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REVIEW

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Low emission engine technologies for future tier 3 legislations - options and case studies

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Abstract

Marine emission legislation such as the current IMO Tier II and upcoming IMO Tier III requirements within the revised Marpol Annex VI have been major drivers for performance development of marine engines during the latest years. These requirements have triggered a vast amount of research activity at the engine OEM's in order to identify and develop the best possible technologies for fulfilling the requirements. A main objective of this research has been to identify the various options available for reducing engine SOx and NOx emissions and to clarify the main criteria engine manufacturers consider to determine the optimum technology. Another objective has been to investigate how ship-owners and operators within the various marine segments are impacted by the new emissions requirements and what key factors they need to consider when identifying the optimum engine technology. Case studies conclude that the optimum solution can vary depending on the vessel application, operating time inside ECAs, as well as prices for fuels and reduction agents. In new-building cases, gas operated engines without after-treatment systems show a strong value proposition as an alternative to liquid fuel engines that require after-treatment solutions - especially for short-haul shipping applications where tighter emission legislations are enforced to a larger extent.

Overall, 2-stage turbo charging, LNG, and SCR technologies are concluded to be the most feasible technologies. Generally, lower operating costs can compensate higher capital expenditures meaning that the owner should carefully evaluate the total cost of ownership of the various alternatives, and not consider only the initial capital expenditure. The choice of best technology option depends on a variety of issues which can change over time - such as the operation profile and route of the vessel and commodity prices. Consequently the ship-owner should evaluate the alternative technologies for a wide range of possible scenarios to find a flexible solution that minimizes exposure to risks related to changing boundary conditions.

With this research, the reasons why certain emission reduction technologies are preferred to others both from OEM's and ship-owner's point of view are quantified and the most feasible technologies for meeting the requirements are identified.

Keywords: Combustion engines, Emissions, Emission control areas, Emission technologies

Introduction

Up-coming marine emission legislations, like for instance the IMO Tier II and III standards within the Revised Marpol Annex VI (2009), have been major drivers for performance development of current marine engines during the latest years. Whilst focus in the past could be put on improving only the engine efficiency, more stringent legislations coming into force have led to a shift in focus towards reduced emissions altogether, focusing on all of nitrogen oxides (NOx), sulphur oxides (SOx) and carbon dioxides (CO2). In addition to the IMO global standards there are also a wide range of local regulations existing for NOx emissions as seen in EU (2015); US EPA (2015); European Clean Marine (2004). The low emission initiatives are mainly focused on the EU and US so far, but there are expectations that for instance parts of Asia and Australia will follow as well.

All these emission legislations have triggered a vast amount of research activities at the marine engine OEM's in order to identify and develop the best possible technologies for fulfilling the requirements. Analysis of the different technology options available, their strengths and weaknesses in respect of fulfilling the demands as well as regarding implications on lifecycle costs have been presented in earlier publications (Wik, 2010 & Wik 2013). There are a large amount of different technology choices existing and operating on gas seems to be one of the strongest options with which all future legislations are fulfilled at a low lifecycle cost.

Application of a Miller cycle in the engine is combining low NOx emissions with a high cycle efficiency. Since the potential of medium-speed engine applications with extreme Miller cycles together with two-stage turbo charging was first reported by Wik and Hallbäck (2007), a lot of continued investigations and applications have been published. Investigations with utilization of 1D simulation codes exploring 2-stage TC system applications on gas engines as well as diesel engines together with EGR have been reported by for instance Christen and Brand (2013); Codan et al. (2010); Millo et al. (2010); Wik et al. (2009), whilst test results from both laboratory and field tests have been presented by Behr et al. (2013); Kurth et al. (2013); Laiminger et al. (2011); Raikio et al. (2010); Ryser et al. (2010); Tinschmann et al. (2012) and Wik et al. (2012) just to mention a few.

The experience of and implementation of 2-stage turbo charging systems on medium-speed diesel and gas engines increases fast and new products fulfilling future IMO Tier III emission limits on diesel engines without after treatment systems, utilizing EGR, like presented by Vervaeke et al. (2013) have emerged as well.

General issues regarding gas engine development and presentation of the whole gas engine portfolio from one OEM, has been reported amongst others by Nylund (2004); Nylund and Ott (2013); Portin (2010). The logical step to take for future products would be to implement 2-stage turbo charging systems also on gas engines as done by other OEM's (Laiminger et al. 2011; Trapp et al. 2013. Test results from natural gas operated engines in combination with high-pressure turbo charging and early intake valve closure timings (Miller cycles) for evaluation of the technology potential on both spark- and diesel-pilot ignited engine types were presented by Monnet et al. (2014) and in 2015 new gas engine products implementing 2-stage turbo charging systems were released from different OEM's (MAN 2015; Wärtsilä2 2015).

"An immediate demand for LNG (liquefied natural gas) as fuel for container shipping in eco-zones, such as North Europe or the United States, can be expected in the near future" said Donche-Gay (2014) at the 2014 SMM Exhibition and Congress in Hamburg, Germany. He is not the only one believing in the future success of LNG in all shipping sectors. One market where LNG is already the prevailing shipping fuel is Norway, where implementation of the Norwegian NOx fund, an Environmental Agreement on NOx between business organizations and the Ministry of the Environment, has led to a radical increase in engines operating on natural gas as according to Hoibye (2011). Within the offshore and ferry sectors almost all ships run on LNG in Norway and major market players like DNV GL (2014) believe it will come for all markets and sectors.

A study has also been conducted by Tzannatos et al. (2014) about implication on fuel, technical, and external (due to exhaust emissions) costs by changing over from liquid to gaseous (LNG) fuel on all ferries within the Greece archipelago, showing a huge overall gain mainly due to lower external costs by changing to LNG. Lloyd's Register (2014) shows in their study and interview of 22 ports, mainly located in the US and European ECAs, that availability of LNG infrastructure is now the second most important driver for the ports after ship owners' demand and "76 % of the ports believe that LNG bunkering operations will commence at their port within 5 years".

Decisions regarding usage of a fuel cannot be taken without a complete lifecycle assessment as well as look upon the global warming potential. This has been studied a lot and even though the potential of LNG usage in reducing NOx, SOx, and PM emissions is acknowledged, there are challenges in total greenhouse gases (GHG) (Brynolf et al. 2014a; Lindstad et al. 2015; Thomson et al. 2015). Brynolf et al. (2014a, b) and Thomson et al. (2015) look at a total fuel-cycle analysis including the extraction, processing and operation stages for Ro-Ro and container vessels as well as tug applications respectively. Whilst LNG would exhibit a GHG benefit directly vs. high-sulphur fuel operation and comparing to low-sulphur fuel operation show a climate benefit within 30 years in container ship applications with diesel-ignited gas engines, a benefit would take longer for tug applications as well as with spark ignited gas engines (Thomson et al. 2015). For the chosen Ro-Ro applications, the global warming potential would be very close to the one of HFO when using LNG as fuel as well as the European electricity mix, being a lot dependent upon coal and natural gas, and due to this considerable reductions would demand usage of liquefied bio gas (Brynolf et al. 2014a, b). Biggest challenges for the gas engines is seen to be the methane slip (CH4) emissions influencing the total GHG emissions radically due to thirty times stronger warming potential for 100-year equivalent mass compared to CO2 (Brynolf et al. 2014a, b; Thomson et al. 2015). Lindstad et al. (2015) focus on the global warming impact (GWI) from engine operations only but include impacts of all emission components as well as operation at high and low power for general cargo ships operating between the two present ECAs i.e. North America and Europe. The average GWI over 20- and 100-year horizons are compared and due to the strong global cooling effect of NOx, SOx, and organic carbon in the atmosphere, high-sulphur fuels show the best result and the authors suggest to still allow usage of high-sulphur heavy fuel oils (HFO) on open seas (Lindstad et al. 2015). Overall it can be concluded that LNG is the fuel of the future at least in short sea shipping and the main question is how to build up the infrastructure and make it available for ships in ports.

