Feasibility of Dual-Fuel Engines in Short Sea Shipping Lines

Projecte Final de Carrera. Enginyeria Tècnica Naval

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Per vosaltres, pares, família i amics que no m'heu deixat de donar suport.

Per tu Júlia, ja hem fet un pas més!

Sense la vostra ajuda encara bi seria...
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La idea bàsica d’aquest treball és descobrir la viabilitat de la modificació de la flota de vaixells de transport de curta distància a motors de combustible dual (Fuel-Oil/Gas-Oil + Gas Natural). El motiu pel qual es planteja aquesta idea és oferir una opció als armadors que els permeti complir les normatives vigents i futures mantenint els costos el més baixos possibles.

Les vigents normatives MARPOL han estat condicionant els vaixells en construcció durant els últims anys però seran les futures normatives les que obligaran als armadors a prendre importants decisions envers tecnologies menys contaminants per poder seguir navegant per moltes de les zones amb un elevat transit marítim.

Aquest treball mostra quines són les possibles opcions que estan oferint les drassanes i els fabricants de motors als armadors per tal de poder acomplir aquestes normatives.

Un cop exposades normatives, tecnologies i la seva implementació als vaixells s’arriba a l’estudi de la viabilitat pròpiament dit. Es prepara una base de dades amb rutes reals de vaixells que passen per l’estat espanyol. S’analitzen els costos que suposa per un armador el retrofit d’un vaixell, ja sigui per convertir-lo en Dual-Fuel com per adaptar-hi un sistema de neteja dels gasos d’escapament. Emprant aquestes variables es plantegen tres escenaris diferents de cara a comparar els costos i períodes d’amortització de cadascuna de les opcions que permetin als armadors seguir navegant i complying les normatives.

Els diferents escenaris exposats i els resultats obtinguts expliquen les conclusions obtingudes en quant a viabilitat de l’explotació d’aquesta tecnologia.
Introduction

The main idea of this project is the feasibility study for retrofitting short sea shipping vessels to work as Dual-Fuel engines (Fuel-Oil + Natural Gas). Improve the performance of the engines to obtain more economical benefits to ship-owner and reduce harmful emissions are the key of this project.

Our environment requires a new attitude concerning human uses of natural resources and any project working in this way it’s a benefit for all of us. We need to work together finding new energies but also improving the existing ones because it’s faster to improve anything existing than create a new one. When we investigate anything we should not forget all the pros & cons because it makes a successful summing-up possible.

To determinate the best way to introduce Dual-Fuel technology we’ll investigate proudly on two main topics: technology in itself and which shipping companies could be interested in adopt it. We consider to ask the opinion and interest to the shipping companies is a must.

Before this work anybody make any PFC about this topic but there are a few ones studying similar topics (in environmental terms) that we can use to take better conclusions and deep analysis.

Finally this work should answer the question if this technology is feasible and do what states.
Objectives

The main objective is to determine the feasibility of Dual-Fuel retrofitting for engines present in Short Sea Shipping vessels.

To accomplish this main objective there are other secondary objectives:

- Integrate future environmental regulations to this paper forcing its achievement in this study
- Determine present day technologies capable to accomplish environmental regulations
- Definition of shipping routes to study the proposed viability
- Determine the study vessel to obtain its measurements
- Study Dual-Fuel, and other main engine types
- Study Dual-Fuel and Scrubber System vessel’s retrofitting
- Review of bunkering prices to do comparisons and to create different future scenarios according to the possible price evolution
Following you will find a short brief of most common used technologies onboard present-day vessels navigating around the world.

1. **Steam turbines**
   Widely used in XX century. At the begging the boiler of this plants burn coal and wood to generate water steam but more modern plants heat water burning gasoil / fuel-oil and finally some ships were equipped with nuclear plants to boil water. Due to its performance steam turbines are not very much used in new vessels because internal combustion engines have a better global performance.

2. **Slow Speed diesel engines**
   Slow speed diesel engines means less than 300 rpm. It’s an important classification because there are important differences between slow and medium engines. If the main engine will move the propeller and also an alternator due to construction properties of the last one, its better to run faster, but if the main engine only must propel vessel this slow speed engine is the best option because usually they don’t need any gearbox between engine and propeller. It gives better fuel consumption, more reliability and simplicity. These engines can burn Heavy Fuel Oil (HFO) or Diesel Oil.

3. **Medium Speed diesel engines**
   As we have said before, medium speed engines usually move the propeller via some gearbox and an alternator or, in some cases, working as electrical generators moving alternators powering electric motors that will propel vessel. Medium speed engines run between 300 and 1000 rpm. Depending on desired electric frequency, the engine will be designed to run at
best performance coinciding on the alternator used. Medium speed engines can burn HFO or Diesel too.

4. High Speed diesel engines
Typically used in yachts and electricity generators (similar to truck’s engine). Usually burn only Diesel, not HFO due to its characteristics. High-speed diesel engines suffered a fast evolution in last few years supposedly to the similarities to car/truck engines and its evolution in terms of efficiency, emissions and performance.

5. Gas turbines
Gas turbines burn Natural Gas, so its fumes don’t contain Sulphur. The $\text{kg of CO}_2/\text{kW}$ emissions are less than steam turbines. Typically used in fast speed vessels and ferries where size and $\text{kg/kW}$ ratio are crucial. Thermal efficiency of gas turbines are worst than Diesel engines but can be improved using waste heat to generate steam that feeds another turbine (known as combined cycle). In this case thermal efficiency could be better than some of the best existing Diesel engines, but they are more complex plants, with more components than Diesel engines.
EVALUATE AIR POLLUTION FROM PRESENT-DAY TECHNOLOGIES

The most important pollutants emissions from shipping transports are:

- **SO\textsubscript{2}**: fuels could contain sulphur and when combustion happens the reaction is:

  \[ S + O_2 \rightarrow SO_2 \]
  \[ SO_2 + \frac{1}{2} O_2 \rightarrow SO_3 \]
  \[ SO_3 + H_2O \rightarrow H_2SO_4 \]

  This resultant sulphuric acid could exit to atmosphere generating *acid rain* and producing elevated corrosion in metals.

![Figure 1: SO\textsubscript{2} metric tons / year](image)

This figure shows the geographical distribution of total annual SO\textsubscript{2} emissions in metric tons per year. Pollution concentration comes only from vessel traffic in year 2000 and show clearly where shipping lanes run. As colours represent logarithmic scale there is a bigger difference in sulphur content if any zone is a shipping lane or not. Black colour is for other purpose in the study where I take it.
- **NO\textsubscript{x}**: when nitrogen present in the air (N\textsubscript{2}) is at very high temperature and pressure could react with oxygen (O\textsubscript{2}) and water as follows:

\[
\text{N}_2 + 2\text{O}_2 \rightarrow 2\text{NO}_2
\]

\[
2\text{NO}_2 + \text{H}_2\text{O} \rightarrow \text{HNO}_2 + \text{HNO}_3
\]

But nitrous acid is not very stable in these conditions so it decomposes:

\[
3\text{HNO}_3 \rightarrow \text{HNO}_3 + 2\text{NO} + \text{H}_2\text{O}
\]

\[
4\text{NO} + 3\text{O}_2 + 2\text{H}_2\text{O} \rightarrow 4\text{HNO}_3
\]

Here we found, mono-nitrogen (NO) that destroys ozone (O\textsubscript{3}) and nitric acid (HNO\textsubscript{3}) that could cause some respiratory diseases.

![Figure 2: NO\textsubscript{x} generation depending on engine Load / Type of engine](image)

This figure from MAN shows the different NO\textsubscript{x} generation curves depending on engine load and type of engine. As we can see, low-speed engines decrease NO\textsubscript{x} generation as load increases while medium-speed vessels do its inversely. Faster engines have more flat curves.
- **CO₂:** Results of a stoichiometric combustion in the Carbon cycle. Very known for its properties as greenhouse gas. If engine uses some Bio-Fuel, which has Carbon that comes from the absorption of it from the air by plants or any photosynthetic organism, CO₂ emission generated from combustion could be virtually zero.

- **CO:** Generated when it’s not enough O₂ present in the combustion chamber (incomplete combustion), is a harmful gas for humans with lethal properties in concentration. Carbon monoxide has an indirect radiative forcing effect by elevating concentrations of methane and tropospheric ozone through chemical reactions with other atmospheric constituents (e.g., the hydroxyl radical, OH.) that would otherwise destroy them. Through natural processes in the atmosphere, it is eventually oxidized to carbon dioxide. Carbon monoxide concentrations are both short-lived in the atmosphere and spatially variable.
- **Particulate Mater (PM):** It’s important to distinguish two types of it:

  - **Soot:** As fuel-oil is a long Hydrocarbon chain, when it burns during combustion usually remain incomplete some part of the chain and results as a Hydrocarbon that could react in the atmosphere, or it sticks to exhaust system or floats in the air and finally falling to sea or buildings like cinders. People and animals breathe it causing illness in lungs and respiratory system.

  - **Persistent Organic Pollutants (POPs):** Similar to previous ones but stables and could persist in the environment with potential significant impacts on food chains and health of humans and animals. The most related POPs to shipping industry are polycyclic aromatic hydrocarbons because in addition to its formation by incomplete combustion they are also present in fossil fuels naturally (coal and oil). They are capable of serious illness because they could react inside bodies causing serious illness or cancer.
**DETERMINE MOST HARMFUL GAS**

A first evaluation entails to talk about Greenhouse Gases (GHG). Considering global warming as a result of human’s technologies emissions, principal greenhouse gases are: Carbon Dioxide, Methane and Nitrous Oxide. Of these, shipping transport generates significantly only CO₂. According to 2005 world statistical results, World Resources Institute generated this visual diagram showing values and origins of its emissions.

![Figure 3: Greenhouse Gas emissions an its generation (2005)](image)

So the contribution in Greenhouse gases from shipping transport is less than 2,5% of total GHGs. It helps us to determinate a strategy for a greener shipping transport, because tells us that until we could change fuel vector in world chain logistics, shipping could not reduce significantly global Carbon Dioxide emissions. In other words, world won’t be warmer
because of shipping transport. We showed it because politicians and non-scientific people use frequently CO$_2$ as world unique pollutant.

