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LNG-Fuelled Hybrid Tug Concept

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SYNOPSIS

LNG fuel is a more environmentally sound fuel than diesel-based fuel. Wärtsilä is developing concepts of LNG-powered vessels to fulfil requirements for owners and operators to employ vessels with less environmental impact than conventional vessels. The inherent characteristics of the low emissions offered by LNG vessels will be welcomed, if not required, by harbours and ports within close proximity to densely inhabited areas. LNG-fuelled workboats are a logical step for LNG terminals with a freely accessible fuel, and harbours requiring lower emissions.

Wärtsilä's high activity in the LNG tanker and supply vessels market is resulting in the development of an understanding of LNG vessel propulsion which is second to none, and places the company in the best position to be at the forefront of LNG-fuelled applications for all relevant vessels.

LNG-fuelled engines for work boats present some new challenges for both the naval architect and the engine designer. Operational profiles of workboats with respect to changes on load demands are presently the most significant, but achievable, challenge to LNG engines. Terminal and harbour tugs should be described as vessels with dual roles. Most of the time, they operate to a known schedule. On occasion they are called upon for emergency towing, fire-fighting or other operation of longer or unexpected duration. Compact general arrangements combined with demanding LNG tank volume result in a concept that will most efficiently utilise LNG, a clean-burning, cheap fuel for normal duties, whilst maintaining a capacity for operation on fuel with higher energy density such as MDO for emergency operations of long duration. Dual fuel capacity is the best answer to such a vessel design brief.

The initial concept to be presented is for LNG terminal operation. The choice of LNG operation is viable due to ready access to the fuel. Operations at terminals have grown to require tugs with large bollard pull capability. Tugs capable of 100 tonne bollard pull in the LNG terminal operations are now being employed.

INTRODUCTION

Wärtsilä has developed an LNG fuelled hybrid tug to meet the demand for more environmentally sound tug operations. The tug features novel machinery based on electrically-driven thrusters powered by a hybrid power plant consisting of batteries and dual fuel engines running primarily on LNG.

INCREASING ENVIRONMENTAL CONCERN

Ship propulsion development is today mainly driven by two challenges: to reduce the environmental impact from shipping and to keep fuel costs reasonable in world of sky-rocketing oil prices. These two targets sometimes go hand in hand when striving to make ships more efficient.

Society is becoming ever more aware of climate change, resulting in pressure on the maritime industry to contribute to reduce emissions. There are both new international regulations and local requirements setting stricter exhaust emission standards. The IMO is in the process of tightening the limits on NOx and SOx emissions from ships. In addition there are national and even more local regulations stipulating stricter limits on exhaust gases. However, most of these rules target NOx and SOx emissions, while society is becoming more focused on greenhouse emissions. This means that we can soon expect more attention on CO_2 emissions from ships. In addition, there is also an increasing awareness of particle emissions owing to health concerns. This has lead to a special focus on emissions from coastal shipping and port operations. Ports are often located close to densely populated areas, so emissions from ships in the port are under increasing scrutiny.

Harbour and terminal tugs operate mainly close to these urban centres and will therefore need to clean up their act. In response to this, Wärtsilä has set upon the task to develop an environmentally sound tug concept based on LNG operation. The design is of a terminal tug, but the same machinery principle can be tailored to suit many different types of tugs. Wärtsilä has already in recent years introduced many novel machinery concepts for various types of vessels using liquefied natural gas (LNG) as the primary fuel. The knowledge and experience gathered from these concepts has been used when designing the LNG tug.

Figure 1: LNG fuelled terminal tug concept.

LNG AS A MARINE FUEL

Switching from diesel to natural gas will significantly reduce all important exhaust gas emissions from a ship, including a 25 per cent reduction in CO_2 emissions. The main reason for this reduction is that the main component of natural gas (NG) is methane, which in turn is the most efficient hydrocarbon when measuring energy content against carbon content. The molecular structure of natural gas has the highest number of bonds to hydrogen of all the hydrocarbons. Essentially this results in the lowest emissions of carbon during energy release. Natural gas is colourless, odourless, non-toxic, and lighter than air.