The main target of this study is to give an overview of the different engine technology options available for fulfilling future NOx and SOx regulations as well as to list down criteria used from engine OEM perspective regarding the choices made. The second target is to via case studies find out the most advantageous technologies on some selected ship applications.

Past research in this area has been focused on automotive industry like the work by Cucchi and Hublin (1989) and Van der Straaten (2000) or regarding influence on costs and prices of short sea traffic as well as possible transportation system modal splits with introduction of emission legislations, like the work by Notteboom et al. (2010) as well as Kalli et al. (2010). With the emerging of ECAs, more studies have been conducted related to emission modelling and possible modal shifts as well as investigations of alternatives for certain markets (Panagakos et al. 2014; Holmgren et al. 2014; Chang et al. 2014). For instance Panagakos et al. (2014) conclude that possible stricter ECA sulphur limits on the Mediterranean Sea might lead to a modal shift towards the land route. Brynolf et al. (2014a, b) made a life cycle assessment of different alternatives to fulfil ECA sulphur and NOx tier III regulations concluding that neither of the alternatives showed any significant impact on climate change compared to HFO operation. A lot of investigations have also focused on influence of vessel speed reduction on emissions but since that is not a solution for NOx Tier III compliance it is not dealt with in this paper. What is anyhow of utmost relevance are economical comparisons of alternatives to fulfil the ECA legislations and for instance implementation of a real option analysis regarding LNG investments for a retrofit case showed a clear trade-off between low fuel prices and capital expenses (Acciaro 2014). Another study including a multi-criteria approach based on the analytic network process (ANP) shows how this tool could help operators select the most optimum technical alternative (Schinas & Stefanakos 2014).

Methods

Method used for the main target of the study, to give an overview of the different engine technology options available for fulfilling future NOx and SOx regulations as well as to list down criteria used from an engine OEM perspective regarding the choices made, is based on both qualitative and quantitative means.

A qualitative analysis has been done of in-house OEM data which have been partly quantitatively compared towards literature data found for competitor OEM's.

Major research questions to get an answer to are:

- How do the engine manufacturers make the final choices of technologies?
- Is the final choice only depending on lifecycle cost or are there other aspects as well?

Major research means to get an answer to the questions include collection of emission abatement technology options based on in-house data. The researcher's company database has also been utilized for collecting input to case studies regarding effects on engine technology choice for different ship applications. Overall influence landscape on customer emission technology choices could be seen in Fig. 1 and this paper's research is related to how important the following aspects are to the owner's technology choices:

- OEM's technology offerings
- Regulation
- Cost issues.

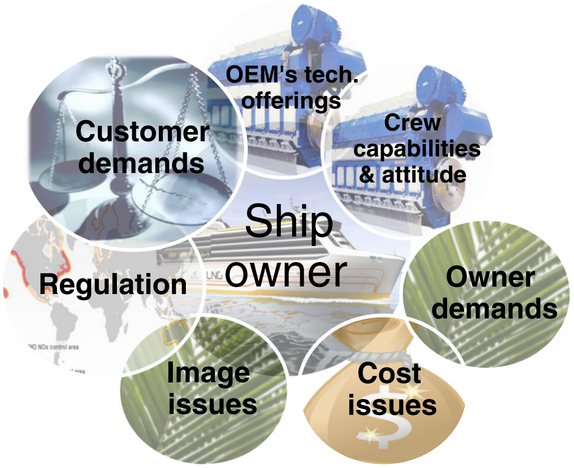

Fig. 1 Landscape of influence on ship owner emission technology choice

First part of the work was to perform a critical screening of different technology options for fulfilling the Tier III NOx emissions on medium-speed diesel engines and ultimately leading to choice of the best suitable technologies. Data has been collected based on engine tests and summarized regarding implications on multiple emissions like NOx, SOx, CO2, and particulate matter in order to get an overall overview. Suitable technology combinations have been proposed in order to reach the targeted emission levels and any eventual challenge seen with the combinations or technologies alone have been listed down with the ultimate target to find out the best options.

The second target was to find out the most advantageous technologies on some selected ship applications via case studies and could be seen as a bridge towards the second phase of the research work where ship owners' and operators' acceptance of technologies to fulfil future emission legislations will be studied. Real operational curves of the ships and thus of the needed engine power has been collected since emissions and operational costs vary a lot according to the engine load (Wik 2010). Investment costs for different alternatives have been collected to show relative differences and calculate eventual payback times for different solutions with simple cash flow analysis. Sensitivity analysis have been made as well due to large fluctuations in prices for consumables in latest years influencing radically the comparisons between technologies.

Results and discussion

Candidate IMO Tier III solutions

At engine OEM's, the general way of comparing different technologies to each other is to make lifecycle cost evaluations including both investment and operating costs and assuming a certain lifetime of the equipment. In these kinds of studies, assumptions for operation profiles, consumption costs, etc. are made to simplify the overall picture and the winning solution is the one where the customer is assumed to reach lowest lifecycle cost.

A brief overview of technologies existing, and taken into the lifecycle cost evaluation for reducing the NOx & SOx emissions, is presented in some more detail below in extension to the general overview shown in the Background section.

Engine emission reductions at the stack outlet are possible with internal engine technologies, after-treatment solutions, or different fuel quality options. In developing new concepts to meet the IMO Tier III emission level, focus is put on all three of the above mentioned methods. Different technologies for NOx reduction have been explored, and some of them have already been implemented in OEM engines. A brief overview of the available technologies is presented in Fig. 2 and was shown by Troberg and Delneri (2010); Wik (2010); Wik (2013).

High pressure TC includes implementation of a 2-stage turbo-charging (TC) system together with an extreme Miller cycle (early inlet valve closure), and has a NOx cycle reduction potential of up to 40…50 % (Wik and Hallbäck 2007; Murayama et al. 2013). If only a minor NOx reduction is needed, another advantage of a 2-stage turbo charging system together with an extreme Miller cycle is a fuel consumption saving of 4…8 % over the whole engine operating range, due to the increased efficiency of the turbo-charging system and the improved cycle efficiency as shown by Raikio et al. (2010); Ryser et al. (2010); Wik and Hallbäck (2007); Woodyard (2009).

Exhaust Gas Recirculation (EGR) is a technology largely applied in the engine industry and on all sizes as for instance GE's marine engines as shown by GE Transportation (2014) as well as truck engines where EGR used to be the choice of Scania shown by Scania (2015) and SCR the choice of Volvo as according to Volvo (2015) but now both OEM's have both technologies to fulfil the latest Euro 6 standards.

