a factor of 3, with a good 80% of this expansion going to e-fuels production. The cost of e-fuels is currently €4.5 / L diesel equivalent, which is still too high. The target cost level of about 1 € / L seems achievable with imports from regions with high solar / wind supply.

- Electrification where technically, economically and ecologically feasible (ferries),
- E-fuels preferred in applications, e.g. in fuel cell systems with reformer,
- For market ramp-up, political, appropriate framework for economically at-tractive applications should be created,
- a strategic agenda for technology development, market development and regulation for e-fuels is useful.

3.4.3 Electrically produced ammonia

The ongoing expansion of wind energy, both onshore and offshore, creates a dilemma for wind millers. Energy policies of the past promoted energy infrastructure close to major consumers and short transmission distances were favored. Renewable energy sources, however, are on the periphery and must travel long distances. This has both physical and financial consequences.

Example Germany. Generated electricity but not fed into the national grid in comparison with used electricity [15]

Table 14 Example Germany. Generated electricity but not fed into the national grid in comparison with used electricity

		GWh_{el} /year used	GWh_{el} "wasted"	
Germany		**515 000**		
Mecklenburg-Vorpommern		**7000**		
	2016		317,57	4,5%
	2017		238,95	3,4%
	2018		156,63	2,2%
Schleswig-Holstein		**16 000**		
	2016		2706,11	16,9%
	2017		3258,34	20,4%
	2018		2860,23	17,9%

In principle, this problem exists in many countries, so ways out are being sought. The production of hydrogen by means of electrolysis has been identified as a viable path and implementation has already begun. For the direct use of hydrogen, an area-wide infrastructure as well as the users are missing. The production of ammonia from electricity is therefore a way to escape the dilemma and provide an energy carrier with good energy density or a chemical feedstock. For use in both internal combustion engines and fuel cells, (see the corresponding section).

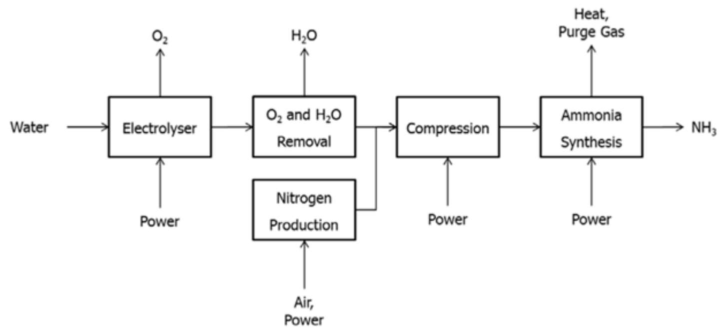

Figure 43 Schematic Diagram Ammonia production as an E-Fuel

Classic processes such as the Haber-Bosch (H-B) process are established for the production of ammonia. The reactants required for the process are hydrogen and nitrogen, which can basically be provided electrically (electrolysis and by means of membrane or gas separation processes (Linde). The exclusive use of electrical energy for the production of ammonia by means of the Haber-Bosch process (E-HB) is possible.

Solid-State Ammonia Synthesis (SAAS)

Work is also being done on the engineering implementation of a direct synthesis of ammonia, the power-to-ammonia process. This involves the direct electrolytic synthesis of ammonia from water and nitrogen using electrical energy, bypassing the detour via hydrogen production from water.

Reactions in the SSAS- Cells

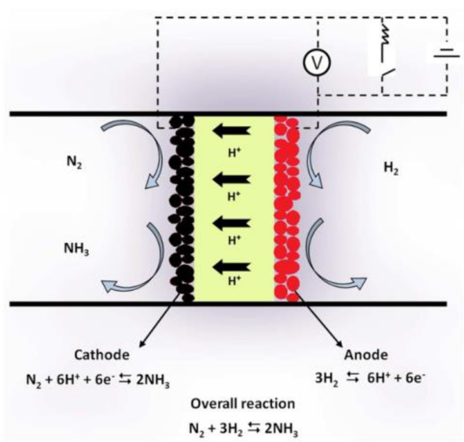

Figure 44 Schematic diagram of NH_3-Synthesis in the H^+ conducting solid state cell. Ammonia Energy Association [16]

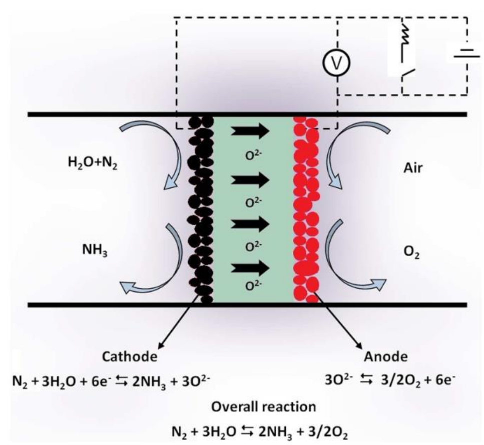

Figure 45 Schematic diagram of NH_3-Synthesis in the O^{2-} conducting solid state cell.

Some statements on Solid-state ammonia synthesis: [17]

- Solid-state electrochemical process,
- Water (steam) is decomposed at the anode,

- Hydrogen atoms adsorb, electrons are stripped off,
- Hydrogen conducts (as proton) through proton conducting ceramic electrolyte,
- Protons escape at cathode, recover electrons and react with adsorbed dissociated nitrogen atoms to form NH_3 ,
- Does not require expensive, energy-consuming electrolyzers,
- High pressures (e.g. for Haber-Bosch synthesis) are not required,
- Co-production of oxygen gas,
- Synthesis reactors in the form of several tube bundles in geometrical arrangement,
- Easy NH_3 capacity expansion by adding synthesis tube bundle modules,
- Patent application - February 2007.

Table 15 Energy density vs. effort of various processes.

	Energy density		Energy effort	
		SAAS	E-HB	H-B Natural Gas
Ammonia	6,25 kWh/kg			
	6250 kWh/ton	8000 kWh	~12.000 kWh	9700 kWh

E-fuels from renewable energies from offshore wind parks

Especially for large offshore wind farms, such as those planned by the DeepWind cluster (Scotland) north of the Shetland Islands, the production of e-fuels such as ammonia could be an immediate purpose. The direct production of ammonia by means of floating production and storage units (FPSO) as well as the delivery of the ammonia to the distributors, the bunkering stations for the large ships in the ports.

3.4.4 XtL Fuels

XtL's were various synthetic fuels grouped under the designation "X to liquid = XtL). Through a chemical process, solid or gaseous energy sources are converted into liquid, carbon-based fuels at room temperature and atmospheric pressure. Depending on the feedstock being liquefied, "X" stands for, see Table 16 Variants of "XtL Fuels" :

Table 16 Variants of "XtL Fuels"

BtL	Biomass-to-Liquid	Primarily bioethanol, biomethane and biodiesel, also methanol. In addition to the formation of sulfur dioxide as a pollutant (often in quantities compared to fossil fuels) and nitrogen oxides, the competition for land with food production and certain environmental impacts during production are disadvantageous.
CtL	Coal-to-Liquid	Use of coal "coal liquefaction," Fischer-Tropsch process. This process found some importance on a large scale in the 1930s for the production of synthetic gasoline (Leuna) from lignite. A number of hydrogenation plants were built in Germany to provide fuels.
GtL	Gas-to-Liquid	Natural gas or biogas. see CtL, but less complex because the synthetic stage (Winkler process) is omitted.

