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Ship Emissions Reduction Using Alternative Fuels and Abatement Technology

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Abstract: **In response to critical ship emission issues, the known devastating impact and strict national and international emission regulations, several options for emission reduction were investigated. In order to achieve the emission reduction goal, a set of practices can be adopted separately or in combination, including but not limited to alternative fuels, energy saving strategies and tools, renewable energy and abatement technology. In this paper, motivational factors, historical background, project development, locations, supply and demand, and reserve quantities of marine fuels are addressed. Potential scenarios involving alternative fuel drivers and emission reduction solution options are discussed. The alternative fuels addressed here include a comparison of their weighting aspects. Further, emission reduction abatement technology is explored. Among the current available alternative fuels (ethanol, methanol, bio-fuel, hydrogen, propane and natural gas), LNG is collectively the best fuel alternative due to measured superiority as the cleanest environmentally, the reasonable cost, suitability for propulsion engines and many other merits.**

Keywords: **Marine Emission-Alternative Fuels-Abatement Technology- Energy and Fuel Savings –Fuel Demands, Reserves, and Consumption Statistics-SCR: Selective Catalytic Reduction –EGR: Exhaust Gas Recirculation.**

NOMENCLATURE:

AAGR: Annual Average Growth Rate

AFC: Alkaline Fuel Cell

BSFC: Brake Specific Fuel Consumption

btoe: billion tons of oil equivalent

C_2H_5OH: Ethanol

CH_3OH: Methanol

CFD: Computational Fluid Dynamic

CO_2: Carbon Dioxide

EIA: Energy Information Administration

EC: European Commission (European Standards)

EGR: Exhaust Gas Recirculation

ECAAs: Emission Control Areas

ESDs: Energy Saving Devices

H2: Hydrogen

H2O: Water vapour

HFO: Heavy fuel oil or Residual fuel oil

IMO: International Maritime Organization

IEA: International Energy Agency

IEO: International Energy Outlook 2013

ISO 8217: 2005 (Specifications Marine Fuels)

ISO: International Organization of Standardization

IFO180, IFO380: Marine Residual Fuel Oil

EIA: U.S. Energy Information Administration

KWh: Kilowatt Hour

GW: Gigawatt

LBF: Liquid Bio-Fuel

NG: Natural Gas

LNG: Liquefied Natural Gas

MDO: (Marine Diesel Oils)

MGO: Marine Gas Oils

M/E: Main Engine

IFO: Marine diesel fuel oil or intermediate fuel oil

MCFC: Molten Carbonate Fuel Cell

MGO: marine gas oil

NO_X: Nitrogen Oxides

NASA: National Aeronautics and Space Administrations

OECD: Organisation for Economic Co-operation and Development

OPEC: Organization of the Petroleum Exports Countries

PM: Particulate Matters

PAFC: Phosphoric Acid Fuel

PEMFC: Proton Exchange Membrane Fuel Cell

SO_X: Oxides of Sulphur

SOFC: Solid Oxide Fuel Cell

SCR: Selective Catalytic Reduction

1. INTRODUCTION

As a result of ship emission magnitude and impact, and of stricter emission regulations worldwide, fuel alternatives are being investigated (e.g. the use of methanol as a fuel and the potential for fuel cells and electrical ships). Natural gas, abatement systems (scrubbers), biofuels, nuclear and fuel cells are all currently being explored.

Before exploring emission reduction options, including fuel alternatives and emission reduction technologies, the need for alternative fuels and conventional marine fuel demand, supply and reserves are examined in the following section.

Conventional marine fuels and their development are highlighted. Prospective scenarios involving alternative fuels drivers and emission reduction solution options are discussed. Categories of energy forms and sources are classified. The potential alternative fuels, including a comparison of weighting aspects, are explored.

Besides the aforementioned alternative fuels, there are also other options for compliance with emission regulations and emission reduction. These options include energy saving strategies and abatements solutions, and they are also investigated.

2. MARINE FUELS: DEMAND, SUPPLY AND RESERVES

The motivating factors, historical background, development including past, current and future projections, locations, levels of marine fuel demands, supplies and reserves are addressed herewith.

Fuel Demand:

Since the era of industrial revolution in the 18th and 19th centuries, there have been many eminent milestones in fuel development, including the discovery of oil in Pennsylvania in 1848 where the first well was drilled (Dake oil well in 1859), the first oil tanker "GLUKAUF" in 1886, the shift from coal to oil, and the monumental use of crude oil as the liquid fuel for the internal combustion engine, designed in 1861 by Nicolaus August Otto. Due to rapid scientific and cultural advancement, many fuel energy sources became essential for human industrial, economic and social activities and development. [1] [2]

Driven by economic structures and population growth, world consumption of primary energy has greatly increased from 3.8 billion tons of oil in 1965 to 11.1 billion tons of oil in 2007. (The current world population is 7 billion. The world population is expected to reach a range from 8 to 9 billion by 2040 and 12 billion by 2050). The global demand for energy is continuing and only expected to increase. [2]

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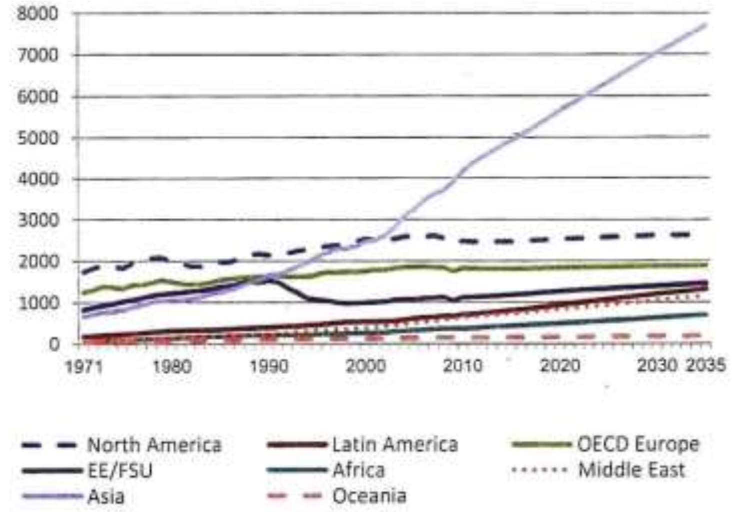
World consumption of primary energy greatly increased from 3.8 billion tonnes of oil equivalent in 1965 to 11.1 billion tonnes of oil equivalent in 2007.

However, this increase has been far from being uniform throughout the world. Members of the Organisation for Economic Co-operation and Development (OECD) accounted for 69% of world energy consumption in 1965. [1]

The world consumption of energy is expected to increase by 41% from 2012 until 2035. [2]

In the reference case outlook, global energy demand is projected to increase from 11.7 billion tons of oil equivalent (btoe) in 2010 to 17.5 btoe in 2035, at an annual average growth rate (AAGR) of 1.6 percent, as shown in Figure (1). [3][4]

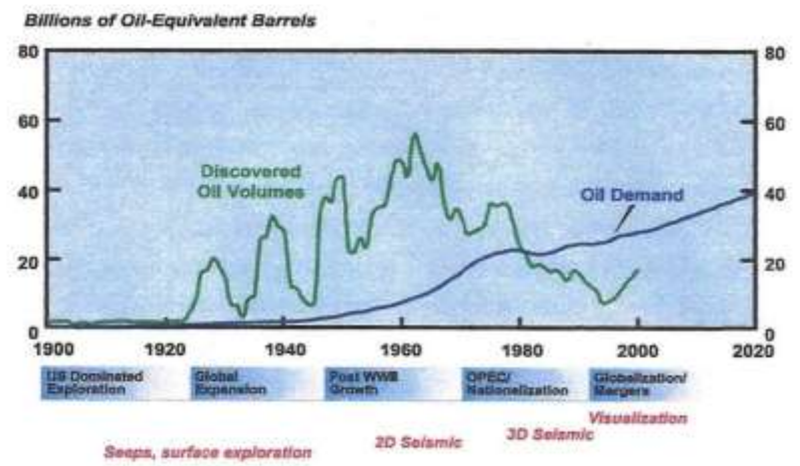


Source: IEA/OECD, op. cit.

Figure (1) Outlook for Primary Energy Demand by Region (mtoe) [3] [4]

The historical trend in discovered oil volumes and oil demands is shown in Figure (2). [3]

In contrast to the continuous increase in demand, new energy discoveries have been in a trend of decline.



Source: H.J. Longwell, "The Future of the Oil and Gas Industry: Past Approaches, New Challenges," *World Energy*, vol. 5, no. 3, 2002.

Figure (2) Historical Trends in Discovered Oil Volumes and Oil Demand [3]

With fuel consumption as a prime factor, in the ECAs (Emission Control Areas) use is estimated at approximately 30-50 million tons of fuel per year and that number is anticipated to increase if more areas are included in the ECAs in the future, as is expected.