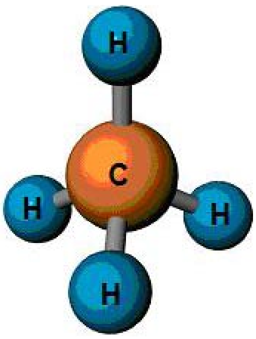


Figure 2: Methane molecule, with four hydrogen atoms for each carbon atom.

In dual fuel engines, the natural gas burns with a low emission of NOx due to the lean burn concept. Sulphur emissions are negligible, as the sulphur is removed from the fuel during the liquefaction process of LNG. Additionally, very low particle emissions, with no visible smoke or sludge deposits, make this fuel an appealing choice for built-up areas such as ports. LNG can also have a highly competitive price, which makes this fuel a very interesting choice. Natural gas consists primarily of methane (CH_4) along with minor concentrations of heavier hydrocarbons like ethane and propane. In normal ambient conditions natural gas is a gas but it can be liquefied by cooling down to -162 degrees C. In liquid form the specific volume is reduced significantly, which allows a reasonable size of storage tanks relative to energy content.

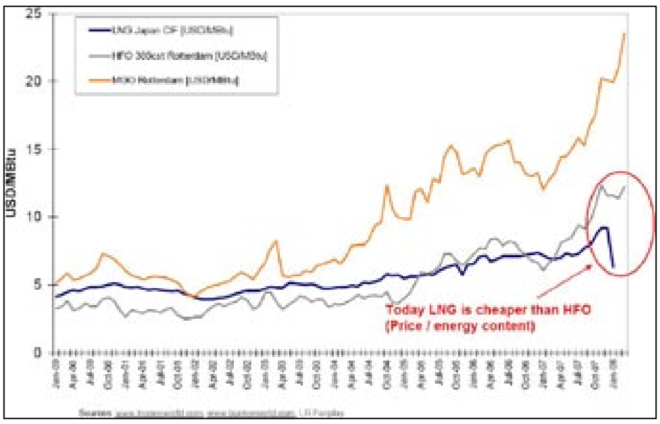


Figure 3: Fuel cost comparison.

STORAGE OF GAS

The most feasible way to store NG in ships is in liquid form. In existing ship installations, LNG is stored in cylindrical, double-walled, insulated stainless steel tanks. The tank pressure is defined by the requirement of the engines burning the gas and is typically less than 5 bar. A higher (typically 10 bar) tank design pressure is selected due to the natural boil-off phenomenon. This means that the heat flow through the tank insulation boils the LNG, which increases the pressure in the tank. In the case of long lay-up periods (greater than two weeks), the gas must be released or burned. In normal use there will be no release of gas.

The main problem with using LNG in ships is the relatively large amount of space required for the LNG tanks. Compared to marine diesel oil (MDO), an equal energy content of LNG requires about 1.9 times more volume than MDO. When adding the tank insulation and bearing in mind the maximum filling ratio of 95 per cent, the required volume is increased to about 2.3 times. The practical space required in the ship becomes about four times higher when also taking into account the squared space around the cylindrical LNG tank.

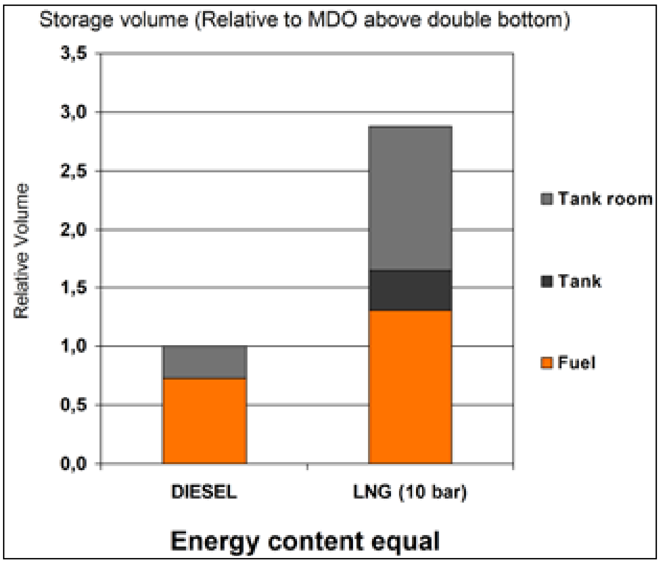


Figure 4: LNG storage volume.