3.4.5 Biofuels

Biofuels are those that are of biogenic origin. They include biodiesel, which is derived from oilseeds or oil plants and refined, ethanol, which is produced biogenically.

As a sustainable energy source for shipping, these fuels would need to be available in the usual required quantities. Furthermore, they can be in collision with other societal areas and goals, such as food competition (with growing population), land use emissions (sustainability certificate).

From an economic point of view, according to Llyods Register Study "Zero-Emission vessels 2030.." [8], it is one of the more attractive ZEV solutions available, since the required capital costs for machinery and storage are low, allowing low relatively low fuel and travel costs.

The engine plant for the use of biodiesel as fuel is a classic diesel engine with only minor modifications.

3.4.6 LNG as a fuel

LNG is considered well established as a fuel in land-based applications. Commercial shipping is still in a deployment phase and is hesitant.

Because of the cost of new construction and conversion, only a relatively small number of ship owners and their financiers so far have made a positive decision to use LNG propulsion with a view to achieving reasonable returns. Nevertheless, there are reasons to believe that the industry is well on its way. [6]

Although some bunkering ports already offer LNG bunkering facilities and LNG, the availability of LNG bunkers is another reason for shipowners' hesitation. On the other hand, ports are also hesitant because they are not sure of the return on their investments, even if long time horizons mitigate the risk. Also, ports may seem reluctant to engage in the provision of new infrastructure and new fuels until technical standards are established and safe and quality-assured refueling practices are regulated. [18]. See references to the Clean Ship Platform's GoLNG project, which addresses this issue.

The engine system for the use of LNG as fuel is basically the classic diesel engine. Modifications concern the mixture formation and ignition as well as the auxiliary aggregates for the treatment of the fuel from the liquid phase (evaporator), furthermore the entire cryo-technology of the storage and supply of the fuel. For further outlines please refer also to section "LNG as marine fuel".

3.4.7 Hydrogen as fuel

Hydrogen as a fuel for heat engines has been discussed since the oil crisis in the 1970s. Corresponding developments were made for gasoline engines, diesel engines and gas turbines. The feasibility in principle has been proven. The main advantage of using hydrogen is the absence of CO_2 in the exhaust gas, which consists of water vapor. Depending on the compression in the combustion engine, nitrogen oxides can theoretically be produced.

Hydrogen has the highest mass-specific energy density of all fuels at 33.3 kWh/kg, but storage, transport and the necessary infrastructure are costly.

Hydrogen is produced from fossil hydrocarbons as part of fertilizer production (ammonia synthesis, Haber-Bosch process). Hydrogen can also be produced by electrolysis using electrical energy from fossil, renewable or nuclear energy sources. in Norway, hydrogen for ammonia synthesis (Birkeland-Eyde process) has been produced on a large scale from hydroelectricity and electrolysis. In the meantime, the sale of electrical energy is more profitable and hydrogen production is also carried out there by means of steam reforming. About 700 billion m³ of hydrogen are produced annually worldwide.

3.4.7.1 Hydrogen in diesel engines

Hydrogen-powered internal combustion engines can be used in the same way as conventional internal combustion engines with diesel fuels or natural gas as fuel, taking into account the special safety requirements. They can be used as: [19]

- Auxiliary power systems for medium-sized and larger ships,
- low-emission propulsion concepts for passenger ships in nature-sensitive regions,
- Special ships
- Stationary as power supply units, etc.

The use of hydrogen in diesel engines produces only water vapor and, depending on the compression ratio, nitrogen oxides NOx as emissions. The formation of NOx is comparable to that when hydrocarbons are used, with a shift from NO to NO2 taking place with decreasing temperatures in the combustion chamber.

Due to the thermal and caloric properties of hydrogen, technical modifications are required in fuel preparation, in energy conversion in the cylinder in safety systems, and increased safety requirements are necessary.

The current unavailability of suitable engine concepts and the lack of supply infrastructure stand in the way of short- and medium-term application.

Due to the thermodynamic and fluidic characteristics of hydrogen, the implementation of such engine concepts poses engineering challenges in terms of design and optimization:

- the introduction of hydrogen into the compression chamber and mixture formation,
- the high burning rate of the hydrogen-air mixture, the high knocking tendency,
- control of the internal mixture formation and the combustion phase with regard to mechanical and thermal stresses,
- thermal stresses in the cylinder when injecting cryogenic hydrogen, and icing of the fuel lines,
- immediate ignition and heat release (without ignition delay), and ignition behavior,
- high safety requirements due to the low ignition energy and the wide ignition range.

3.4.7.2 Hydrogen as fuel for fuel cells

Primarily, a fuel cell requires as pure hydrogen as possible as fuel.

The advantage of fuel cell systems is the direct generation of electrical energy from the fuel. Heat engines need a downstream generator set. Another advantage is that even at low temperature levels, fuel cells show high efficiency in the conversion of electrical energy. If the upper temperature level is changed, as in the operation of a heat engine, the efficiency increases further. The efficiency is also higher in part-load operation. This means that the average efficiency of a fuel cell is several times greater than that of internal combustion engines in mobile applications.

The operation does not produce any noise if the auxiliary units are designed in such a way that they are also quiet. The emissions of a fuel cell is only water. Thus, besides high efficiency, environmental friendliness is an outstanding advantage.

Fuel cell systems are still comparatively expensive, have lower performance than diesel engines, and their service life depends heavily on the fuel used. The ideal fuel is hydrogen and the purer it is, the better the parameters of a fuel cell system. With regard to the supply of hydrogen, the same applies as in the section 3.4.7.1 "Hydrogen in diesel engines".

The technical design of a fuel cell system comprises the following components:

- the fuel cell stack,
- Auxiliary units for the control of automatic and safe operation,
- measurement systems, voltage, current, temperatures,
- inverters, power output and feed-in,
- Air compressors for oxygen supply,
- Fuel gas regulation (hydrogen), valves, recirculation,
- Cooling system, pump, heat exchanger,
- Humidification device for MEA,

When using alternative fuels for fuel cell systems, such as natural gas, propane, butane, but also ammonia, methanol and gasoline, a reformer stage is required to provide the hydrogen or a hydrogen-rich gas. This requires additional components: reformer stage/gas cracker with heating, desulfurization and air compressor; furthermore a PrOx stage for CO purification and shift stage ($CO \rightarrow CO_2$).

It is also worth mentioning the different applications and fuel cell concepts:

- PEM -Polymer Electro Membrane Fuel Cell,
- DMFC -Direct Methanol Fuel Cell,
- SOFC -Solid Oxyde Fuel Cell.

There are also others of lesser importance, such as AFC - Alkaline Fuel Cell, PAFC - Phosphoric Acid Fuel Cell, MCFC - Molten Carbonate Fuel Cell.

The chemical reactions in fuel cells, which essentially correspond to the reversal of water electrolysis, will not be discussed here.

