Analysis of Fuel Alternatives for Commercial Ships in the ECA Era

- There is no Silver Bullet -

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Abstract

In the new era of ECA's and alternative fuels, vessel owners/operators are faced with important decisions with significant cost and financial risks. The days of just using HFO without exhaust cleaning are over in the ECA's and worldwide after 2020. Several alternative solutions for meeting the new emission regulations for a variety of ship types and sizes operating in a selection of trades are analyzed to determine their relative merits and costs. Three primary fuel alternatives were considered:

a) Using MGO full time in the ECA now and worldwide after 2020
b) Using HFO with Scrubbers
c) Using LNG

The advantages and disadvantages of each fuel alternative are discussed, including the impact on emissions, and cost and benefit analyses are developed for a midsize tanker and midsize containership, which can also be applied to other ship types, such as bulk carriers, RoRo vessels, and multi-purpose vessels. No single fuel option stood out as the "best" solution for all ships in all services. It is hoped, however, that the analyses presented in this paper will demonstrate how owners can evaluate their service requirements, as well as the costs and benefits of the various options, to determine the best fuel alternative for their ships.

Background

MARPOL Annex VI (Ref. 3) contains regulations to reduce harmful air emissions from marine sources. First written in 1997, and entering into force in May 2005, Annex VI established a worldwide 4.5% limit on the sulfur content of marine fuel, and established Sulfur Emission Control Areas (SECA) in the North Sea and Baltic Seas, where sulfur was limited to a maximum of 1.5%. Annex VI also established limits on nitrous oxide emissions (NOx) from ships' exhaust. Annex VI was revised in 2008 with the revisions entering into force in July 2010. The revised Annex implemented a progressive global reduction of sulfur in fuel and NOx emissions and established a North American Emission Control Area (ECA) with lower limits on sulfur in fuel and NOx emissions.

The sulfur content of fuel is covered by Regulation 14 of the revised Annex VI. The revision changed the title of Regulation 14 from "Sulphur Oxides (SOx)" to "Sulphur Oxides (SOx) and Particulate Matter." The regulation does not place numerical limits on either SOx or Particulate Matter (PM) emissions, but focuses on the sulfur content allowed in fuel to achieve the desired emissions standard. The reason for this is that much of the PM in diesel exhaust results from the sulfur content in fuel. The U. S. Environmental Protection Agency (EPA) explained in their discussion of the final rules for "Control of Emissions from New Marine Engines at or Above 30 Liters per Cylinder" that "Sulfur in the fuel is emitted from engines primarily as SO_2; however a small fraction is emitted as sulfur trioxide (SO_3) which immediately forms sulfate and is emitted as PM by the engine. In addition, much of the SO_2 emitted from the engine reacts in the atmosphere to form secondary PM. Reductions in residual fuel sulfur levels will lead to significant sulfate PM and SO_2 emission reductions which will provide dramatic environmental and public health benefits." In addition, EPA stated "…in most cases, fuels that meet the long-term fuel sulfur standards will likely be distillate fuels, rather than HFO. In addition to reductions in sulfate PM, switching from HFO to distillate fuel may reduce black carbon emissions, fine particle counts, organic carbon, and metallic ash particles." "Using cleaner distillate fuel is the most effective means to achieve significant PM and SOx reductions for Category 3 engines."[1]

As an alternative to burning low sulfur fuels, Annex VI also allows for the use of exhaust gas cleaning systems that limit the emissions to no more than what would be produced by burning fuel with the required low sulfur content.

As of January 1, 2012, the global limit for sulfur in fuel is 3.5% when outside ECA's, but this limit will be lowered to 0.5% globally on January 1, 2020. Sulfur in fuel within SECA's was limited to 1.5% by the original Annex VI regulation and was lowered to 1.0% on August 1, 2010 by the revised Annex VI. On January 1, 2015 fuel sulfur content within the SECA's and ECA's was further limited to 0.1% or less.

MARPOL Annex VI also places limits on NOx emissions from marine diesel engines using a Tier I, II, and III system. Tier II emission limits are in effect for engines installed worldwide on or after January 1, 2011. A more stringent Tier III emission limit is in place for engines installed on or after January 1, 2016 when operating within an ECA subject to Annex VI Regulation 13 for control of Nitrogen Oxides (NOx). At this time, the only NOx ECA's (where Tier III requirements would apply) are the North American and US Caribbean ECA's. The North Sea and Baltic Sea ECA's currently only control sulfur content, but the same Tier III NOx limits will apply in these ECA's for engines installed on or after January 1, 2021. The U.S. EPA has additional NOx requirements for engines with displacements less than 30 liters per cylinder that are used as propulsion engines (EPA category 1 and 2 diesel engines).

CO_2 and Greenhouse Gas (GHG) emissions are not directly regulated by MARPOL, but they are part of the environmental impact of engine operation, and so discussions are included on how they are affected by the fuel selection options.

Solutions Available

There are several options available to meet the requirements of MARPOL Annex VI within an ECA today and in all locations after 2020. While some of these options are relatively new to the industry, they have been shown to be effective in some vessels currently in service. All vessels must comply with the sulfur limit regulation, but the Tier III NOx limits apply only to ships operating in an ECA, as follows:

i) under MARPOL regulations, new ships with keel laying dates after January 1, 2016 or

ii) under EPA regulations, new ships with engine test bed dates after January 1, 2016;

except in ECA's where the start date of Tier III NOx requirements is delayed.

[1] Federal Register/ Vol. 75, No. 83/ Friday April 30, 2010, page 22914, 22916

Burn Marine Gas Oil with Maximum Sulfur of 0.1%

The simplest option for meeting the upcoming low sulfur limits is to burn Marine Gas Oil (MGO) with sulfur content at or below 0.1% in the ECA or 0.5% worldwide starting in 2020. Virtually all ships that currently burn diesel oil can successfully burn MGO and meet Annex VI requirements. This solution has no effect on the NOx emissions and would require some additional technology to reduce NOx for ships that have to meet Tier III levels. Some modification to fuel tankage and transfer arrangements may be necessary to increase the storage capacity of MGO on board, and it may be necessary to install fuel cooling equipment to increase the viscosity of the MGO. Outside of the ECA's (or outside other areas where low sulfur fuel is required, such as EU ports) HFO can still be used without exhaust treatment until 2020. Development of residual fuel oils with low sulfur content is underway so that ships can meet the ECA and worldwide low sulfur content requirements without having to use pure distillate fuel (MGO), however, the feasibility and cost of these fuels is not known at this time. Owners should not assume that these new fuels will become available, nor should they plan to use these fuels as their only option for meeting the ECA requirements.

Exhaust Gas Cleaning Systems

Another option for meeting the low sulfur limit is to install exhaust gas cleaning equipment. This allows the use of HFO with sulfur content higher than that allowed normally in the ECA because the resulting exhaust gas is processed through an exhaust gas scrubber. Outside the ECA, where it is permitted to burn HFO within the existing 3.5% sulfur limit, the scrubber can be bypassed (if a bypass is provided), or run dry, which some scrubbers may allow. Bypassing the scrubber or operating it dry saves on operating costs, which can be significant.

Any installed exhaust gas scrubber must be capable of removing SOx from the exhaust gas to an acceptable level, i.e. equivalent to that obtained by burning fuel with no more than the allowable sulfur content. This option has no effect on NOx emissions and additional technology is still required to reduce NOx on ships that must meet Tier III levels. Technical details of scrubber certification, exhaust monitoring, and data recording are specified in IMO Resolution MEPC 185(59) (Ref. 4).

The installation of scrubbers in an existing vessel may be quite difficult due to their size. One scrubber is required for each fuel burning device, or a single larger scrubber can be installed with multiple inlets for each device. If a single scrubber is used, valves need to be installed to isolate each engine or boiler exhaust system, plus an induced draft fan or fans may be required to assure proper flow/back pressures. For some scrubbers bypasses are required in each exhaust line to allow operation of the engines when the scrubber is not available. Most scrubbers can provide a reduction in SOx sufficient to meet the levels obtained by burning 0.1% sulfur fuel, but may not achieve the same low PM levels as obtained by burning 0.1% sulfur fuel.

One significant risk with the use of scrubbers is the availability of low cost HFO with higher than allowed sulfur after 2020 when its use will not be allowed on ships without exhaust gas treatment. The possible low demand for such HFO may cause it to be no longer easily or widely available, or the cost could become closer to the cost of MGO or alternative low sulfur residual fuels because of limited demand.