We should divide the other pollutants that escape from the exhaust depending on where we can reduce it. Here we’ll show most usual methods:

- **Before combustion**
  - SO$_x$: using fuel-oil without sulphur content.
  - PM: using fuel-oil with short Hydro-carbonic chains.

- **During combustion**
  - CO: an engine in good conditions doing an stoichiometric combustion should not emit it.
  - NO$_x$: the use of EGR (Exhaust Gas Recirculation) benefits a reduction of NO$_x$. A part of exhaust gas is redirected to intake reducing combustion temperature and consequently NO$_x$ generation (performance decreases too).
  - PM: as lowest speed of the piston more the combustion could finish better for all fuel.

- **After combustion**
  - SO$_x$: using Wet Scrubber to avoid sulphuric acid exit exhaust.
  - NO$_x$: known as Selective Catalytic Reduction (or without Catalyst) it needs low sulphur fuel-oil to work. Exhaust gas is mixed with a solution of water and urea and then the solution passes to a catalytic reactor.
  - PM: using dry Scrubber or Electrostatic Precipitator to take floating particles avoiding exiting with fumes.

It’s difficult to evaluate most harmful gas, because any of them have different consequences: for humans, flora, atmosphere, oceanic acidification… So considering that technology permits to reduce significantly all levels of pollutants the best thing that future regulations could it do will be to force to accomplish strict regulations on emissions.
SUMMARY ABOUT IT

MARPOL ANNEX VI limits air pollutants present in exhaust gas including sulphur oxides and nitrous oxides, prohibiting also deliberate emissions of ozone depleting substances, regulates shipboard incineration and the emissions of organic compounds from tankers.

Chronology:
- 1997: Adoption. Known as 1997 Protocol or Tier I
- 2005: Forced adoption
- 2005: MEPC (Marine Environment Protection Committee) decides to strengthen emission limits
- 2008: MEPC publishes a revised Annex VI considering technological improvements and implementation experience in ships. Also defines designated sea areas called ECA (Emission Control Areas) with special (stronger) limitations. Known as 2008 Protocol or Tier II/III
- 2010: Revised MARPOL Annex VI entered into force

FUTURE REGULATIONS

Last reviews of Marpol Annex VI, known as Tier II and Tier III have been approved and entered into force. It means stronger limitations on pollutants and forced modifications on existing ships to accomplish it. Ship owners will have enough time to prepare and do these modifications coinciding with periodical ship services. Considering regulation’s long time schedule another option could be adopted it in new-build vessels.
NO\textsubscript{x} LIMITATION:

![NOx Limitation Chart](chart.png)

Table 1: MARPOL Annex VI NO\textsubscript{x} limitations depending on engine speed

<table>
<thead>
<tr>
<th>Regulation</th>
<th>Date</th>
<th>NO\textsubscript{x} Limit, g/kWh Depending on engine speed = n (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tier I</td>
<td>2000</td>
<td>\begin{align*} n &lt; 130 &amp; : 17,0 \ 130 \leq n &lt; 2000 &amp; : 45 \cdot n^{-0.2} \ n \geq 2000 &amp; : 9,80 \end{align*}</td>
</tr>
<tr>
<td>Tier II</td>
<td>2011</td>
<td>\begin{align*} n &lt; 130 &amp; : 14,4 \ 130 \leq n &lt; 2000 &amp; : 44 \cdot n^{-0.23} \ n \geq 2000 &amp; : 7,70 \end{align*}</td>
</tr>
<tr>
<td>Tier III (ECA)</td>
<td>2016</td>
<td>\begin{align*} n &lt; 130 &amp; : 3,4 \ 130 \leq n &lt; 2000 &amp; : 9 \cdot n^{-0.2} \ n \geq 2000 &amp; : 1,96 \end{align*}</td>
</tr>
</tbody>
</table>

Figure 4: Chart representing MARPOL Annex VI NO\textsubscript{x} limitations depending on engine speed
SOX LIMITATION:

<table>
<thead>
<tr>
<th>Date</th>
<th>Sulphur Limit in Fuel (x1000 ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ECA</td>
</tr>
<tr>
<td>2000</td>
<td>1,5</td>
</tr>
<tr>
<td>2010</td>
<td>1,0</td>
</tr>
<tr>
<td>2012</td>
<td>3,5</td>
</tr>
<tr>
<td>2015</td>
<td>0,1</td>
</tr>
<tr>
<td>2020/2025</td>
<td>0,5</td>
</tr>
</tbody>
</table>

Table 2: MARPOL Annex VI SOx limitations evolution in time

Figure 5: Chart representing MARPOL Annex VI SOx limitations
EMISSION CONTROL AREAS (ECAs)

The following graphic show a visual reference of the established ECAs and which zones are under consideration:

![Map of Emission Control Areas (ECAs)](image)

**Figure 6:** Existing and possible future Emission Control Areas

The prevention of air pollution by ships list and time in effect from:

- Baltic Sea, from 2006/05/19
- North Sea, from 2007/11/22
- North American, from 2012/08/01
- United States Caribbean Sea, from 2014/01/01
Figure 7: Detail of North Sea and North American ECA's
COMPARISON OF TECHNOLOGIES THAT MUST FULFIL REGULATION REQUIREMENTS

Scrubber system

The Scrubber system is an aftertreatment technology to reduce SOx emissions. There are two types of scrubbing technology, wet and dry, and the main chemical principle is the same in two systems, wash exhaust gases before emitting to the atmosphere.

Wet SOx Scrubber

Wet scrubbing need at least the following components:

- Scrubber unit: main component, which bring water into intimate contact with exhaust gas usually, mounted high up in or around the funnel
- Treatment plant for wash-water conditioning before discharge overboard
- Sludge tank for residues separated from the wash-water
- Control and emissions monitoring system
- And also auxiliary pumps, pipes, coolers and tanks necessary to the system
- Some installations could need a reheater to increase temperature of exhaust gases above the dew point and/or a demister to remove water droplets

Wet scrubbing can’t create a backpressure exceeding the combustion unit manufacturer’s limit and/or engine’s NOx certification limits. A correct evaluation of the required scrubber’s size will help to reduce the space required for system installation, manufacturer costs, vessel’s modifications and the associated structures needed.
Open Loop type:

Figure 8: Seawater, wash-water and sludge schemes

Seawater is pumped from the sea through the scrubber at an approximately flow rate of 45m3/MWh but depending on temperature sulphur solubility varies causing more seawater will be required to maintain the SOx removal rate close to 98%.

Reactions occurred inside scrubber:

for SO$_2$:

\[
\begin{align*}
SO_2 + H_2O & \rightarrow H_2SO_3 \rightarrow H^+ + HSO_3^- \\
HSO_3^- & \rightarrow H^+ + SO_3^{2-} \\
SO_3^{2-} + 12O_2 & \rightarrow SO_4^{2-}
\end{align*}
\]

for SO$_3$:

\[
\begin{align*}
SO_3 + H_2O & \rightarrow H_2SO_4 \\
HSO_4^- + H_2O & \rightarrow HSO_4^+ + H_3O^+ \\
HSO_4^+ + H_2O & \rightarrow SO_4^{2-} + H_3O^+
\end{align*}
\]
All closed loop scrubber uses sodium hydroxide (NaOH and also known as caustic soda) to treat fresh water and causing a reaction to sodium sulphate.

Reactions:

**for SO₂:**

\[
\begin{align*}
\text{Na}^+ + \text{OH}^- + \text{SO}_2 & \rightarrow \text{NaHSO}_3 \\
2\text{Na}^+ + 2\text{OH}^- + \text{SO}_2 & \rightarrow \text{Na}_2\text{HSO}_3 + \text{H}_2\text{O} \\
2\text{Na}^+ + 2\text{OH}^- + \text{SO}_2 + 1/2\text{O}_2 & \rightarrow \text{Na}_2\text{SO}_4 + \text{H}_2\text{O}
\end{align*}
\]

**for SO₃:**

\[
\begin{align*}
\text{SO}_3 + \text{H}_2\text{O} & \rightarrow \text{H}_2\text{SO}_4 \\
2\text{NaOH} + \text{H}_2\text{SO}_4 & \rightarrow \text{Na}_2\text{SO}_4 + 2\text{H}_2\text{O}
\end{align*}
\]

Fresh Wash from the fresh water system is introduced to the scrubber system via Process tank and a pump takes water from and pumps it to the NaOH unit before cool it in the seawater intercooler. When wash-water is ready it will be introduced in the scrubber at approximately 20m³/MWh rate. The discharge rate to the water treatment unit is approx. 0,1m³/MWh to maintain wash water in perfect conditions. NaOH consumption is about 15 litres/MWh.
Wash water level is reduced by scrubber evaporation but to reduce fresh water consumption it’s possible to install a capture system in the exhaust to reuse wash water again. Water treatment unit separates sludge and seawater to avoid contamination to the sea using centrifugal separators or multi-stage oily separators. To be capable to operate without discharging seawater, closed loop scrubbers have a sludge holding tank where it could be stored until vessel could throw out. A manufacturer’s size recommendation for the sludge tank is around 0,5m²/MW. Sludge tank only could be discharged ashore to authorized MARPOL companies.

Storage tanks, pipes and fittings for the whole system should be made with some material resistant to corrosion because it’s very corrosive.
Dry SO\textsubscript{x} Scrubber

Dry scrubbing needs the following main components:

- **Scrubber unit**: main component, which bring the exhaust gas into contact with calcium hydroxide granules. Due to the characteristics of the reaction scrubber could be situated before any waste heat recovery or SCR equipment because the reaction releases heat.

- **Granule supply silo and screw conveyor** for discharge positioned at the top and bottom of the scrubber respectively.

- **Control and emissions monitoring system** capable of adjusting correct flow of fresh granules through the scrubber.

- **Pneumatic system with flexible pipework** to transport granules from and returning to onboard storage.