3.4.8 Ammonia (and hydrogen)

Ammonia can be used as a fuel in fuel cells as well as in combustion engines. When ammonia is used in a diesel engine, combustion produces nitrogen oxides NO, NO2 and only water vapor. Ammonia is toxic, but people can smell ammonia even at very low, harmless concentrations.

The energy density of ammonia is 5.2 kWh/kg, which is lower than that of diesel fuel.

Approximately 200 million tons of ammonia (NH3) are produced worldwide each year, about 3/4 of which is used for fertilizer production. The energy input for ammonia production corresponds to about 2% of the world's energy production. The most common process is the Haber-Bosch process, which catalytically combines nitrogen and hydrogen ($N_2 + 3H_2 \rightarrow 2NH_3$). The world's largest green hydrogen/ammonia production project has been decided with an investment of 4.4-billion euros. The cooperation of ACWA Power (USA) and NEOM (Saudi Arabia), produces green ammonia for export to global markets using renewable energy. [20]

Lower capital costs for onboard storage of ammonia, a rudimentary infra-structure for transporting and storing ammonia on land (chemical industry as well as agriculture) make ammonia relatively more advantageous than hydrogen. However, whether hydrogen or ammonia are interchangeable as competitive energy sources depends on ship type, technology, deployment scenario, and price.

- Ammonia (NH_3) can directly combusted in engines – splits up to H_2 and N_2, no use has no CO_2 emissions
- NH_3 has the highest volumetric energy density, the H_2 content is 110 kg/m^3 … Compared with other C-free fuels (LHG: 71 kg/m^3, LOHC: 60 kg/m^3)
- NH_3 is an efficient fuel for shipping (combustion engines or fuel cells).
- Large commercial production chain is established.
- Change to green NH_3 production is possible, NOx emissions can be controlled.
- Safety standards are well established in chemical industry, for refrigeration systems, in agriculture etc.

For instance, Japan develops a strategy to replace fossil energy in power industry with Blue Ammonia from Australia (< 340 $/t; 2 $/kg H_2). [21] cited from [15]

3.4.8.1 Ammonia as fuel for fuel cells

The combination of fuel cell and electric motor as propulsion is considered disadvantageous due to the relatively low energy density of the overall system, higher capital costs, reduction of cargo hold capacity due to larger storage space. These disadvantages could be reduced by shortening the range between bunkering. However, this is not an economic option. See also the section 3.4.7.2 "Hydrogen as a fuel for fuel cells".

3.4.8.2 Ammonia as fuel in internal combustion engines

Use in diesel engines represents a simpler technology change. Dual-fuel or even tri-fuel systems are possible. Depending on the availability and price of the fuel, a switch is possible. Compared to fuel cells plus electric motors, the use of ammonia as a fuel for internal combustion engines is generally superior according to current estimates.

The permanent use of ammonia in diesel engines is likely to require some design changes in terms of materials, comparable to the conversion to LNG.

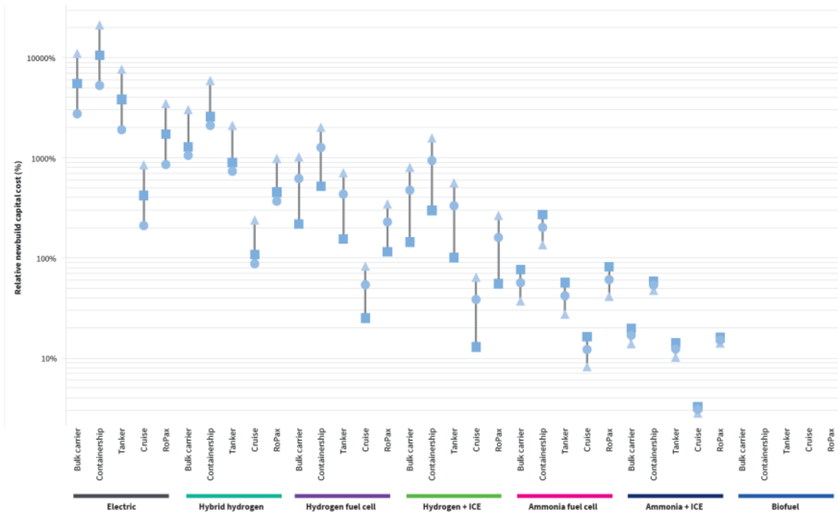

Figure 46 Relative technology capital costs for ZEV - ship types and scenarios [8]

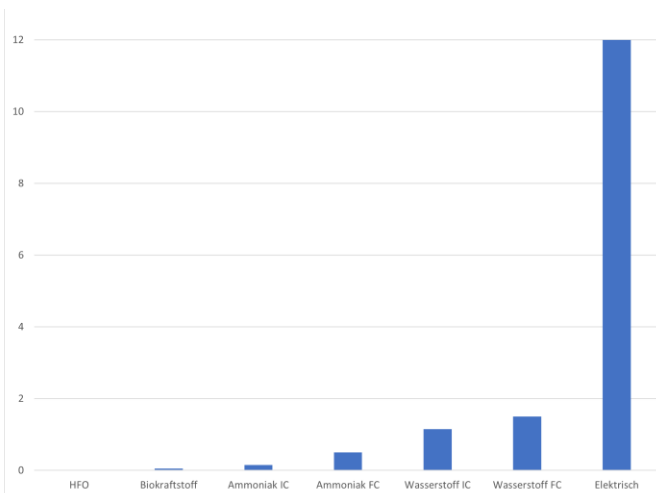

Figure 47 Relative additional costs for investments of different ZEV options (rounded [8])

In the Lloyds Study on Zero Emission Vessels [8], the relative costs of different ZEV options are shown. From left to right follow: HFO (traditional diesel), biofuel, ammonia (in diesel engine), ammonia (fuel cell), hydrogen (diesel engine), hydrogen (fuel cell), electric drive (battery).

3.5 All-electric power supply with electric motors as propulsion system

3.5.1 Electric Motors for Ships propulsion

Electric motors are used in many applications. They are small, quiet and light weight, clean, very durable and reliable and have high efficiencies of up to 98%. They come in a wide power range from a few milli-watts to many gigawatts. These characteristics makes them the predominant drive in multiple applications and very interesting as drives for ships, because electric motors develop full torque at very low speeds, from standstill. Compared to diesel engines in the power range for ships, say 70 MW, electric motors in ships applications[4] are true lightweights.

Figure 48 : Wärtsilä-Sulzer RTA96-C [22]

Figure 49 SIMOTICS HV Series HS-modyn, high voltage motor [23]

Table 17 Example: Wärtsilä-Sulzer RTA96-C [22]

Bore	960 mm
Stroke	2.500 mm
Displacement	1.820 liters per cylinder
Mean piston speed	8.5 meters per second
Engine speed	22–102 RPM
Torque	**7.603,85 kNm** (5.608.310 lbf·ft) @ 102 rpm
Power	up to 5 720 kW per cylinder, **34 – 80 MW**, depending on cylinder count
Mass of fuel injected	~160 g per cylinder per cycle at full load
Crankshaft weight	300 tons (crankshaft only)
Efficiency	Up to 45 % (estimated)

[4] A very early variant was diesel-electric operation, which is a combination of a diesel-powered "power plant" and an electric motor as the ship's main propulsion system. The first ship, a Russian tanker launched in 1903, was equipped with such a combination.