By re-circulating cooled exhaust gases into the combustion chamber, the heat capacity of the cylinder charge increases, leading to a decreasing tendency of the cycle temperatures. The effective lambda (air/fuel ratio) is also reduced without, however, affecting the engine's thermal load and the oxygen concentration decreases. As a result, a remarkable reduction in NOx emissions can be achieved (about 60 %). Main drawbacks of this technology are the incompatibility with high sulphur fuels, unless effective cleaning equipment is installed, as well as an increase in the fuel consumption in the order of magnitude of 8 % and up to 10-fold increase of low-load smoke with high EGR rates. Remedies for the increased smoke emissions would be to apply high injection pressures at part loads, requiring a CR system, post injection strategies, or a fuel/water emulsions which are all well-known ways to reduce smoke emissions (Higashida et al. 2013; Pueschel et al. 2013; Weisser et al. 2011; Wik et al. 2011; Wik et al. 2012).

According to Wik (2010), water is another well-known means for reducing NOx emissions. Water vapour acts as a temperature damper and dilutes the oxygen

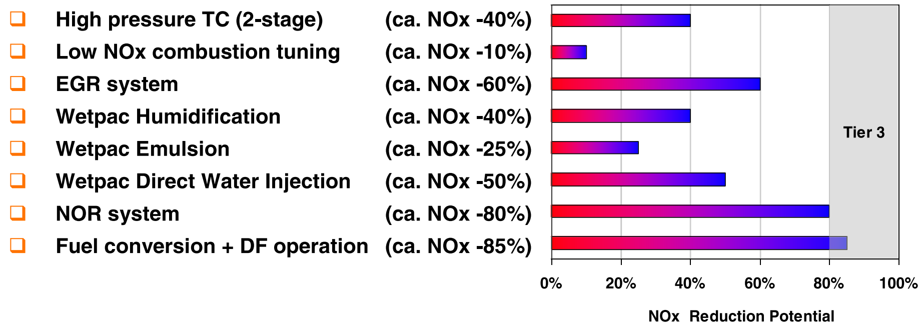

Fig. 2 Different technologies available for NOx emissions reduction from Wik (2010)

concentration in the combustion air, thus reducing the formation of NOx. If water is directly injected into the combustion chamber it also has the effect of directly cooling the combustion process (latent heat of evaporation). Different technologies have been developed for water injection: inlet air humidification, water/fuel emulsions, and direct water injection showing potential reductions in NOx of 25…50 %, and corresponding increases in fuel consumption of 0.5…2 % (Wik 2010). Park et al. (2013) tested a combination of EGR and inlet air humidification reaching IMO Tier III NOx with roughly 2 % increase in fuel consumption.

One of the biggest challenges with both EGR and Wetpac technologies is that NOx reduction is lower at low loads, i.e. an increased EGR rate or water volume is needed at low loads to reach the cycle average. Another challenge is the increased need for engine flexibility, since NOx reduction is different at different loads and because fuel consumption should always be minimized in the most important operating areas. Changes in inlet valve timing (VIC) and fuel injection parameters (Common Rail or corresponding system) are needed for this, and could be used to optimize the different load points so that the 50 and 75 % load points are on the cycle limit value to get the best fuel consumption, whilst the 25 % load point NOx is on the maximum accepted, i.e. 1.5*cycle average, and the 100 % load point where SFOC is not important, should have NOx as low as necessary to reach the cycle value.

Selective catalytic reduction (SCR) is one of the most effective ways to reduce NOx emissions and all OEMs have reported activities with this technology since it is the most straight forward way to reach IMO Tier III NOx compliance (see for example Briggs & McCarney 2013; Hanamoto et al. 2013; Hiraoka & Imanaka 2013; Izumi et al. 2013; Murayama et al. 2013; Soikkeli et al. 2013; Steffe et al. 2013). Injected urea in the exhaust pipe vaporizes and decomposes to form ammonia (NH3), which reacts on the catalytic substrate thereby reducing the NOx to N2 by as much as 95 %. However, due to cost and layout constraints, it is typically in the region of 80…85 %. The total hydrocarbon (THC) and particulate matter emissions are also positively affected. The biggest challenge seen with SCR operation is that exhaust gas temperatures of at least 330…350 °C are needed with residual fuels having high sulphur content in order to avoid clogging by the formation of ammonium sulphate. Alternatively, if the exhaust gas temperature is too high, oxidizing of the SO2 to SO3 starts to happen in the SCR reactor, forming a so-called “blue haze”, which is visible as a blue exhaust gas plume. As a result, some means of control, such as a waste gate or by-pass arrangement, is needed with an SCR unit to keep the exhaust gas temperatures within a certain range. All engine concepts developed for SCR applications would allow the best possible specific fuel consumption, and in the case of utilising 2-stage TC systems, would give fuel consumption savings of 4…8 % over the entire engine operating range.

Dual fuel (DF) engines able to run on both natural gas and heavy fuel oil (HFO) represent one of the best options for the flexible handling of different emission limits and is also under development by most of the engine OEMs. When operating as a lean burn gas engine, the NOx emissions are about 85 % lower than in HFO operation. Furthermore, sulphur oxide emissions are practically zero, since natural gas does not normally contain any sulphur, while the CO2 emissions are about 30 % lower due to the low carbon/hydrogen content of methane. As such, a DF engine would be IMO Tier II compliant in HFO mode and Tier III compliant in gas mode.

The removal of sulphur oxide emissions can be achieved using either dry or wet methods. Typical absorbents for a wet sulphur removal process are limestone, caustic soda, seawater, ammonium hydroxide, or magnesium hydroxide, of which caustic soda and seawater are the most feasible options for ship installations. Closed loop systems can also be operated with zero discharge in enclosed areas. The other solutions offered are either seawater scrubbers, needing no additional absorbent, or a hybrid scrubber able to operate in both modes.

A common problem with after treatment equipment is that the back pressure increases as more systems are installed in the exhaust pipe (SCR and scrubber) and this leads to higher fuel consumption. A low temperature after the scrubber might also lead to a coloured plume if not properly designed. Combination of SCR and scrubber units have been tested and reported with good results in both SOx as well as NOx emission reduction (Juergens 2013).

Most of the technologies used for reducing NOx levels are not on their own sufficient to achieve the IMO Tier III emission level. The Nitrogen Oxide Reducer (SCR) and the gas engine technology are today the only possible means to immediately reach the future NOx emission target. An overall summary regarding influence on different emissions with some technologies is seen in Table 1.

Potentially, a combination of different technologies can be utilized to reach the limit. It is crucial to test the compatibility of the different technologies, to evaluate the technical risks involved, and to understand the implications on the overall cost of ownership.

As an example, some candidate Tier III solutions for a 4-stroke medium speed engine have been analysed from a lifecycle cost point of view, covering a 25 years operation time and assuming two very simplified operating profiles. Assumptions taken as well as other input could be found from Wik (2010) but the following is assumed as prices:

- Heavy Fuel Oil (HFO) price: 375 €/t
- Low Sulphur Fuel (MGO) price: 1.6 * HFO (€/ton)
- Natural Gas (LNG): 1.1 * HFO (€/ton)
- Urea price (100 %): 600 €/t.

According to the calculation results shown in Fig. 2, the most promising solutions are to utilise a Dual Fuel (DF) engine running on natural gas in the ECA, or to use a combination of 2-stage turbo charging and SCR, although none of the selected solutions give equal or better operating costs than the baseline (running on HFO) in regional trade (20 % of the time in non ECA (75 % load) and 80 % within ECA (25 % load)).