- **Granules** are Calcium hydroxide spheres with a size between 2 and 8mm in diameter.

![Figure 10: Dry Scrubber with granulate systems](image-url)
Calcium hydroxide (Ca(OH)$_2$) reacts with sulphur oxides to form gypsum as follows:

### for SO$_2$:
- SO$_2$ + Ca(OH)$_2$ $\rightarrow$ CaSO$_3$ + H$_2$O
- 2CaSO$_3$ + O$_2$ $\rightarrow$ 2CaSO$_4$
- CaSO$_4$ + 2H$_2$O $\rightarrow$ CaSO$_4$·2H$_2$O

### for SO$_3$:
- SO$_3$ + Ca(OH)$_2$ + H$_2$O $\rightarrow$ CaSO$_4$·2H$_2$O

Typical consumption of granules is a rate of 40 kg/MWh with a granule density of 800kg/m$^3$, in other words 0.05m$^3$/MWh. Electrical power consumption is lower than for wet systems being a 0.15-0.20% of total power being scrubbed.

Granulates have to be stored before and after use in special separated compartments.
Comparison chart:

<table>
<thead>
<tr>
<th></th>
<th>Wet scrubber, open loop</th>
<th>Wet scrubber, closed loop</th>
<th>Wet scrubber, hybrid</th>
<th>Dry scrubber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation without discharge to sea</td>
<td>No</td>
<td>For a limited time depending on size of wash-water holding tank</td>
<td>For a limited time depending on amount of fresh granules and compartments to store used ones</td>
<td></td>
</tr>
<tr>
<td>Weight (typical values for a 20MW SOx scrubber)</td>
<td>30-55 tonnes (excluding wash-water system, treatment equipment, and tanks)</td>
<td>30-55 tonnes (excluding wash-water system, treatment equipment, and tanks)</td>
<td>30-55 tonnes (excluding wash-water system, treatment equipment, and tanks)</td>
<td>Aprox. 200</td>
</tr>
<tr>
<td>Power consumption</td>
<td>1-2%</td>
<td>0,5-1%</td>
<td>0,5-2%</td>
<td>0,15-0,2%</td>
</tr>
<tr>
<td>Scrubbing chemical consumable</td>
<td>No</td>
<td>Sodium hydroxide solution (in closed loop)</td>
<td>Sodium hydroxide solution (in closed loop)</td>
<td>Sodium hydroxide solution (in closed loop)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aprox. 6 l/MWh-%S</td>
<td>Aprox. 6 l/MWh-%S</td>
<td>Aprox. 6 l/MWh-%S</td>
</tr>
<tr>
<td>Compatible with waste heat recovery system</td>
<td>Yes if scrubber is installed after it</td>
<td>Yes if scrubber is installed after it</td>
<td>Yes if scrubber is installed after it</td>
<td>Yes if scrubber is installed after it</td>
</tr>
<tr>
<td>Compatible with SCR system</td>
<td>No, unless a reheater is fitted after the wet scrubber to raise the exhaust gas temperature</td>
<td>No, unless a reheater is fitted after the wet scrubber to raise the exhaust gas temperature</td>
<td>No, unless a reheater is fitted after the wet scrubber to raise the exhaust gas temperature</td>
<td>Yes</td>
</tr>
<tr>
<td>Compatible with EGR system</td>
<td></td>
<td></td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Remove PMs present in exhaust gas</td>
<td></td>
<td></td>
<td></td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 3: Comparison chart between different Scrubbers
Selective Non-Catalytic Reduction (SNCR)

NO\textsubscript{x} emissions in the flue gas are converted into elemental nitrogen and water by injecting a nitrogen-based chemical reagent, most commonly urea (NH\textsubscript{2}CONH\textsubscript{2}) or ammonia (NH\textsubscript{3}; either anhydrous or aqueous). The chemical reactions, in a simplified form, are as follows:

\[ \text{NH}_2\text{CONH}_2 \rightarrow \text{NH}_3 + \text{HNCO} \]
\[ \text{HNCO} + \text{H}_2\text{O} \rightarrow \text{NH}_3 + \text{CO}_2 \]

\[ 2\text{NO} + 2\text{NH}_3 + \frac{1}{2}\text{O}_2 \rightarrow 2\text{N}_2 + 3\text{H}_2\text{O} \]
\[ 2\text{NO} + 2\text{NO}_2 + 4\text{NH}_3 \rightarrow 4\text{N}_2 + 6\text{H}_2\text{O} \]
\[ 6\text{NO} + 8\text{NH}_3 \rightarrow 7\text{N}_2 + 12\text{H}_2\text{O} \]

Because the highest NO\textsubscript{x} reduction is achieved at temperatures between 870 and 1,200°C the reagent should be introduced before exhaust gas will be cooled. The typical removal efficiency is 30-40%. In the case of SNCR the ammonia slip may be a more important issue than for SCR but can be managed.
Selective Catalytic Reduction (SCR)

SCR is similar to SNCR in that it uses ammonia injection in the flue gas to convert NOx emissions to elemental nitrogen and water. The key difference between SCR and SNCR is the presence in SCR systems of a catalyst, which accelerates the chemical reactions. The catalyst is needed because SCR systems operate at much lower temperatures when compared with SNCR system. Typical temperatures for SCR are 340 to 380°C, compared with 870 to 1,200°C for SNCR. The catalyst active surface is typically metal, ceramic or fibre reinforced. The catalysts are usually made of heavy metal oxides, consisting of the base material TiO2 and active components vanadium, tungsten, molybdenum, copper and chromium. As these catalysts are not chemically modified in the process, their service life is generally very long and its rejuvenation is only required after 4 to 6 years of use. The rejuvenation process usually involves the removal of solid particles on the catalysts by vacuum cleaner, washing of the catalysts in acid baths and drying of the washed catalysts. The solid particles removed generally consist of ash particles and therefore can be disposed of in a similar manner.

The SCR process is a post-combustion NOx control technology that removes the NOx from the flue gas. When the flue gas passes upstream of the SCR catalyst reactor, the NOx in the flue gas reacts with the ammonia gas (a reagent) and is reduced to N2 and water vapour. No solid or liquid by-products will be generated from this process.

The ammonia gas will be generated from an urea to ammonia conversion system: when urea reacts with water under a heated environment, it hydrolyses to ammonia, carbon dioxide and water.

The typical NOx removal efficiency of SCR is 80%. When compared with SNCR, there would be a slight increase in auxiliary power consumption while ammonia slip can be more easily controlled within acceptable limit because of the presence of catalysts.
**Low Sulphur fuels**

To avoid SOx emission regulation an easy way is to use fuels containing a very low amount of sulphur. This type of fuels costs approximately about 50% more and theoretically this difference will be increased as demands rises up. However it simplifies the possibility to navigate in ECAs because it’s just to bunker some tanks with MGO and others with HFO without modifications in the engine or modifications in the funnel to put a scrubber inside. It’s the easiest way to accomplish ECAs sulphur control and by adjusting the engine probably the vessel could also accomplish NOx regulation too.

But due to changes in viscosity, lubricant proprieties and pH differences (it’s more acid) of MGO, some engines (typically oldest ones) can’t burn this fuel, so in this cases this vessels should take other options to fulfil ECA requirements. In brief MGO causes fastest mechanical wear in cylinders, rings, joints, etc.
Abbreviation of Exhaust Gas Recirculation is a technology mature in automotive field but new to ships. It feeds the turbocharger intake with a portion of the coming from the exhaust and reintroduces it to the cylinders. This lowers the oxygen content and increases the heat capacity resulting in a reduction of peak combustion temperatures and hence the formation of NOx is lowered. First tests in marine diesel (MGO or HFO) engines using EGR showed an increase in particulate emissions (PM), an oil acidification and reduced engine performance.

But the solution to acidification comes by using a Scrubber to clean at least the 80% present sulphur in the exhaust before bleeding to turbocharger. The engine performance could be improved (more than without using EGR system) by adjusting whole parameters of the injection and combustion process. About PMs only filtering techniques could be applied to avoid emitting it to the atmosphere.

First-generation EGR systems with scrubber system can clean approximately 80% of sulphur content.
Figure 11: EGR arrangement combined with Scrubber system
Future engines could integrate EGR system by fitting it in the same way as for instance an intercooler. The next image shows a first concept of the EGR parts in yellow:

**Figure 12:** Second generation EGR system integrated with the engine

Is planned to achieve Tier III NOx compliance by using new EGR systems due first results are interesting. Exgaustr gas NOx presence using EGR is reduced by 50% at this conditions:

- 20% exhaust recirculation rate in the turbocharger
- HFO with 3,0% sulphur content
- Scrubber capable of removing the 80% of sulphur before admitting to the turbocharger to prevent acidification

Presumably increasing recirculation rate to 40% NOx generated will be lower than new IMO requirements.
Direct water injection / Water fuel emulsion / Charge air humidification

All three methods are equivalent and consist as seems. Working similar to an EGR system, this method reduces combustion temperature to avoid NOx generation. Increasing humidity level above standard air or mixing water directly with fuel before combustion are techniques based on the heat absorption capability of the water or in other words the temperature in the combustion chamber is reduced.
High pressure 2 stage Turbo Charger / Miller Cycle

Another way to reduce NOx is the Miller Cycle, an offshoot of the Otto Cycle. Main difference comes in the opening times of the inlet valve. It maintains opened while piston is goes up (until approximately 1/5 of the total stroke) causing a reduction in the Temperature of the air before the combustion happens. To make it possible an engine of this type needs a compressor capable to increase the air pressure so it should be higher than the piston compression to avoid air exit through intake valve. The way that the temperature falls compared to Otto Cycle is because one part of the compression is done outside of the cylinder and cooled through the intercooler.

Engine manufacturers use a two stage Turbo Charger because they are specially designed with different sizes and connected in series to reduce individual space needed to it and presumably the lag in operation due to mechanic’s inertia. After every compressor comes an intercooler to keep air cool and denser.