If we take the "SIMOTICS HV" as an example of an electric motor suitable for marine propulsion, we can guess at the differences in size and weight. However, this is only half the truth, because it does not show the facilities of the power supply system. The electrical energy is supplied to the electric motor via so-called drive converters, which is provided by batteries or a different power source.

Table 18 Example SIMOTICS HV HP synchronous IEC [24], *[25]*

Output power	**8 to 70 MW**
Number of poles	2 to 6
Voltages / Frequencies	3 to 13,8 kV / 50 Hz/60 Hz
Cooling types	Water cooled: IC 81W / IC 86W; Aircooled: IC 616/IC 666/IC01/IC31/WPII
Speed	Up to 3.600 RPM
Torque	Up to **700 kNm**
Efficiency	Up to 98,8 %

If the electrical energy is to be provided exclusively from batteries, it quickly becomes evident that a very large battery is required due to the relatively low energy density of modern batteries. Even then, battery-electric operation in these necessary power ranges is only possible for a very short period of time.

For electric propulsion on large ships, therefore, electric power is generated by means of generator sets driven either by turbines or diesel engines, which in turn are supplied with conventional or alternative hydrocarbon-based fuels, or steam turbines powered by nuclear power.

For a comparison of diesel and electric propulsion, the weight of the total system: engine-generator combination (the "power plant") on board with corresponding buffer battery, the drive converters and controls, and the actual electric motor must be considered. If a corresponding amount of power is required for the drive, which is only supplied to the propeller by electrical means, then the great weight advantage of an electric motor is quickly lost.

3.5.2 Battery electric energy for ships propulsion

In recent years, electric passenger shipping on inland waterways and protected sea waters has been developed in the Federal Republic of Germany and also in the Baltic Sea region.

Depending on the shipping area, fully battery-electric propulsion systems or hybrid systems are used. Especially on German waterways for drives of smaller power energy supply systems consisting of battery system in combination with solar energy systems are used. An example are the produced vehicles of the company Ampereship GmbH from Stralsund, which have created a quasi-standard, which is taken up by other shipyards, as the example Suncat120 shows.

Figure 50 Suncat 120 is a type of passenger ship built by the shipyard Kiebitzberg GmbH & Co KG for the Berlin-based shipping company Solar Circle Line. The first ship was delivered in December 2019 and the second ship in July 2020. [26]

Figure 51 Solar energy systems on the passenger ships/ ferries of the company Ampereship GmbH. [27]

Electrically powered ships are in operation in the Baltic Sea region and in Norway mainly as ferries and as passenger ships. Depending on the purpose of operation, distance of the voyage, waters, prevailing weather and sea conditions, and given infrastructure, the dimensioning of the vessels varies.

The supply of electrical energy, especially at mostly remote ferry locations, is associated with technical and economic challenges. Examples include the "Ampere" and the passenger ship "Future of the Fjords" (both in the Sognefjord / Norway).

Figure 52 Ferry "Ampere" of the company Norled at the pier in Lavik [28]

Figure 53 Passenger ship "Future of the Fjords" at the pier in Gudvangen [29]

Typical of the ships built so far that are designed for electric propulsion is the catamaran design. Lightweight construction and materials such as aluminum are used. A good example is the almost 43-meter-long "Future of the Fjords," which is built entirely of carbon fiber composites. The motorization of this vessel, two 450 kW electric motors (port and starboard), is also found on other ferries and passenger ships of this size.

Figure 54 Loading dock of the "Future of the Fjords". [30]

Figure 55 Cavotec loading crane with connector and pantograph (Stemmann Technik) in the background for the "Ampere". [31]

Recharging of battery-electric ferries takes place at the berth (dock) and must be done during the limited berthing time. This poses a challenge depending on the infrastructure. In the case of the "Ampere", the berthing time is max. 15 minutes. The approx. 300 kWh for one crossing must be charged into the batteries (total capacity 1040 kWh) within this time. This requires a power of at least 1.2 MW, which is not available in the case of the power grid available on site. For this purpose, the charging infrastructure of the "Ampere" has an additional buffer battery on land of the size of a crossing.

The "Future of the Fjords" charges its battery (total capacity 2.4 MWh) at a special "power dock", which also has a buffer battery (700 kWh). The installed charging power of 2.4 megawatts allows charging within 20 minutes.

The electrical voltage of the charging ports on this type of vessel is 1000V (1kV).

Other electric ferries are already in operation in the Baltic Sea region. For example, the ferry "Ellen" (7.2 MWh battery) operates in the Danish Baltic Sea waters.

Scandlines is also discussing the electrification of even larger ferries, e.g. on the "Vogelfluglinie" between Rodby and Puttgarden. The energy requirement for a crossing is about 5 MWh, which requires a charging capacity of at least 20 MW if recharging of the battery storage is to take place within about 10 minutes. This represents a technical challenge in that the required connected load is not available from the power grid in Puttgarden. The project has not yet been realized.

For this power class, the electrical voltage is 10kV /11kV.

The requirements in terms of drive power, battery capacity, charging power and voltage levels for electric vehicles of the size class "Suncat" or "Ampereship" (see Figure 50 and Figure 51) are very low compared to i. e. “Ampere”. The charging infrastructure for those ships consists of simple 220V/ 380V connectors.

Figure 56 Battery racks of the port energy storage system of the "Future of the Fjords". [8]

Figure 57 Battery modules (LG Chem) of the "Future of the Fjords". [8]

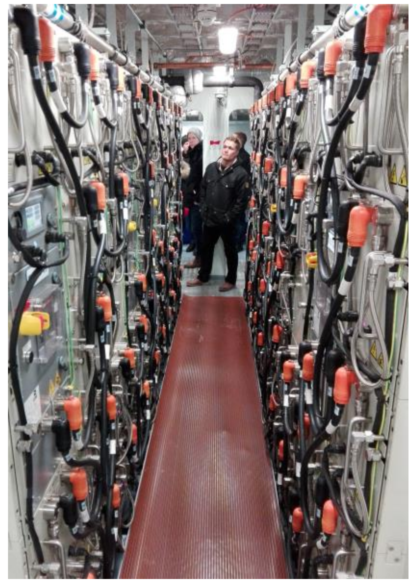

Figure 58 Battery room of the 500 kWh battery (System Corvus) of the "Elektra" (Finferries). [9]

There are also developments on the subject of the electrification of freight transport systems on water, for example with the "Electra" project, an electric push boat.

Another project idea from Tallinn envisages, for example, the transport of goods by small autonomous boats which can independently couple with each other, independently find their way to goods hubs, can independently load and unload themselves and can be distributed over a supply area, all autonomously. A plan is to test this idea through a demonstration operation on a section of Berlin's waterway network and to find out the feasibility and effectiveness of such a system (by 2022).