TERMINAL TUG CONCEPT DEVELOPMENT

The focus for this design exercise is on the machinery configuration of the tug. The tug type will be considered as a terminal tug with an Azimuth Stern Drive configuration. The ASD's operational flexibility, thrust efficiency and seakeeping potentials are desirable for this terminal tug application. However, the principle machinery system is suitable for many types of tugs with different propulsion setups.

The machinery system will provide a flexible load profile with rapid response, to a maximum 100 tonnes.

However, the properties of gas and the special nature of gas-burning engines means that the tug design and machinery configuration will differ from conventional tugs.

The tug machinery is of a hybrid type consisting of both batteries and two dual fuel engines. The propulsion is driven by electric motors with variable frequency drives. The battery technology selected is Nickel Metal Hydride. It is a current optimal choice between life and ability to handle the rigorous charging regime. Battery technology is in a rapid state of development, driven by small mobile devices. The technology is expected to see continued focus, performance development, and increase in market use. All this will aid fringe industries using the technology to enjoy a reduction in cost, weight and volume requirement.

The larger fuel storage volume needed for LNG in combination with the hybrid machinery means that the tug will become larger than conventional tugs. However, the designer must try to keep the growth modest, as a larger vessel will increase cost. The volume required for the LNG tank requires extra consideration, compared to a diesel tank. This has been solved in this solution by placing the tank in a near-vertical position, close to the longitudinal centre of buoyancy. Here the gas follows an efficient path from the cold box, gas valve unit, to the engine. This type of engine technology does not require separate enclosures for each engine; therefore the engine room is quite simple for a gas configuration. The dimensions of the LNG tug are shown in the table below.

Principal particulars			
Bollard Pull	[m. tonnes]	100	
Installed power	[kWe]	6080	
Generator 1	[kWe]	2600	Wärtsilä 6L34 DF
Generator 2	[kWe]	3480	Wärtsilä 8L34 DF
Length OA	[m]	35.6	
Length WL	[m]	32	
Beam OA	[m]	13.8	
Draft	[m]	6,8	
*Output of engines considering generator efficiency			

The LNG tank must be located inside the B/5 line according to the classification rules[1]. This limits the number of feasible locations for the LNG tanks, and the tank will end up in the centre of the vessel, thus posing a big challenge for the designer. The LNG tank in the terminal tug is located in forward part of the deckhouse in a vertical manner to save footprint area inside the tug. This is also a better orientation for the LNG tank construction.

BURNING THE BEST FUEL THE BEST WAY

The Wärtsilä Dual Fuel (DF) technology employs a lean burn concept, which results in high efficiency and low emissions. The gas fuel feed pressure is low, enabling benefits from classification in the form of general arrangement flexibility. The engine's ability to burn diesel fuel as well provides benefits in classification in a more compact redundant fuel system. In the case of a tug, this ability represents an advantage to run long duration on the high energy density fuel of MDO. Whilst this is counter to the idea of the low emission concept, the ability to occasionally transfer independently from port to port of great distance, or perform a long duration fire-fighting task or emergency towage, eclipses the need for low emissions. Here the dual fuel capability is unequalled. An example of one such marine installation has been documented[2].

Figure 6: Wärtsilä 34DF generating set.

ENERGY TRANSFER

Matching the engine's load characteristics to the propulsive load characteristics whilst maintaining high efficiency is a challenge, considering the variability in load demand of a tug, and the characteristic of reciprocating engines being most efficient at constant load. The operational profile which the vessel is expected to perform is one side of the equation to understand.