LNG Fueled Ships

A third option for complying with Annex VI is to burn natural gas, which has negligible sulfur content. The combustion process when burning low pressure natural gas using the Otto cycle (most medium speed diesels and WinGD low speed diesels) also produces much lower levels of NOx as a result of lower peak temperatures in the cylinders, therefore, an engine of this type operating on natural gas will meet Tier III NOx limits. Diesel engines that operate with direct gas injection in the cylinder using the Diesel cycle (MAN low speed diesel engines) produce NOx at similar levels as engines burning oil fuel so they will require NOx reduction systems to meet Tier III requirements.

The natural gas fuel is stored on board as liquefied natural gas (LNG) in specially designed storage tanks. Natural gas is currently a low cost fuel at the well head, however, it requires special handling and expensive equipment to liquefy, transport, store, re-gasify and deliver to the engine(s). As its popularity grows for shore based processes, such as land transportation, electric power plants, chemical process plants, etc., it is uncertain if the price will allow LNG to remain competitive with other marine fuels.

Some LNG fueled ships can also operate on HFO, so it may be possible to operate on HFO outside the ECA or low sulfur area until 2020. The value of this dual-fuel operation needs to be examined carefully as there are additional costs for installing HFO burning equipment on the vessel. Furthermore, the cost of LNG has traditionally been similar to that of HFO, so the fuel cost savings would be small, if any. In some cases, dual-fuel operation could make sense if LNG storage tank volume is limited and it is necessary to burn HFO to achieve the desired vessel range.

Merits of Available Fuel Alternatives

Burning MGO with 0.1% Maximum Sulfur

Advantages

This option probably has the lowest risk of the three fuel options, as it is not much of a change from existing ship operations. As noted above, most HFO burning ships are already capable of burning MGO without modifying the main engine(s), except for some possible fuel system modifications to allow use of low viscosity fuel, such as installation of fuel chillers, and implementation of specific fuel switching procedures. Burning MGO will result in less maintenance for diesel engines, and, when the final worldwide sulfur cap is in place after 2020, the HFO heating equipment can be eliminated, greatly reducing maintenance and operating expense. Operating procedures require little change from current practice, reducing training costs. Vessels on international voyages that sail outside of an ECA for an appreciable period of time can still use conventional HFO for part of the voyage until 2020, and thus would be able to benefit from HFO's lower cost for several years.

Disadvantages

The primary disadvantage to this option is the cost of fuel. MGO typically costs about 50% to 70% more than HFO. As the world moves to lower sulfur limits for land based diesel fuel, (EPA has mandated 15 PPM (0.0015%) sulfur), it is anticipated that the distillation process will produce fuels with lower viscosities than can be tolerated by the large propulsion engines designed to operate on HFO. Many ships have added a system to cool the MGO in an effort to increase its viscosity at the engine inlet sufficiently to satisfy the engine's requirements. These systems are not complicated, usually consisting of a closed loop fresh water cooling system with a heat exchanger to cool the fuel. The fresh water is in turn cooled by a small refrigeration plant, since the required fuel temperature may be lower than the ship's fresh water cooling system can provide.

There have been some difficulties in existing ships with the change over from heated HFO to cool MGO when entering or leaving an ECA, but the process can be done safely following the engine manufacturer's instructions and guidance from the Classification Societies. (See Reference 1). After 2020, ships using this option may burn MGO at all times and will not have the problem of switching from heated fuel oil to unheated or chilled distillate fuels. Minor modifications to the engines at that time should make for simpler operation once only distillate fuel is being burned. Long time or full time operation on MGO also requires a change in cylinder oil (change to low base number oil) from HFO operation for low speed diesel engines.

Emissions Impacts

A vessel currently using HFO will experience a favorable impact to the exhaust emissions profile by switching to MGO only operation. In some cases, treatment systems are still needed to meet upcoming Annex VI emission requirements, but for other emission requirements, the change in fuel alone will be sufficient.

NOx

NOx reduction to meet Tier III IMO levels inside ECA's, when required, can be accomplished with Selective Catalytic Reduction (SCR) units. These units require hot exhaust gas (350°C or higher) in order to reduce the NOx to acceptable levels. Ammonia, usually as urea, is injected into the exhaust stream where it reacts with the NOx in the presence of a catalyst and converts the NOx into N_2 and water. This process cannot work if there are high levels of SOx in the exhaust gas flow or if the temperature is too low.

Another possibility for meeting Tier III NOx levels is to use Exhaust Gas Recirculation (EGR). This process reduces the maximum flame temperature in the cylinders, thereby reducing NOx formation. For this process, a small portion of the exhaust gas is diverted through a small exhaust gas scrubber and then is returned to the charge air by a motor driven blower.

SOx and PM

SOx and Particulate Matter (PM) reduction happen naturally as a result of the reduction in sulfur content in the fuel and because MGO is a distillate fuel with few impurities. Compared to high sulfur HFO, the reduction for SOx is about 96%. The impact on PM is not as clear because PM is composed of a variety of particles and unburned hydrocarbons. Estimates on PM reduction from use of MGO range from about 50% to up to about 85%. As a result of the uncertainty of the PM reductions, the US EPA has requested engine makers to take measurements, so the reductions can be better documented. If a 0.1%

sulfur IFO blend fuel is made available, it will have a similar SOx reduction as MGO, but less reduction in PM.

CO_2 and GHG

Different types of oil fuel have only minor differences of CO_2 emissions, which is the primary Green House Gas (GHG) emitted by diesel engines burning oil fuel. MGO has a 5% higher heat value compared to HFO, so the quantity of fuel consumed is reduced by about 5%, leading to a similar reduction in CO_2 emissions.

Burning HFO with Exhaust Gas Cleaning

Advantages

The primary advantage of this option is that the ship can continue to operate on HFO in an ECA with significant fuel cost savings over low sulfur MGO. As noted before, MGO is typically 50% to 70% higher in cost than HFO. In order to be considered equivalent to burning low sulfur HFO, the exhaust cleaning system must be capable of removing SOx generated in the engine to a level matching that from low sulfur MGO.

Disadvantages

While there is no specific limit on the PM level in the cleaned exhaust, the change in the title of Regulation 14 to include “Particulate Matter” implies that the PM levels in the exhaust from a scrubber system should be close to those obtained from burning low sulfur MGO. Although scrubbers reduce PM, it is not clear that any of the scrubber systems can match the PM levels of low sulfur MGO. If at some point regulatory approval of scrubbers as “equivalent means” of meeting the regulation is withdrawn due to PM reductions, and/or if actual PM limits are established, scrubbers may no longer be a viable solution for meeting Regulation 14.

Depending on the scrubber system selected, the maximum sulfur content in the fuel that can be cleaned to be “equivalent” to low sulfur MGO may be less than the presently allowed 3.5% sulfur. At this time, 1% sulfur HFO is roughly 9% to 12% more expensive than ordinary HFO in Houston and Singapore, but about 20% to 35% more in Los Angeles. Ships burning 1% sulfur HFO using scrubbers currently available in the market should easily achieve equivalent SOx levels in the exhaust to 0.1% sulfur fuel.

After the 2020 implementation date of the IMO worldwide requirement to limit fuel sulfur content to 0.5% for vessels without scrubbers, the cost benefit of high sulfur HFO may be significantly less and its availability may be limited compared to low sulfur fuels. This is a risk that is hard to quantify at this time, but is one faced by any owner deciding to install scrubbers.

Exhaust gas cleaning equipment requires a substantial amount of space to fit into the upper casing along with exhaust bypass pipes and valves. Multiple units with bypasses and diverter valves may not be practical to install in some ships. Associated systems for cooling/scrubbing water, and possibly water dosing and cleaning equipment if a closed loop system is installed, are also necessary. All of this equipment must be built of high quality corrosion resistant materials due to the corrosive nature of the scrubbed products. For closed loop systems, additional tanks for caustic soda and buffering, separators to remove sludge, and a sludge storage tank are necessary. See Reference 2 for more information on exhaust gas scrubbers.

Emissions Impacts

Using HFO with scrubbers will significantly reduce SOx emissions compared to current operation without scrubbers, but they will provide little or no reduction on other emissions.

NOx

Scrubbers have little, if any effect on the NOx in the exhaust gas stream. This means that the NOx reduction required for Tier III compliance must be achieved before the gas enters the scrubber, since the scrubbing process cools the gas to a level that makes use of an SCR impractical. MAN Diesel and Turbo have developed two solutions for their low speed engines to meet Tier III NOx emission levels. One solution uses an SCR in the exhaust system between the engine and the turbocharger inlet – this solution requires lower sulfur fuel (about 1% or lower) in order to prevent clogging of the SCR. Low load operation may also require the exhaust gas temperature to be raised by reducing air flow through the engine with variable turbochargers or possibly bypassing the turbine with some exhaust gas.