The global demand on energy is about 285 million barrels/day. Out of that approximate amount, 34% is derived from oil, 26% from coal, and 22% from natural gas. In other words, 82% of the energy is from fossil fuel. The remaining 18% can be broken down to 5.5% from nuclear energy, 2.2 % from hydro-electric energy and 12.5% from renewable energy (the biggest portion of which is from biomass) [2] [5]

Fuel Supplies:

Although some oil analysts and experts have suggested that peak oil accumulation has passed and oil production is expected to decrease, oil supply outlook indicates that global oil production will continue to rise from 87 mbpd in 2011 to 114 mbpd in 2035 to meet growing demand. The global energy supply projection to 2055 from multiple sources, including oil, gas, coal, nuclear, hydro, renewables, wind and solar energy, is given in Figure (3). [6]

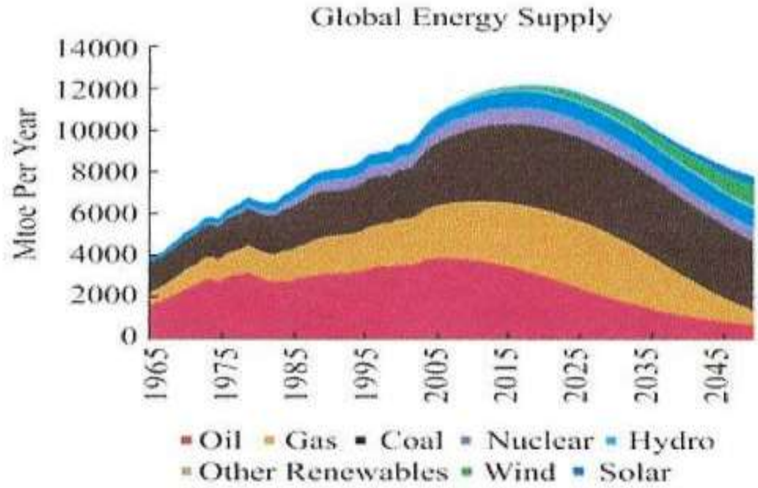
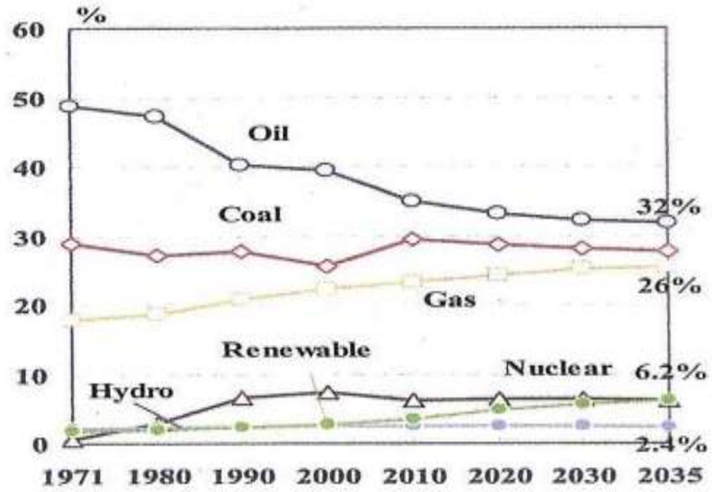


Figure (3) Global energy supply projection to 2055[6]

The figure reveals a gradually declining supply trend. Currently, 86% of the world population are living in countries where demands on nature exceed what the eco-system can provide. Average calculations reveal that the world will need the energy and other resources of three earths by the next century. [7]

Moreover, according to Figure (4), although the share of oil in total primary energy is projected to decrease to 32 percent in 2035, oil will still maintain the largest share, followed by coal (at 28 percent in 2035), while natural gas share is expecting to increase to 26 percent. [3]



Source: IEA/OECD

Figure (4) Outlook: Share of Energy Sources in Total World Energy [3]

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For the last twenty years most projections of global energy supply and demand have portrayed essentially the same picture for the next quarter century: continued growth in demand for and continued reliance on the classic fossil fuels for at least 80 percent of primary energy supply. However, projections also show that the shares of alternative fuels (natural gas and other renewables) will increase, while coal and nuclear will be reduced and oil's share will continue to shrink. It is expected that NG production will increase by 55% between 2013 to 2040, a yearly growth of 1.6%. [2] [3]

Fuel Reserves:

The locations and quantities of global oil reserves in existing and potential reservoirs always contain a margin of uncertainty due to some national, market and even political considerations. In addition, the world largely depends on oil supplies from potentially politically volatile regions, which can have an adverse effect on fuel supply security and sustainability.

However, it is estimated that international Fossil Fuel Oil reserves will be consumed in about 50 years. Figure (5) shows the crude oil reserves worldwide. [8]

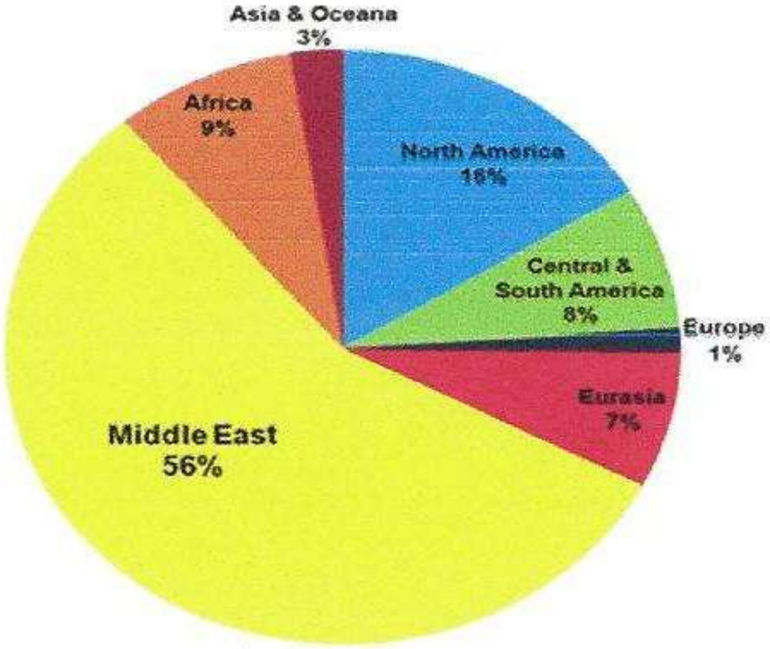

Figure (5) World crude oil reserves locations [8]

To sum up, the projections show the potential future decline of available conventional fuel, as well as the increased demand and consumption of said fuel, due to rapid expansion in populations and industrial and transportation activities, including developments in marine propulsion systems. Taken together, these trends demonstrate the necessity to explore more options for fuel alternatives. In the next chapter, we explore the marine fuel alternatives and ship emission reduction options.

3. SHIP MACHINERY FUEL CONSUMPTION AND EMISSIONS:

The development of marine power plants is linked strongly to the rate of fuel consumption and the plant efficiency.

Figure (6) visualizes a typical energy flow (based on the preferred Matthew H. Sankey concept diagram) from fuel to utilization for a ship in sailing condition. The figure shows the flow of energy related to the total input, and indicates the area of energy (power) losses that need to be re-considered for possible savings or recovery. The efficiency of the power plant can be improved especially from remedying the exhaust losses. [9]

The total input of power relies mainly on the fuel type, quality and heat input, and the type and design features of the power plant, also crucial to improve plant efficiency.

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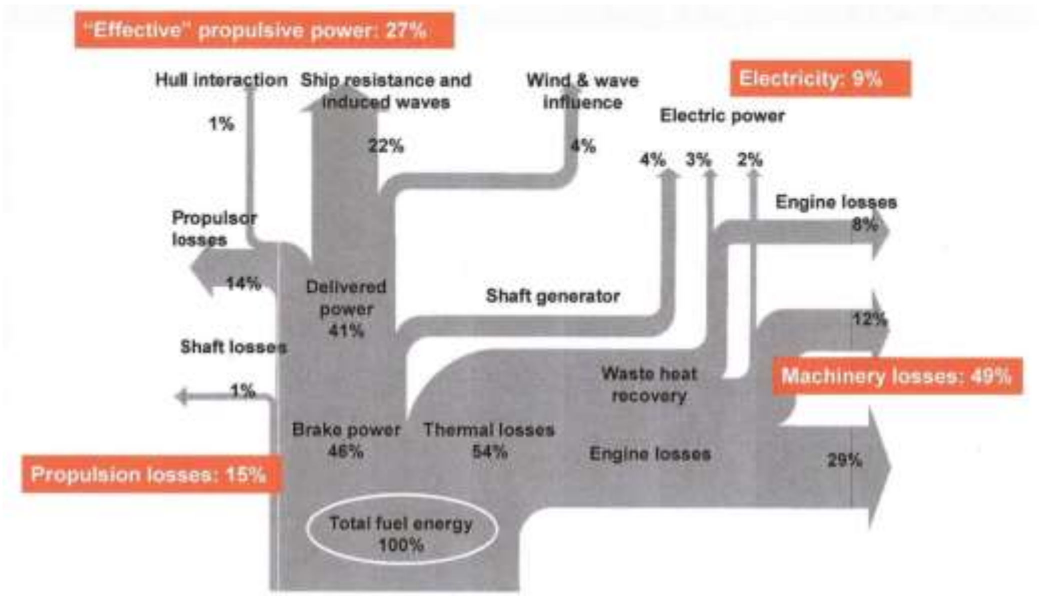

Figure (6) a typical energy flow (Sankey concept diagram)
from fuel to utilization for ship in sailing condition. [34]

Brake Specific Fuel Consumption (**BSFC**) is a measure of the fuel efficiency of any prime mover that burns fuel and produces rotational or shaft power. It is typically used for comparing the efficiencies of internal combustion engines with a shaft output. It is the rate of fuel consumption divided by the power produced. The specific fuel consumption graph shows how many grams of fuel are burned over the course of an hour per horsepower generated at a given RPM. In general, the engine is most efficient at the middle of the RPM range, although efficiency in this RPM range may be decreased by the drag induced by a displacement hull at higher ship speeds.

A modest increase in speed produces a sharp increase in fuel burn rates because of the non-linear, exponential increases in wave-making resistance.

The propeller power curve and specific fuel consumption graphs in the engine manual are based on optimal, new-engine conditions. The amount of fuel an engine burns to generate the horsepower needed to reach a given RPM may be adversely affected by poorly functioning injectors, a lack of clean air, dirty oil, or the maintenance condition of the turbocharger and other engine parts. Time between dry-docking and the cleanliness of the under-water hull envelope will have an adverse effect as well.