OPERATIONAL PROFILE

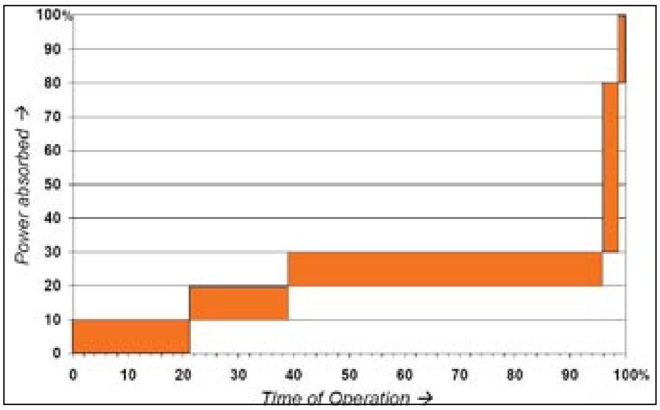


Figure 7: Generic tug operational engine loading.

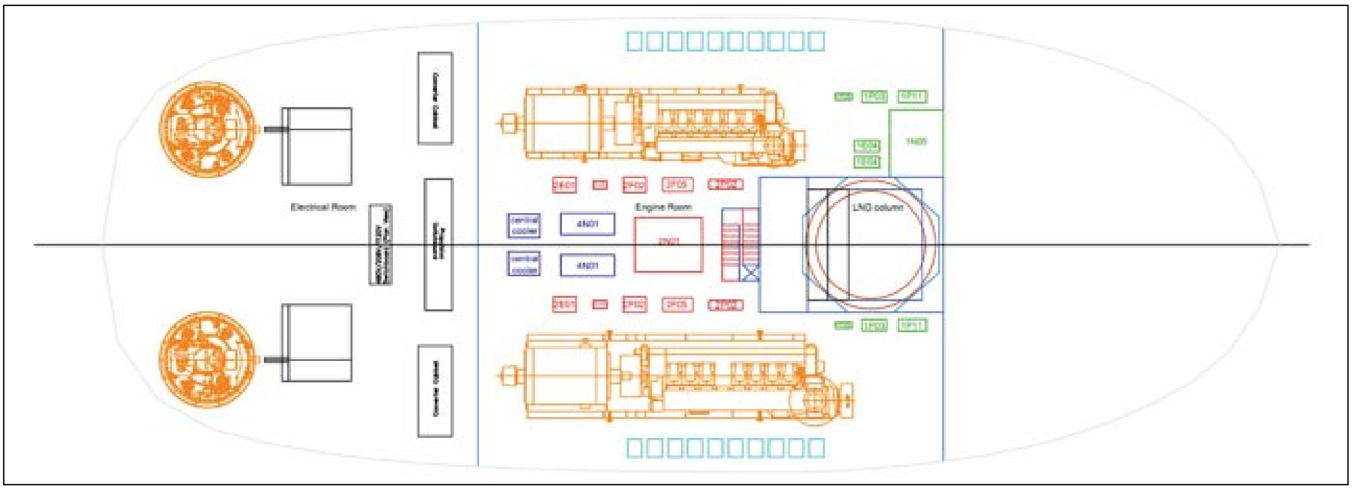


Figure 5: Machinery space arrangement.

The operational profile of a tug is very challenging. It spends a lot of time at very low load with short peaks of high power. A typical profile is shown in *Figure 7* (previous page).

The power breakdown, the time spent, and powers absorbed by this operational profile, are of a conventional system, with mechanically driven FP or CP propellers. What is reported as power used, may not be power required.

The graph does not reveal the reality of the tug's operational profile. The load time history of such a vessel comprises long periods of low, stable load requirements with clusters of high magnitude peaks and troughs in load requirement. Conventional direct drive engines have been required to respond quickly to these load jumps, and so low inertia systems have been favoured to achieve this.

The foibles of diesel engine application in tug boats have been accepted in the past by accepting larger engine installations de-rated to lower total BMEP to deliver a healthier power curve for part loading and load response. As a result, the tug market has not enjoyed the full benefits of operating a high pressure charge system at constant load.

THE HYBRID SOLUTION

The operational profile of a tugboat lends itself well to a hybrid concept. Long periods of low load demand, and short peaks of high power, are consistent with operational profiles of other engineering projects where the hybrid solution has proved itself. Further emission gains can be realised with the use of gas engines.