The second solution is an exhaust gas recirculation system. This system uses a small scrubber to remove sulfur and PM from a small portion of the exhaust gas. This gas is then cooled and returned to the engine which lowers the combustion temperature and reduces NOx emissions. Since the gas leaving the turbocharger in this solution has had its NOx level reduced sufficiently to meet Tier III without a large drop in temperature, a scrubber will still be effective to clean the SOx, and fuels with higher sulfur levels can be used.

No similar built-in systems for NOx reduction are available at this time for medium speed engines, making compliance for the generator engines difficult unless an SCR is provided for each engine. Since the SCR systems cannot work with cooled exhaust gas, a scrubber cannot be used before the SCR. These engines would have to burn oil with the required low sulfur content to avoid problems with clogging the SCR elements. Clogging occurs because of the reaction of the ammonia added to the exhaust, usually as urea, with the sulfur. This forms ammonia sulfur compounds which precipitate out and coat the catalyst elements preventing the catalyst from contacting the gas. The elements must then be cleaned in order to restore their effectiveness.

SOx and PM

The reduction in SOx emissions by use of scrubbers is required by Annex VI to match the reduction from using 0.1% sulfur MGO, so they will offer similar reductions of about 96% in SOx emissions compared to high sulfur HFO. The typical scrubbing action with water will reduce PM by about 30% to 60% (Ref. 2) which is not as much as from using MGO.

CO_2 and GHG

No reduction in CO_2 and GHG from current levels will occur when using exhaust gas scrubbers and HFO. In fact, due to the additional back pressure the scrubber places on the engine (reducing its thermodynamic efficiency) and the additional auxiliary power needed to run the scrubber supporting equipment, scrubbers may increase the ship's overall fuel consumption rate by a small degree, which will proportionally increase CO_2 emissions.

Burning Liquefied Natural Gas

Advantages

In recent years, the available supply of natural gas has increased greatly in some areas of the world resulting in very low cost per unit of energy. Depending on the area of operations and the source of the fuel, LNG may be substantially cheaper than any of the petroleum based fuels. Note that the actual delivered price of the LNG in the location where bunkering will occur must be used for comparison purposes – not the source price of gas (before liquefaction) at a pipeline hub.

Natural gas is virtually free of sulfur and ash. Its combustion products are, therefore, virtually free of SOx compounds and the associated PM. In addition, the lower combustion temperature produced by burning natural gas in an Otto Cycle Engine results in lower NOx emissions, which are within the Tier III limits. Natural gas is principally composed of methane and contains about 13% to 15% less carbon than typical petroleum based oils on a mass basis. This, combined with a 10% to 13% higher heating value per kilogram, results in 25% to 30% lower CO_2 emissions.

Disadvantages

LNG is inherently more dangerous on board than HFO or MGO, however, the risk of fire or explosion can be reduced by following the regulations for designing the fuel handling system and by rigorous crew training, as has been demonstrated by the safety records of the LNG carrier fleet over the last 50 + years. As a cryogenic liquid, special precautions must be taken when handling the liquid to avoid contact with personnel and with the ship's structure. Only special materials unaffected by cryogenic temperatures, such as stainless steel, aluminum, and Invar, can be exposed to the liquid. When in the gaseous state, it is run in double wall pipes with the annular space either inerted or ventilated and monitored to detect any leakage.

The volume required for LNG fuel storage is significantly greater than for oil fuel since its density is less than half that of HFO. Typically, LNG fuel is stored in specially designed tanks, which are built according to the requirements contained in the International Gas Code (IGC). In most cases, Type C tanks are used for fuel tanks because they allow a pressure buildup of 7 to 10 bar, which is sufficient to contain boil off gas for 10 to 20 days. Besides requiring more volume for equivalent weight than oil tanks, Type C tanks also take up more space because of their cylindrical shape, making the space requirement even greater, particularly for below deck tanks. Compounding the inefficiency in space utilization is the fact that fuel oil tankage for the ship's full range may still need to be provided if there is no certainty of gas supply. More space efficient LNG tank types are prismatic tanks; either the more commonly used membrane type or independent type A or B tanks. These tanks can utilize most of the available volume in a compartment. The difficulty with prismatic tanks is that they cannot contain pressurized gas (pressure limited to about 0.7 bar) and thus cannot hold LNG without a means of continuously consuming boil off gas for any but short periods of time.

Power output from medium speed dual-fuel engines and low speed diesel engines operating on the Otto Cycle is reduced compared to the oil fuel only version of the same engine. Low speed gas injected engines have the same output as the oil fuel only engine.

Fuel systems for gas engines are expensive compared to oil fuel systems. For low speed gas injected diesel engines, the fuel system operates at up to 300 bar, which requires high priced, special equipment and piping that may need frequent maintenance, and also offers higher risks from the high pressure gas.

Bunkering is a more complex operation when using LNG, requiring special training to assure that no spillage onto the ship's structure occurs, that vapor return lines are properly connected, and that all lines are purged after bunkering. In addition, for LNG bunkering and cargo operations to occur simultaneously, special arrangements need to be made to create exclusion zones around the LNG bunkering area and some types of cargo operations may not be allowed. Special approval is required for the simultaneous operations from regulatory authorities.

For medium speed dual-fuel engines, operation at low load may not be possible on gas, possibly requiring a switch to MGO for maneuvering operations. Both medium speed and low speed dual-fuel engines require burning small quantities of MGO (1-5% of total energy consumption) as pilot fuel during normal operation.

Emissions Impacts

NOx

The degree of NOx reduction depends on the operational design of the engine. For engines operating on the Otto cycle during gas operation (low pressure gas at about 5 bar is injected into the air intake manifold), such as most medium speed diesel and Winterthur Gas & Diesel (WinGD) low speed engines, there is a significant reduction in NOx emissions. This reduction is on the order of 90% compared to engines using oil fuel (Ref. 5) because of the lower compression pressures and combustion temperatures that occur in engines operating on the Otto cycle. This reduces NOx formation during the combustion cycle, thereby reducing NOx in the exhaust. The lower compression pressures and combustion temperatures do result in less power per cylinder, so engines of this type will need to be a larger displacement or have more cylinders than oil fuel engines of the same output.

For engines operating on the Diesel cycle during gas operation (high pressure gas directly injected into the cylinder), such as MAN low speed engines, there will be little reduction in NOx emissions compared to oil fuel engines. This is because the compression pressures and combustion temperatures are similar to oil fuel engines. However, one benefit of using direct gas injection is that engine output is comparable to oil fuel engines. As a result of having NOx emissions similar to oil fuel engines, countermeasures to reduce NOx emissions are required to meet Tier III NOx standards. These typically include installation of an SCR or use of exhaust gas recirculation.

SOx and PM

SOx and PM emissions are reduced nearly to zero when using natural gas as the primary fuel. This reduction is because natural gas contains almost no sulfur and contains very few impurities, so the main causes of SOx and PM are eliminated.

CO_2 and GHG

Because of its higher heat content and chemical makeup, burning natural gas reduces CO_2 formation by about 25% compared to oil fuel burning engines (Ref. 5). However, engines operating on the Otto cycle experience some unburned methane passing through the engine during the scavenging process (methane slip). Since methane, the primary component of natural gas, has a greenhouse gas impact about 25 times higher than CO_2, methane slip negates most of the GHG reduction from lower CO_2 emission. Engines operating on the Diesel cycle with high pressure direct gas injection have little methane carry over (low methane slip), so they will achieve GHG reductions of about 22% compared to oil fuel engines of the same output (Ref. 5).

Selecting the Right Option

Some members of the marine industry are assuming that LNG is a “no brainer” solution for meeting the ECA requirements. The thinking is that the relatively low cost of LNG fuel compared to MGO will provide owners with substantial annual fuel cost savings throughout the life of the vessel, while meeting all ECA emission regulations imposed by MARPOL. The assumption is that fuel cost savings would quickly pay back the owner for the large initial cost of installing an LNG plant. Similarly, proponents of exhaust gas scrubbers believe continuing to burn cheap HFO, while cleaning the resulting exhaust gas, is the most economical way to meet emissions regulations. Again, the assumption is that the annual fuel cost savings compared to burning MGO would quickly pay back the owner for the large capital expense of an exhaust gas scrubber.

While both options appear to be easy solutions to the low emissions issue, it is difficult to argue that one option will always be the best option for all vessel owners (the so called *Silver Bullet*). There are several perspectives for an owner to consider when determining which option is best for him. There is the investor’s perspective, where the option with the lowest cost would be preferable. There is also the vessel operator’s perspective, where the vessel that is the safest and simplest to operate and maintain is preferable. The “right” option should try to create a balance between these perspectives.