![Figure 13: Drawing showing circulation of the intake air in a 2-stage turbo charger](image-url)
Low NOx combustion tuning

It is possible to adjust combustion process to reduce NOx emissions basically acting in the injection process. In fact, NOx is produced due to of the speed and temperature combustion, so we could act in three ways: increasing Compression Rate to help particles movement, reducing the speed in the fuel injection (or just retarding it) to reduce maximum temperature and finally optimizing combustion chamber to do the same effects but modifying space where air reacts with fuel in the combustion.

Using just this system is not possible to accomplish latest regulations.
% Reduction compared to HFO | NOx | SOx | CO2 | PM | Fuel Efficiency
---|---|---|---|---|---
Scrubber | 85% | 95% |  | 75-80% | -5%
SCR | 80% |  |  |  |  
SNCR | 30-40% |  |  |  |  
Low Sulphur Fuels (MGO) |  | 95% |  |  |  
EGR System | 50-60% |  |  |  |  
Direct water injection | 25-40% |  |  | Marginal loss |  
Water Emulsion |  |  |  |  |  
Air humidification |  |  |  |  |  
High-Pressure 2-Stage Turbo | 40-80% |  |  | Marginal |  
Low NOx combustion tuning | 10% |  |  | Marginal |  
Dual-Fuel in LNG operation | 85% | 100% | 20% | >99% | Possible

Table 4: Comparison chart between different technologies

Note about Possible annotation in Fuel Efficiency column of LNG: Due to NG’s octane number and its inherent characteristics, engine’s thermal efficiency could be increased comparing to the use of HFO. But key factors to do it are related to engine design, structure, dimensions and condition.

This chart summarizes up the capabilities of different technologies seen in this section to reduce pollutants outgoing funnel and how much it does. Seems clearly that there are two main ways to accomplish new regulations: Scrubber and Dual-Fuel LNG. There is a subsequent section in this paper comparing them.

With a set of the others technologies it’s also possible but usually ship owners will prefer the easiest and more reliable solution.
Fuel Prices

<table>
<thead>
<tr>
<th></th>
<th>bunkerworld.com</th>
<th>bunkerworld.com</th>
<th>bunkerworld.com + ychats.com</th>
<th>Rotterdam + LNG supposition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2010/06/01</td>
<td>2011/09/01</td>
<td>2012-11-18</td>
<td></td>
</tr>
<tr>
<td>HFO</td>
<td>€/mmBTU</td>
<td>€/mmBTU</td>
<td>€/mmBTU</td>
<td></td>
</tr>
<tr>
<td>2010/06/01</td>
<td>8,85</td>
<td>11,57</td>
<td>11,68</td>
<td></td>
</tr>
<tr>
<td>MGO</td>
<td>13,28</td>
<td>16,41</td>
<td>17,94</td>
<td></td>
</tr>
<tr>
<td>LNG</td>
<td>9,02</td>
<td>11,22</td>
<td>11,08</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Bunkering prices

Figure 14: Chart showing bunkering prices evolution in time

This chart and graph is made in euros because its data will be useful for our purpose but the world talks about US$/BTU and US$/ton. Bunker business is a global market with many players (ship owners, refiners, marketers and ports) trading with it in behaviour like stock exchange with instant prices, futures, forward, net back...
Right values are obtained consulting directly this websites and converting values to euros and mmBTU, from US dollars and tonnes.

Original charts extracted from these websites make to see the behaviour of these prices in time possible. A larger time scale was desired but bunkerworld.com does not offer this option to free users.

BTU unit of energy is typically used in marine bunker business because it is useful to do comparisons between fuels equalling its energy (British Thermal Unit). Note that 1BTU equals to about 1,0055KJ kilojoules in SI units. As the order of magnitude referring to fuels is $10^6$ many companies talk about mmBTU meaning $10^6$ BTU. About US$ it’s generally known that is the main currency exchange value rate in the world.

![Figure 15: Chart showing 10-year evolution bunkering prices](image-url)
Chart in the previous page shows historical values since 2001 and it’s important to remark the difference in price trends of LNG and fuel oil (HFO and MGO). Fuel oil had a higher growing trend while LNG depending on its source is near stable (Natural Gas Henry hub) or with lower rate (LNG Japan) than fuel oil.

The expected future scenario is very similar to this one. Considering lower world resources and difficulties on extraction is expected that crude derivatives prices experience an accelerating growing trend. MGO will also experience a supply and demand price increase because new mandatory regulations will force its consumption in some areas.

Distribution costs of LNG probably will not increase over time due to scale economy optimisation (today it’s distribution as a fuel is marginal) so future growing rate will be lower than fuel oil derivatives.

To determinate current fuel prices I’ve been searching on internate to obtain updated prices information, but I cannot found a web giving me this information for all three fuels. Finally I used these two websites:

- www.bunkerworld.com to know HFO and MGO prices in Rotterdam

- www.ycharts.com to know LNG and NG prices in Japan and Europe, respectively

Converting tons to mmBTU and US Dollars to euros I could use this data to make calculations. To create future scenarios I used apart from multiple reports and papers historical prices charts. Below are the three most updated charts:
Figure 16: Rotterdam HFO in blue. BunkerWorld Index (BWI) in orange.

Figure 17: Rotterdam MGO in blue. BunkerWorld Index (BWI) in orange.
Figure 18: Europe Natural Gas (Import Price) in blue. Japan LNG (Import Price) in orange.
A dual-fuel engine is an internal combustion engine usually adapted to operate using heavy fuel-oil that also can burn natural gas in any range, from mere 5% to 100%. Its development comes from technical modifications based on commercial heavy fuel engines with intake and power strokes, due to obvious differences between fuels.

**DIFFERENCES BETWEEN CONVENTIONAL ENGINES AND DUAL FUEL ONES**

**2-Stroke**

Two-stroke engines are usually classified as more polluting than four-strokes, but today technology helps to modify this statement. Let’s see how this is done:

Simplest two stroke engine uses exhaust and intake ports, but an improvement in fuel efficiency and pollution emissions is the Uni-Flow scavenging which have exhaust valves and intake ports:
Main difference between a conventional two stroke and a Dual-Fuel is the addition of a new injection system. As a part of this system a gas block is fitted to engine, incorporating an accumulator, a shut down valve and purge valves. Shut down valve works strictly timed with cylinder position. Gas block controls gas injection to accumulator, purge valves and correct gas pressure to injection.
### 4-Stroke

<table>
<thead>
<tr>
<th>4-stroke Conventional</th>
<th>4-stroke Dual-Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intake</strong></td>
<td></td>
</tr>
<tr>
<td>At the beginning, intake stroke the piston is in the TDC (Top Dead Centre) and descends to BDC (Bottom Dead Centre) while intake valve or valves are opened. In this movement piston creates a depression inside the cylinder that sucks clean air.</td>
<td>At the beginning, intake stroke the piston is in the TDC (Top Dead Centre) and descends to BDC (Bottom Dead Centre) while intake valve or valves are opened. In this movement piston creates a depression inside the cylinder that sucks a mixture of clean air and gas through a special injector.</td>
</tr>
<tr>
<td><img src="image" alt="Intake Diagram" /></td>
<td><img src="image" alt="Intake Diagram" /></td>
</tr>
</tbody>
</table>

<p>| <strong>Compression</strong>        |                   |
| From BDC piston goes up to TDC compressing the air (and mixture air-gas in Dual-Fuel) because intake valves are closed. Pressure rises up and temperature of air too. | |
| <img src="image" alt="Compression Diagram" /> | <img src="image" alt="Compression Diagram" /> |</p>
<table>
<thead>
<tr>
<th></th>
<th>4-stroke Conventional</th>
<th>4-stroke Dual-Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Combustion</strong></td>
<td>Injecting fuel in the combustion chamber full of hot and dense air causes the ignition. Piston will go down to BDC as a result of the combustion.</td>
<td>Injecting fuel in the combustion chamber full of hot and dense air with gas causes the ignition. Depending on proportions between gas / fuel-oil Piston will go down to BDC as a result of the combustion.</td>
</tr>
<tr>
<td><img src="image1.png" alt="Combustion Diagram" /></td>
<td><img src="image2.png" alt="Combustion Diagram" /></td>
<td></td>
</tr>
<tr>
<td><strong>Exhaust</strong></td>
<td>With the exhaust valve or valves opened piston will go up to TDC cleaning the residue of the combustion.</td>
<td></td>
</tr>
<tr>
<td><img src="image3.png" alt="Exhaust Diagram" /></td>
<td><img src="image4.png" alt="Exhaust Diagram" /></td>
<td></td>
</tr>
</tbody>
</table>

**Table 6**: Comparison between 4-stroke conventional and Dual-Fuel engines

---

Feasibility of Dual-Fuel Engines in Short Sea Shipping Lines 42
Gas Injection System:

Typical Dual-Fuel injection system consists in electronically controlled valves for gas injection and fuel oil valve actuator (FIVA) capable of different injection profiles. FIVA valve also supplies pilot oil in dual fuel operation mode monitoring constantly gas pressures and fuel oil injection valve to assure a correct timing and performance and if any parameter goes wrong gas injection will shut off automatically and engine will switch to fuel oil mode. Security system also check scavenge air receiver pressure and combustion pressure to detect any gas leakage. Just after an automatically switch to fuel oil gas pipes will be purged with inert gas.

Figures 20&21: Sections of the injection system in Dual-Fuel engines
Injector:

Gas injection design complies with traditional design principle in fuel-oil injectors of compact design. Cylinder cover has a new bores where gas is admitted. To prevent gas leakage between injector, cylinder cover, valves housing and spindle, guide sealing rings should be replaced to gas resistant ones. If some leakage happens, existing sensors in the double wall piping will detect it. Control oil should always be at higher pressure (25-50 bars) than gas pressure.

![Figure 22: Section of the injector](image1)

Pilot oil injector is a standard fuel oil ones except for its nozzle that now contains gas inlet:

![Figure 23: Scheme of the injector](image2)
**RETOFIT FOR CONVENTIONAL ENGINES**

Far away than new vessels an important use of Dual-Fuel technology is retrofitting existing ships, from largest LNG carriers to short distance shuttle ferries. This section will show the most common systems and services needed and its implementation aboard.