This hybrid solution is particularly appropriate for gas engines, as the electric power can assist in their inherently slower load changing. It is anticipated that the time to start up engines will be covered by electrical power in the scenario when high power is required immediately.

PARALLEL OR SERIES HYBRID

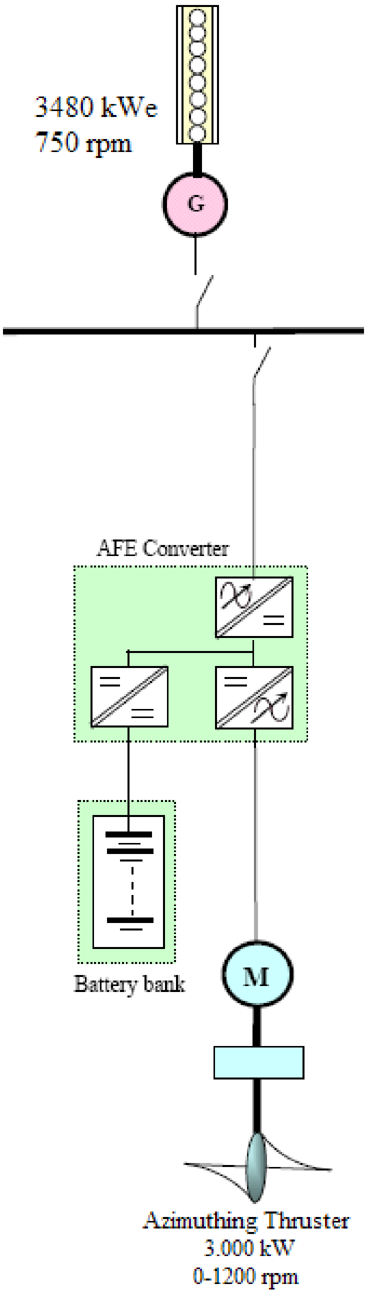
This concept is classified as a series hybrid, as the propulsion is purely electric. A generator and a battery bank supply electric power to one electric motor per thruster. This allows for the best propulsive response: it is almost immediate. In a parallel hybrid, the electric motor and mechanical engine feed into one transmission, and the load response of the mechanical engine affects the load response. A direct drive or parallel system may be acceptable under industry standards; however a fully electric, series hybrid concept will produce a load response that has not been available before, significantly enhancing ship assist and manoeuvring capabilities.

An electronics system such as the one described changes the direction of increasing load response times of modern diesels to a system which can provide power in an instant, placing the limitation of load response on the propulsion. This requirement may not have been desirable in recent times, but with the emergence of operations in more exposed environments, and with sea state tug interaction resulting in dynamic amplification, doubling bollard forces at the ship's hull, the emergence of a capability to provide an intelligent propulsion system would be valuable. This system allows for such a possibility.

MECHANICAL/ELECTRICAL POWER RATIO

In this particular concept, the bollard pull is required to be 100 tonnes. This is achieved entirely from mechanical power. The battery power that exists is for autonomous low powering, and load response. The power on charge that exists in addition to maximum mechanical power is restricted to limit the load to the propulsors. This does not have to be the case. An alternative option could be a complement of battery power and mechanical power to achieve maximum bollard pull. Considering the operational profile above, if the time history of such a tug was understood with more detail, it may be feasible to reduce the mechanical power. This design may be rated for a maximum bollard pull, and a sustained bollard pull, and its success is dependant on how it would be perceived by the industry. There exists a great deal of flexibility in the configuration of the series hybrid. Battery capacity and mechanical generators can be of various types and technologies. It is the development of the Active Rectifiers (AR) in the power electronics that makes this possible.