Especially in passenger/ferry shipping, electrification is a viable option. On ferry routes, with short voyages, electric drives can show their advantages: good maneuverability, with frequent load changes, with short response times. Because of the fixed connection, the energy supply can be ensured by a shore infrastructure.

In principle, larger ferries/ro-ro ships can also be electrified. With the scaling of production for the most expensive components, the energy storage units, the economic efficiency will also increase for larger ships. One bottleneck is the energy supply for recharging at remote ferry stations.

For the use in transoceanic shipping, current battery technology is not competitive due to energy density, high costs, and other parameters.

All-electric propulsion solutions are reserved only for special applications, such as ferries operating on fixed routes with appropriate infrastructure. In addition, applications for short trips to the same area are conceivable using battery-electric drives.

On this subject and their applications for ferries of different sizes was reported in the Interreg project "BSRelectric" [32]. Please refer to that paper.

Battery electric propulsion solutions are not relevant for ocean shipping with voyages of several days in high seas conditions.

3.5.3 Wireless power transmission – a future possibility for electric shipping

A technical memo on the subject of electrical power transmission [33] reviewed information and the literature on the state of the art and research. An in-depth evaluation has not yet been conducted.

The technology transmits electric power by means of Zenneck surface waves. This effect was discoverered and first described by Karl Uller (Rostock) and later by Jonathan Zenneck and Arnold Sommerfeld. According to Zenneck, the energy propagates along the boundary layer between two media of different impedance (ε_e and ε_a), e.g. the earth's surface or water surface and air. The so-called Zenneck surface wave set up a standing wave by which the transmission is created. Reportedly the energy transporting wave is bound to an infinitesimal layer between the two impedances (ε_e and ε_a) and is not radiated / emitted into space. This wave is initiated by and propagated very high voltages and at relatively low frequency ("AC-Current"). This technology enables

- energy transmission over long distances and with (basically) arbitrary power,
- the construction of low-cost, virtual power grids for energy transmission,
- saving of expensive cable routes, no maintenance and servicing,
- unassailable systems by weather, EMP, terrorism etc.

The connection of energy sources as well as the supply of energy in remote areas is not only interesting for military applications, but also for the connection of and he energy transfer from e.g. offshore wind farms or the connection of energy users, like mining companies, agriculture, research etc. at remoted places.

Experimental setups exist, e.g. in the USA/Texas since the end of 2018. Operational systems are not yet available. Such a technology would be particularly relevant for large-scale shipping. Electrically driven ships are not only possible but would be the alternative at all. [33]

3.6 Nuclear energy for (electric) ship propulsion systems

Nuclear energy must be evaluated as a promising alternative in any case. According to the current state of the art, it represents the energy with the lowest impact on the environment (and climate) in direct operation. The current safety and waste problems are being researched all over the world. Small nuclear power generation plants in the single-digit MW range are also under development.

Of all the current fuels used under the current "metaphor", nuclear fuel is the one with the greatest energy density

Table 19 Energy density: Diesel vs. Nuclear

Diesel/ Fuel Oil	vs.	Nuclear fuel
12 kWh/kg		1.056.084 kWh/kg

- Nuclear propulsion enables clean shipping.
- If CO2 emissions, sulfur emissions are the criteria, nuclear propulsion is an opti-on.
- The nuclear fuel is "fixed" and only needs to be "refueled" a few times.
- Very high safety requirements and standards are needed. Consequences for
- -the qualification of the seafarers,
- ship operation, maintenance and repair,
- port operations and shipyard operations,
- ship design: larger ships, long service life, standard overhauls.
- Almost military standards would be required for the shipping industry, this is contrary to a "free" market.
- Small reactors of newer generation (e.g. thorium) are not currently available

In nuclear propulsion, the released (heat) energy of the nuclear processes is used and converted into electrical energy in a known engineering manner via turbines and generator sets (or directly by means of thermo-wall generators). The actual propulsion of the ship is either by means of steam turbines or, in the more modern variant, by means of electric motors. The all-electric ship propulsion concept of nuclear (military) ships was derived from propulsion systems of cruise ships and has great advantages for ship design, equipment placement, for optimizing stability, and for the intended use of the ship. [34]

If one compares the daily fuel consumption of a conventional ship (e.g., 85 tons of heavy fuel oil) with a nuclear power plant of the same capacity (about 55 grams of nuclear fuel), the differences become clear: for a six-day crossing, e.g., from Southampton to New York, it is 510 tons versus 330 grams. Also, a nuclear-powered ship rarely needs "bun-kerning." For example, aircraft carrier nuclear reactors use up their nuclear fuel after 25 years, about halfway through the ship's normative service life. The nuclear fuel, as a solid, is located in the core of the reactor, is "fixed," so to speak.

Due to strong neutron radiation from the reactors, extensive shielding and safety requirements are necessary and require a larger installation space than conventional propulsion systems. In principle, however, almost all types of larger ocean-going vessels are capable of carrying nuclear propulsion instead of conventional diesel engines without difficulty. Particularly in the case of large ships of several tens of thousands of gross tons, a nuclear power plant of adequate capacity is likely to considerably outperform, in terms of weight, the existing engine plant, including fuel supplies for long voyages.

During operation, the core becomes critical and highly radioactive nuclear fission products are formed. In a Refueling and Complex Overhaul (RCOH), the ship is "refueled" and undergoes a complex overhaul. This process typically takes 46 months [35] The logistical and infrastructural challenges for "refueling" with nuclear fuel are significant.

For "refueling," the spent core is removed from the reactor and a new core containing fri nuclear fuel is installed. Because of the strong radioactive radiation, elaborate precautions are required. All materials of the inner surfaces, the cooling water, etc., which have come into contact with the critical core are considered radioactively contaminated and require special precautions and special disposal . Further, the work requires specially trained personnel, special infrastructure and precautions, constant monitoring of exposure limits and contamination of all materials, tools etc.

Experience with nuclear-powered naval vessels shows that operation can only be implemented with specially trained sailors, and maintenance and repair as well as "refueling" can only be implemented in special shipyards. Military/government standards for RCOH would have to apply with equal rigor to commercial use of nuclear propulsion. The commercial maritime transportation industry would have to submit to almost military regulations and structures, which will have consequences on training standards, operating regimes, safety standards in ports, in shipyards, up to the ownership structure. With the right political will, however, this could be implemented without problems, but it would be an intervention in the free market.

So far, four nuclear-powered ships have been built for civilian shipping and are still partially in service. These ships have steam turbine propulsion, such as the ice-breaking merchant ship "Sevmorput" [36], which is in service specifically for the Northeast Passage. Further, there are four nuclear-powered icebreakers in operation and others under construction that are equipped with electric propulsion. [37]

3.6.1.1 Nuclear Alternative: Molten Salt Reactor

Reports of thorium reactors are currently appearing in the press. This refers to a type of reactor, where the entire reactor contents consist of fuel, coolant, and fission products in form of molten salt. With the exception of a possible graphite moderator, the fluids circulate continuously between the reactor vessel and the first heat exchanger. The salt melt is critical only in the reactor core, since only here the graphite moderator is present and the ratio of volume to surface area is large enough. A core meltdown in the classical sense is thus excluded. They also operate at atmospheric pressure, which means that a steam explosion is not possible. The thermal energy is extracted via a second cooling circuit, also with a liquid salt.