Furthermore, the feasibility and cost effectiveness of the available options can depend very much on the vessel type and service. Factors that affect the feasibility of an option are length of time operating in an emission controlled area, required crew training and certifications (for LNG), additional maintenance requirements and costs, potential lost cargo capacity and revenue, potential need for higher voyage speeds if cargo and fueling operations are not simultaneous, available fuel supply given the vessel’s route, and the most difficult factor to consider – expected future fuel prices. All of these questions and unknowns prove the need for a complete engineering study for the proposed vessel new build or conversion to determine which option best suits the vessel and will be the most economical and practical for the vessel’s owner. To illustrate this point, sample Equivalent Uniform Annual Cost (EUAC) analyses of the options were prepared, as presented below and in further detail in the Appendix, and the results and remaining considerations that should be made before selecting a fuel option are discussed.

Equivalent Uniform Annual Cost (EUAC) Analyses

Of the three fuel options, MGO, HFO with exhaust gas scrubbers, and LNG, it should be expected that the MGO option will be the cheapest to build and have the lowest maintenance cost, but have the highest annual fuel cost. The HFO/scrubber and LNG options will both be more expensive to build and have higher maintenance and operating costs, but potentially lower annual fuel costs. Obviously, this is not enough information to determine which option will be the most economical over the life of the vessel. In order to make this determination, an Equivalent Uniform Annual Cost analysis can be made to take into account the additional capital cost for the special equipment, tanks, piping, etc., for each fuel option above what is required for the MGO option; and for the annual maintenance, operation, fuel, and lost revenue costs, where applicable, over the first 10 years of operation. Beyond 10 years, fuel cost is highly uncertain as is the reliability of the installed equipment (major components may need replacement), so it seems the decision on which fuel option to select should be justifiable based on its value over the next 10 years.

Equivalent Uniform Annual Cost is a method of economic analysis widely used in engineering economics and is based on calculating the present worth of costs (similar to net present value) of the initial capital investment of the special equipment needed above the cost of the MGO fuel system, and the operating costs related to fuel for the designated time period of 10 years. The present worth costs are then converted into an annual cost for the 10 year period based on an interest rate for cost (same rate as the discount rate used for calculating present worth of costs) and a separate interest rate for financing capital costs. The EUAC value is representative of the annual cost impact of the fuel option over the 10 year period and can be useful as in input to calculating required freight rate and breakeven point for a ship acquisition analysis.

While this analysis can give a good estimate as to which vessel option is the most economical, it is not advisable to make a decision based on this analysis alone. Although simplified EUAC analyses, such as that found below, can provide an initial focus for selecting a fuel option, an owner must also consider the uncertainty contained in the analysis and the non-monetary issues that affect the final selection. Some other factors to consider include equipment and machinery purchase cost uncertainty, shipyard and equipment availability, crew training requirements, vessel scrap value, and public image/marketability. Furthermore, it may be valuable to conduct several EUAC analyses with varying input assumptions and factors to determine the sensitivity of the analysis to changes in the main input factors. A single variable, such as the price of fuel in 5 years, can completely swing the analysis in favor of a different fuel option.

The following analysis was conducted for two common vessel types and the EUAC was found for each vessel type operating on:

- MGO full time,

- MGO in ECA's and HFO outside ECA's,
- HFO with an exhaust gas scrubber, and
- LNG.

The initial vessel construction cost was estimated for both U.S. and Asian construction for each fuel option. The cost of the vessel with MGO was set as the baseline cost and the cost difference between the other fuel options and the MGO only vessel was calculated. The cost difference for each fuel option compared to the MGO only vessel was designated as the capital cost for the fuel option. The assumed discount rate, which discounts future costs to the present value, was 14%. This percentage is a typical return on investment rate for higher risk investments. The assumed interest rate for financing the capital cost difference was 6%, typical for a ship acquisition loan interest rate. The assumed annual inflation rate applied to annual costs was 2%.

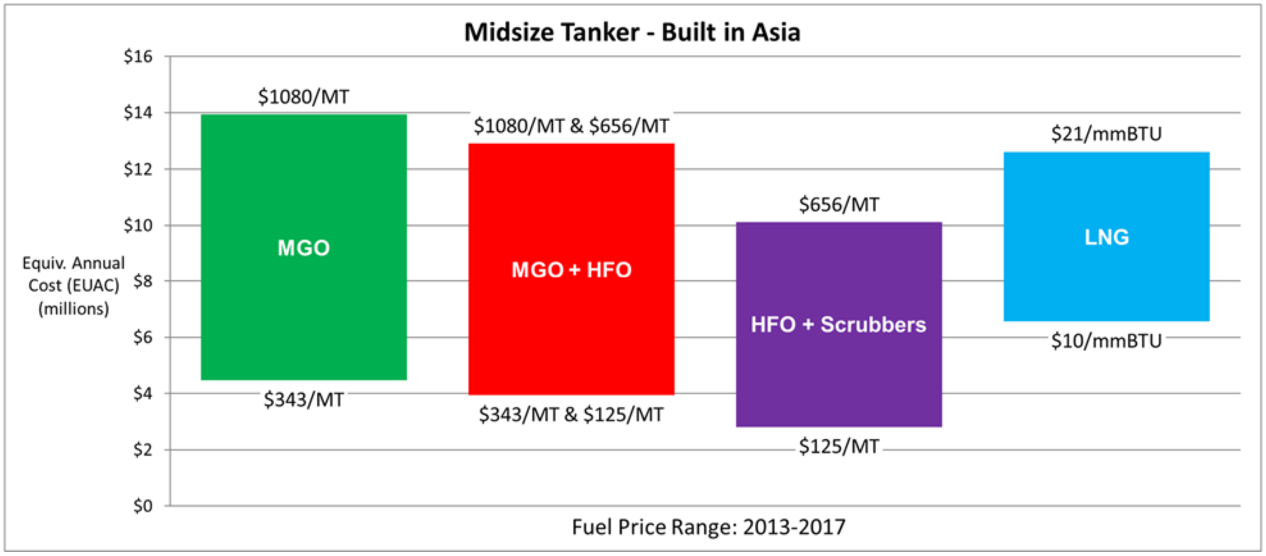
It is important to note that this analysis is not intended to provide a recommendation for which fuel option is best for these specific vessel types. The numbers used in this analysis are only rough estimates. The cost factors for construction, maintenance, operation, fuel, and lost revenue are representative numbers and will vary from vessel to vessel. It is also assumed that the vessel's schedule is unaffected by the fueling operation, i.e. the LNG bunkering can take place while the vessel is at its loading berth handling cargo.

Details on how the EUAC analyses were made and the factors used as input are presented in the Appendix.

Summary – Equivalent Uniform Cost Analyses

(Over 10 years with a 14% Discount Rate, 6% Finance Rate, and 2% Annual Inflation Rate)