Table 1 Summary of emission reduction technology options based on Wik (2010); Wik et al. (2012); Portin (2010)

	NOx	SOx	CO2	PM
SCR	−90 %	±0	±0	±0
Scrubber	±0	−97 %	±0	−40…65 %
LNG	−85 %	−99 %	−20 %	−95 %
2-s TC + EGR	−80 %	±0	±0	±0

The superiority of the DF engine is explained with its high efficiency and relatively low cost of LNG vs. MGO being assumed. The LNG price is much dependent on the area of operation, and is very beneficial within the US where low gas prices are prevailing, whilst in places with bad LNG availability infrastructure, 2-stage turbo charging and SCR would be the best solution.

In worldwide trade (80 % of the time in non ECA (75 % load), 20 % ECA (25 % load)), the clear winner is a combination of 2-stage turbo-charging and SCR, due to the high engine efficiency in Tier II mode. The gain in fuel consumption due to the higher efficiency partly compensates the increased cost of using Low Sulphur Fuel (LSF) in the ECA. Increased lifecycle cost from using LSF instead of HFO in the ECA is shown in Fig. 3 as “Baseline (LSF in ECA)”.

This study thus suggests that the exhaust scrubber technology, also enabling operation with residual fuel in the ECA, would have a relevant impact on the ship’s operating costs.

Other parameters, except OPEX and CAPEX, that are taken into account by engine OEM’s in the process of evaluating different technologies include:

- Reliability of the technology
- Serviceability of the technology
- Flexibility of the technology
- Compatibility with other technologies
- Compatibility with different fuels.

In the final end, the choice of the technologies to be used is a compromise between many issues but the OPEX and CAPEX analysis as seen via case studies in different applications give the basis for which ones are attractive to pursue further.

Any decision made could also change as the assumptions made change over time, like for Brittany Ferries that decided to go fully for LNG as their option, but needed to revise the same and move over to installation of scrubbers on all ships, when their hope

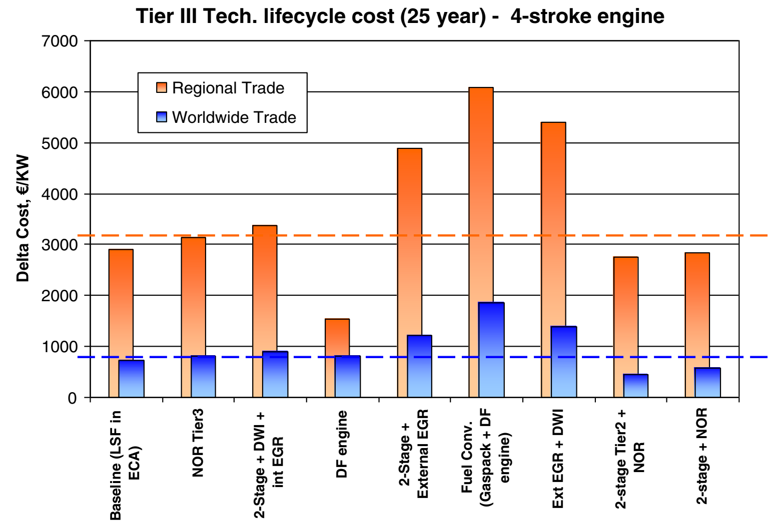

Fig. 3 Tier III solution lifecycle cost calculation example from Wik (2010)

for dispensation to allow them to continue using low-sulphur residual fuels until the new ships have arrived was not approved (Motorship 2015).

Case examples for Tier III compliant ships

A study has been carried out with examples of different ship types and with different IMO Tier III technologies applied, to show the differences in installation, as well as the eventual implications on the operating routes and profiles. The chosen cases were also partly presented by Wik (2013) and include a Panamax tanker, cruise ship, platform supply vessel (PSV), and a Ro-Ro/Pax vessel.

Case 1: panamax tanker

The first case presented is a Panamax tanker with a deadweight of 60 000 DWT and a cargo capacity of 85 000 m3. According to statistics, based on a survey of approximately 50,000 vessels over a period of 45 days, tankers of this size operating in the NAFTA region spend roughly 17 % of the time in ECAs and since the US ECA extends 200 nautical miles from the coasts of the United States and Canada territories, some part of the operation will be at full speed.

Only half of the port time will be in an ECA since the other port will be in a country from where oil is imported to the region, all being located outside of the North American ECA. The U.S. oil import statistics by Terzic (2012) indicate that the top 5 countries, accounting for 70 % of the imports, are as follows (in correct order): Canada, Saudi Arabia, Mexico, Venezuela, Nigeria. Based on the studies regarding typical operating profiles and annual cost structures for Panamax tankers, it is clear that a solution for the ECAs should focus on achieving the best fuel efficiency. Thus, assuming price differences vs. HFO of 1.6 and 1.1 times price per ton for MGO and LNG respectively, avoidance of these fuels would be preferable as according to Wik (2013).

The best Tier III technology option for a tanker would then be to use SCR and scrubber solutions, which would increase the annual capital cost of the engine by roughly 50 % increasing its share to 1,9 % of the total annual costs. The increase in operating costs will be in the magnitude of 0.6 % due to the additional urea, caustic soda, and fresh water consumption. An additional fuel consumption increase of about 0.5 % should be accounted for due to the increased back pressures with the SCR and scrubber units. This would result in a voyage cost distribution as illustrated in Fig. 4, and still the main influence derives from the fuel cost due to the relatively short operating time in ECAs.

The total 1.7 % increase in annual costs (CAPEX + OPEX) would be already compensated for by a 2 % drop in bunker costs, or alternatively with a 2 % improvement in fuel consumption through other means, such as improving the propulsion system.

Operational and route changes for tankers are expected primarily if ECA compliance is to be attained using MGO/LSF. Lower ship speeds are then most probably opted for within the ECA, and the overall route timetable recovered with higher speeds outside the ECA where fuel costs are lower. Special situations can arise with any additional reducing agent needs, like urea and caustic soda, which might not be available in all harbours and thus might affect route choices.

A special case is also expected for ships operating between the US and Canada that might find it more advantageous from an operating cost point of view to go outside the US 200 nautical miles ECA zone before heading towards next harbour, despite the

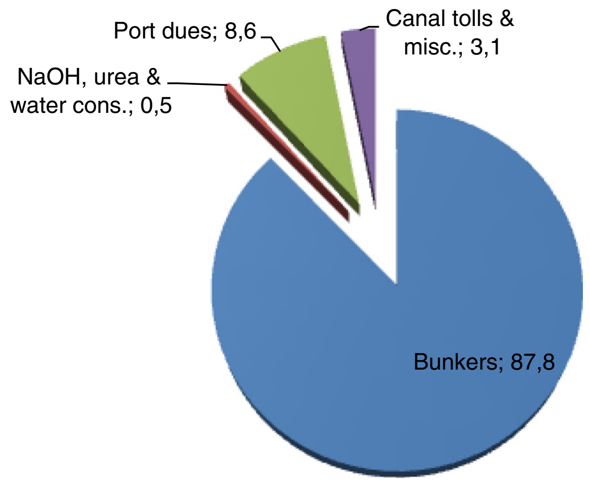

Fig. 4 Tanker voyage cost with SCR + scrubber

longer overall distance involved. This will most probably be the case for ships choosing LSF for ECA compliance.