POWER ELECTRONICS



At the heart of the hybrid power electronics coordinating the charging/discharging to supply the required propulsion load is an Active Rectifier. This allows the propulsion system to draw on power from the battery bank, directly from the mechanical generator, or a combination of the two. Likewise, it can instantly change to a regime of providing propulsion power solely from the generator, and the surplus charge flowing to the battery bank. Primarily, this coordination facilitates anticipated gains in engine efficiency through load smoothing. Secondly, the AR has practically no time constant restrictions in the systems. Safety limits can be set on the torque, speed and power that are required by the propulsion system. *Figure 8* shows the active front end and where it is placed in the system.

Figure 8, left: Active front end.

OPERATIONAL REGIME

This hybrid system suits the operation profile of a terminal tug very well. The vessel is required to stand by at low required power levels, operate at fluctuating intermediate power levels for unspecified periods, and provide maximum loads of short duration. One example of how the hybrid system could be used with a tug operational profile is set out below.

Mode 1: Low power standby – battery power;
Mode 2: Low or intermediate power – idealised engine loading, battery power for load smoothing;
Mode 3: Low or Intermediate power – idealised engine loading, charging batteries;
Mode 4: Peak power – constant load peak engine power, battery power for load smoothing.

The relationship between these four modes affects the capacity of installed engine power and battery power. Optimisation of a generic solution will come through more experience with varying operational profiles, and the understanding of load response of installed engines.

EFFICIENCY GAINS AND EMISSION REDUCTION

There are two significant aspects of this design that contribute to an emission reduction, but at this stage of development, only one can be well quantified. Reductions from fuel choice are known for constant loading conditions, and will form the basis of comparison in this paper. The gains in efficiency and emission reduction from utilising a hybrid system are yet calculable. Understanding fuel consumption of an engine over load changing of various rates and magnitudes is required to fully appreciate the gains a hybrid system could offer, considering its ability to slow and shorten load steps in comparison to a mechanical drive equivalent.

The hybrid system and its mechanical equivalent are compared, to show what gains could be initially expected. *Figure 9,* at the foot of the page, illustrates the systems.

Bearing in mind the operational profile in *Figure 7*, and the operational regime described above, the required propulsive power is shown by *Figure 10*, below.

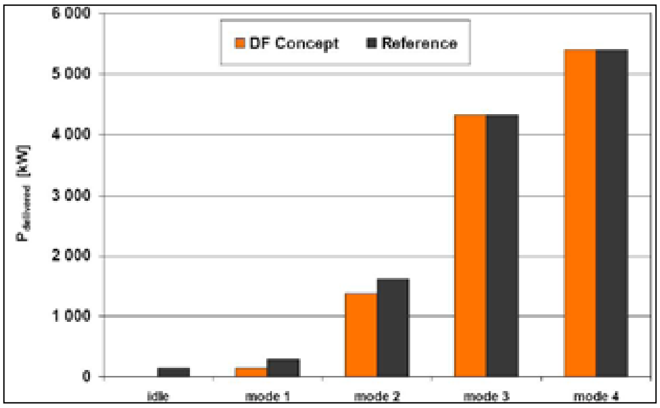


Figure 10: Propulsive power requirement.

There is a lack of power requirement in the Dual Fuel Hybrid system where typically the mechanical reference system will be required to idle. Also, a reduction in power in mode 1 and 2 can be realised in the hybrid system with its fixed pitch propellers and electric motors at zero speed, consuming no energy, in comparison to the mechanical equivalent running controllable pitch propellers which consume power even at zero pitch.

Combined gains over the operational profile show a benefit from running a hybrid system and LNG fuel. *Figures 11, 12* and *13* (next page) show emission reduction, fuel saving and energy consumption of the hybrid system and an equivalently-powered diesel mechanical.