In the below graphs, the total EUAC for each vessel and range of fuel prices is listed, considering either Asian or U.S. construction. The EUAC is calculated from the capital cost difference between the selected fuel option versus the MGO option and the net present worth of annual operation costs over a 10 year period starting in 2018 with an annual cost inflator of 2% and discounted to the present with a 14% discount rate for costs and a 6% interest rate for capital purchases. The primary difference between Asian and U.S. construction in the analysis is the capital costs for the fuel options are higher for U.S. construction, while fuel costs are the same. Note that the MGO + HFO fuel option represents MGO operation in the ECA and HFO operation outside the ECA until 2020, after which time there would only be MGO operation.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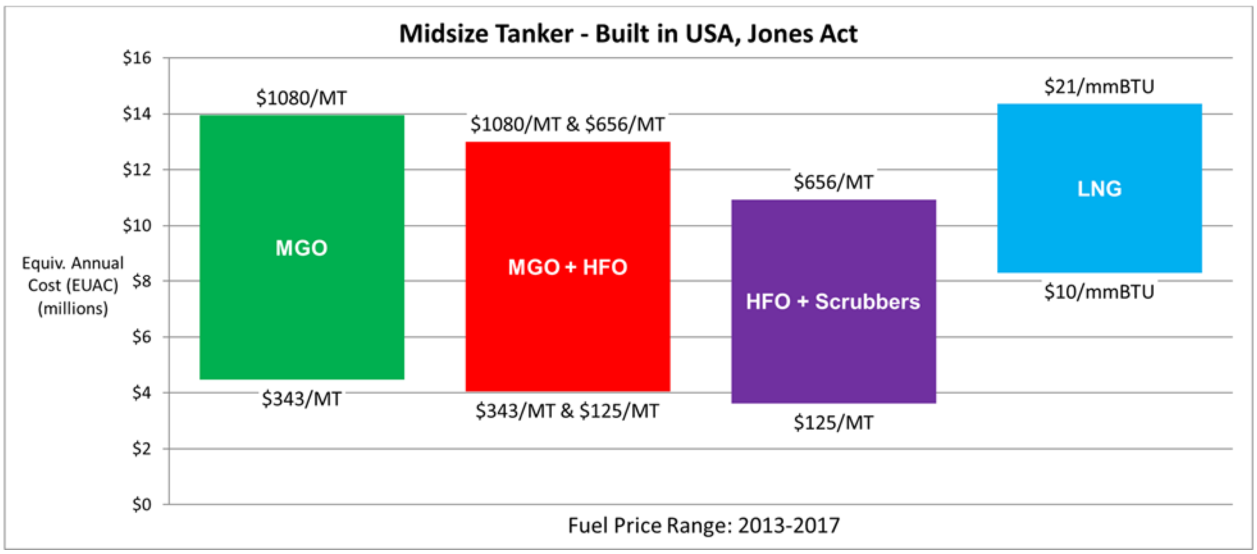
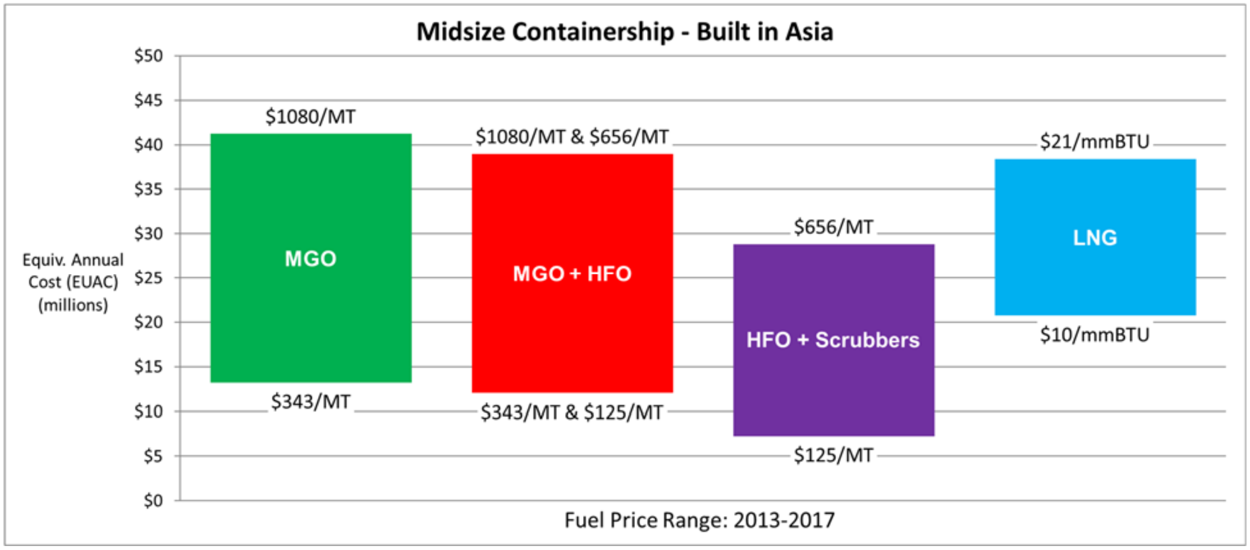
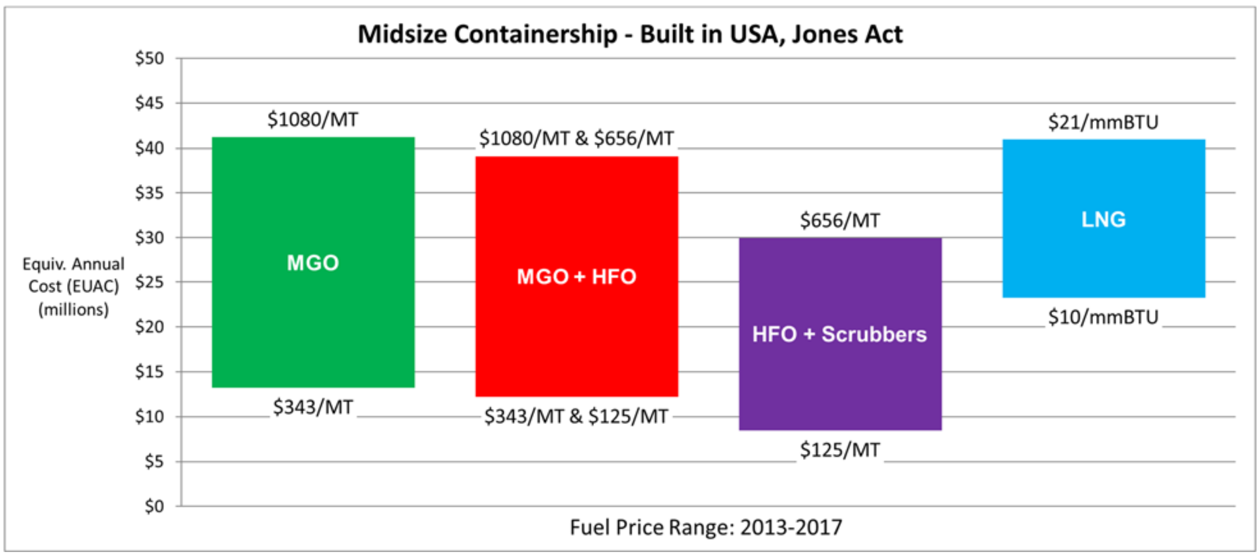
$12
$10
$8
$6
$4
$2
$0
Equiv. Annual Cost (EUAC) (millions)
$1080/MT
MGO
$343/MT
$1080/MT & $656/MT
MGO + HFO
$343/MT & $125/MT
$656/MT
HFO + Scrubbers
$125/MT
$21/mmBTU
LNG
$10/mmBTU
Fuel Price Range: 2013-2017


Midsize Tanker - Built in USA, Jones Act
$16
$14
$12
$10
$8
$6
$4
$2
$0
Equiv. Annual Cost (EUAC) (millions)
$1080/MT
MGO
$343/MT
$1080/MT & $656/MT
MGO + HFO
$343/MT & $125/MT
$656/MT
HFO + Scrubbers
$125/MT
$21/mmBTU
LNG
$10/mmBTU
Fuel Price Range: 2013-2017



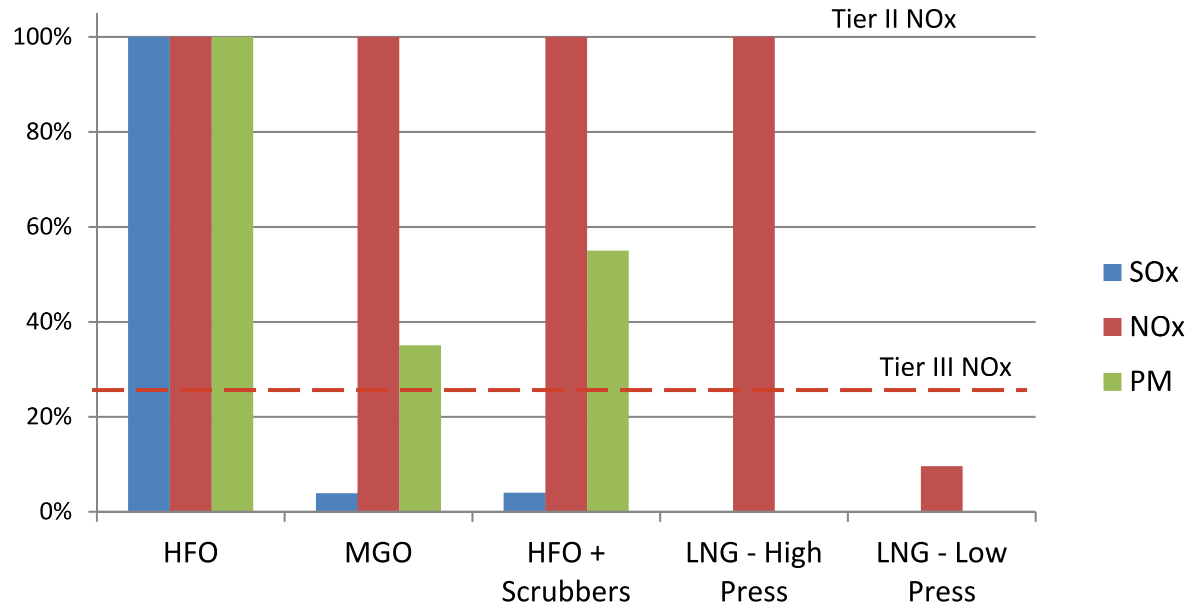


All costs provided in the graphs above are approximate and can vary considerably in magnitude and relative to each other given different input variables.