BSFC data may vary due to changes in weather, tides, temperature, wind direction, hull & propeller condition and load conditions. A typical BSFC is shown in Figure (7). [11]

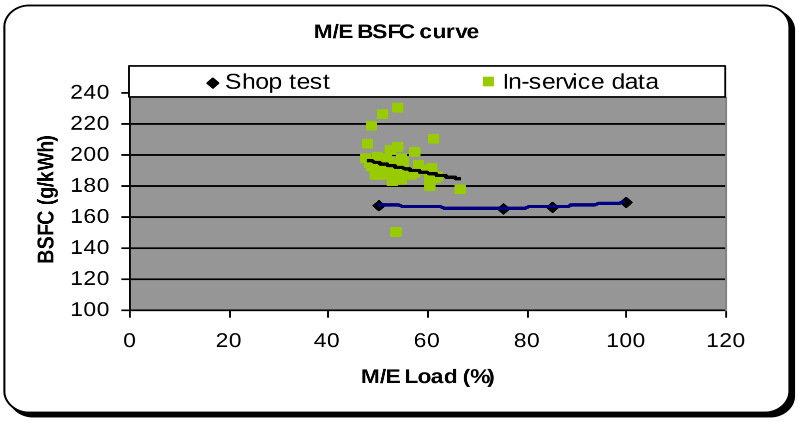

Figure (7) Typical BSFC [11]

Marine power plants are mainly classified according to the type of the prime mover responsible for the propulsion power generation. Three main prime movers exist: internal combustion engines, gas turbines and steam turbines.

The fuel consumption rate for marine diesel engines is 160-180, 165-210, and 200-250 g.kw/hr. for low speed, medium speed and high speed, respectively.

This rate is higher in steam turbines (260-360g.kw/hr.) and the highest in gas turbines (210-400 g.kw/hr.).

A typical Specific Fuel Consumption Comparison chart of Diesel Engines and Gas Turbines is shown in Figure (8).[6][13]

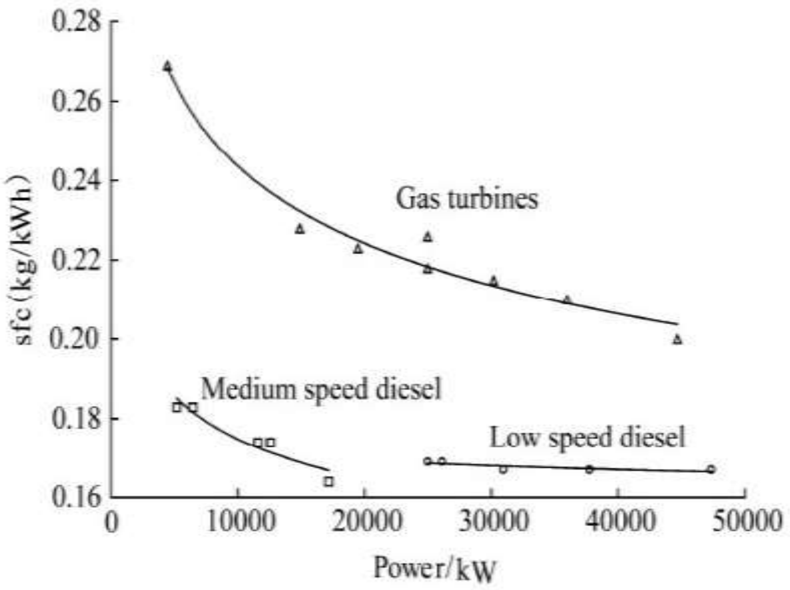

Figure (8) Specific Fuel Consumption Comparison of Diesel Engines and Gas Turbines [6] [13]

4. FUEL ALTERNATIVES AND EMISSION REDUCTION TECHNOLOGIES FOR PROPULSION MARINE POWER PLANTS

In this section, the conventional marine fuels and their development are highlighted. Scenarios of the alternative fuels drivers and emission reduction solution options are discussed. Categories of energy forms and sources are classified. The potential alternative fuels addressed include a comparison of their weighting aspects. The emission reduction technology and abatements are explored.

Conventional Marine Fuels:

Ever since the Industrial Revolution took off in the 18th century, vast quantities of fossil fuels have been used to power the economy and deliver unprecedented affluence to huge numbers of people. As standardly defined, fossil fuels are organic matter made from the remains of flora and fauna subjected to immense pressure and heat deep within the earth over millions of years. Petroleum, coal, and natural gas are major fossil fuels.

During the Industrial Revolution, fossil fuels seemed to be the ideal energy source. Steam locomotives, the quintessential machines of the era, used coal as a fuel source from early on to compensate for a lack of firewood and charcoal. Not only was there a seemingly inexhaustible supply of coal available from easily exploited seams near the surface, but it could be used in its natural form.

Since the modest beginnings of the oil industry in the mid-19th century, petroleum has risen to global prominence. Initially kerosene, used for lighting and heating, was the principal product derived from petroleum. However, the development of drilling technology for oil wells in mid-19th century America put the petroleum industry on new footing, leading to mass-consumption of petroleum as a highly versatile fuel used primarily for powering transportation in the form of automobiles, ships, airplanes and so on.

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Ever since that time, fossil fuels have served as the backbone of the new industrial civilization that transformed our world.

It was a revolutionary movement to convert from coal to fossil liquid fuels as the primary source of energy for industrial and transportation applications, an adjustment that began as early as the beginning of the 20th century.

Although coal has the significant advantages of availability, adaptability, low cost, and relatively safe operation, it is considered a nonrenewable energy resource and due to its substantially high sulfur content, it is completely outside IMO regulations and is not seriously considered by nations looking for green and clean environment fuel options.

As a result of the oil embargo and the oil price shock following geopolitical factors in the Middle East (the Arab-Israel war in 1973 and the Islamic revolution of Iran in 1979), fuel prices between the early 1970s and the 1980s sharply increased, eight fold compared to preceding decades. Developed countries drastically changed plans to reduce reliance on foreign oil, while attempting to avoid any possible interruption in oil supply, and began looking for other fuel options and technologies to both compensate for the oil reserve decline and also to mitigate the emission issue. (Ellian. Osama, LRTA, Lloyd's Register 2015).

Marine transport has traditionally used heavy oils and marine distillates as fuels. The most common fuel on ships, Heavy Fuel Oil (HFO), is considered a residual product, since it remains after the lightest components of crude oil have been extracted through the refining process. HFO contains a wide range of undesirable contaminants, such as sulphur, ash and sodium, which make its post-combustion exhaust a danger to the environment and to human health.

Marine distillates are marine diesel oil (MDO) and marine gas oil (MGO). MDO has traditionally contained lower concentrations of sulphur than HFO. Permissible sulphur content by weight has remained quite high at 1.0%. As discussed earlier, oil-fueled engines produce many gaseous emissions and PM, which have undesirable effects on human health and on the environment.

The international standard organization (ISO) list 19 different marine fuels which meet the requirements for world-wide onboard ships. Out of these 19 fuels, the most important marine fuels are IFO180, IFO380, MDO (Marine Diesel Oils) and MGO (Marine Gas Oils). These relate to ISO grades RME24, RMG35, DMB and DMA respectively as specified in ISO 8217: 2005. [14][15]

Diesel fuel types for current marine applications are shown in Table (1). [16][17]

Table (1) Diesel fuel types for marine use. [16][17]

Fuel Type	Fuel Grade	Common Industrial Name	Characteristics
Distillate	DMX, DMA(called MGO), DMB(called MDO) & DMC, DMX	Marine gas oil (MGO) or marine diesel oil (MDO) or	Light distillate fuel, low viscosity, low levels of impurities. Heavier distillate, may contain some residual components.
Intermediate	IFO 180-IFO 380	Marine diesel fuel oil or intermediate fuel oil(IFO)	Heavy fuel oil that might contain distillate fuels.
Residual	RMA-RML	Heavy fuel oil or Residual fuel oil(HFO)	Residual fuel with the highest viscosity and highest levels of impurities.

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5. SCENARIOS OF ALTERNATIVE FUELS

There are some main ways to reduce emissions:

- Use alternative clean fuels such as less carbon-intensive fuels, low sulphur fuels (1%) , ultra-low sulphur fuels (0.03%), bio-fuels, NG and Hydrogen.
- Removal of pollutants before, during or after combustion (emission reduction abatement technology) and improving energy efficiency.

Alternative fuels have attracted keen attention from various stakeholders. While ship owners have started to look at different options to comply with the future challenges with regard to ship fuels and legislations, researchers have been investigating non-conventional fuels including other non-fossil petroleum fuels to avoid harmful consequences to the environment. Oil analysts, motivated by the political pressure to reduce the dependency on foreign fuel supply, have proposed some strategic solutions to compensate for the anticipated future decline in oil productions and the increasing trend of energy demand. Many are very keen not to rely on only one fuel source for energy security.

MARPOL (Annex VI) Air Pollution Prevention regulations and the continuation of fuel price increases are the driving forces for the shipping industry to reconsider the possible fuel options.

In 2004, John L. Hallock Jr. predicted the year of conventional fuel peak and subsequent decline to be within 2019-2035, and outlined the range of solution options for both the supply issue and emission reduction issue with the following scenarios:

1. Enhancement of oil recovery by improvement of currently utilized methods.

2. Effective use of non-conventional fuels including liquefied natural gas, bio-fuel, liquefied hydrogen, etc.

3. Expansion of the share of renewable energies such as solar, wind, sail kites, bio-mass, etc.

4. Adoption of energy saving tools and strategies (i.e. tackling the problem from the demand perspective rather than from the supply perspective).

According to a recent study on Global Marine Fuel Trends, developed jointly by Lloyd's Register and University College London, that explores the future of the shipping industry in three potential situations up to 2030, heavy fuel oils will continue to dominate the marine fuels market with an increasing demand for distillates between now and 2030. Lloyd's Register foresees in said study that LNG will increase to comprise 11% of total marine fuel demand in 2030, it remains to be seen if that demand will continue its upward trend beyond that point. [19]

Hence, in order to achieve the target of ships emission reduction process, a set of techniques could be applied separately or in combination, including but not limited to: the use of alternative fuels, emissions reducing technology, and fuel saving strategies.