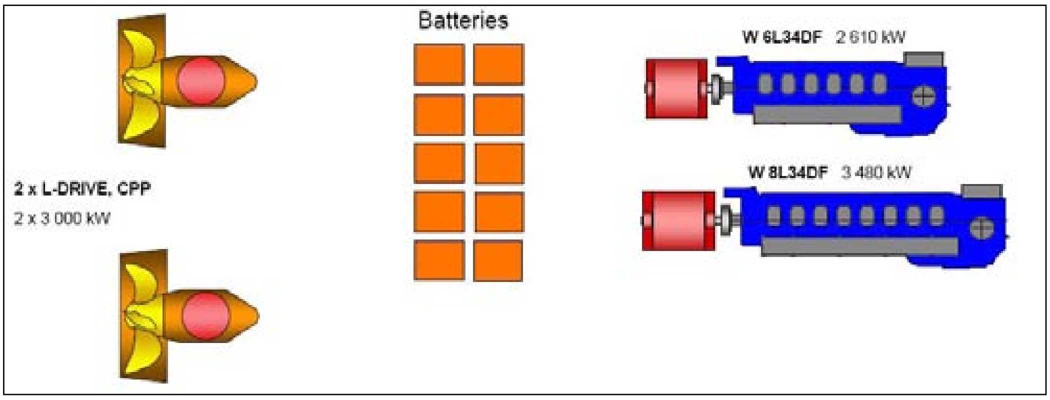
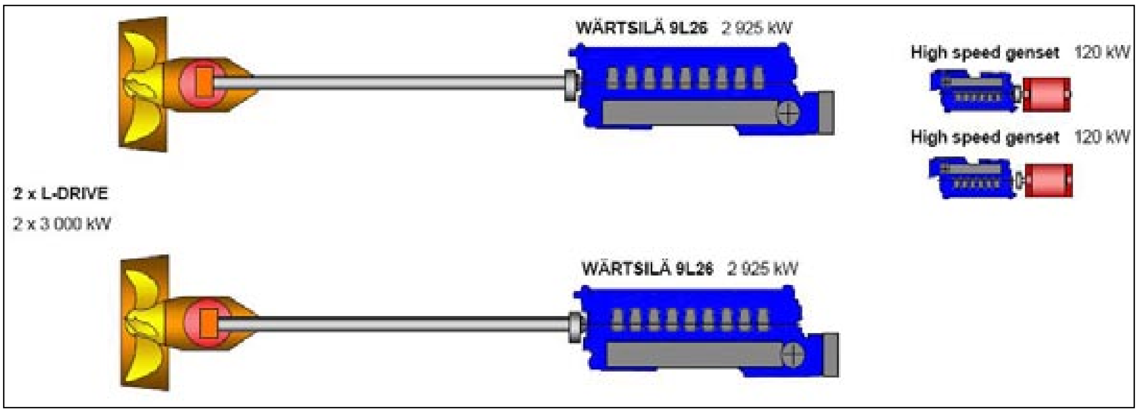


Figure 9: Dual Fuel Hybrid (left) vs Diesel Mechanical (below).



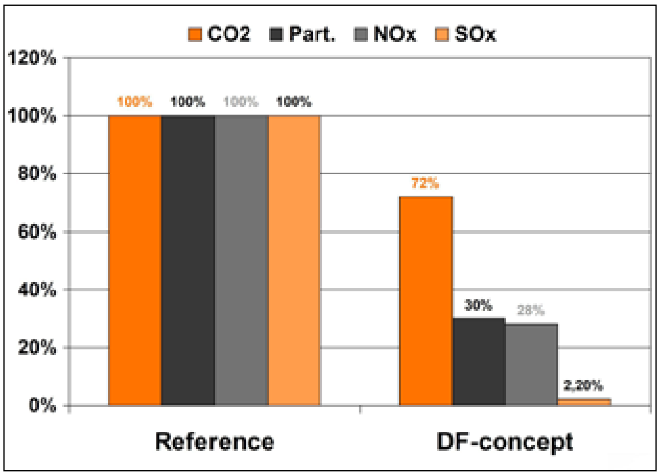


Figure 11: Relative emissions comparison.