Summary – Emission Impacts

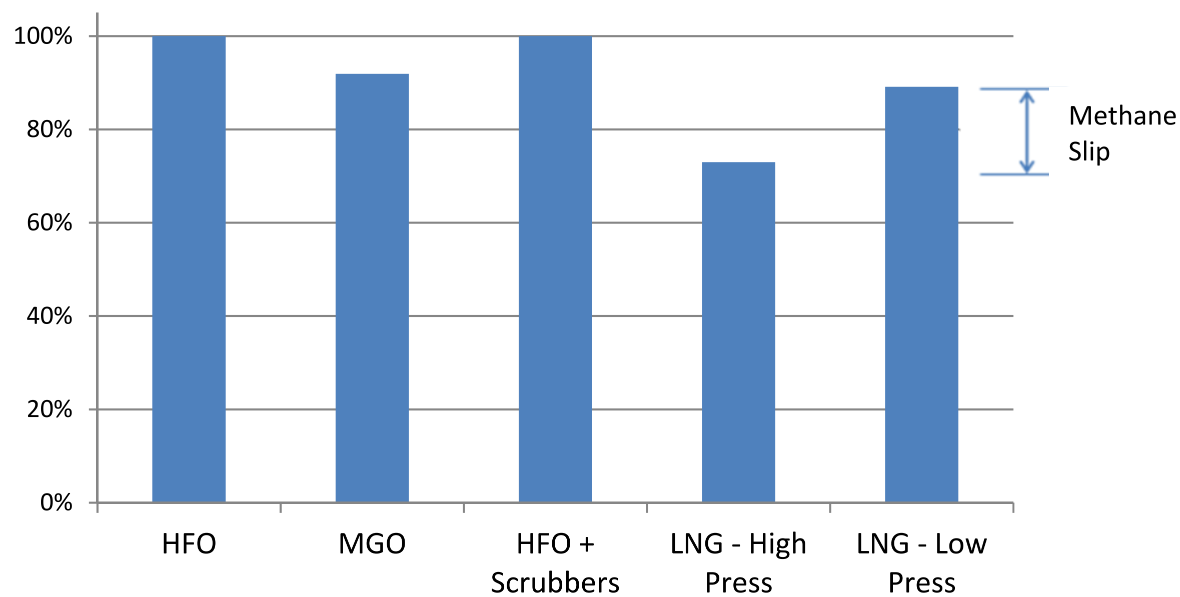
The below charts illustrate the emission impacts of the four fuel options considered in the EUAC analyses. Included are charts for NOx, SOx, PM, CO_2 and GHG emissions. The emission impacts are similar for all vessel types so one set of charts can be widely applied. It should be noted two options are shown for LNG operation; one is based on low pressure gas engines (Otto cycle) and the other is based on high pressure gas injection engines (Diesel cycle). Both options are shown because they have different emission values for NOx and GHG.

Relative SOx, NOx, and PM



Note: PM can vary significantly depending on fuel quality and scrubber type.

Relative Greenhouse Gas Effect



Note: Greenhouse Gas is comprised of CO_2, N_2O, and CH_4. The effect of each gas is scaled relative to CO_2 and added together to get the total effect.

Discussion of the Results

The cost analyses show that some options, such as the HFO and scrubbers option, are more economical than others depending on fuel prices. However, it is not obvious for all scenarios as the equivalent annual cost values overlap considerably. Therefore, the cost analysis has only helped point an owner in a certain direction, but much thought must be put into the impact these different options will have on vessel operations.

An important note about this analysis is that annual cost savings typically have a larger effect on the EUAC than higher construction costs. This is understandable as annual fuel costs can be up to 40% of the vessel's construction cost for a containership built in Asia. Over 10 years, this represents a large investment cost, even with a 14% discount rate. Unfortunately for owners, while the annual costs are more important, they are also highly variable. Construction costs can be rather simple to estimate, especially after similar vessels utilizing the proposed fuel options are constructed. Annual costs are difficult to predict without an in-depth analysis because some costs are hidden. While maintenance and operation costs can be predicted with more certainty after more vessels are in service, future market predictions of fuel costs will remain speculative since they are based on so many factors, including geopolitical factors. It is considered useful to perform a series of analyses with various factors modified, such as future fuel prices, maintenance costs, design speeds/engine sizes, etc.

While performing a simplified analysis is useful for initial design proposals, it can also be misleading if taken at face value. There are hidden costs not included in this analysis, which only become apparent after initial development of a particular vessel design. For example, perhaps an owner selects HFO and scrubbers. As noted above, there is currently no built-in method (EGR) of NOx reduction for medium speed diesels, such as those used for ship generators (SSDG's). To meet the required NOx levels, these engines must use SCR's. However, as previously discussed, SCR's cannot operate if there are high levels of SOx in the exhaust gas flow. Furthermore, SCR's will not work if the exhaust gas temperature is too low, as it would be after passing through a scrubber to remove the SOx. Therefore, the only available option for SSDG's is to operate on MGO or LNG. The vessel would then need an MGO fuel system and tanks in addition to the HFO tanks, and the apparent savings over an MGO only fueled vessel begin to diminish.

A vessel fueled by LNG may not be able to bunker while cargo handling operations are in progress. This could increase the vessel's port time, lower revenue, and demand higher voyage speeds to maintain a similar schedule. Another consideration is that besides the full capacity of LNG fuel required, there might be the need for a backup supply of fuel oil (MGO). This diesel fuel supply could be required to prevent the vessel from becoming dead in the water if there is a problem with the LNG fuel supply system or if the LNG supply from ports is unreliable, which is a likely scenario until the LNG infrastructure is built up in marine ports. The required fuel oil capacity must be at least half that required for the longest passage, so the vessel can always get back to port, but it could be as much as that required for an entire voyage.

Some owners are also considering the emissions impact when deciding on a fuel option for the future in order to reduce the environmental impact of their vessels to the maximum practical extent. In this way they can enhance the "green" profile of their company. As was shown in this report, the lowest emission results can be achieved by using LNG, but the reductions do vary by engine type. These variations should be considered by an owner when selecting engines, if emission reductions are a primary goal.

Besides cost and emissions, there are other considerations that should be taken into account. For example, a vessel with the LNG option might have a higher scrap value than vessels with one of the other options because of the added value in the expensive stainless steel tanks and piping. In some scenarios, the simplicity and guaranteed effectiveness of burning MGO might outweigh the potential cost savings associated with LNG or scrubbers.

Some other considerations not directly reflected in cost estimates are listed below:

- In 10 or 15 years, what will be the state of the LNG plant? Will large amounts of equipment need to be replaced as it ages to meet high reliability and safety standards that will be applied by regulatory organizations for LNG fueled vessels?
- What about crew turnover? Much more complex training is required with LNG operation. New crew must receive training.
- How long will scrubbers last? This big and expensive equipment is subject to corrosion. Will they need to be replaced every 10 years?
- What will the fuel prospectus be? If everyone switches from HFO to MGO to meet MARPOL Annex VI requirements in 2020, will HFO still be readily available or will production be focused on MGO resulting in a drop in MGO prices and sharp increase in price and/or lack of availability for HFO for the marine fleet. What are the future prospects for the price of LNG? It is relatively cheap now compared to MGO because it is currently in abundance. What happens when half the fleet and most shore based power plants, railroads, and trucks switch to LNG?

References

1. "Fuel Switching Advisory Notice" - American Bureau of Shipping, March 2010
2. "Exhaust Gas Scrubber Systems - Status and Guidance" - American Bureau of Shipping, March 2013
3. MARPOL, Annex VI *Regulations for the Prevention of Air Pollution from Ships*, Regulation 13 *Nitrous Oxides* and Regulation 14 *Sulphur Oxides and Particulate Matter*
4. IMO Resolution MEPC 184(59) *2009 Guidelines for Exhaust Gas Cleaning Systems*
5. "Natural Gas for Waterborne Freight Transport: A Life Cycle Emissions with Case Studies", J. Corbett, H. Thomson, J. Winebrake, June 6, 2014,

Appendix

Vessel Types

Midsize tankers and containerships were selected for this analysis as they are both likely candidates for alternative fuels. These vessels generally operate in coastal, short voyage or island trades and do not have the large fuel consumptions typical of large trans-ocean vessels. For large trans-ocean vessels, the effects of the ECA are less significant because the vessel only spends port time and part of each voyage in the ECA. There is less incentive for owners of these vessels to make a large investment in an alternate fuel option, such as scrubbers or LNG, for use while in the ECA. This is illustrated in the sample vessel calculations for international voyages. The midsize tanker used in the example can be considered representative of tankers of 30,000 to 125,000 tons deadweight. The midsize containership can be considered representative of containerships of 2,000 to 5,000 TEU. Furthermore, midsize tankers are similar to bulk carriers with regard to size, construction cost, and annual operating cost. Likewise, midsize containerships are similar to Roll-On, Roll-Off type vessels. The selected vessel types are, therefore, representative examples that can be used over a wide range of vessels.