There are several available alternatives to HFO, MGO and MDO that can be found today. The main alternative marine fuel types may be found in three forms: liquid, gaseous and solid fuels. Liquid marine alternative fuels include Bio-liquid fuel (Bio-diesel) and alcohols (Methanol, Ethanol). The main alternative gaseous fuels include Liquid Hydrogen and natural gas.

The solid fuel form is nuclear propulsion (U238), which is beyond the scope of this study.

Before going into detail concerning the alternative fuel scenarios, it is necessary to highlight that there are many categories and classification schemes for the energy forms and sources. For simplification, the author has compiled the forms of energy and energy sources in Figure (9) and Figure (10), respectively and Figure (10), respectively. [9]

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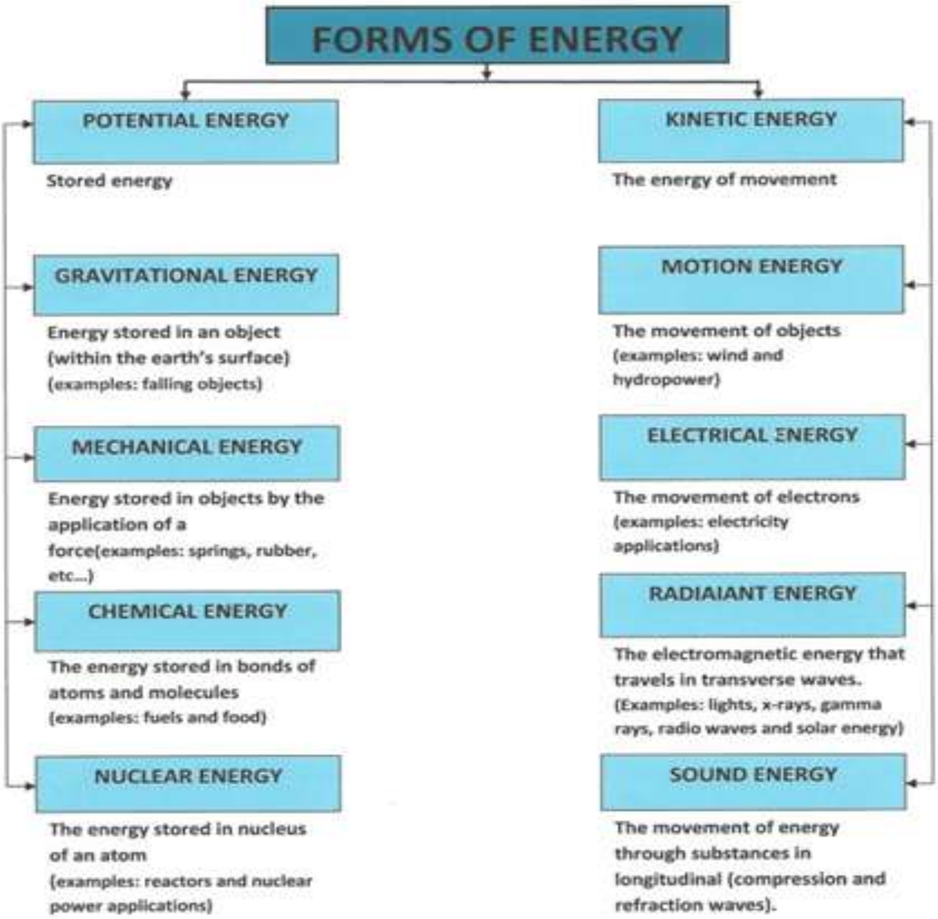
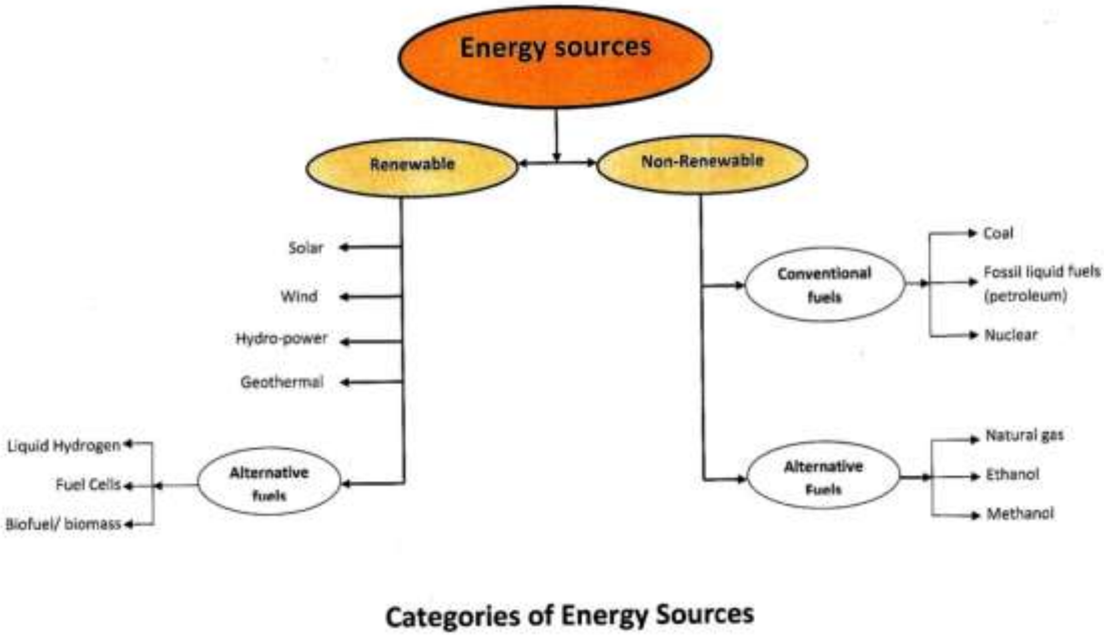


Figure (9) Various Forms of Energy [9]



(*Source:* The Author)

Figure (10) Categories of Energy Sources*

In the following sections we will briefly explore some of the main alternative fuels.

Liquid Hydrogen:

Hydrogen as an element was discovered by the British scientist Henry Cavendish in 1766. Hydrogen is classified as a renewable source of energy and has been considered to be the fuel of the future for decades. The name “hydrogen” first appeared in 1788 when the French chemist Antoine Lavoisier coined the term. [8][20]

Hydrogen produces fewer emissions of CO_2, SO_X and PM in both partial-load and full-load engine operations.

The main problems associated with the application of hydrogen in internal combustion engines include the fact that high combustion temperatures in hydrogen engines usually lead to an increase in NO_X emissions. Hydrogen produces 270% more NO_X than diesel use without any control measures besides the result of a slight increase in the engine thermal efficiency with a decrease in engine output power and torque. [21]

The engine knocking is one of the primary problems; air fuel ratio and intake temperature were found to be the main causes for this problem and their optimization is a must to have a knock free engine. Due to hydrogens high flame speed and low ignition energy, problems observed include the steep rise of cylinder pressure and possibility of fuel pre-ignition, leading to potential explosions inside the engine systems.

One of the more serious draw-backs in this potential scenario is the storage limitation. One gram of hydrogen gas occupies about 11 liters of space at atmospheric pressure at the extremely cold temperature of -253 °C. Therefore, use of hydrogen as an alternative fuel is still very limited due to the fact that it is an extremely difficult gas to store, drawbacks regarding economic feasibility, adaptability, safety operation issues and some technical problems. These issues drastically diminish and limit hydrogen use and application in marine field. [2] [20] [22] [23]

Fuel Cells:

The Swiss scientist Christian Friedrich Schoenbein discovered the fuel cell effect in 1838, and English scientist William Robert Grove invented the fuel cell in 1945. Although Hydrogen fuel cells were discovered prior to Internal Combustion (including diesel engines), they were initially put into application in the 1960s by NASA, for producing power advantageously due to emission free operation. In principal, water is the only product of the hydrogen fuel cell since hydrogen can be derived from water through electrolysis.

A fuel cell is simply an electrochemical power plant which converts the chemical form of energy by mixing hydrogen and oxygen to produce water. In this process, it produces the electrical form of energy. The main difference between fuel cells and ordinary batteries is that fuel cells can function without limit, theoretically, if the supply of fuel is not interrupted. There are several kinds of fuel cells and each operates a bit differently.

Currently, only five types are dominant and the others are variations of these main types. The five types are: Proton Exchange Membrane Fuel Cell (PEMFC), Alkaline Fuel Cell (AFC), Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC). Among all types of fuel cells, only two are candidates for use onboard ships; the PEMFC and the MCFC, powered by hydrogen-rich fuels like natural gas or alcohols. [24]

Hydrogen is used in fuel cell development, especially in naval ship application, for auxiliary power generation due to its damped sound signature characteristics in submarines. For commercial ships, fuel cells are still not attractive enough to be adopted as a technology.

The fuel cells main drawbacks are high capital cost, fuel cell life issues and the necessity of periodic replacement of fuel cell stacks.

The implementation of said technologies is likely to demand extensive refitting and alternation or even replacement of present engines, which hinders application in a widely commercial use.

Biofuel:

Biofuels are one of the suggested options of alternative fuels. Historically, they have been recognized since Rudolph Diesel, the inventor of the diesel engine, used vegetable oil as fuel for his invention. He actually operated the first diesel engine on peanut oil.

Biofuel is a renewable fuel which can be derived from three primary sources: edible crops, non-edible crops including waste, and algae, which can grow on water and does not compete with food production. Bio-diesel is most commonly produced from soybean oil, rapeseed oil, sunflower oil, corn oil and olive oil, along with some wastes, such as used waste frying oils.

Use of biofuels in marine vessels is rather limited, but they are more widely used in some engines designed for inland transport and in power generation plants, compared with marine distillate fuels. A great reduction in SO_2 emission is expected when introducing biofuels in shipping and inland transportation. Biofuels also biodegrade rapidly, posing far less of a risk to the marine environment in the event of a spill.