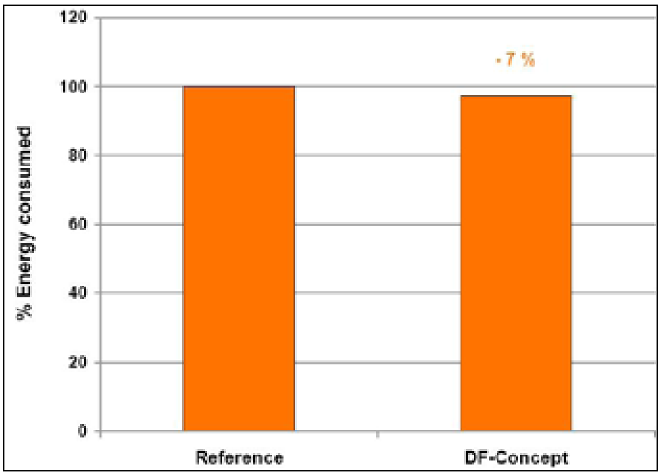


Figure 12: Energy used.

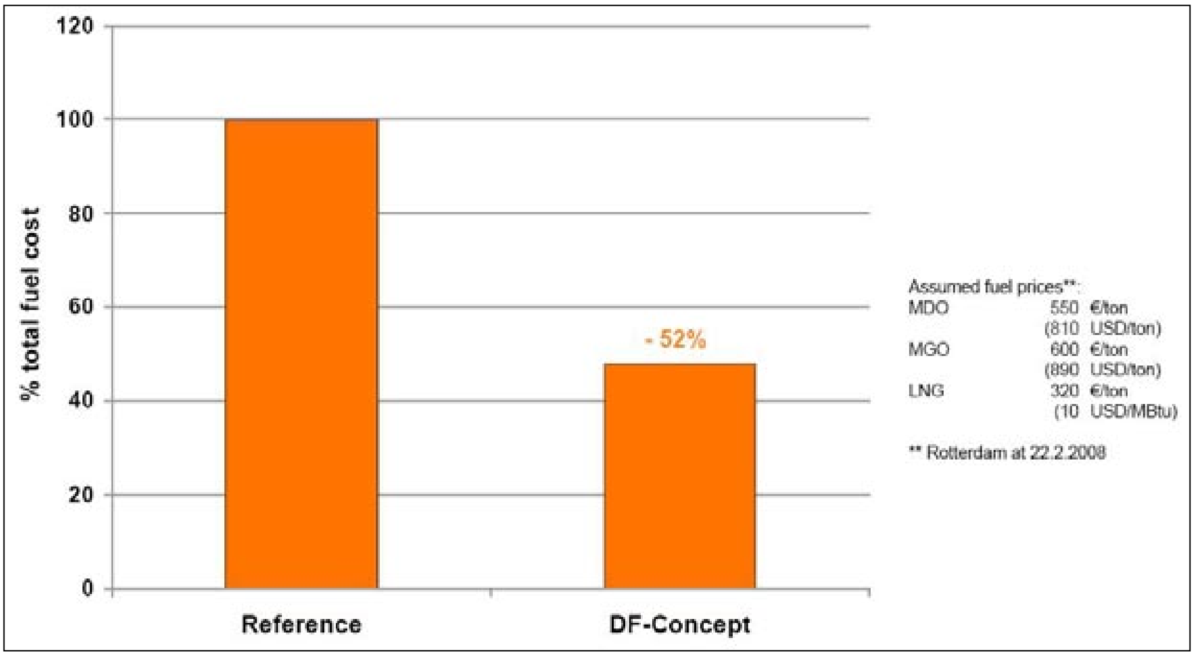


Figure 13: Fuel cost reduction.

CONCLUSION

What results from joining LNG technology with tugboat requirements is a vessel with a higher than normal initial capital expenditure. However, the benefits of LNG, with reduced operational costs, and an emission credential to be welcomed by legislators and the public alike, means the concept could have a promising future development. What lies ahead is optimisation of the design, with increased input from operators and users for increased efficiency regarding cost and use of resources. What remains unique about this concept is that whilst it has cut fuel costs by half, and reduced emissions significantly, the functionality of the vessel has been increased, with an ability now to supply instantaneous load response.

REFERENCES

[1] *DNV Rules for Classification*, Part 6, Chapter 13, Gas Fuelled Engine Installations.

[2] LNG Fuelled reference support vessel http://www.wartsila.com/Wartsila/global/docs/en/ship_power/media_publications/marine_news/2004_3/wartsila_df_offer_fuel_flexibility.pdf