Thorium-based nuclear power generation is mainly driven by nuclear fission of the isotope uranium-233, which is produced from the fertile element thorium. The reactor can use thorium to produce (theoretically) enough 233uranium for its own operation. According to proponents, a thorium fuel cycle has several advantages over a uranium fuel cycle, such as the much larger amount of thorium on Earth, less nuclear waste, and better physical and nuclear fuel properties. Further, the low weapons potential is cited as an advantage of thorium. [38]

With fourth-generation reactors, it is hoped that [39]

- High safety standards.
- Very low probability of severe reactor damage.
- Elimination of the need for external emergency supplies,
- No uranium enrichment required for operation.
- As unattractive as possible as a source for theft of fissile material.

- As secure as possible against terrorist attack.
- Prevention of fires by filling the containment with inert gas.

Just 19 reactors, mostly small research reactors, were in operation. Today, only five are in operation, three in Russia, one in China, and one in India. [40]

For shipping, this option currently plays no role. Today, in early 2021, there are no operational thorium reactors in the world.

3.6.1.2 Nuclear Alternative: Radioisotope Generators

So-called nuclear batteries use the decay heat or radiation from specific atomic nuclei and convert it directly into electric current. The generation of electric current by thermal means is achieved by thermionic, thermoelectric, thermophotovoltaic conversion or by Stirling engines and generators. The non-thermal methods are, for example, electrostatic, electromechanical, radiovoltaic conversion. These power sources have found some use, especially in space travel and for powering remote beacons. For ship propulsion, these power sources have too low power ratings. [41]

3.6.1.3 Other notes on energy density and research.

Another focus of research in nuclear technology concerns nuclear transmutation, the conversion of one chemical element (isotope) into another. Transmutation technology aims at recycling unstable isotopes from nuclear waste by converting them into nuclear substances with shorter and therefore more acceptable half-lives. [42]

Figure 59 Icebreaker „50 Let Pobedy“ [43]

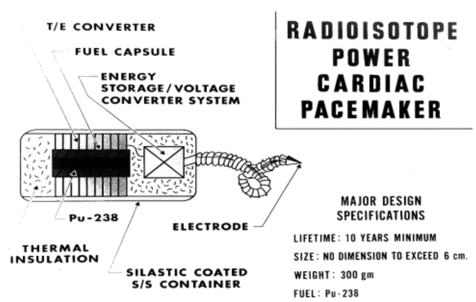

Figure 60 Radioisotope-powered cardiac pacemaker being developed by the Atomic Energy Commission, is planned to stimulate the pulsing action of a malfunctioning heart. Circa 1967. [44]

3.7 Wind-Propulsion as a propulsion support

The natural power of wind can also be used to power ships. Our ancestors led the way. Currently, there are various approaches, from Flettner rotors and kite sails to modifications to the classic sail.

Figure 61 Scandlines "Kopenhagen" mit Flettner-Rotor [45]

Figure 62 Wind Propulsion can be an essential tool in Shipping's Decarbonisation Efforts [46]

Notable applications are known from the yacht sector. In addition, there are ambitious projects addressing the issue of wind propulsion. The International Windship Association, with its more than 40 member companies and organizations, claims to be in a position to help the shipping industry meet the ambitious carbon reduction targets set by the International Maritime Organization (IMO), among others. [46] However, apart from projects and large-scale trials, there are no widely known production ships in operation.

Figure 63 As a passionate sailor, my friend and skipper, Helmut Risch, together with Jochen Bertholdt, published a paper on this subject as early as 1988. [5]

Figure 64 Beluga Projects Sky Sail. (a well known example) [47]

Currently, the WASP project [48] (Wind Assisted Ship Propulsion) is in execution. Here, among others, the use of a Flettner rotor as an assisted ship propulsion system is being tested on a Scandline's ferry-ship on the line between Rostock (DE) and Gedser (DK).

3.8 Influences of ship design and shipbuilding on energy demands

Ship design is an factor, but will not be the only one decisive factor for low energy requirements. In the future, too, especially if electric drives are chosen, the aim will be to achieve a minimum in specific energy requirements. The decisive factor should be the answer to the question that must be clarified in the context of numerous framework conditions, namely for an optimal overall solution which encompasses all aspects, such as the purpose of use, location/area of use, overall energy balance, production of all necessary materials, operation, dismantling up to scrapping of the vehicle, and recycling of resources.

Shipbuilding factors, such as technical solutions with regard to ship design for the surface and underwater hull, e.g. monohull or multihull, propulsion, energy sources and energy carriers (with regional approvals/prohibitions where applicable), materials used for the ship's main assemblies, etc., form a mix in this respect to optimize the overall solution. However, technical developments and innovations must comply with the relevant construction regulations of the classification societies (safety of people and the environment).

Parameters that significantly influence the energy demand are

- the fluid dynamic resistance, which counteracts the propulsive thrust to achieve the cruising speed, which is composed of detachment resistance, frictional resistance, wave resistance, the aerodynamic ship resistance depends on the shape and the surfaces of the surface ship and is analogous to the hydrodynamic resistance of the underwater ship. The resistances can be specifically influenced by suitable shaping.
- the energy requirements of on-board operations, air conditioning refrigeration, lighting, pumps, etc.
- the shipbuilding materials used and, for example, lightweight construction technologies.
- the propulsion concept and propulsion efficiency. Improved propulsion efficiency in drives leads to lower operating costs, robust design and gearless drive train ensure high availability, azimuthing capability and thrust in all directions ensures high maneuverability and safety Rudder propellers, azipod drives and rotary jet drives represent energy-optimal technical solutions that are installed below the ship's hull and are consequently exposed to an undisturbed inflow. They also have advantages in terms of noise and vibration, but can be problematic in shallow water.

These parameters can be optimized by ship design decisions.

4 Conclusion

4.1 State of Play

The **current predominant method of energy conversion** for propulsion and operation of ships is in a manner that requires the necessary energy to be carried in the form of fuels (energy carriers).

The energy carriers (fuels) are mainly provided as **chemical compounds** (carbon-hydrogens, nitrogen-hydrogens), which are converted by redox reactions (**combustion**) first into thermal energy and then into mechanical propulsion energy. In the process, oxidation products of the fuel are produced as **emissions**, depending on its composition, which are the subject of regulations. The fuel and energy conversion system form a single technological unit and can only be modified within narrow limits.

Internal combustion engines have become established as an economical alternative because the common fuels (MDO, etc.) with their relatively high **energy density** allow good power density.

The energy conversion of an overall system, from the source to the final energetic use (wake-to-well), results from the series connection of the individual conversion stages with their **partial efficiencies**, and the **overall efficiency results from the multiplication of the partial efficiencies**. There is a strong link to economy via efficiency. The goal should be to minimize the number of energetic conversion stages, since many stages increase the costs and reduce the overall efficiency.