The evidence suggests that biofuels are only used on a limited basis within the marine sector. Interestingly, a great number of projects involving biofuels in marine vessels have been conducted in the region of the Great Lakes in North America. [5][23]

The versatility of diesel engines allows a variety of fuels to be used. Currently, many well-known engine manufacturers like MAN and Wartsila make engines designed for biofuel.

The disadvantages of biodiesel are issues with cold weather starting, some storage instability, and slight increase in NO_x emissions (+2: +5%) due to the higher oxygen content of the fuel. Additionally, its availability is limited and securing the necessary production volume can be a challenge. [20]

Due to the corrosiveness of biofuels, questions have been raised as to whether or not the fuel tanks could manage the biofuel. Deposits in the storage tanks can cause clogging of filters, as mentioned in the previous section.

A debate between ethics and business is raised and considered as a resistance block in some countries: to what extent does the production and use of biofuels affect the price of foodstuffs and what impacts may it lead to for the impoverished people of the world?

Some predict that the implementation of biofuels may cause an increase in prices on agricultural products and that the correlating rising food prices will have negative effects on poor communities.

Ethanol and Methanol:

Alcohol fuels are of two types, ethanol (C_2H_5OH) and methanol (CH_3OH), which can be produced from sugarcane waste and many other agricultural products. Both are considered to be special types of bio-fuels and also renewable resources. This is not a new concept; they have been used in motor vehicles since 1954. [20] The Availability as a fuel source, ease of handling, low emission and the high-thermal efficiency obtainable with their use make these fuels a logical alternative for the future, especially to hydrogen generation for fuel cells.

Recent studies showed the potential of using methanol as an alternative fuel, especially in dual-fuel engines.

Renewable Energy:

Renewable energy are those sources of energy which can be regained naturally in a short period of time such as solar, wind, hydropower, geothermal, biomass, liquid hydrogen and fuel cells. Wind kites and solar panels have already been installed on numerous ships to supplement marine diesel engines. Both have some potential to mitigate carbon emissions. Certainly, vessels equipped with sails, wind kites or solar panels may be able to supplement existing power generation systems, but the relative unreliability of these energy sources render them appropriate to solve the problem only partially, in special cases and when favorable weather conditions allow. Renewable energy is not seen as a viable alternative for commercial shipping.

However, when feasible, alternate sources of power are encouraged in principal, and they may be considered for use principally and/or supplementally, especially as their cost is expected to be reduced with time.

According to a recent U.S. Energy Information Administration (EIA) International Energy Outlook 2013 (IEO), "…wind and hydropower account for nearly 80% of the projected increase in renewable electricity generation. The contribution of

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wind energy, in particular, has grown rapidly over the past decade, from 18 GW of net installed capacity at the end of 2000 to 183 GW at the end of 2010- a trend that continues into the future. Of the 5.4 trillion KWh of new renewable generation added over the projection period, 2.8 trillion KWh (52%) is attributed to hydroelectric power and 1.5 trillion KWh (28%) to wind energy". Renewable energy represents about 7% of the total world energy consumption.

Whether this will be a relevant substitute or supplement to engine power remains to be seen. Additionally, hybrid technologies involving sails, solar, waves and hydropower solutions may become more relevant in the future. Economically, the future seems bright for renewable energy as the cost is decreasing with time. Based on year 2015, solar energy cost is 129 USD/KW. hr, wind cost energy on land is 85 USD/KW.hr and at sea is 203 USD/KW.hr. [10] [26]

Comparison of Alternative Fuel Options:

The alternative fuels are still difficult to apply extensively on board ships in full because some are completely outside the IMO regulations, such as coal, and because some have the problem of low energy content, such as methanol and ethanol. Other possible marine fuels have limited applications owing to the problems of price and of storage issues on board ships, such as hydrogen, which has to be liquefied at -252°C.

Based on the preceding detailed discussions, the different alternative fuels including coal, biodiesel, alcohol, natural gas and hydrogen should be evaluated and assessed in terms of availability, renewability, adaptability to existing engines, storage, safety, cost, engine performance, economy, compliance with regulations and finally, the outcome on environmental emissions.

The weighting matrix and comparison between alternative fuels for marine use given in table (2) may be used to determine a relative guide for the optimum selection of alternative fuel in maritime transportation and considered as a qualitative comparison tool. [18] [20]

Table (2) Weighting Matrix and Comparison between Alternative Fuels for Marine use [20]

Comparison Aspects	Ethanol	Methanol	Liquid Bio-Fuel (LBF)	Bio-diesel	Hydrogen	Propane	Natural gas (NG)
Availability	**	**	***	**	***	**	**
Renew ability	**	**	**	*	***	-	-
Safety	***	***	***	***	-	**	***
Adaptability	**	**	**	***	*	**	***
IMO Compliance (Emissions Regulations)	*	*	**	*	***	**	***
Performance	*	*	**	**	*	**	***
Cost	*	*	**	**	-	***	***

*** Excellent **Very good *Good-light

The comparison revealed that LNG is collectively the best alternative fuel for marine use due to its superiority as the cleanest environmentally, reasonable cost, acceptable adaptability to existing engines and availability. The sole drawback is that it is nonrenewable, as compared to hydrogen, which comes in the second grade after LNG.

The details of LNG fuel merits, pros and cons will be discussed in detail in the next chapter. Figure (11) illustrates the position of LNG among the potential alternative fuels in the next generation ships. [28]

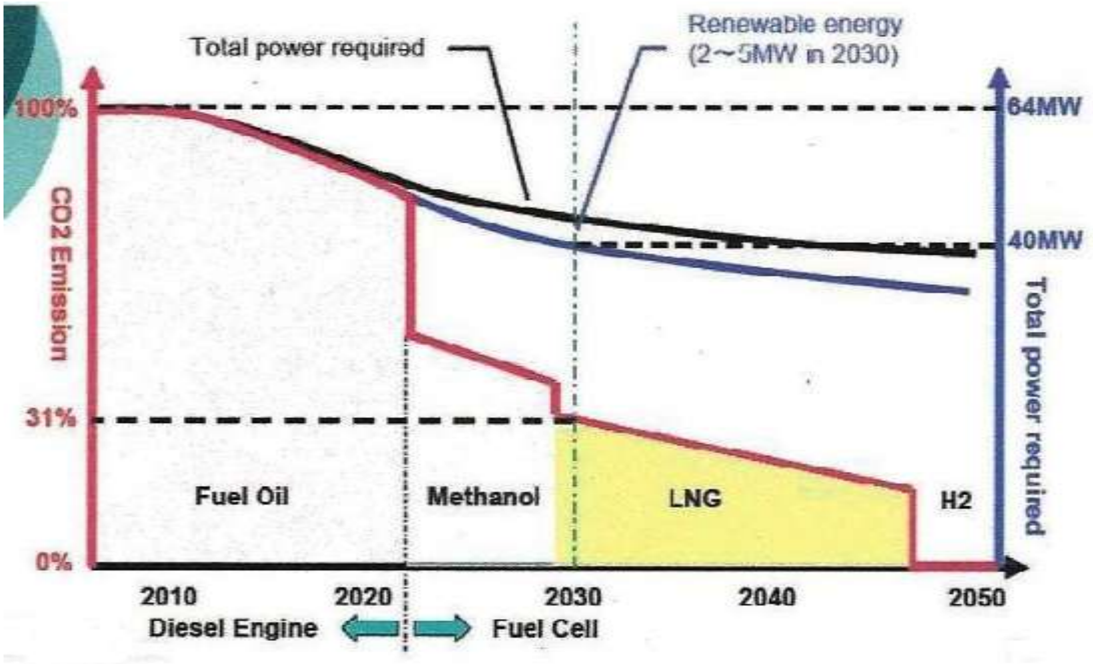

Figure (11) The position of LNG fuel among other alternative fuels in the next generation ships. [28]

6. SHIP EMISSION REDUCTION TECHNOLOGY AND ABATEMENTS

Besides the aforementioned alternative fuels, there are also other options for compliance with emission regulations and emission reduction. These options include energy saving strategies and tools in addition to several emission reduction technology solutions.

Ship Energy Saving Strategies and Tools:

The strategies for fuel saving and improving efficiency in ships relies mainly on four main fields: [9]

- **Reduction of Hull resistance**
- **Improvement of Propulsion efficiency**
- **Improvement of Power plant efficiency**
- **Improvement of Operational and Voyage efficiency (including Energy efficiency management)**

Improvement solutions may be initiated and actioned solely or introduced at design inception, through the assumption of suitable technologies and management systems procedures.

It is important to note that the above mentioned four improvement categories with their subsequent stemming details are strongly interrelated. For instance, the ability to slow-steam efficiently depends on the power plant as well as the propulsion system and hull. Striking this balance relies on finding the correct operating profile [9]

As evidence and guidance, Figure (12) shows typical Energy Saving Devices and their impact on Energy Saving, as compiled and developed by the author. The devices mentioned in this table are by no means an exhaustive list of ESDs available to the marine industry. In order to simplify the details of the above listed “Ship Energy Saving Strategies and Tools”, Figures (13) and (14) were developed by the author as pragmatic guidelines in the form of conceptual block diagrams for fuel and energy saving strategies and solutions on board ships for both new construction ships and existing ships, respectively [9]

The listed items and measures in these figures are not meant to be absolute. There are many ways to reduce fuel consumption and emissions and to improve efficiency on ships, but there is no easy and straightforward single solution or “quick fix”. For instance, engine technology is improving slowly; no quantum leaps can be expected in the near future.