Case 2: cruise ship

The second case is a 100 000 GT cruise ship, 300 m in length and with a passenger capacity of 3200 persons. The fully electric propulsion power need of 34 MW, and the hotel load need of 10 MW, is met using a 4-engine installation having a maximum output of 48 MW. Estimating the total time spent inside and outside ECAs to be 5 months and 7 months respectively, gives an annual operating profile as shown in Fig. 5.

For the study, the reference case assumes 2*12V46F + 2*8L46F engines, running on MGO all the time in ECAs and on 4.5 % S HFO outside ECAs. Fuel and other consumable prices are assumed to be as in earlier studies in this paper, while the NaOH price is assumed to be 235 €/m3.

The different alternatives studied are:

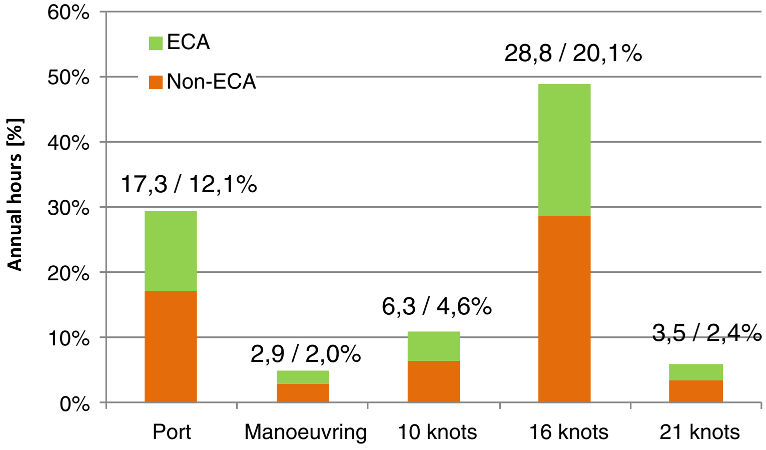

Fig. 5 Annual operating profile for a cruise ship

- The same engines running on HFO all the time except in the harbour where it runs on MGO. SCR is in operation all the time in the ECA, while the scrubber reduces the emitted SOx from the 4.5 % S HFO down to 3.5 % outside the ECA, and to 0.1 % inside the ECA
- The engines are replaced with 4*12V50DF running on LNG all the time
- In the case where a 2-stage TC system is installed for additional fuel savings, the power output of the engine can be raised and 4 cylinders less are needed, thus the engines are 2*12V46F + 2*6L46F.

Except for the additional cost of urea, caustic soda, and fresh water, the SCR element replacement is also taken into consideration. Based on the test results, with the assumed operating profile as in Fig. 5, and the loads of each engine as in Table 2, a reduction in fuel consumption of 5.7 % is estimated for the 2-stage TC case.

Added machinery costs as a percentage of the reference engine price, as well as annual savings in operational costs vs. the reference engine (running on MDO in ECA), are shown in Fig. 6.

It is seen that the scrubber and SCR option is more expensive than replacing the original engines with DF engines. This is despite the fact that for the DF engines large gas tanks need to be installed covering about four times the volume of those needed for MDO due to the lower density of LNG, as well as heavier tanks being needed because of the high LNG pressure (about 10 bar), and the extra tank room needed for safety (see Fig. 7).

The extra installation space needed has some influence on the available cargo or passenger capacity affecting the incoming cash-flow and OPEX of the ship. Regarding the required capacity of the LNG tank, it is dimensioned according to the amount needed for 7 days operation with an assumed fill ratio of 95 %, as well as a margin of 20 % for unexpected issues. Back-up, and eventualities of an extended range, are covered with the bunkered MDO.

The increased costs with 2-stage TC engines, due to the double amount of TC’s and coolers and the heavier design of the SCR system needed because of the higher pressure levels, are partly compensated for by the 10 % higher output from the engines, making it possible to remove four cylinders in total. In the study, an overall cost increase for the engine and SCR systems having a 2-stage TC setup is estimated at almost 3 %.

Annual savings are also the largest with the DF engines, mainly due to the fairly large difference in the price between LNG and MGO. Payback times vs. running on MGO for the different solutions will be within 0.8…1.4 years and the internal rate of return over a ten year period will be between 11 and 25 %, as shown in Fig. 8.

Overall, the difference in fuel prices - as well as spreads between the prices - is very important to the results. For instance, reducing all fuel prices by 20 % will increase the

Table 2 Engine load distribution assumed

	Port	Man	10 kn	16 kn	21 kn
W12V46F	72 %	83 %	-	83 %	86 %
W12V46F	-	83 %	-	83 %	86 %
W8L46F	-	-	72 %	-	86 %
W8L46F	-	-	72 %	-	86 %

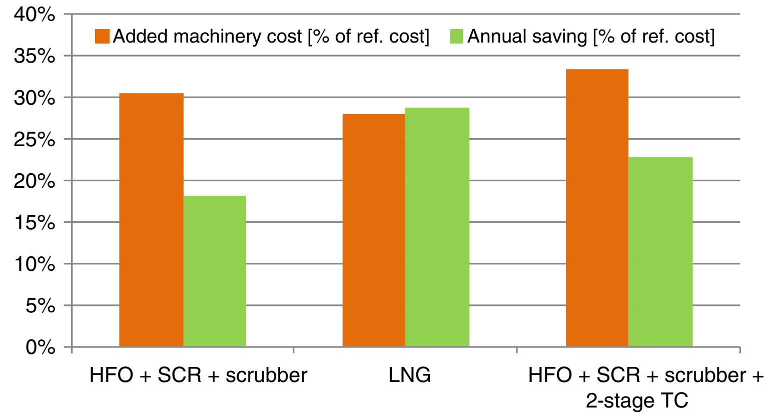

Fig. 6 Added machinery costs and annual saving vs. reference case for studied alternatives

payback times by 23…28 %. Increasing only the LNG price to a ratio of 1.29*HFO, instead of the assumed 1.1*HFO price, will also increase the LNG case payback time to the same level as for the HFO + SCR + scrubber case and especially eventual drops in the price of MGO vs. HFO will have large implications as seen in Table 3.

The operational parameters for cruise ships are expected to be influenced mainly by optimisation towards lower ship speeds inside an ECA when MGO/LSF is used for compliance. Special situations can also arise with any additional reducing agent needs, such as urea and caustic soda, or the need for LNG, which might not be available in all harbours and might affect route choices.

Case 3: PSV application

According to Wärtsilä Höglund (2014), platform supply vessels are chartered either on long term or short term basis where long term basis are so called charter contracts that normally lasts several years and are based on a fixed day-rate, whilst short term contracts are so called spot market contracts, which are defined for specific tasks lasting days or weeks and to a higher rate than long term contracts. Wärtsilä Höglund (2014) states that having short term contracts thus means a potential of higher earnings but