**Main Engine conversion**

First thing to consider is if engine’s manufacturer has developed a retrofit for this engine. Another important thing is the consideration of enough space to hold LNG tanks, compressor, evaporator and any other required equipment.

When doing a main engine retrofitting conversion, sometimes shipowner could be interested to retrofit the auxiliary engines too. Problems with auxiliary engine’s manufacturers are the same than main one’s, but the rest of auxiliary infrastructure could be shared with this.

We talk about official conversions due to manufacturers will provide highest warranty and reliability expected in commercial operation. Probably will appear small shipyards that will use spare parts and other equipment to modify engines to work in Dual-Fuel or Natural Gas mode but this goes beyond purpose of this paper.

After doing a search in principal vessel’s main engines manufacturers, the conclusion is that progressively they have a wider range of Dual-Fuel engines. All this engines are developments from a conventional engine, typically which one that have great reliability and customer’s satisfaction. They share the same footprint features and system interfaces than some other engine of its product range to help retrofitting possibilities.

Man and Wärtsilä have a wide range of Dual-Fuel engines all of them capable of retrofitting previous engines. They cover from 1MW to 18MW for any purpose required in shipping business.
LNG Gas supply system

- Storage Tank placing: First step to put the LNG storage tank is the piping, electrical cables and any other pipe removal or rerouting (i.e. water, fuel, air…) to prepare its foundations. Another consideration is the structural analysis, the distance from engines and compatibility with piping from other existing systems.

- Storage Tank type: usually shipowner will demand less space used to storage tank so recommended option is to transport gas liquefied (specific volume relation is 1/600 comparing liquid/gas)

- Piping from storage tank to main/auxiliary engines avoiding pass through accommodation spaces, service spaces or control stations. Also all pipes conducting gas inside should be double wall pipes. Pressure in the fuel supply system inside engines compartment cannot exceed 10 bar.

- Valves: beside standard rerouting and closing pipes there are three mandatory valves: two valves in series closes the main supply pipe of the engine when an automatic shut-off occurs. The other valve is vent valve that also will be opened automatically in these conditions.

- Bleed valves and piping: bleed valves require additional piping airing to a secure area outside vessel.

- Master Gas Fuel Valve: a remote controlled valve should be installed for any dual fuel engine and should be closed within its compartment, at the engine control station and at the navigation bridge.
Evaporation System

Gas used in Dual-Fuel engines is stored liquefied meaning that before being injected should take next process:

- Booster pump pumps LNG to supercritical pressure to avoid stratification of gas when evaporating it. Typically discharges LNG at 11-15 bar.
- If pressure is higher than supercritical a heat exchanger will heat LNG to required temperature. Heat source could be steam or hot water from engine room.
- The evaporator could exchange its cool temperature to chill reliquefaction system which maintains LNG storage tank liquid. In this case we talk about Optimiser, no just an evaporator.
- A buffer system is needed to make a constant flow and in case optimiser exists it could act as it.
- After that process, LNG becomes gas and high pressure (HP) pumps will fuel pump it at a pressure between 150-300 bar to Dual-Fuel engines.

![Figure 24: LNG evaporation system to generate NG](image)

Feasibility of Dual-Fuel Engines in Short Sea Shipping Lines
Natural Gas Compressor:

Most of ship retrofits will be for LNG tankers due to could use boil-off gas (BOG). Considering it the compressor used in the process from LNG to injected gas in the engine becomes a key factor. If it could be used to increase the gas pressure and help to maintain LNG in cryogenic state the global efficiency of the vessel could be increased. For any other ships it’s not a key factor but in this segment we’ll talk about one of the most used and advanced compressor system for this purpose.

Two companies (Burckhardt and Hamworthy) have built the Laby-Gi a vertical 6 crank inline, low speed reciprocating compressor. Due to its architecture, it will not stimulate the connected offshore structure or interfere with the structural analysis of the naval architecture.

![Laby-Gi reciprocating compressor](image-url)

**Figure 25:** Laby-Gi reciprocating compressor
It’s an oil-free compression with labyrinth sealing with piston rings. It’s non-sensitive from suction conditions (pressure and temperature) and capable of wide range of output pressures maintaining a high-energy efficiency.

The design of Laby-Gi make possible to eliminate an extra compressor. After the first or second stage (depending on conditions) the gas can be diverted to the reliquefaction system and send the rest to the engine. If the engine don’t need any gas injection, Laby-Gi will send all gas to the reliquefaction system. Today they are investigating in a way to combine a gas compression cascade (compressing one gas that will exchange heat with another one) using Laby-Gi as part of the process to reduce the liquefaction system’s quantity of compressors.
Reliquefaction system:

First systems are based on a closed nitrogen expansion cycle extracting heat from BOG. Next generation systems modified cycle, doing partial liquefaction and separating non-condensable items. Next diagram show how it does:

![Reliquefaction system diagram](image_url)

**Figure 26:** Reliquefaction system diagram

In green appears the N2 (nitrogen) compression cycle with a three compression and freshwater heat exchanges cascade. The expansion of nitrogen is been done inside the *Cold Box* (as its known the reliquefaction cryogenic heat exchanger and marked in light orange) where BOG heat is exchanged with it (BOG appears in red and when cooled to LNG in blue).

After the *Cold Box* BOG passes to a separator vessel (appears drown in red and blue) that will extract any non-condensable item (as nitrogen) mixed in LNG before returning it to the tanks after a brief expansion to increase its pressure and reduce its temperature to adjust it to the
prevailing in tanks. The next image will show a render of a realistic system with a new improvement: the preheater. It exchanges BOG with just compressed N2 before BOG its compressed reducing system power consumption by some 15%.

![Image](image.png)

**Figure 27**: Rendering of reliquefaction system, cold box, inert gas system and LNG system

Laby-Gi could help to reduce system power consumption by doing one or two of the cascade BOG compression.
There is lots of ways to store LNG in appropriate conditions but the key to choose between different options concerning tanks is the vessel and the needed amount of LNG. Types:

- Membrane or semi-membrane: those tanks are integrated in hull forms like fuel-oil ones. Due to they are non-pressurized they are very sensitive against atmospheric pressure variations. There are three main types depending on manufacturer. One of the most usual is Mark III type represented in this drawing.

![Membrane type tank](image)

**Figure 28: Membrane type tank**

- Type A: prismatic with straight planes adapted to hull shape, non pressurized and with a very voluminous ventilation system.

![Type A tank](image)

**Figure 29: Type A tank**

- Type B: most known of this type is Moss tank the spherical ones, typical in LNG vessels. They lose lots of space due to its form, but is a very reliable system.
- Type C: they are unique pressurized (<2 bar) but even so space requirements compared to MGO are 3-4 times more. They have a very solid design with flexible pressure, easy installation, very reliable and without leakages. Some of them are mounted as 40 feet standard container and one of the most used type C nowadays is jointly with boil-off gas compressors, fuel gas vaporizer and fuel gas heater/cooler (in some cases also with submerged motor pumps) known by commercial names as Wärtsilä LNGPac.

![Type C tank](image)

**Figure 30:** Type C tank
Safety equipment

In modern vessels safety equipment usually should not suffer big modifications because basic rules are the same, and just should add specific gas detectors:

- Ventilation: A minimum of 30 air changes per hour is the requirement for the engine room and two fans (either one capable of at least 50% of the required flow). Ventilation ducts have to be situated in such manner to ensure immediate evacuation of leaked gas guaranteeing no existence of any hide depot of gas in room corners. Inlet and discharge ducts come from and to safe locations with non-sparking type fans (with electric motor outside the airflow stream too).

- Gas detection: a minimum of two independent fixed gas detection systems is required for any engine compartment for continuous monitoring of leaked gas presence. Arrangement of the system is a key factor in its effectiveness, so should be determined upon gas dispersal analysis or physical smoke test. Maintenance and testing will vary depending on each system, but should be included in general maintenance procedures onboard vessel. Each system should comply with:
  
  A. Self-monitoring type
  B. After any gas detector fails and self-monitoring system diagnoses it system will disconnect this detector to avoid any false detection that will shutdown plant
  C. Each system is to be arranged guaranteeing functional redundancy when either one of the systems fails
  D. Easy check and maintenance system

- Electrical equipment: If exists, any electrical equipment which can create an electrical spark (i.e. magnetic contactors, circuit breakers, motor starters, switchboards…) should be located outside of compartments containing gas, any Dual-Fuel engine or system
- Access: Same machinery spaces access rules from SOLAS 1974 is required but if pressure in engine room is the same that in the vessel an air lock arrangement should be installed for any compartment. It may be waived if ventilation on these rooms are always negative in pressure relative to the adjacent compartments

- New alarms and procedures due to Dual Fuel implementation:

<table>
<thead>
<tr>
<th>Monitored Parameters</th>
<th>Alarm</th>
<th>Automatic activation of the block and bleed valves</th>
<th>Automatic switching over to fuel oil mode</th>
<th>Engine shutdown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas fuel injection systems – Malfunction</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Pilot oil fuel injection systems – Malfunction</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Exhaust gas after each cylinder, temperature – High</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Cylinder pressure or ignition – Failure</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Oil mist in crankcase, mist concentration or temperature in crankcase – High</td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Engine stops – Any cause</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Failure of the control-actuating medium of the block and bleed valves</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7: New alarms and procedures to add to the safety protocols after retrofitting a vessel to Dual-Fuel
Inert Gas System (IGS):
According to one of the main inert gas generator’s manufacturer, Alfa Laval, the right inert gas for a LNG installation is CO2. Its systems burn some fuel (bunker fuel, diesel, gas…) in highly controlled combustion inside a horizontal or slightly lean chamber. Inert gas resulting on this combustion contains below 8% oxygen with a very low soot formation. To assure that inert gas is clean after combustion it is cleaned in its own scrubber system and when is cleaned it is stored under pressure in a tank connected to the inert gas system to fill the entire double wall piping. The generation capacity is totally adjustable controlling the oxygen admission and the fuel pump feeding.