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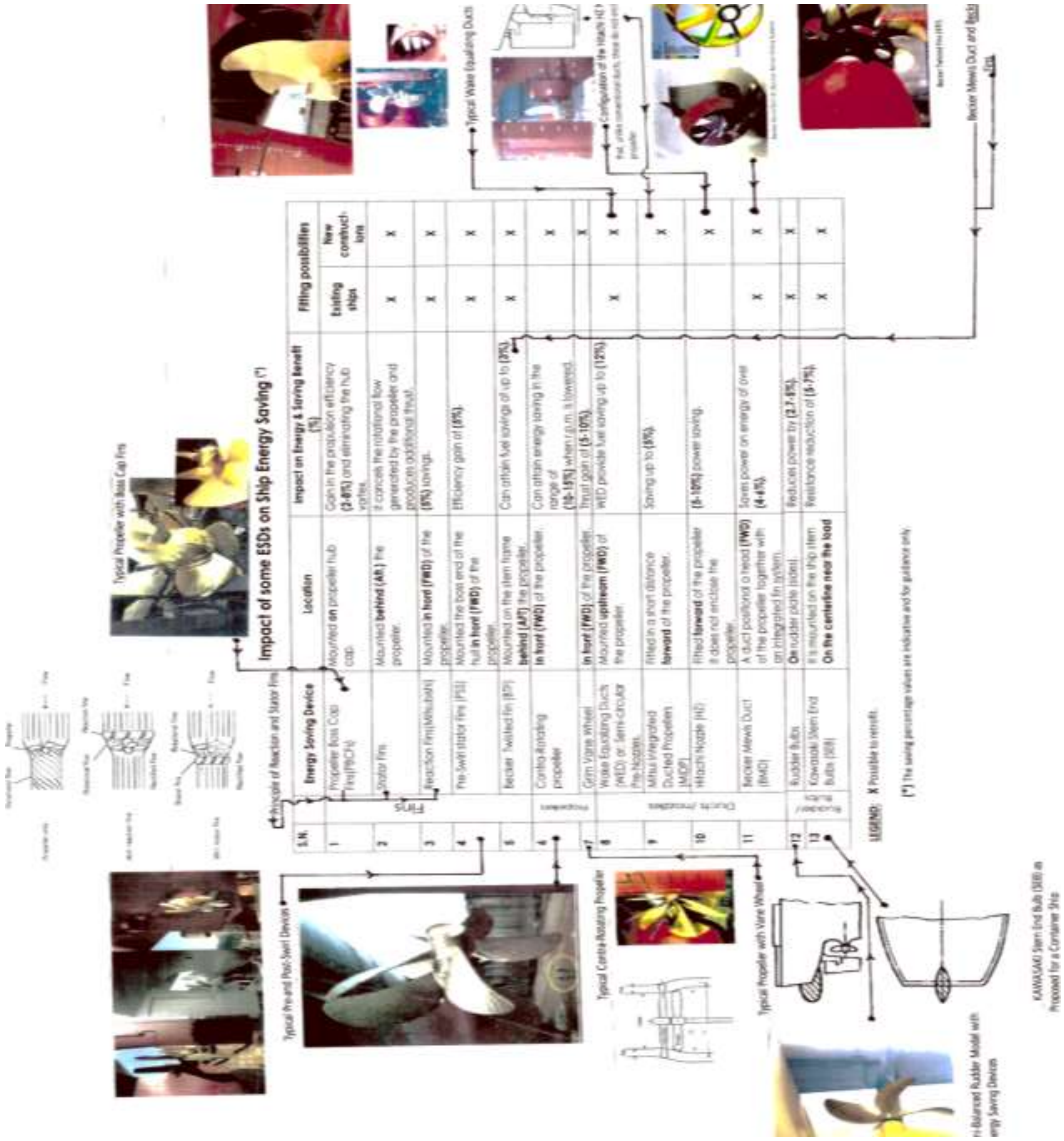
Furthermore, an improvement in engine efficiency can often lead to an increase on other emissions, such as NOx. Power demand reduction offers more options for reducing emissions, but large improvements are by no means easy to achieve there, either. One way that propulsion power can be decreased is to adopt new innovative propulsion solutions, and to optimise the hull form. Another example involves cruise ships, as they offer large power reduction potential on the hotel side. The hotel loads represent a very large share of the total energy consumption. Yet another possibility for achieving fuel savings is to change the operating parameters of the vessel, notably by selecting the right speed. However, this is not by any means to be considered the end of the story, since more potential areas for ship energy saving and efficiency improvement still need to be explored.



S.N.		Energy Saving Device	Location	Impact on Energy & Saving Benefit (%)	Fitting possibilities: Existing ships	Fitting possibilities: New constructions
1	Fins	Propeller Boss Cap Fins(PBCFs)	Mounted **on** propeller hub cap.	Gain in the propulsion efficiency **(2-8%)** and eliminating the hub vortex.		
2		Stator Fins	Mounted **behind (Aft.)** the propeller.	It cancels the rotational flow generated by the propeller and produces additional thrust.	X	X
3		Reaction Fins(Mitsubishi)	Mounted **in front (FWD)** of the propeller.	**(5%)** savings.	X	X
4		Pre-Swirl stator Fins (PSS)	Mounted the boss end of the hull **in front (FWD)** of the propeller.	Efficiency gain of **(8%)**.	X	X
5		Becker Twisted Fin (BTF)	Mounted on the stern frame **behind (AFT)** the propeller.	Can attain fuel savings of up to **(3%)**.	X	X
6	Propellers	Contra-Rotating propeller	**In front (FWD)** of the propeller.	Can attain energy saving in the range of **(10-15%)** when r.p.m. is lowered.		X
7		Grim Vane Wheel	**In front (FWD)** of the propeller.	Thrust gain of **(5-10%)**.		X
8	Ducts /nozzles	Wake Equalizing Ducts (WED) or Semi-circular Pre-Nozzles	Mounted **upstream (FWD)** of the propeller.	WED provide fuel saving up to **(12%)**.	X	X
9		Mitsui Integrated Ducted Propellers (MIDP)	Fitted in a short distance **forward** of the propeller.	Saving up to **(5%)**.		X
10		Hitachi Nozzle (HZ)	Fitted **forward** of the propeller it does not enclose the propeller.	**(5-10%)** power saving.		X
11		Becker Mewis Duct (BMD)	A duct positioned a head **(FWD)** of the propeller together with an integrated fin system.	Saves power on energy of over **(4-6%)**.	X	X
12	Rudder/ Bulbs	Rudder Bulbs	**On** rudder plate (sides).	Reduces power by **(2.7-5%)**.	X	X
13		Kawasaki Stern End Bulbs (SEB)	It is mounted on the ship stern **On the centerline near the load**	Resistance reduction of **(5-7%)**.	X	X

LEGEND: X Possible to retrofit.

(*) The saving percentage values are indicative and for guidance only.

Figure (12) Typical Ship Energy Saving Devices and Impact on Ship Efficiency [9]

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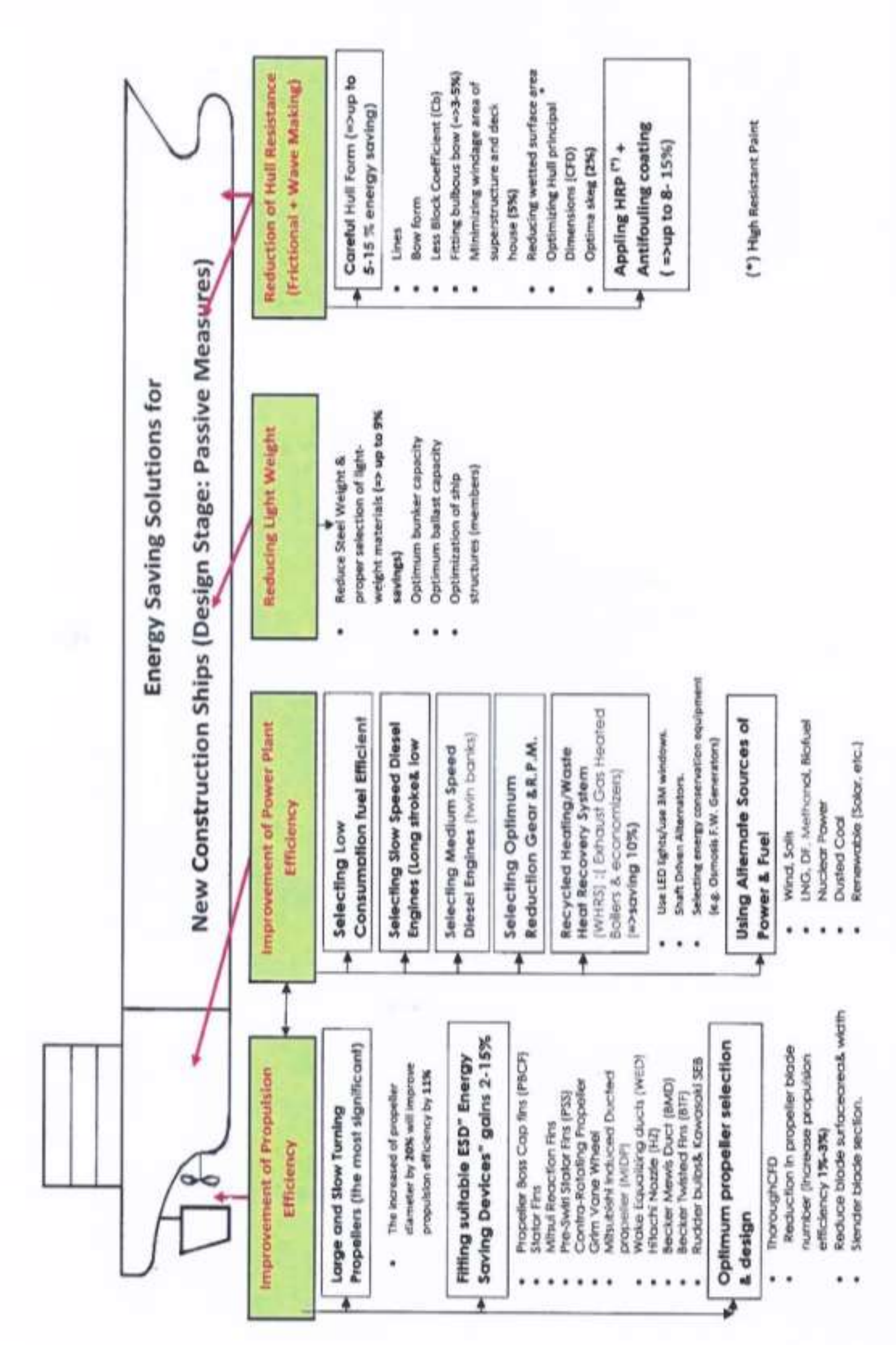