In addition to economic efficiency, political conditions also provide a framework for shipping that addresses emissions. For the implementation of clean shipping in terms of reduced emissions and higher efficiencies, the relevant factors are therefore: energy conversion and the energy carriers are essential starting points, which in turn imply a multitude of detailed considerations. The most important ones at present are:

- Use of **cleaning processes for exhaust gases** for further use of traditional fuels e.g. scrubber (temporary technology),
- Search and use of **alternative and cleaner fuels with sufficiently high energy density** e.g. LNG, biofuels, e-fuels,
- Use of **electric power as well as hydrogen** for short connections and existing infrastructure ferries, excursion vessels, inland waterway vessels,
- Modified modes of operation to reduce energy use and emissions e.g. **slow steaming**,

Regulatory and political interventions are forcing the shipping industry to consider future clean shipping issues. But optimization requires a holistic economic and technical view. **Merely shifting problems from one field to another is not meaningful.**

On the basis of current concepts, with regard to energy carriers, storage systems and energy converters for shipping, a distinction must be made between the size classes of the units and their radii of action: Ships for long voyages, barges, ferries, etc.

The question of which energy carriers, and thus storage systems, will take precedence in the future is currently uncertain

Large-scale shipping requires large amounts of energy, which can only be optimized to a limited extent by ship design and operating regimes.

Candidates for future fuels of a clean shipping are identified from today's point of view, considering the intended use and the required quantities:

- Methanol,
- Ammonia,
- Some biofuels and
- Highly refined mineral oils.

In addition, electro-based fuels (e-fuels) have good prospects in certain application areas.

In the case of **biogenic fuels**, special attention should be paid to market mechanisms in the course of demand, which experience has shown can lead to problem shifts, such as changes in land use, hidden environmental impacts.

Hydrogen, as an alternative fuel is again, under the label "green fuel", moving into the focus of attention and raises hopes. However, its use has been difficult for decades, as the properties of hydrogen make it difficult to transport and store under economic conditions. The chemical bonding of hydrogen to nitrogen (ammonia) as well as to carbon (methanol, methane) leads to a feasible path, but in this case further conversion stages with partly low efficiencies are added to the conversion chain. For the time being, therefore, hydrogen is not very suitable for large ships because of its physical properties. For special applications, for ferries, there are possible uses.

The use of **electrical energy** is the most elegant variant, but this form of energy eludes direct storage due to its fundamental property as - "dynamic energy", electricity. Applicable electrical energy storage systems are based on chemical, mechanical, thermal or even biological conversion processes, multiplied by an efficiency at each conversion stage.

4.2 Future needs

The future needs are always based on the present ones and therefore it is difficult to formulate them. Therefore, some examples of perspective concepts will be given.

- **Wind energy**: One possibility that deviates from the concept of on-board propulsion energy is the use of wind energy as auxiliary propulsion. Despite the relatively low energy density, a good effect can be achieved by large sails in the form of towed kites at relatively low cost. This use of energy is both historical and perspective.

- **Electrical energy**: A more perspective concept of the type - use of field energy, of energy not carried - is wireless energy transmission. If this technology reaches market maturity, it could be widely used. The power plants remain on shore, transmission takes place, and the on-board energy conversion system "receives" the energy with required power. Power plants of any type are interconnected according to the same principle.
- **Electric power**: Another concept for perspective clean shipping presupposes the availability of energy sources and energy converters with sufficiently high energy and power density, comparable to nuclear energy. Fusion reactors of various types have been discussed in the literature for some time. This technology is also not yet available on the market.

5 Appendix

5.1 Designation and explanation of abbreviations

Table 20 Description of abbreviations

Abbr.	**Meaning**
Accu-B	Accumulator-Buffer system
C-Gas	Combustion gases
chem	Chemical energy
Pull	The pull exerted on the sail by the wind generated by the wind. (incorporates mechanical energy)
E_i & P_i	Energy form (i) which enters an appliance with a certain Principle (i) of transformation.
E_in	Energy form that enters the transformation chain of E_i & P_i members.
E_out	Energy form that is used for the final purpose
E-Curr	Electric current from the national grid. (incorporates electric energy)
E-Field	Electric field of power transmission. (incorporates electric energy)
E-Gen	Electric generator. Transforms mechanic rotational energy into electric energy.
E-Storage	Battey storage for electric energy.
elec	Electric energy.
F-Cell	Fuel cell system, transforms chemical energy directly into electric energy.
H	Hydrogen.
H-C; C	Carbon (coal), Hydro-carbons in its vast varieties from fossil fuels, biogenic and e-fuels.
mech	Mechanical energy
Med	Intermediate storage of electric energy inside the transformation chain of an electric energy system.
nukl	Nuclear energy.
Rad	Radiation energy, sent out by transmitters which itself powered by electric energy provided by power stations, working according known principles.
R-Core	Reactor core in which the nuclear fuel is built in.
R-Gas	Reaction gases, hydrogen from fuel system and oxygen from air system. (incorporates chemical energy)
Steam	Steam to drive either an Piston engine or a turbine. (incorporates thermic energy)
Wind	Wind energy. (incorporates mechanical energy)
E_2	These are categories for different energy forms: thermic, mechanic, electric, chemical

5.2 Combustion properties of Hydrogen and Methane

Table 21 Combustion properties of Hydrogen and Methane

	Unit	Hydrogen	Methane
Methane number	-	0	100
Density (1)	kg/m3	0,09	0,718
Mass-specific calorific value	MJ/kg	119,9	50,01
Volume-specific calorific value	MJ/m3	10,78	35,89
Reversible reaction work	kWh/m3	2,832	9,939
Minimum air requirement	m3/m3	2,384	9,573
Mixture heating value (3)	kWh/m3	0,89	0,95
Diffusion coefficient in air (2)	cm2/s	0,61	0,16
Combustion rate in air (3)	cm/s	237	42
Max. Combustion rate in air	cm/s	346	43
Combustion temperature in air (3)	K	2318	2148
Extinguishing distance in air (2,3)	cm	0,064	0,203
Detonation limits in air (2)	Vol-%	18,3 - 59	6,3 - 14
Ignition limits in air (2)	Vol-%	27485	5,3 - 15

Legend: 1: 273,15 K, 101315 Pa; 2: 293,15 K, 101315 Pa; 3: stoichiometric mixture

Table 22 Marine diesel engines [49]