Figure 31: IGS scheme
The key of a good retrofitting is the correct installation of all systems and equipment making possible a good interaction minimizing complexity of maintenance tasks to obtain shorter and more efficient overhauls. Every vessel has its own structure, tanks, spaces, engines and auxiliary systems so it’s impossible to elaborate a guide like “How to retrofit my ship”.

In this vessel Dual Fuel engines generate electricity to feed electrical azipod engines:

**Figure 32**: Wärtsilä’s rendering of new supplier type Dual-Fuel vessel with main engines only generating electricity to feed electrical propulsion engines
Here is a schematic representation of main components to retrofit a ship with Dual Fuel engines. In the first image considering the installation of Type C Tanks on deck, and in the second one near to the engine room:

**Figure 33:** Main components to retrofit a vessel. Rendering View

**Figure 34:** Main components to retrofit a vessel. Schematic View
Figure 35: Scheme showing all systems together of a Dual-Fuel vessel
Pros & Cons

After reading previous sections probably you know that today technologies capable to accomplish future regulations are only Scrubber system and Dual-Fuel engines. They are comparable in terms of required space, economical rates and total performance.

The basic working principles set two techniques apart each other: one does not emit pollutants and the other cleans emitted pollutants. It means that Scrubber will need storage onboard and an auxiliary process (done ashore) to neutralize these pollutants. But apart from this difference there is a problem with one solution: Can this engine be a Dual-Fuel one? If the engine onboard any hypothetical vessel cannot be refitted to Dual-Fuel working there is no reason to debate more, Scrubber is the solution.

For vessels with engines capable to suffer a retrofitting for Dual-Fuel operation the decision will remain on this key notes:

- Easiness to do any particular retrofit due to specific characteristics of the vessel
- Difficulties to bunker LNG
- Presence of authorised MARPOL companies in vessel’s route to deplete sludge
- Some economical reason favouring one of them (i.e. Retrofitting a LNG carrier or a Sludge barge)

In terms of final cleanliness and euros the choice is very balanced so particular studies will determinate more pros or cons to Dual-Fuel or Scrubber, but in general terms they are analogue.
Definition

About studied SSS lines it’s not important that today they exist because the main idea of this section is to do the feasibility study of Dual-Fuel engines in SSS, so these routes are representative ones to do correct analysis-involving costs. With ship characteristics the idea is similar due to main objectives of this paper are not the in-depth study about the particular case of a SSS vessel. Searching on other papers to obtain corroborated information I elaborated a chart with main vessel’s characteristics doing SSS in Europe to calculate the average and check it later with another paper of a ROPAX development. Some important information is extracted from these papers and needed to support our calculations.

Case Study Routes

First idea was to ask four of the main shipping companies operating in Spain (Transfennica, Grimaldi, Flota Suardíaz and Acciona) about their ideas of Dual-Fuel in Short Sea Shipping business but as I have received no answer I decided to find information for myself searching on papers and formal reports of competent authorities.

Using an Anave document about SSS where are presented all routes passing through Spanish its possible to elaborate a spread-sheet with 23 different routes (inside and outside current and future ECAs) with an average 600nm per one-way route.
Followed methodology to prepare all data is:

- Use of distance routes between ports (not lineal distances) \(^4\)
- Lots of routes run outside ECA, because all the Atlantic coast of France, Portugal and Spain doesn’t are present in Tier III ECA regulations and they are not proposed for future ones.
- Due to this paper is oriented in near and mid-future regulations Mediterranean Sea was considered as ECA regulated sea.
- Routes are very heterogeneous what implies a more accurate view.

Summarizing the most relevant data:

- Total distance travelled doing one time every route is near 15,000nm
- At a supposed cruise speed of near 19kn sailing times are more than 780 hours
- An assumption of a 50% of sailing time to port idle time, services and other stopped time is plausible, so near 400 hours will be spent docked.
- Mooring times will be near 70 hours and loading and unloading tasks will be another 80 hours
- Consumption in all ports will be zero, because will be the same for all cases: electric consumption from port power supply. Lots of ports are built near cities and aiming to reduce it’s pollution most of this cities have installed electrical connection to force vessels to stop engines.
- When ships are in mooring and loading/unloading tasks we’ll consider the same consumption as when sailing. This is an excessive consideration, but it will compensate some of the idle time considered as 0, due to the ship is on port. In any case this consideration would affect our comparison in the same way so final result will be realistic.
- A mooring time of 45 minutes in every port exit/entrance is considered
**Studied SSS Routes from ANAVE:**

<table>
<thead>
<tr>
<th>Shipping Line</th>
<th>Considered Routes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Buquebús – Lauro</strong></td>
<td>Tarragona – Génova</td>
</tr>
<tr>
<td><strong>Compañía Transatlántica Española</strong></td>
<td>Valencia – Barcelona – Pireo – Estambul – Izmir</td>
</tr>
<tr>
<td><strong>Acciona</strong></td>
<td>Vigo – St. Nazaire</td>
</tr>
<tr>
<td><strong>Flota Suardíaz</strong></td>
<td>Bilbao – Zeebrugge – Flushing – Southampton</td>
</tr>
<tr>
<td></td>
<td>Flushing – Zeebrugge – Santander</td>
</tr>
<tr>
<td></td>
<td>Gijón – Saint Nazaire – Southampton – Vigo – Setúbal</td>
</tr>
<tr>
<td></td>
<td>Setúbal – Vigo – Gijón – Flushing</td>
</tr>
<tr>
<td></td>
<td>Tarragona – Livorno</td>
</tr>
<tr>
<td></td>
<td>Tarragona – Civitavecchia – Salerno</td>
</tr>
<tr>
<td><strong>Geest North Sea Line / Naviera del Odiel</strong></td>
<td>Bilbao – Rotterdam – Tilbury</td>
</tr>
<tr>
<td><strong>Grandi Navi Veloci</strong></td>
<td>Barcelona – Génova</td>
</tr>
<tr>
<td><strong>Grimaldi Napoli</strong></td>
<td>Valencia – Livorno – Salerno – Túnez – Malta</td>
</tr>
<tr>
<td></td>
<td>Barcelona – Civitavecchia</td>
</tr>
<tr>
<td><strong>Naviera Pinillos</strong></td>
<td>Bilbao – Southampton – Felixstowe – Thamesport</td>
</tr>
<tr>
<td></td>
<td>Bilbao – Dublin – Liverpool – Greemock</td>
</tr>
<tr>
<td><strong>OPDR Hamburgo:</strong></td>
<td>Hamburgo – Bremen – Amheres – Le Havre – Felixstowe</td>
</tr>
<tr>
<td></td>
<td>Southampton – Rotterdam – Lisboa – Leixoes – Vigo</td>
</tr>
<tr>
<td></td>
<td>Rotterdam – Bilbao – Le Havre</td>
</tr>
<tr>
<td></td>
<td>Felixstowe – Bilbao – Felixstowe</td>
</tr>
<tr>
<td><strong>Transmed</strong></td>
<td>Tarragona – Génova – Salerno</td>
</tr>
<tr>
<td><strong>UECC</strong></td>
<td>Bilbao – Pasajes – Portbury</td>
</tr>
<tr>
<td></td>
<td>Barcelona – Genova – Livorno – Fos</td>
</tr>
</tbody>
</table>

*Table 8: Considered routes to create distance and times’ database*
DISTANCE CALCULATIONS

According to www.vesseldistance.com we elaborated a chart of whole distances between ports. Let’s see an example using OPDR Hamburg line in the Rotterdam – Lisboa stretch:

Figure 36: Exemplification of one route. Total distance: 1133nm.
After doing that we defined how much nautical miles have been sailed in ECA zones and how much outside ECA with the help of Google Earth\(^5\). Emission Control Areas in the English Channel begin in 5W meridian but the Longitude it’s not determined as a point, so we considered 49N (near Traffic Separation Scheme point\(^6\)). Establishing the point “entrada ECA” (text in green in the screenshot below) in Google Earth en using it’s tool “Ruler” in “Track” we can draw (in yellow) the approximate route over the map and calculate nautical miles outside ECA:

![Google Earth exemplification](image)

**Figure 37:** Google Earth exemplification.

In this case we found 696,66nm, but we’ll just consider the integer because it’s an approximation (696nm).

Applying this method for every route we make the Excel chart you will see in Annex part.
SHIP OPERATION

According to ANAVE routes and considering ECA areas (existing and future one’s) showed below we obtained the next ship operation chart.

![Ship operation chart image](image)

**Figure 38:** All this ECAs (existing and future ones) are considered in force in this paper

<table>
<thead>
<tr>
<th>Ship operation</th>
<th>Non ECA</th>
<th></th>
<th>ECA</th>
<th></th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Days</td>
<td>Annual %</td>
<td>Days</td>
<td>Annual %</td>
<td>Days</td>
</tr>
<tr>
<td>Days at sea</td>
<td>85</td>
<td>23 %</td>
<td>140</td>
<td>38 %</td>
<td>225</td>
</tr>
<tr>
<td>Idling &amp; Loading/Unloading</td>
<td></td>
<td></td>
<td>121</td>
<td>37 %</td>
<td>120</td>
</tr>
<tr>
<td>Mooring</td>
<td></td>
<td></td>
<td>20</td>
<td>6 %</td>
<td>20</td>
</tr>
<tr>
<td>TOTAL</td>
<td>85</td>
<td></td>
<td>281</td>
<td>77 %</td>
<td>365</td>
</tr>
</tbody>
</table>

**Table 9:** Results after processing routes’ database

It’s important to remark that this ship operation chart will be very different if we don’t consider Mediterranean Sea as an Emission Control Area, but as future regulations looks like and thinking in the usefulness of this paper we think it’s better to consider that.
A SHIP FOR THIS STUDY

Avoiding an exhaustive study to determinate the optimal vessel to do Short Sea Shipping in Europe we take two papers to base our vessel on it:

- **Comparativa entre el transporte por carretera y el transporte marítimo en rutas del norte de España al norte de Europa**. Author: Álvarez Vivas, Borja. Tutor: Martínez de Oses, Francesc Xavier. Trabajo de Final de Carrera Facultad de Náutica de Barcelona. 2010

- **ROPAX 3400 DWT 1300 ml**. Author: Martínez Barrios, Israel. Tutor: Arias Rodrigo, Carlos. Proyecto fin de Carrera nº 1736 Escuela Técnica Superior de Ingenieros Navales.