For each of the two vessel types, three propulsion systems were considered. The base design uses diesel engines burning MGO full time, representative of a vessel that does not travel outside of the ECA for extended periods of time. The base design was also analyzed for a vessel engaged in international voyages burning MGO inside the ECA (assumed to be port time and 25% of the voyage time) and HFO outside the ECA. The first alternative design uses diesel engines burning HFO with an exhaust gas scrubber able to meet ECA emission standards. The second alternative design uses an LNG propulsion system. Each propulsion design was evaluated based on construction cost and operating costs that are affected by fuel type, which include fuel consumption costs, system operation costs (such as scrubber operation costs), and maintenance costs. Also included was any revenue impact from lost cargo capacity, when applicable.

Construction Cost

Base Propulsion Design – MGO in the ECA

The base propulsion design for both the midsize tanker and containership is a two-stroke, low speed diesel engine with a fixed pitch propeller. MGO is burned in this engine; therefore, the vessel would comply with all MARPOL Annex VI emissions limits[2], even after 2020. The base propulsion design represents the lowest vessel purchase price as it does not require the large upfront cost of additional equipment, such as an exhaust gas scrubber or an LNG plant, to meet emissions limits. Construction of the vessel is quicker, easier, and thus cheaper than the other propulsion design options because it requires the least amount of equipment to be installed and it is based on proven technology that is identical or very similar to many existing vessels.

[2] For engines installed before January 1, 2016. Engines installed after that date would require additional equipment to meet Tier III NOx limits in the ECA.

The construction cost estimate for the base design midsize tanker and containership are derived from Herbert Engineering's in-house ship estimating program, SEP. The program can provide construction cost estimates for vessels built in Asian shipyards and in U.S. large or mid-tier shipyards with an overseas shipyard design, purchasing, and support package. These estimates can be considered applicable to foreign flagged vessels, most of which are built in Asia, as well as U.S. Flag vessels in foreign trade (built in Asia) and U.S. Flag vessels in Jones Act trade (U.S. built).

For a vessel that operates part time in an ECA burning MGO and burns HFO when outside of the ECA, additional equipment is required such as HFO purifiers, tank heating coils, additional steam capacity, and heat tracing of heavy fuel oil piping. The additional cost of this equipment adds about 1% to the total cost of the vessel.

Alternative Design 1 – HFO + Scrubbers

All vessel types designed to burn HFO will require some form of exhaust gas treatment system in order to clean the exhaust gas and meet MARPOL Annex VI sulfur emissions limits either in the ECA now or worldwide after 2020. For this propulsion design, an exhaust gas scrubber was selected because they have been shown to work and there is cost information available from several vendors.

The scrubber and other required support equipment add to the base purchase price of the vessel. The main engine and ship's service diesel generators (SSDG's) were assumed to remain the same as those used in the base design. The addition of required equipment when operating on HFO, such as larger purifiers and a fuel heating system, were assumed to add an additional 2.5% of the base design's machinery cost. Based on information obtained from a variety of sources, a scrubber system and associated outfitting adds an additional 30% to 35% to the machinery costs. The net effect is a 7% increase to the U.S. built vessel's total construction cost over the MGO fueled base design. The vessel built in Asia sees an 8% increase to the total construction cost. The percentage is higher because the additional equipment costs are roughly the same regardless of where the vessel is built, meaning the cost is a higher percentage of the total vessel price in Asia than in the U.S. since equipment cost is a higher percentage of overall cost for ships built in Asia. The actual cost of adding this additional equipment will still be higher in the U.S., though, because of higher labor costs.

Alternative Design 2 – LNG

When using LNG as fuel, it is now possible to continue to use low speed diesel engines since gas injection or dual-fuel diesel engines are now available from both primary low speed diesel makers (MAN and WinGD). It is assumed LNG fueled low speed diesel engines cost about 20% to 25% more per kW than conventional engines. The range in price depends on whether a larger engine has to be supplied to obtain the same power based on reduced power per cylinder from some models of LNG fueled engines (e.g. WinGD engine). The SSDG's also must be special gas-compatible engines. These engines cost about 30% more on a per kW basis than medium speed engines without the LNG option. Assuming 75% of the machinery cost is for the vessel's engines, the expected additional machinery cost is 23% over the base propulsion design when equipped for burning LNG. No allowance has been made for higher speed that may be required if cargo handling and LNG bunkering are not allowed to proceed simultaneously.

Assuming that the commonly used "C" type tanks are used, the LNG propulsion design requires stainless steel LNG storage tanks designed for about 10 bar, high-pressure cryogenic pumps if a gas injection low speed diesel engine is used, gas vaporizers, gas heaters, double-wall piping, gas stop valves with automatic control systems, additional ventilation and inert gas systems, additional fire-fighting capabilities, and stainless steel drip trays under all LNG pipe joints and fittings. This equipment is expensive and is assumed to add a similar cost to the additional machinery costs, resulting in a total 40% increase in machinery costs.

The net effect is a 15% increase to the U.S. built vessel's total construction cost over the MGO fueled base design. Again, the vessel built in Asia will see a higher increase of 17% added to the total construction cost because of the greater impact of equipment cost on overall vessel cost.

The below table presents the construction costs for the two vessel types for Asian and U.S. construction based on four fuel alternatives, MGO only, MGO & HFO (for international voyages), HFO with Scrubbers, and LNG. For purposes of the EUAC analysis, the construction cost difference for each fuel option versus the baseline MGO only option was included in the cost basis for that option. This construction cost difference was assumed to be financed over the 10 year period of the analysis at the finance interest rate of 6%.

Summary – Construction Cost

	Midsize Tanker (Bulk Carrier similar)			
	MGO	MGO + HFO	HFO + Scrubber	LNG
Cost per Ship - Asia:	$ 50,000,000	$ 50,500,000	$ 54,000,000	$ 58,500,000
Cost Per Ship - USA:	$ 125,000,000	$ 126,250,000	$ 135,000,000	$ 146,250,000

	Midsize Containership (RoRo similar)			
	MGO	MGO + HFO	HFO + Scrubber	LNG
Cost per Ship - Asia:	$ 72,000,000	$ 72,720,000	$ 77,760,000	$ 84,240,000
Cost Per Ship - USA:	$ 180,000,000	$ 181,800,000	$ 194,400,000	$ 210,600,000

Maintenance & Operating Cost

Base Propulsion Design - MGO

The annual maintenance cost for the base propulsion design is the lowest of the three propulsion options. This lower cost is possible because burning distilled MGO alleviates the need for operating large heavy fuel purifiers and a fuel heating system, which are necessary for HFO. Furthermore, maintenance of the main engine and SSDG's is lower when burning cleaner MGO. The cost of maintenance used in this analysis was $0.85 per MW/hr for burning MGO in both the main engine and SSDG's. The small purifiers for MGO fuel were assumed to add an additional 10% of this maintenance cost. For vessels planned for operation on international voyages outside an ECA, HFO capability is likely to be included and the maintenance costs for the MGO vessel are increased to cover the additional costs for part time operation on HFO (75% of the at sea time until 2020). This increase is about 30%. After 2020 this vessel is expected to operate on MGO only without the increase in maintenance cost.

Alternative Design 1 – HFO + Scrubbers

The maintenance cost for the HFO propulsion design comprises the additional maintenance costs resulting from burning HFO instead of MGO and also additional maintenance costs of the exhaust gas scrubber system. Maintenance of the main engine and ship service diesel generators (SSDG) is higher when burning HFO than MGO. The cost of maintenance used in this analysis was $1.00 per MW/hr for burning HFO in both the main engine and SSDG's. The larger purifiers and fuel heating system required for HFO operation were assumed to add an additional 30% to the total engine maintenance cost.

Based on previous work done by Herbert Engineering, the annual operating cost for closed loop wet scrubbers is estimated to be $14.25 per MW/hr and $3.25 per MW/hr for open loop wet scrubbers. Most vessels, particularly those in the island trades, could benefit from hybrid scrubbers which operate as a closed loop system when in coastal waters and ports, and operate as an open loop system when in open waters. Hybrid scrubbers are estimated to have an average annual operating cost closer to that of an open scrubber with the assumption that the vessel will operate in open waters with the scrubber in the open loop mode more often. This operating cost is estimated to be $6 per MW/hr.

For a typical midsize vessel, the maintenance and operating costs are about 8 times higher for the HFO fueled design with scrubbers compared to the MGO fueled base design, with the large increase due mostly to the scrubber operating costs.