Manufacturer	Type	Design	Bore (mm)	Stroke (mm)	Displace-ment/cyl. (L)	Power/ cyl. (kW)	Speed (1/min)	Mean piston speed (m/s)	Application	Examples
MAN B&W	K98ME-C6	2S TC slowspeed R6 – R12, R14	980	2.660	2.006,40	5.720	94	8,3	ContainerC	
Wärtsilä-Sulzer	RT-flex96C	2S TC slowspeed R6–R12, R14	960	2.500	1.809,60	5.720	102	8,5	ContainerC	Emma-Mærsk-Class
Wärtsilä-Sulzer	RTA84T	2S TC slowspeed R5–R9	840	3.150	1.745,70	4.200	76	8	Tanker Gen-eralC	
Wärtsilä	64	4S TC middlespeed R6, R8, R9, V12, V16	640	900	289,5	2.010	333	10	GeneralC CruiseS	
MAN B&W	58/64	4S TC middlespeed R6–R9	580	640	169,1	1.400	428	9,1	GeneralC CruiseS	Pacific Jewel, Queen Elizabeth 2
Wärtsilä	46	4S TC middlespeed R6, R8, R9, V12, V16	460	580	96,4	1.050	514	9,9	GeneralC CruiseS	Oasis of the Seas, Queen Mary 2
MaK	M43C	4S TC middlespeed R6, R7, R8, R9, V12, V16	430	610	88,6	1.000	500	10,2	GeneralC CruiseS	Sphinx-Klasse BBC Everest
Sulzer	ZA40S	4S TC middlespeed R6, R8, R9, V12, V16	400	560	70,4	720	510	9,5	GeneralC CruiseS	Destiny-Klasse, Queen Victoria
Caterpillar	C280	4S TC highspeed R8, V12, V16	280	300	18,5	339	1.000	10	GeneralC Passg	
MTU	Serie 8000	4S TC highspeed V20	265	315	17,4	455	1.150	12,1	Passg, Tugs	

Legend : 2S = Two stroke; TC = Turbocharger; I-I indirect injection; GeneralC = general cargo ship; CruiseS = Cruise ship; Passg = Passenger ship; ContainerC = Conainer Carrier; Tanker= Tank ship

5.3 Relevant terms and explanations for classic fossil fuels and emission monitoring

ECA	Emission Control Area. Emission Control Area. Since January 1, 2015, only ships with a fuel sulfur content of less than 0.1% are allowed to pass through Emission Control Areas (ECAs). The areas currently covered are the Baltic Sea, the North Sea, the east and west coasts of the United States (US), Canada and parts of Asia. For the rest of the world, a different rule applies: under the IMO 2020 Regulation, marine fuel may still contain 0.5% sulfur as of January 1, 2020.
HFO	Heavy Fuel Oil. Heavy fuel oil; heavy oil, a residue of the distillation of crude oil. main marine fuel. HFOs have high viscosity and density. To ensure the quality levels of HFOs, residual fuels are blended with lighter fuels such as marine gasoil or marine diesel oil to form intermediate fuel oils. Depending on their viscosity, they are classified and named as IFO 180 and IFO 380 (viscosities 180 mm^2/s and 380 mm^2/s, respectively). According to the MARPOL Marine Convention of 1973, heavy fuel oil is defined either by its density of more than 900 kg/m^3 at 15°C or by a kinematic viscosity of more than 180 mm^2/s at 50°C. Heavy oils have a high proportion of heavy molecules, such as long-chain hydrocarbons and aromatics with elongated side chains. A main distinguishing feature is the sulfur content. According to ISO 8217, their maximum sulfur content must not exceed 3.5%. The average sulfur content of today's heavy oil bunkers is 2.7%.
HSFO	High Sulphur Fuel Oil). Max. Sulfur content 3.5%.
IFO	Intermediate Fuel Oils. E.g. IFO380, IFO180 with viscosity specification.
LSF	Low Suphur Fuel. Fuel with low sulfur content. Also Low Sulphur Fuel Surcharge, LSS or LSF. Introduced in January 2015 by the International Maritime Organization (IMO) to reduce the amount of sulfur-containing fuel used by ships. Carriers charge a fee to cover the cost of this more expensive fuel type. These charges are called LSS, LSF, or emission control area (ECA) surcharges. The LSF surcharge is not a fixed amount; it varies by shipping company and routing.
LSFO	Low Sulphur Fuel Oil, fuel oil with low sulphur content. Max. 1.0% sulfur. IFO 180 or IFO 380 marine fuels.
LSS	Low Sulphur Surcharge. Surcharge for low sulfur fuel (see SECA). Carriers charge a fee to cover the cost of this more expensive fuel option. These surcharges are called LSS (Low Sulphur Surcharge), LSF (Low Suphur Fuel), or ECA surcharge.
MDO	Marine Diesel Oil
MGO	Marine Gas Oil, Marine Gas Oil colloquial term called.
NECA	Nitrogen Emission Control Area. Nitrogen emissions monitoring area. The Baltic Sea is to become a monitoring area for nitrogen emissions from shipping. Stricter requirements for NOx emissions from ships (Tier III) will be imposed from 2021.
SECA	Sulfur Emission Control Area, emission control area for sulfur. Carriers charge a fee (ECA surcharge) to cover the extra cost of more expensive fuel options that must be used because of the regulations.
ULSFO	Ultra Low Sulphur Fuel Oil, ultrta-low sulfur fuel oil Max. 0.1% sulfur. Consists exclusively of distillates.
VLSFO	Very Low Sulphur Fuel Oil / Low Sulphur Fuel Oil (LSFO). Fuel oil with low or very low sulfur content. This type of marine fuel contains less sulfur and therefore complies with IMO 2020 regulations.

5.4 A Policy recommendation – Reduction of Sulphur as a business model

Issue: **Reduction of Sulphur input in seawater by establishing a Circular economy approach in Sulphur reduction in ships engines exhausts**

Recomen-dation

A) Prevention of input of Acids and other compounds from Scrubbing of Ships Engine exhausts by implementation of a circular process.

B) Using the generated products as an raw material for i. e. agriculture.

C) Initiation of project(s) for development and implementation.

D) Adaptation of air pollution regulations therefor.

Rationale

1)

State of the art is the technology of scrubbing of ships engines exhausts for the purpose of reduction of Sulphur contents in that exhausts. This is performed in special designed scrubbers (reactors) by a gas washing process whereby seawater is sprayed into the gas stream in opposite directions for a most possible effectiveness.

The product of that process contains Sulfurous / Sulfuric acid and other compounds like soot (carbon), nitrous acid and others. Currently the products together with the seawater are led back to the sea. The lowered pH (increased acidity) is well buffered by the higher pH (alkalinity).

Sulphur and nitrogen compounds acting as fertilizers of aquatic species and lead to algae blooming.

2)

On the other hand in the agriculture sector emissions of ammonia continue to rise, while emissions of most air pollutants remain on a downward trend across the European Union. This is posing a challenge for EU Member States in meeting EU air pollution limits, according to updated data released by the European Environment Agency (EEA) today. [AmmEU]

Widespread research efforts have been done over the years on mitigation ammonia emissions. Newly results on that issue came up.

By acidification of slurry (liquids form of pig or cattle manure) and other NH3 emitters has been developed, tested and been proven as a probate means of mitigation of odors.

This simple technology was tested by the Danish Environmental Protection Agency and it was proved that this way farms can reduce their ammonia emissions to 36%. This acidification of slurry technique were developed in Denmark over ten years. [Sindhöj]

3)

The product from exhaust scrubbing could be enhanced by a modified gas washing process (contact process / double contact process [Wiki]). The implemented machinery could be used by little modifications. Infrastructural and processual prerequisites must be prepared respectively developed, like storage capacities, logistics and delivery chains, contractual and legal issues.

4)

The implementation could establish a means of a circular economy approach by meeting environmental regulations and creating a business model at the same time.

This approach could find an adaptation in the specific rules for air and environment protection.

5)

For a meaningful development and implementation specific project(s) should be initiated.

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