(*Source: The Author)

Figure (13) Energy Saving Solutions for New Construction Ships (Passive Measures) [9]*

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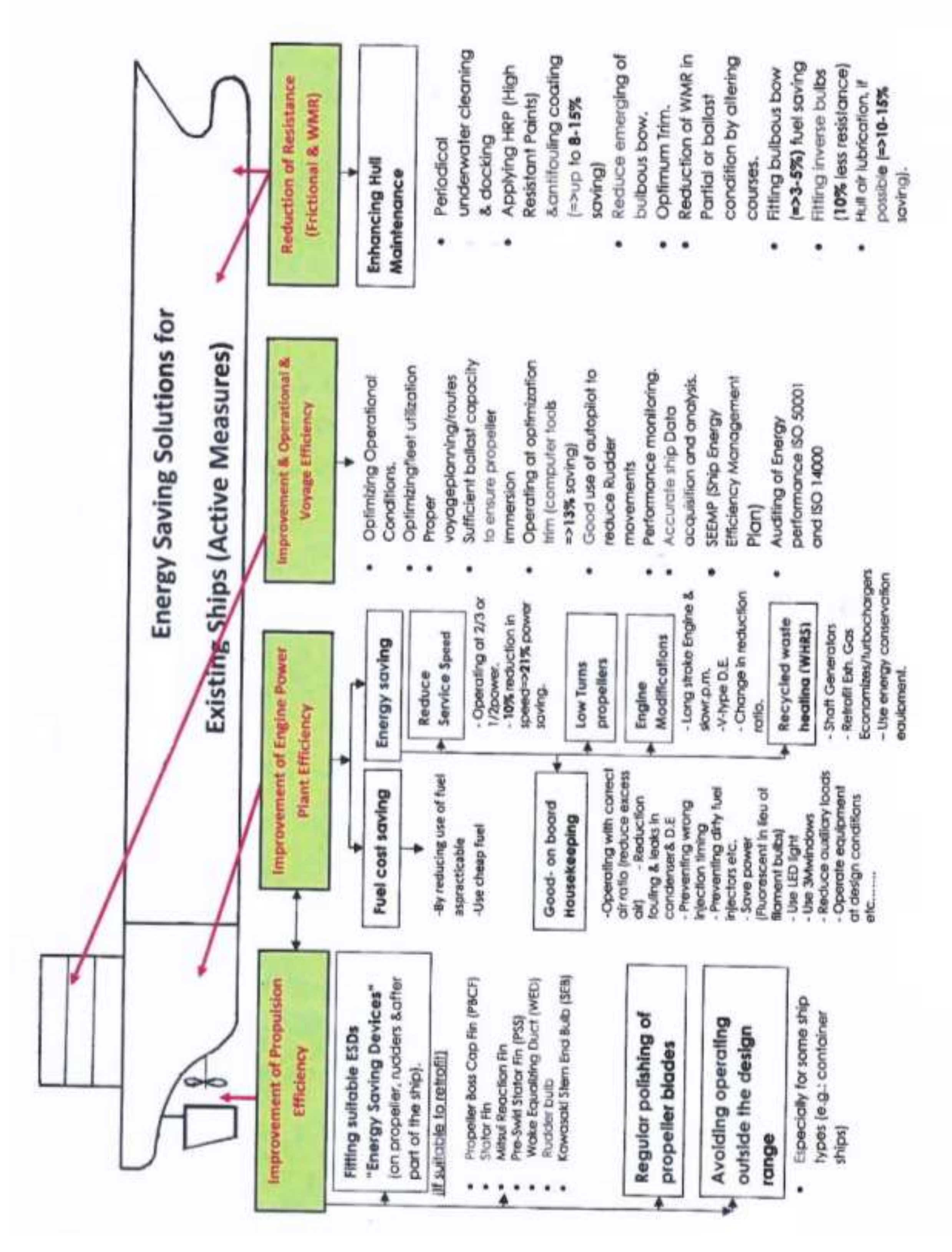

(*Source: The Author)

Figure (14) Energy Saving Solutions for Existing Ships (Active Measures) [9]*

One way that propulsion power can be lowered is to adopt new innovative propulsion solutions, and to optimise the hull form. On the other hand, cruise ships also offer large power reduction potential on the hotel side. The hotel loads represent a very large share of the total energy consumption. Another possibility for achieving fuel savings is to change the operating parameters of the vessel, notably by selecting the right speed. However, this is not by any means can be considered the end of the story, since more potential areas for ship energy saving and efficiency improvement still needs to be explored. [9]

All related energy technology should play a significant role in reducing CO_2 emissions, while the role of energy savings (reduced energy demand and consumption) will represent the largest reduction of 6.2 billion tons (45 %) of total CO_2 emissions. [3]

Emission Reduction Abatement Technology Solutions:

Historically, diesel engine manufacturers have controlled NOx emissions with (internal) on-engine changes, rather than using (external) exhaust after-treatment.

However, in order for ship propulsion engines running on Heavy Fuel Oil (HFO) or Marine Diesel Oil (MDO) to reduce emissions and to comply with the new NOx emission standards of IMO, there are several viable multi-solution approaches and options existing, apart from alternative fuel options including using ultra-low sulfur fuels/ distillates. Exhaust gas cleaning and treatment systems (currently referred to as “abatement technologies”), off-engine EGR (Exhaust Gas Recirculation) and SCR (Selective Catalytic Reduction) systems, and exhaust gas scrubber systems were introduced to remove pollutants from the emission stream. Techniques such as SCR or EGR might be used for reducing the NO_X emissions, whereas exhaust scrubbers or separate low sulfur fuel systems can be installed onboard for addressing the SOx emissions.

The replacement of the conventional mechanical system by the more flexible Diesel-Electric propulsion system is also one of the existing options.

Introducing exhaust gas after-treatment systems, or exhaust gas recirculation (EGR) such as SO_x scrubbers, allows for the use of less expensive, high sulphur fuels, provided they will reduce the level of SOx to less than 6g/kWh, and also urea-based catalysts for NO_X reduction. Scrubbers can reduce the SOx content of the exhaust by 90-95%. [14]

Selective Catalytic Reduction (SCR) systems are currently used onboard many ships and considered an efficient method of NOx reduction, due to their durability and compliance with most commercial ships.

These solutions, while effective to some degree, may be relatively costly and disadvantageous in other aspects. The main drawbacks of these systems onboard are space-demand issues, added weight, impact on stability resulting in some hazardous materials, increase in operating costs, negatively impacted power loss and increase in fuel consumption by 2-3% which can add significantly to the cost of a ship. [5][29]

The above mentioned technologies are considered solution options for short term or mid- term (1-10 years) plans. Long term (15-30 years) plans will be more suitable with sustainable alternative fuels.

When seeking to identify long-term solutions, especially for new construction, there is a more effective option which owners and operators should consider. Reference [35] is recommended for readers due to the valuable contents.

A typical SCR (Selective Catalytic Reduction) and a typical SCR and Scrubber arrangement on board are shown in Figure (15) [30] [31]

1. Diesel Engine and Generator set

2. SCR

3. Exhaust Gas Boiler

4. Scrubber

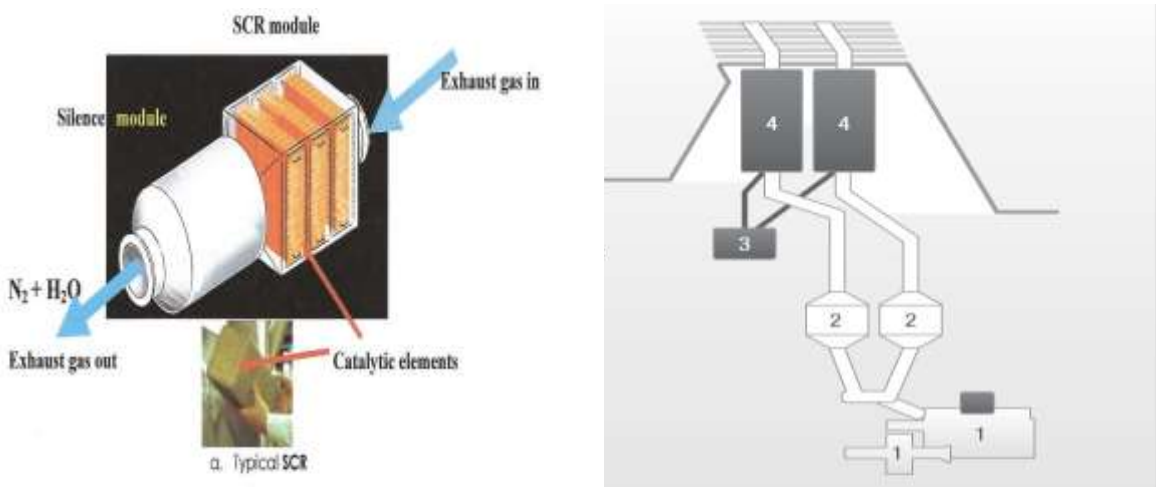

Figure (15): Typical SCR and Scrubber arrangement on board [30] [31]

The main current available methods for reducing ship emissions on ships are tabulated in Table (3). [23]

Table (3) Current available methods for reducing ship emissions
[Partly from reference 23]*

Ship Emission	Reduction method	Potential reduction
NO_x	Exhaust Gas after treatment systems(EGR), e.g. scrubber	90-95%
	Selective catalytic reduction (SCR)	95%
	Emulsification	20-25%
	Humid air	70%
	Engine tuning	50-60%
	Exhaust gas re-circulation	10-30%
	Using LNG as fuel	80%
SO_x	Switching from residual fuel to distillate fuel	60-90%
	Using LNG as fuel	100%
	Sea water scrubbing, Exhaust below water line	Up to 95%
CO_2	Using LNG as fuel	70-80%
	Energy saving strategies and tools	1-15%
PM	Electrostatic filters and PM Traps	Up to 85%
	LNG as fuel	98%

*Remark: LNG added to the table by the author, based on the recent literature statistics

The Future of Fuel Scenarios and Abatement Technology

The Future of Fuel Scenarios and Abatement Technology

In view of the previously discussed alternative fuel options and abatement technologies used for the sake of ship emission reduction, it is evident that, despite manufacturers' propaganda, abatement technology might provide interim solutions and transition options for short term and midterm situations despite their adverse impact on space and cost, but it is recommended that every application be considered on case by case basis. Energy saving tools are encouraged and need to be optimized for each case as well.