Alternative Design 2 – LNG

LNG, like MGO, is a cleaner fuel than HFO and results in lower engine maintenance costs. The cost of maintenance used in this analysis was $0.85 per MW/hr for burning LNG, the same cost as for burning MGO. Theoretically, maintenance costs for the LNG system should be low. However, the LNG fuel delivery system is complex and contains a substantial amount of expensive equipment, resulting in expensive replacement parts. The actual cost of maintenance on a vessel with an LNG system of this type is presently unknown, so for simplicity, the cost of maintenance for the LNG system was assumed to be an additional 50% of the total engine maintenance cost.

For a typical midsize vessel, the maintenance and operating costs increase by about 35% for the LNG fueled design compared to the MGO fueled base design.

Fuel Cost

In addition to the initial investment cost for alternative fueled ships, the annual fuel consumption cost drives the overall EUAC of the ship. Future fuel prices are difficult to predict, so prices for the calendar years 2013 to first quarter 2018 from Houston, TX were used in the calculations. These prices are similar to prices worldwide, including Singapore and northern Europe. The discount rate used in the net present value calculations takes into account the uncertainty of future cash flows, in this case annual fuel costs, and discounts the costs such that uncertain fuel costs in the future have less effect on the net present value.

Base Propulsion Design - MGO

MGO currently has the highest cost of the three fuels. The MGO price range used in the analysis was between $1,080 and $343 per metric ton based on high and low prices for 2013 to first quarter 2018 in Houston. MGO has a lower heating value (LHV) of 42,700 kJ/kg.

For vessels sailing outside of the ECA and burning HFO for part of the voyage, fuel costs are only about 55% to 75% of the cost of burning MGO full time.

Alternative Design 1 – HFO + Scrubbers

The HFO price range used in this analysis was between $656 and $125 per metric ton based on high and low prices for 2013 to first quarter 2018 in Houston. HFO has a LHV of 40,500 kJ/kg. This represents a 5% decrease in energy content from MGO, therefore, the fuel oil consumption of the main engine and SSDG's is about 5% higher when burning HFO than when burning MGO. The scrubber system consumes power, so the SSDG's must supply an additional 1.5% of the main engine's and SSDG's normal operating power, thereby increasing fuel consumption further.

The net result is that for a typical midsize vessel, the fuel costs when operating on HFO are 40% to 65% of the MGO fueled vessel's fuel cost.

Alternative Design 2 – LNG

The price of LNG as a marine fuel is difficult to determine. The fuel is not readily available in most places; therefore, determining an exact price is currently impossible. While it is true that natural gas is abundant and cheap in some places, liquefying and shipping this fuel is expensive. Furthermore, the infrastructure required to fuel vessels with LNG is only now being developed. Based on studies done by Herbert Engineering and others, the price of bunkered LNG in the U.S. currently (2017) was assumed to be about $12/mm BTU ($560 per metric ton) where a well established bunkering system is in place. This is based on Henry Hub gas prices of $4/mm BTU and includes other costs for liquefying the gas and transporting it to the vessel. In Europe and Asia, the price of natural gas is higher than in the U.S. and even the prices in the U.S. have increased by several dollars recently before returning to a lower price. It is also possible that the price might be slightly lower for some vessels depending on their location relative to LNG supply terminals. Therefore, the range used for this analysis was $10 to $18/mm BTU ($465 to $836 per metric ton) with 2018 prices occupying the lower end of the range because the LNG bunkering infrastructure is becoming more established, lowering the liquefaction and delivery costs from gas at the hub to LNG delivered to the ship.

LNG has a LHV often stated as 50,000 kJ/kg by the engine manufacturers, but more realistically about 49,000 kJ/kg. This represents a 15% increase in energy content from MGO, therefore, the fuel oil consumption of the main engine and SSDG's is about 15% lower when burning LNG than when burning MGO. Also included is approximately 5% by weight MGO as pilot fuel.

The net result is that for a typical midsize vessel, the fuel costs when operating on LNG can be as low as 60% of the MGO fueled vessel's fuel cost when the price of gas is low relative to oil. However, when the price of gas is relatively high compared to oil, as it was during the past few years due to the large decline in oil prices, then the fuel costs when operating on LNG can be 50% higher or more compared to the MGO fueled vessel's fuel cost.

Other Costs

For some vessel types, such as containerships, cargo space becomes significantly impacted as more equipment is added. Exhaust gas scrubbers might pose an impact on cargo space for a containership retrofit project, but for a new build, it should be possible to incorporate the scrubbers into the exhaust funnel design without affecting container space. However, for LNG propulsion systems, there is little question that container stowage space will be affected. If the LNG tanks are located in the hull, the vessel will lose valuable hold space. If the tanks are located in the weather, above deck container capacity will be lost.

Lost container capacity results in lost revenue. This lost revenue can be accounted for as an additional cost associated with the LNG propulsion option. The assumed market rate for one TEU was $1,300 per voyage leg. Normally, containerships are only full for about 33% of the year. The rest of the time, the lost container capacity does not impact the vessel as there is still a reserve left in other container stacks. When the vessel is full, it is assumed that only 70% of the lost container space is missed because some of the containers that would normally be in this lost space can be placed in other container stacks. Therefore, the net annual revenue lost is only 23% of the potential lost revenue per year. This lost revenue can be considered as an increase in operating costs of 7% for a midsize containership.

Summary – Annual Maintenance, Operation, Fuel, & Lost Revenue Cost

In the below tables the combined annual operating costs for fuel, maintenance, operation directly related to fuel type, and lost revenue (if applicable) are estimated using 2016, 2017, and 2018 fuel prices. A 2% annual increase in costs is applied to estimate the costs in future years. Four fuel alternatives are shown and for each, three different starting fuel prices are given to illustrate how the costs of each alternative are sensitive to fuel cost.

- MGO only, base design;
- MGO + HFO, for vessels on international voyages outside an ECA, but with HFO usage only for 5 years until 2020;
- HFO + Scrubber, with the assumption that HFO continues to be available after 2020, if not then vessel would operate similar to the MGO only vessel after 2020 (this possibility was not priced in this simple analysis);
- LNG.

Annual Operating Cost - Midsize Tanker (Bulk Carrier similar)					
Houston 2016 – Low Fuel Price	Houston 2016 – High Fuel Price	Houston 2017 – Low Fuel Price	Houston 2017 – High Fuel Price	Houston 2018 – Low Fuel Price	Houston 2018 – High Fuel Price
MGO - $343/MT	MGO - $528/MT	MGO - $415/MT	MGO - $605/MT	MGO - $550/MT	MGO - $653/MT
$ 4,170,000	$ 6,390,000	$ 5,030,000	$ 7,310,000	$ 6,650,000	$ 7,880,000
MGO + HFO	MGO + HFO	MGO + HFO	MGO + HFO	MGO + HFO	MGO + HFO
$ 2,320,000	$ 4,640,000	$ 3,710,000	$ 5,400,000	$ 4,670,000	$ 5,540,000
HFO - $125/MT	HFO - $312/MT	HFO - $250/MT	HFO - $368/MT	HFO - $308/MT	HFO - $366/MT
$ 2,110,000	$ 4,510,000	$ 3,720,000	$ 5,230,000	$ 4,460,000	$ 5,210,000
LNG - $10/mmBTU	LNG - $18/mmBTU	LNG - $10/mmBTU	LNG - $18/mmBTU	LNG - $10/mmBTU	LNG - $18/mmBTU
$ 5,040,000	$ 8,960,000	$ 5,080,000	$ 9,000,000	$ 5,160,000	$ 9,030,000

Annual Operating Cost - Midsize Containership (RoRo similar)					
Houston 2016 – Low Fuel Price	Houston 2016 – High Fuel Price	Houston 2017 – Low Fuel Price	Houston 2017 – High Fuel Price	Houston 2018 – Low Fuel Price	Houston 2018 – High Fuel Price
MGO - $343/MT	MGO - $528/MT	MGO - $415/MT	MGO - $605/MT	MGO - $550/MT	MGO - $653/MT
$ 8,810,000	$ 13,510,000	$ 10,640,000	$ 15,460,000	$ 14,060,000	$ 16,670,000
MGO + HFO	MGO + HFO	MGO + HFO	MGO + HFO	MGO + HFO	MGO + HFO
$ 4,860,000	$ 9,770,000	$ 7,800,000	$ 11,380,000	$ 9,830,000	$ 11,650,000
HFO - $125/MT	HFO - $312/MT	HFO - $250/MT	HFO - $368/MT	HFO - $308/MT	HFO - $366/MT
$ 4,330,000	$ 9,390,000	$ 7,710,000	$ 10,910,000	$ 9,280,000	$ 10,850,000
LNG - $10/mmBTU	LNG - $18/mmBTU	LNG - $10/mmBTU	LNG - $18/mmBTU	LNG - $10/mmBTU	LNG - $18/mmBTU
$ 12,730,000	$ 21,250,000	$ 12,740,000	$ 21,260,000	$ 12,760,000	$ 21,270,000