We used the first paper to obtain a chart with Short Sea Shipping vessels in service in 2010. With this chart we'll obtain an avarage ship that will be useful to compare with the proposed vessel of the second paper.

The table is in the next page of all ships doing SSS in spanish ports the year 2010.
<table>
<thead>
<tr>
<th>Buque</th>
<th>Shipbuilding</th>
<th>LOA (m)</th>
<th>Beam (m)</th>
<th>Draught (m)</th>
<th>GT (Tm)</th>
<th>Operation speed (kn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Malta Express</td>
<td>1980</td>
<td>116,07</td>
<td>21</td>
<td>7,5</td>
<td>11457</td>
<td>18,0</td>
</tr>
<tr>
<td>Montserrat B</td>
<td>1980</td>
<td>176,7</td>
<td>25,3</td>
<td>10</td>
<td>16712</td>
<td>19,0</td>
</tr>
<tr>
<td>Salerno Express</td>
<td>1982</td>
<td>127,2</td>
<td>19,2</td>
<td>6,8</td>
<td>8428</td>
<td>16,0</td>
</tr>
<tr>
<td>Velazquez</td>
<td>1983</td>
<td>138</td>
<td>21,5</td>
<td>6,7</td>
<td>16021</td>
<td>14,5</td>
</tr>
<tr>
<td>Cervantes</td>
<td>1984</td>
<td>138</td>
<td>21,5</td>
<td>6,7</td>
<td>15575</td>
<td>14,5</td>
</tr>
<tr>
<td>Arroyofrio I</td>
<td>1984</td>
<td>107,9</td>
<td>18,4</td>
<td>6,45</td>
<td>8126</td>
<td>14,0</td>
</tr>
<tr>
<td>Arroyofrio II</td>
<td>1985</td>
<td>107,9</td>
<td>18,4</td>
<td>6,45</td>
<td>8126</td>
<td>14,0</td>
</tr>
<tr>
<td>Gema B</td>
<td>1985</td>
<td>165,5</td>
<td>23,1</td>
<td>10,1</td>
<td>13769</td>
<td>15,0</td>
</tr>
<tr>
<td>Sieltor</td>
<td>1990</td>
<td>116,28</td>
<td>16,6</td>
<td>6,1</td>
<td>5025</td>
<td>15,5</td>
</tr>
<tr>
<td>Alexandra</td>
<td>1992</td>
<td>118,3</td>
<td>20,2</td>
<td>8,29</td>
<td>7361</td>
<td>17,0</td>
</tr>
<tr>
<td>Sven Oltman</td>
<td>1992</td>
<td>108,77</td>
<td>17,9</td>
<td>6,86</td>
<td>5006</td>
<td>16,0</td>
</tr>
<tr>
<td>Setúbal Express</td>
<td>1992</td>
<td>152,74</td>
<td>23,8</td>
<td>8,85</td>
<td>16925</td>
<td>17,0</td>
</tr>
<tr>
<td>Gerdia</td>
<td>1994</td>
<td>108,77</td>
<td>17,9</td>
<td>6,86</td>
<td>5026</td>
<td>16,5</td>
</tr>
<tr>
<td>Eurostar Roma</td>
<td>1995</td>
<td>158,85</td>
<td>24</td>
<td>8,8</td>
<td>23663</td>
<td>25,5</td>
</tr>
<tr>
<td>Norse Mersey</td>
<td>1995</td>
<td>160,9</td>
<td>24,4</td>
<td>7,5</td>
<td>16009</td>
<td>19,5</td>
</tr>
<tr>
<td>Fantastic</td>
<td>1996</td>
<td>164,21</td>
<td>26,8</td>
<td>6,8</td>
<td>35186</td>
<td>23,0</td>
</tr>
<tr>
<td>Rheintal</td>
<td>1996</td>
<td>100,53</td>
<td>16,5</td>
<td>5,9</td>
<td>3824</td>
<td>14,5</td>
</tr>
<tr>
<td>Mira J</td>
<td>1997</td>
<td>132,4</td>
<td>19,4</td>
<td>7,34</td>
<td>6393</td>
<td>16,5</td>
</tr>
<tr>
<td>EuroCargo Valencia</td>
<td>1999</td>
<td>178,5</td>
<td>25,2</td>
<td>8,6</td>
<td>20883</td>
<td>19,0</td>
</tr>
<tr>
<td>La Surprise</td>
<td>2000</td>
<td>141,25</td>
<td>21</td>
<td>6</td>
<td>15222</td>
<td>19,5</td>
</tr>
<tr>
<td>Eurostar Barcelona</td>
<td>2001</td>
<td>198,93</td>
<td>25</td>
<td>9,9</td>
<td>30860</td>
<td>28,0</td>
</tr>
<tr>
<td>Gran Canaria Car</td>
<td>2001</td>
<td>132,45</td>
<td>21,2</td>
<td>5,2</td>
<td>9600</td>
<td>16,0</td>
</tr>
<tr>
<td>Bouzas</td>
<td>2002</td>
<td>141,25</td>
<td>21</td>
<td>6</td>
<td>15224</td>
<td>19,5</td>
</tr>
<tr>
<td>Tenerife Car</td>
<td>2002</td>
<td>132,8</td>
<td>21,2</td>
<td>5,2</td>
<td>13112</td>
<td>20,0</td>
</tr>
<tr>
<td>Eurostar Valencia</td>
<td>2003</td>
<td>169,84</td>
<td>25,62</td>
<td>9,15</td>
<td>25984</td>
<td>23,5</td>
</tr>
<tr>
<td>Eurostar Salerno</td>
<td>2003</td>
<td>169,84</td>
<td>25,62</td>
<td>9,15</td>
<td>25995</td>
<td>23,5</td>
</tr>
<tr>
<td>Galicia</td>
<td>2003</td>
<td>149,38</td>
<td>21</td>
<td>5,85</td>
<td>16361</td>
<td>17,0</td>
</tr>
<tr>
<td>Suar Vigo</td>
<td>2003</td>
<td>149,38</td>
<td>21</td>
<td>5,85</td>
<td>16361</td>
<td>19,5</td>
</tr>
</tbody>
</table>

**Table 10**: Vessel’s database

This table serves us to obtain the first idea of the average measures of a vessel to do calculations. It’s important to remind that in this list appear a wide variety of ship types: Container Ships, General Cargo, Ro-Ro Cargo and Pax Ro-Ro Cargo.

Combining this with the information of the other paper we will determine the ship specifications to do subsequent calculations.
As we can see excepting Gross Tonnage, the rest of magnitudes are quite similar. Isolating the chart to Ro-Ro and Ro-Pax vessels the result it’s more similar to the Martinez’s paper.

<table>
<thead>
<tr>
<th>Source</th>
<th>LOA (m)</th>
<th>Beam (m)</th>
<th>Draught (m)</th>
<th>GTs</th>
<th>Cruise speed (kn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chart average</td>
<td>141.52</td>
<td>21.56</td>
<td>7.4</td>
<td>14.722.64</td>
<td>18.3</td>
</tr>
<tr>
<td>ROPAX 3400 DWTs</td>
<td>142.45</td>
<td>24.30</td>
<td>5.70</td>
<td>20.160.0</td>
<td>19.0</td>
</tr>
<tr>
<td>Chart isolated average</td>
<td>146.77</td>
<td>22.34</td>
<td>7.2</td>
<td>17.455.90</td>
<td>19.1</td>
</tr>
</tbody>
</table>

**Table 11:** Vessel’s comparison between paper, complete database and isolated database

Considering these results it’s correct to use Martinez’s paper data to make calculations:

- Main engine(s) power: 2 x 6300 kW Wärtsilä 6L46
- Fuel range: 3800 nm + 15%
- Cruise speed (85% power): 19 knots
- Fuel consumption (HFO / MGO) according to engine’s data tables: 172g/kWh

The problem of using this engine as an example is that Wärtsilä does not offer a Dual-Fuel (DF) solution yet. According our purpose we’ll choose the next biggest engine capable of doing a DF retrofit and that in terms of consumption will be worst than an exact equivalent. So the new engine (in DF option) is:

- Main engines power: 2 x 7600 kW Wärtsilä 8L50DF
Calculating to an oversized engine forces us to make equivalences and interpolations as it follows:

- Percentage load to obtain 19 knots (6L46): 85%
- Energy needed to navigate at 19kn: 2 \cdot 6300 \cdot 0,85 = 10.710kW
- Percentage load to obtain 10.710kW = 70,46% considering lineal behaviour

\[
\frac{1}{2 \cdot 7600} \cdot 10710 = 70,46
\]

- Fuel consumption (HFO / MGO) according to engine’s data tables: 194,18g/kWh
  Interpolating from consumption at 75% (192g/kWh) and 50% (204g/kWh)

\[
\frac{204 - 192}{50 - 75} (70,46 - 75) + 192 = 194,18
\]

- Fuel consumption (LNG) according to engine’s data tables: 7669,33g/kWh
  Interpolating from consumption at 75% (7562kJ/kWh) and 50% (8153g/kWh)

To evaluate costs we need to talk about €/h of the main engines as a unique feasibility unit of measure for retrofit to Dual-Fuel or not.