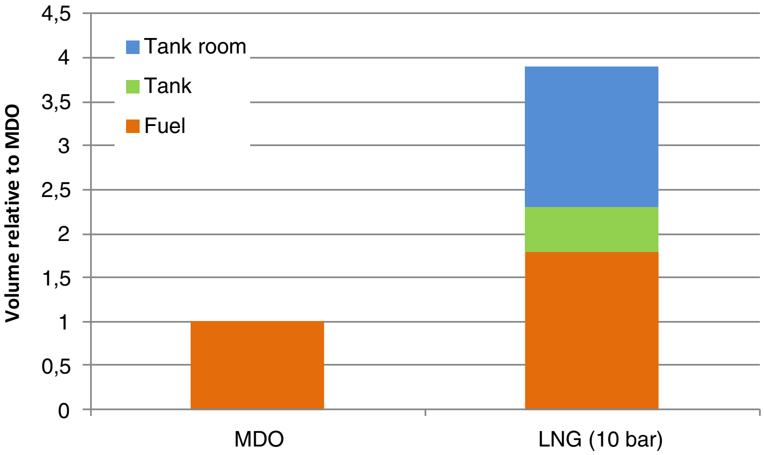

Fig. 7 Relative storage volume MDO vs. LNG

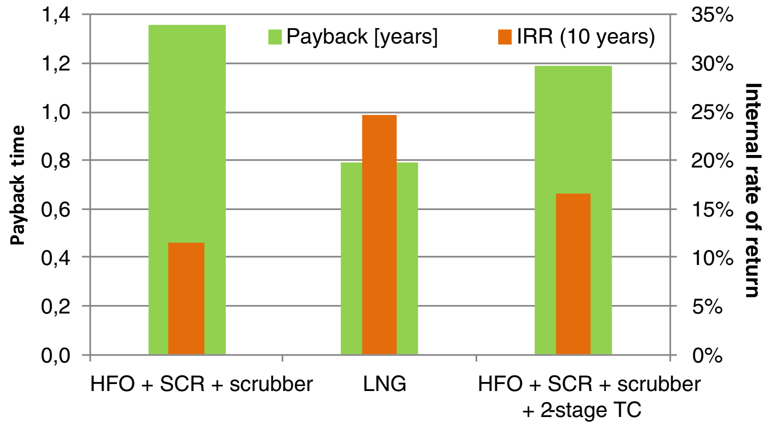

Fig. 8 Payback times and IRR for the cruise ship cases

increase the risk of having the vessel on idle but in order to secure financing for vessels, though, long term contracts are normally required.

Typical tasks of PSVs include carrying of supplies to offshore platforms, transporting liquids in tanks as well as other large equipment on deck, perform rescue operations, or doing firefighting and thus the selection criteria include following according to Wärtsilä Höglund (2014):

- Supply tank capacity
- Deck size
- Dynamic Positioning class
- Vessel speed
- Emissions requirements
- Crew competence
- Multi-purpose possibilities: Rescue/FiFi.

A small case analysis was performed for a 4 500 DWT PSV operating in an ECA and thus needed to be IMO Tier 3 compliant. A total annual running hour of 8 760 is assumed and the operating profile is seen in Fig. 9.

A total installed engine power of 6 660 kW is needed and the fuel alternatives HFO or ULSFO together with an SCR and a scrubber or LNG usage on a DF engine in the ECA evaluated.

Assuming that the harbour operation as well as transit at 10 kn and half of the transit on 12 kn, i.e. 35 % of the time, is happening inside an ECA, the operating costs can be estimated for the different alternatives. This assumption is made on the basis that a lot

Table 3 Fuel price sensitivity analysis

Change in payback time			
Case	HFO + SCR + scrubber	LNG	HFO + SCR + scrubber + 2-stage TC
All fuel prices -20 %	28 %	23 %	27 %
LNG 1.3*HFO	0 %	73 %	0 %
LNG 0,9*HFO	0 %	−31 %	0 %
MGO 1.4*HFO	70 %	35 %	49 %

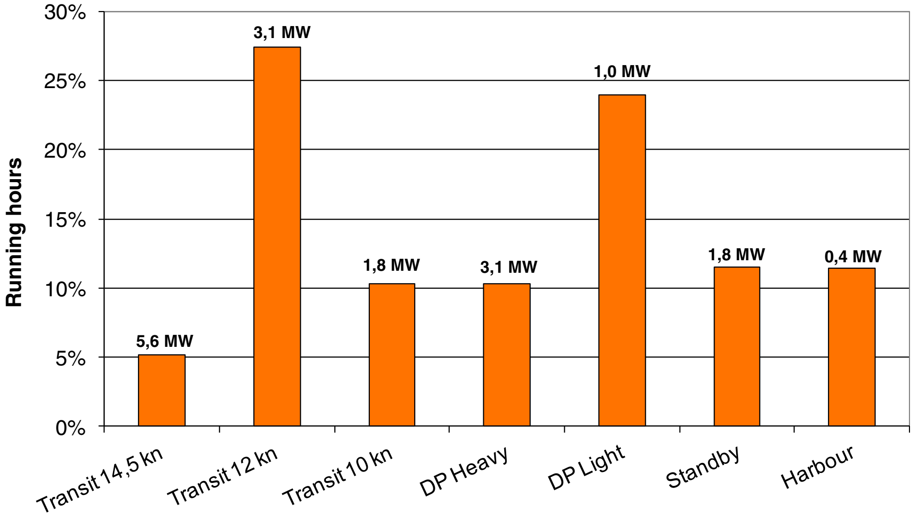

Fig. 9 Assumed operating profile of a PSV according to Wärtsilä Höglund (2014)

of areas where offshore oil exploration is happening are outside of an ECA but the closest harbour is inside.

Since the engines used are rather small, the gas system on the ship will become fairly expensive and the CAPEX comparison is seen in Fig. 10 with very small differences between the DF engine + LNG equipment vs. diesel engine with SCR and scrubber but with the gas engine alternative showing slightly higher costs. The MDO engine SCR CAPEX is slightly lower since it could be dimensioned smaller with less amount of elements due to a lower NOx reduction need and clogging risk vs. operation with HFO. The engine generating set would be of the same cost but the auxiliary equipment needed, like fuel boosters, could also be reduced and is here estimated to influence the overall generating set price with some percent-units.

Payback of the difference between gas engines and diesel engines equipped with SCR and scrubber is achieved within only 6 months due to the difference in OPEX when running on gas in the ECA instead of consuming urea and caustic soda. This is achieved when assuming HFO as a fuel and that the fuel consumption increases with

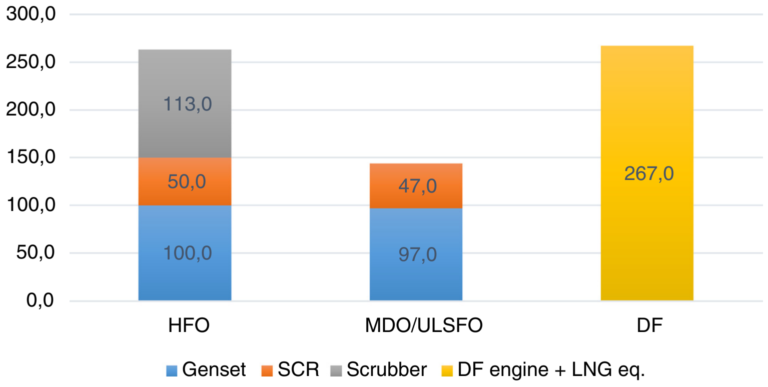

Fig. 10 CAPEX for the evaluated engine alternatives on a PSV. Relative differences: 100 = HFO engine generating set (Genset)

0.5 % due to the higher back pressure with the SCR and scrubber in operation. Assuming that low-sulphur MDO (ULSFO) is used instead, the payback would be about 3 years due to the avoidance of a scrubber investment for the diesel engine. Thus, the Dual-Fuel engine running on gas would be the best alternative, despite the higher CAPEX needed, mainly due to the LNG price relationship assumed. The OPEX comparisons in Fig. 11 show this fact clearly and with only a small reduction in LNG price vs. HFO from the current assumed one of 1.1, a DF engine operating on gas all the time would be the preferable option.