Oil products such as gasoline and diesel have proven to be very effective fuels in marine operations due to their easy handling, high energy density and notable safety characteristics. Expectations and debate still favor the opinion that HFO will not completely disappear from the menu of marine fuels. Combined with scrubbers that capture more than 90 per cent of the sulfur from the exhaust gas, HFO will continue to play an important role. One of the leading Classification Societies, Lloyds Registry, expects that HFO will represent about 40 per cent of fuel use by 2030.

Many fuel options were technically acceptable but are discouraged and found not commercially feasible, such as the biofuels. The unprecedented rise in fuel oil prices throughout the last several years in conjunction with the increasing availability of natural gas resources around the globe render the use of natural gas as a marine fuel an attractive alternative, particularly when stored cryogenically as liquefied natural gas (LNG). LNG fuel is presently established as a clean and reliable fuel for propulsion and auxiliary power generation, and its use allows for a very efficient way for reducing emissions. There has been widespread recent interest in this environmentally friendly fuel option.

Presently, LNG is considered by many supporters to be the only realistic fuel alternative that is technically mature enough to compete with conventional heavy fuel oil (HFO) or distillate fuels on a large scale. Hence, among the many fuel options, the use of natural gas as a marine fuel, particularly in the form of Liquefied Natural Gas (LNG), has attracted much attention and become a hot topic in the marine industry and with related stakeholders lately.

The LNG era is about to begin, as many supporters are predicting, and most consider the change as significant as when ships first shifted from coal to oil. [32][33]

Some oppositionists argue that most alternative fuels require new types of vehicles and extensive investments in new infrastructure that make it difficult to be viable for application and attractive to ship owners. Work is still in process to establish the alternative fuels to be part of the fuel chain world-wide and to tackle all encountered challenges. These efforts are supplemented with many studies confirming that the costs of the new alternatives and technology will decrease with time.

7. CONCLUSIONS

The paper presents ship emissions reduction by alternative fuels and abatement technology. From the study, the following can be concluded:

The motivation for emission reduction:

- Driven by economic and population growth (the current world population is 7 billion, while it is expected to reach between 8 to 9 billion by 2040 and 12 billion by 2050), the world's global demand for energy is continuing and expected to increase.
- World consumption of primary energy (in its conventional form of fuel) has greatly increased from 3.8 billion tons of oil in 1965 to 11.1 billion tons of oil in 2007, and is expected to increase significantly by 41% from 2012 until 2035.
- The global demand for energy is about 285 million barrels/day. Out of that, 34% is from oil, 26% from coal, and 22% from natural gas. In other words, 82% of the energy is from fossil fuel. The remaining 18% can be broken down to 5.5% from nuclear energy, 2.2 % from hydro-electric energy and 12.5% from renewable energy (the biggest portion of which is 9% is from biomass).
- The projections point to shares of alternative fuels, natural gas and renewable, increasing while coal and nuclear will be reduced and oil's share will continue to shrink.
- It is expected that NG production will increase by 55% from 2013 to 2040, a yearly growth of 1.6 to 1.7%.
- In order to achieve the target goals of ship emission reductions, a set of techniques could be implemented separately or in combination, including but not limited to: the use of alternative fuels, the application of emissions reducing technology for removal of pollutants before, during or after combustion (by emission reduction abatement technology) and the improvement of fuel saving and energy efficiency tools and strategies.

Alternative Fuels Options:

Expectations and predictions still favor the opinion that HFO will not completely disappear from the menu of marine fuels and will represent about 40 per cent of fuel use by 2030.

- The main alternative marine fuel types may be found in three forms: liquid, gaseous and solid fuels. Liquid marine alternative fuels include: alternative clean fuels such as less carbon-intensive fuels, low sulphur fuels (1%), ultra-low sulphur fuels (0.03%), bio-fuels (Bio-diesel), and Bio-liquid fuel alcohol (methanol, ethanol). The main alternative gaseous fuels include: Liquid Hydrogen and natural gas. The solid fuel form is nuclear propulsion (U238).

- Many fuel options were technically acceptable but were discouraged and found still not commercially feasible in the marine industry, such as the biofuels.
- The weighting matrix and comparison between alternative fuels for marine use, given in table form, may be used to determine a proximate guide for the optimum selection of alternative fuel in maritime transportation and additionally considered as a qualitative comparison tool.
- The comparison revealed that LNG is collectively the best alternative fuel for marine use due to its superiority as the cleanest environmentally, the reasonable cost, its adaptability to existing engines and its availability. The sole drawback is being nonrenewable, as compared to hydrogen, which comes in the second grade after LNG.
- The increasing availability of natural gas resources around the globe render the use of natural gas as an alternative marine fuel attractive, particularly when stored cryogenically as liquefied natural gas (LNG).
- LNG fuel is presently established as a clean and reliable fuel for propulsion and auxiliary power generation, and its usage comprises a very efficient way of reducing emissions. There has been widespread recent interest in this environmentally friendly fuel option.
- Presently, LNG is considered by many experts to be the only realistic fuel alternative that is technically mature enough to compete with conventional heavy fuel oil (HFO) or distillate fuels on a large scale. Hence, among the many fuel options, the use of natural gas as a marine fuel, particularly in the form of Liquefied Natural Gas (LNG), has attracted much attention and become a hot topic in the marine industry and with related stakeholders lately. The LNG era is about to begin, as many supporters predict, and the change is considered to be as significant as when ships first changed from coal to oil.
- Some opponents argue that most alternative fuels require new types of vehicles and extensive investments in new infrastructure that make it difficult to be deemed viable for application and attractive to ship owners. Work is still in progress to establish the alternative fuels as part of the fuel chain world-wide and to tackle encountered challenges. These efforts are supplemented with many studies confirming that the costs of the new alternatives and technology will decrease with time.

Strategies for Ship Energy Saving:

The strategies for fuel saving and improving efficiency in ships rely mainly on four main fields, which can be further broken down and stemmed to more sub-details:

- **Reduction of hull resistance**
- **Improvement of propulsion efficiency**
- **Improvement of power plant efficiency**
- **Improvement of operational and voyage efficiency (including energy efficiency management)**

-These strategies and tools cover a wide range of devices and options which can be adopted in design, construction and operational phases. Energy saving tools need to be optimized and considered as a case by case basis. This necessitates a shift in marine industry stakeholders' approach and mind set.

- "Ship Energy Saving Strategies and Tools" are presented by the author as pragmatic guidelines in the form of conceptual block diagrams for fuel and energy saving strategies and solutions on board ships for both new construction ships and existing ships, respectively.

- All related energy technology should play a significant role in reducing CO_2 emissions, while the role of energy savings (reduced energy demand and consumption) will represent the largest reduction of 6.2 billion tons (45 %) of total CO_2 emissions.

-Technical measures such as EEDI are underway. Operational measures including best practices such as EEOI (Energy Efficiency Operational Indicator) and SEEMP have been introduced. Alternative technologies have been developed and applied for reduction of frictional resistance (air lubrication, coating, etc.) and for future propulsion power systems (fuel cells, wind power, etc.). Improvement of propulsion efficiency including adoption of a wide range of ESDs and the utilization of CFD for optimum hull/propulsion interaction are being considered. CO2 capture and storage is a new technology and still under development.

Abatement Technology:

Combined with scrubbers that capture more than 90 per cent of the sulfur from the exhaust gas, exhaust gas cleaning and treatment systems (currently referred to as “abatement technologies”), off-engine EGR (Exhaust Gas Recirculation) and SCR (Selective Catalytic Reduction) systems and exhaust gas scrubber systems have been introduced to remove pollutants from the emission stream. Techniques such as SCR or EGR might be used for reducing the NO_X emissions, whereas exhaust scrubbers, or alternatively, separate low sulfur fuel systems have to be installed onboard to address SOx emissions.

-Introducing exhaust gas after-treatment systems, exhaust gas recirculation(EGR) such as SO_x scrubbers (provided they will reduce the level of SOx to less than 6g/kWh), and urea-based catalysts for NO_X reduction allows for the use of less expensive, high sulphur fuels.

- Scrubbers can reduce the SOx content of the exhaust by 90-95%.

- Selective Catalytic Reduction (SCR) systems are currently used onboard many ships and considered an efficient method of NOx reduction, due to their durability and compliance with most commercial ships.

- The main drawbacks of these systems onboard are that they are bulky and space-demanding, that they increase operating costs, and that they negatively impact the power loss and increase fuel consumption by 2-3%, which can add significantly to the cost of a ship.

- They can be considered solution options for short term or midterm (1-10 years) plans. Long term (15-30 years) plans will be more suitable with sustainable alternative fuels, especially LNG.

- It is recommended that every abatement technology application be studied and considered on a case by case basis.

-The mentioned IMO emission prevention and reduction instruments will eventually have a significant impact on ship operation, design, and construction in both ship new buildings and conversion retrofits.

The philosophy of ship design is being changed drastically to become more efficient and eco-environmentally friendly and the green design concept is being encouraged and pushed vigorously.

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