- Conversion from mmBTU to grams for HFO & MGO and kJ for LNG

\[
\begin{align*}
172 \text{ g/kWh} & \text{ conversion to mmBTU/h} \\
1 \text{ Ton} &= 39,7 \text{ mmBTU} \\
1 \text{ gr} &= 39,7 \cdot 10^{-6} \\
172 \cdot 39,7 \cdot 10^{-6} &= 0,0068 \frac{\text{mmBTU}_{\text{HFO}}}{\text{kWh}} \\
7669,33 \text{ kJ/kWh} & \text{ conversion to mmBTU/h} \\
1 \text{ mmBTU} &= 1054615 \text{ kJ/kWh} \\
\frac{7669,33}{1054615} &= 0,0073 \frac{\text{mmBTU}_{\text{LNG}}}{\text{kWh}}
\end{align*}
\]
- Using \( \text{g/kWh} \) obtaining fuel consumption

\[
10710kW \cdot 0.0068 \, \text{mmBTU/kWh} = 73,132 \frac{\text{mmBTU}_{\text{HFO}}}{h}
\]

\[
10710kW \cdot 0.0073 \, \text{mmBTU/kWh} = 77,880 \frac{\text{mmBTU}_{\text{LNG}}}{h}
\]

- Considering latest fuel prices described in previous chapter this is the hourly fuel consumption at cruise speed in euros:

\[
\frac{11.44 \, \text{€/mmBTU}_{\text{HFO}}}{73,132 \frac{\text{mmBTU}_{\text{HFO}}}{h}} \cdot 11.44 \frac{\text{€}}{\text{mmBTU}_{\text{HFO}}} = 836,63 \frac{\text{€}_{\text{HFO}}}{h}
\]

\[
\frac{15.85 \, \text{€/mmBTU}_{\text{MGO}}}{73,132 \frac{\text{mmBTU}_{\text{HFO}}}{h}} \cdot 15.85 \frac{\text{€}}{\text{mmBTU}_{\text{HFO}}} = 1159,14 \frac{\text{€}_{\text{MGO}}}{h}
\]

\[
\frac{9.72 \, \text{€/mmBTU}_{\text{LNG}}}{77,880 \frac{\text{mmBTU}_{\text{LNG}}}{h}} \cdot 9.72 \frac{\text{€}}{\text{mmBTU}_{\text{LNG}}} = 757,04 \frac{\text{€}_{\text{LNG}}}{h}
\]

This obtained values are a key factor in final results of this paper, so I’ll define different bunkering prices to simulate different conditions. Input values and corresponding output results will be showed in the Results section of this section and will be possible to be modified with a computer using the CALCULATIONS.xlsx file.
Estimate retrofitting cost for typical SSS ship

We will consider prices appeared in the *Green Ship of the Future* as they are an approximation to incorporate a Scrubber system or a Dual-Fuel retrofitting to a 38,500dwt tanker. It’s a bigger vessel with a very different configuration, with smaller engine, slower cruise speed and much more industrial design, so I think it’s viable to assume the same retrofitting price in our study because installation will be similar and components will be the same (engine power at cruise speed is barely the same). We can summarize that this will be the worst situation to favour Dual-fuel conversion and the best to use MGO.

**Wet scrubber retrofitting:**

Equipment and structures removal:
- Funnel structure
- Deck platforms and ladder
- Exhaust gas pipes
- Any near funnel equipment that could disturb to foundation structure or scrubber directly

Installation of the following equipment and structures:
- Deck extension, pillars, ladder and platforms
- Sludge tank (internal structure tank)
- NaOH compartment and tank
- Scrubber
- Exhaust gas pipes, scrubber water pipes, valves etc
- Funnel top structure
- Scrubber auxiliary machinery and pipe connections
- By-pass chimney to avoid the scrubber if it’s necessary
Dual-Fuel retrofitting:

Equipment and structures removal:
- Deck pipes and electrical cable pipes in area for LNG storage tank foundation and deck houses for LNG equipment
- Reserve space for the new LNG storage tank foundation’s in CL at A-deck

Installation of the following equipment and structures:
- Foundations for LNG storage tanks
- Deck houses for LNG equipment including foundation
- Rerouting / reinstallation of deck pipes, electrical cable pipes and pipe foundations
- New grating, platforms and ladders around LNG storage tanks
- Foundations for new LNG pipe system
- Main engine conversion by manufacturer (Wärtsilä, Man, Caterpillar Mak…)
- Fuel gas supply system
- Block and bleed valve arrangement
- Gas piping system
- Ventilation system
- Inert gas system
- Sealing oil system
- LNG Tanks
- Fuel gas supply system
- LNG pipping system and valves
- Auxiliary systems
- Safety equipment
- Instrumentation and control system
Costs:

<table>
<thead>
<tr>
<th></th>
<th>Scrubber</th>
<th>Dual-Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machinery and equipment</td>
<td>2.050.000</td>
<td>3.400.000</td>
</tr>
<tr>
<td>Steel/pipping/electrical installations and modifications</td>
<td>1.900.000</td>
<td>1.600.000</td>
</tr>
<tr>
<td>Design and classification cost</td>
<td>400.000</td>
<td>400.000</td>
</tr>
<tr>
<td>Off-hire cost @14000€/day</td>
<td>(20 days) 280.000</td>
<td>(40 days) 560.000</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>4.630.000 €</td>
<td>5.960.000 €</td>
</tr>
</tbody>
</table>

Table 12: Retrofitting costs for Scrubber and Dual-Fuel options

Scrubber operation adds a cost of approximately between 0,5 to 2% more power needed. We will consider a 1,5% to add urea price too. After this consideration HFO hourly operating costs are:

\[
\frac{73,132 \text{ mmBTU}_{\text{HFO}}}{h} \cdot \frac{11,44 \epsilon}{\text{mmBTU}_{\text{HFO}}} \cdot 1,015 \% \text{ SCRUBBER} = \frac{849,18 \epsilon_{\text{HFO}}}{h}
\]

It is considering 2012/04/01 fuel bunkering prices, but in the Excel spread sheet this consideration will be applied in any prices scenario.
EXPLOITATION COSTS. SCENARIOS

Considering retrofitting estimated prices now it’s time to search the best way to redeem the expenditure. In this paper we have exposed 4 ways to accomplish new Tier III regulations and its expenditures:

- Case A: HFO + Scrubber when entering ECAs
  - Retrofitting the vessel with scrubbing system: 4.630.000 €
- Case B: LNG everywhere
  - Retrofitting the vessel with Dual-Fuel system: 5.960.000 €
- Case C: HFO + MGO when entering ECAs
  - No refitting cost
- Case D: HFO + LNG when entering ECAs
  - Retrofitting the vessel with Dual-Fuel system: 5.960.000 €

Combining this 4 possibilities with 3 possible scenarios in terms of bunkering prices:

- **Scenario 1**: bunkering prices from the average of our three values from different times

- **Scenario 2**: an equal and lineal price increasing of the three fuels from latest known prices (10%)

- **Scenario 3**: different increasing of the three fuels proportional to theoretical behaviour from average of our three known values (HFO: +10%, MGO: +15%, LNG: +7,5%)

The full results list and capable of making modifications to adjust to your interest could be found in the Microsoft Excel file, but most important results are described in next page. In this table the reference is the Case C (HFO + MGO) and other cases are compared to it.
An option using just LNG is considered theoretically but not plausible due to initial difficulties in LNG supply on every port. It is the most economical option in the Scenario 3, identical to Scrubber option in the Scenario 2 and the 2nd cheapest option in Scenario 1. So a shipowner that today makes a retrofitting to Dual-Fuel, when LNG is in all ports of his shipping line will save lots of money, but today it’s not an option.
ENVIROMENTAL BENEFITS – ECONOMICAL LOSSES = VIABILITY OF THE PROPOSAL

As we have seen in graphics, charts and summaries the worst way to operate a shipping line when new ECAs are established will be the use of MGO. Compared to the worst other cases and scenarios the redemption time for any refitting expenditure will be 5 years and from then on any refuelling will cost more for this option.

Considering main principle of Scrubbing system as a washing fumes and the LNG option of do not emitting pollutants, I think it's more ecological to burn natural gas inside cylinders than washing exhaust gases, generating noxious sludge that have to be processed on land.

Having said that, I can state that the Dual-Fuel proposal is economically viable and more environmentally friendly than other options.
FUTURE SCHEME FOR TYPICAL SSS COMPANIES

In order to accomplish IMO Annex VI regulations shipping companies should make a decision on its vessels and future ship purchases. As Dual-Fuel and Scrubber technologies are capable to pass future regulations, probably the decision will depend on availability to implement Dual-Fuel/Scrubber in every vessel, and the possibility & costs to refuel LNG in operation ports will decide the technology of future vessels. Key factors will be:

- Extended bunkering network of LNG

- Extended Urea and MARPOL authorised companies to handle sludge from Scrubber

- Bunkering prices for HFO, MGO and LNG
Conclusion

Considerate objectives at the begging of the paper have been accomplished. After all this pages is possible to ask the answer if Dual-Fuel retrofitted engines can accomplish new mandatory regulations and be economically feasible for ship-owners.

To abstain this paper to be an exhaustive study of vessels and Short Sea Shipping routes I make some general considerations, supported on other papers, generating small inaccuracies to the results. This is not worrying because the order of magnitude will be the same, but probably this paper would be useful to somebody that needs to do this calculations but have it’s own numbers, I mean who wants to see if his ship would have the best retrieval retrofitting with a Scrubber or with a Dual-Fuel engine.

Finally I want to give a few ideas to improve this paper:
- Determine the vessel according to its Short Sea Shipping routes to study particularly the case and obtain a particularized result
- With the vessel decided ask for budgets to shipyards (at least 4 of different continents) to refit the ship to Dual-Fuel and Scrubber
- If you are a shipowner ask for your bunkering company to obtain a reliable price of bunkering fuels in your routes and their future expansion of LNG bunkering
Feasibility of Dual-Fuel Engines in Short Sea Shipping Lines
References

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- Lloyd's Register: http://www.lr.org/
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- Marco Polo: http://ec.europa.eu/transport/marcopolo/
- G Captain: http://gcaptain.com/
- Y charts: http://ycharts.com/
Annex

In the original CD-Rom gift to the University you will find two files:

- The paper in pdf format: “FEASIBILITY OF DUAL-FUEL ENGINES IN SSS LINES.pdf”

- The spread sheet in Excel format: “CALCULATIONS.xlsx”

It is strongly recommended to open Excel file and after recognising input values modifying it to your own data values to obtain new results. Do not forbid to navigate trough different Tabs and to see all lines and columns.