Wärtsilä Höglund (2014) states that PSVs have traditionally been running on MDO fuels since the whole infrastructure is built up around that fuel. He continues that out of PSVs built 2012 and after, only 5 % utilise LNG as fuel, whilst 95 % are still built with MDO as fuel and not one single has been built with HFO as fuel after 2005. Due to this fact, the comparison against HFO operated PSVs is mainly theoretical and the LNG operated engine would be the preferable choice, but changing over to gas will take time and be a lot dependent on the LNG terminal build-up rate.

Case 4: Ro-Ro/Pax vessel

Looking at the usage of Ro-Ro/Pax vessels world-wide in 2014, it can be seen that 51 % of all vessels operate in ECAs and that 33 % of the operating time is spent in the same zones according to Wärtsilä Zotti (2014) and seen in Fig. 12.

This means that choice of engine emission abatement technologies is very important for this shipping sector with a large requirement for low emissions already now and a probable large increase in the future with more ECAs implemented worldwide. Statistics collected by Wärtsilä Zotti (2014) show that HFO is used as fuel in 80 % of the cases and only 0.5 % of the vessels use LNG as fuel whilst SCR's are installed in only 2 % of the vessels and scrubbers even less (0.3 %). Thus there is a large increase of emission solutions still to be seen for Ro-Ro/Pax vessels.

The ship case chosen is a 5000 DWT Ro-Pax ship operating at 27 kn speed on a route inside an ECA and demanding an engine installed propulsion power of 58 MW and 9 MW of auxiliary power. An operating profile as seen in Fig. 13 is assumed.

Gas system costs would be much easier to absorb on this big engine installation compared to the PSV case, but despite of this the LNG engine is the most expensive case as

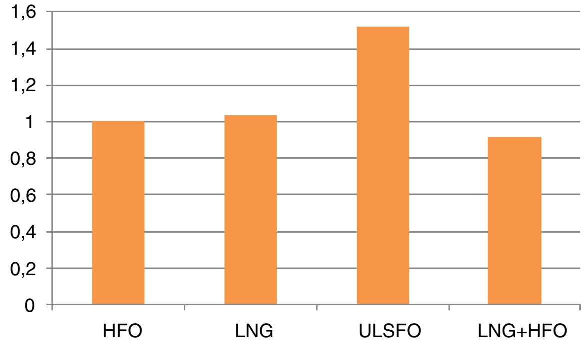

Fig. 11 OPEX differences with different fuels and alternatives (LNG = using LNG all the time whilst LNG + HFO = HFO is used outside ECAs). Relative differences: 1 = costs running on HFO

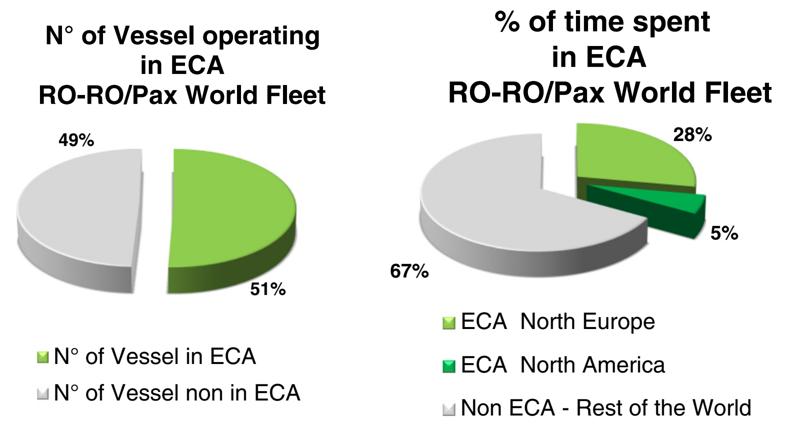

Fig. 12 Ro-Ro/Pax vessels usage in ECAs worldwide according to Wärtsilä Zotti (2014)

seen in Fig. 14. This since the SCR as well as scrubber costs/MW decrease radically as well with larger engine installations.

With the assumed fuel and chemicals prices as shown before, running on LNG would anyhow show the lowest operating costs as seen in Fig. 15 and thus the higher investment vs. the HFO case would be paid back within about 4.3 years' time. The payback time would reduce to 2.7 years only with an assumed price difference LNG/HFO of 1.05 instead of the original 1.1. Comparing to operation on ULSFO, the payback time would be around 1 year only with an investment in an LNG system. Thus, the best solution for the assumed Ro-Pax vessel case would be to invest in an LNG operated ship.

These final case conclusions are also confirmed in another case study by Bui (2011) made for medium-sized RoRo's sailing between Trieste and Istanbul where the assumption was that north Mediterranean Sea would be an ECA which means that of the total distance, 29 % will be covered within an ECA.

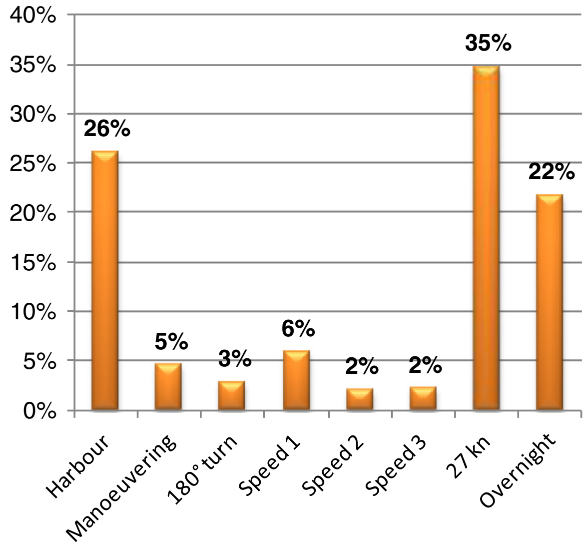

Fig. 13 Ro-Pax vessel operating profile according to Wärtsilä Zotti (2014)

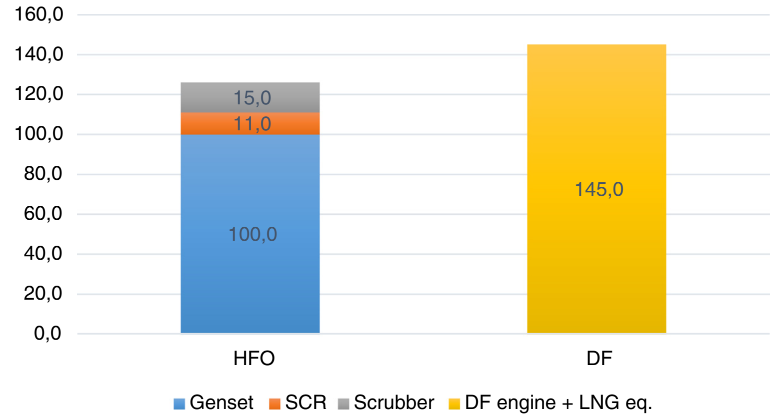

Fig. 14 CAPEX for the evaluated engine alternatives on a Ro-Pax vessel. Relative differences: 100 = diesel engine generating set (Genset)

The conclusions by Bui (2011) were that when spending relatively little time in emission control areas (10…30 % of the time), running on HFO, utilising a scrubber and a SCR unit is the best option, as long as the LNG/HFO price ratio is above ~1.05. With lower gas prices, running on LNG only all the time is the best solution. Inclusion of a 2-stage TC system would have shifted the benefits of an HFO solution towards even lower LNG/HFO price ratios.

The study clearly points towards LNG being a very attractive option from cost point of view as long as the price of LNG is maximum +10 % vs. HFO. Another benefit comes from the environmental side with reduced NOx, SOx, and CO2 emissions. Here another economical advantage could be found if and when carbon taxes start to apply to the shipping industry.

Conclusions

Many different technologies are either available or under development for complying with the future ECA requirements. Parameters taken into account by engine OEM's in the process of evaluating different technologies include analysis of OPEX and CAPEX but also reliability, serviceability, and flexibility of the technologies as well as compatibility with other technologies and with different fuels. In the final end, the choice of the technologies to be used is a compromise between all these issues but the OPEX

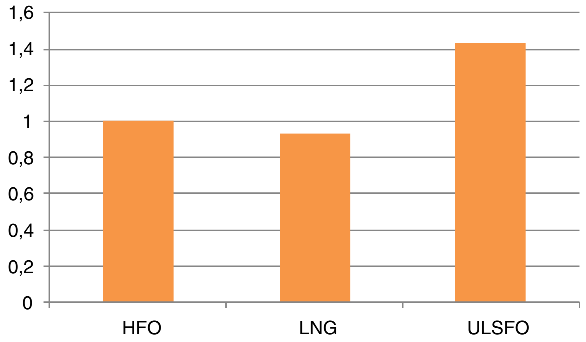

Fig. 15 OPEX differences with different fuels and alternatives. Relative differences: 1 = costs running on HFO

Table 4 LNG price need vs. HFO with same total costs (CAPEX + OPEX) over 10 years operation

Case	100000 GT cruise ship	4500 DWT PSV	5000 DWT Ro-Pax	5000 DWT Ro-Pax
Time in ECA	41 %	35 %	30 %	100 %
Engine power [MW]	48	6,66	58	58
Scrubber cost vs. gensets	35 %	113 %	15 %	15 %
Gas engine + eq. vs. diesel engine	145 %	267 %	145 %	145 %
LNG vs. HFO [€/ton]	129 %	117,5 %	105 %	114,5 %

and CAPEX analysis as seen via case studies in different applications give the basis for which ones are attractive to pursue further.

From case studies on a different ships, it was concluded that an SCR + scrubber is the correct solution for a tanker operating rarely inside ECAs (17 % of total time) where fuel costs are clearly the highest annual cost because of the relatively low cost of ships and crew, etc. The total increase in annual cost of 1.7 % (CAPEX + OPEX) with this option is already compensated for by a 2 % drop in bunker fuel costs. For a cruise ship, operating about 40 % of the time in an ECA, the best lifecycle costs are given when changing to Dual Fuel engines operating on LNG. This would have a payback time of 0.8 years with the assumed fuel and installation prices. The drawbacks would be the larger fuel tanks needed, and thus less passenger capacity, as well as the dependency on having LNG bunkering station availability around the world. But as more capacity is built, the trend is clearly moving towards LNG as a valid option for cruise ships and other ships operating fairly much in ECAs. Furthermore, a DF engine is fully capable of running on any liquid fuel in case no LNG is available.

The PSV is assumed to operate for about 35 % of the time in an ECA, and being rather small in size, the engine installations for lower emissions as SCR and scrubber equipment get rather expensive. The same goes for the gas equipment needed for a DF engine. Anyhow, the gas engine alternative seems to be the strongest one also here at least when comparing against operating on MDO which is the clearly most common fuel within the offshore sector. Finally, the Ro-Ro/Pax vessel studies point towards LNG being a very attractive option as well and the higher investment needed vs. the HFO + SCR + scrubber solution is paid back within only a couple of years' time.

The ship's operation and route choice is expected to be influenced mainly if ECA compliance is attained using MGO/LSF, which is anyway seen as being one of the least cost-efficient ways forward. Moreover the development of infrastructures for reducing agents (urea and caustic soda) and LNG bunkering is needed not to influence the optimised ship routes established.

One factor influencing the choice of technology is also the implication on storage space in the ship and thus how much footprint all the extra needed technologies take. Often the cargo space size is what defines the rate a shipping company can charge for its services and thus it will have large implications on the choice of technology. Importance of this is one of the topics planned to be investigated with the customer interviews and questionnaires. New technologies as prismatic LNG tanks also enable placement of the same in spaces already not utilizable as cargo space due to its strange shape (Mohn 2014).

As concluded from all case analysis, price differences between fuels as well as investment costs for the different technologies play the largest roles in choice of technology and thus a sensitivity analysis is needed to find the triggering points. A summary is shown in Table 4 regarding the different applications and comparing the HFO + SCR + scrubber case with the DF engine case running on LNG in ECA and HFO outside. General conclusions to draw are the following:

- Less time of operation in an ECA ➔ lower LNG prices needed
- Scrubber & gas system investment size plays a crucial role; the higher vs. engine price, the lower LNG prices are needed
- Less engine power ➔ larger relative CAPEX need for scrubber, (SCR), and gas systems.

Also the economic analysis method plays a role in order to find the correct technology and especially to get the correct timing for the investment. Implementation of real option analysis or a multi-criteria approach based on an analytic network process (ANP) would help out here in order to select the most optimum technical alternative as shown by Acciaro (2014) and Schinas & Stefanakos (2014) and this would also be a logical continuation of the research work.

Overall, the studies show that the best option always depends on many different issues, but LNG is a very strong candidate for taking the biggest market share in short-haul shipping when emission legislations are enforced to a larger extent.

Abbreviations

BDC, Bottom dead centre; CAPEX, capital expenditures; DF, dual fuel; DP, dynamic positioning; DWI, direct water injection; DWT, dead weight ton; ECA, emission control area; EGR, exhaust gas recirculation; FiFi, fire fighting; GT, gross tonnage; GWP, global warming potential; HFO, heavy fuel oil; HP, high pressure; IMO, International Maritime Organization; IRR, internal rate of return; ITSCR, inter-turbine SCR; LNG, liquefied natural gas; LP, low pressure; LSF, low sulphur fuel; MDO, marine diesel oil; MGO, marine gas oil; MW, mega watts; NAFTA, North American Free Trade Agreement; NECA, NOx emission control area; NOR, nitrogen oxide reducer (Wärtsilä's SCR system offering); NPV, net present value; OEM, original equipment manufacturer; OPEX, operating expenditures; PSV, platform supply vessel; Ro-Pax, Roll-on/Roll-off & Passenger; Ro-Ro, Roll-on/Roll-off; SCR, selective catalytic reduction; SECA, SOx emission control area; SFOC, specific fuel oil consumption; TC, turbo charging/turbo charger; THC, total hydrocarbons; ULSF, ultra low sulphur fuel; VIC, variable Inlet valve closure

Competing interests

The main author, Christer Wik, works at the company Wärtsilä Finland Oy from where a large part of the information for the research has been obtained. Financing for the research work has been obtained from the natural gas fund of Gasum Oy via Tekniikan edistämissäätiö. Both of these have shown no competing interest or influenced the research results by any means and thus there exist neither financial nor non-financial competing interests regarding this research.

Authors' contributions

The main author, CW, has been responsible for collecting all research data as well as for the analysis of data and writing of the manuscript. The second author, professor SN, has been revising the manuscript and given valuable input to its construction and setup. All authors read and approved the final manuscript.

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