NATIONAL TECHNICAL UNIVERSITY OF ATHENS

SCHOOL OF NAVAL ARCHITECTURE AND MARINE ENGINEERING

DIVISION OF MARINE ENGINEERING

DIPLOMA THESIS

Techno-economic Evaluation of Various Energy Systems for LNG Carriers

ANDRIANOS KONSTANTINOS

ATHENS, JULY 2006

SUPERVISOR PROFESSOR: CH. FRANGOPOULOS

Devoted to my family for their love, patience and support and especially to my beloved mother Aimilia S. Rakka-Andrianou who will live forever in our hearts.

CONTENTS

Foreword

Acknowledgements

I would like to express my special thanks to my supervisor professor Mr. Christos A. Frangopoulos who devoted much of his valuable time to help me complete this diploma thesis. His advice and mentorship as well as his careful reading and critical eye were for me not only a great actual help but also a lesson of ethics and professionalism and for all these I am really grateful.

Also I would like to acknowledge my professors Mr. Dimitrios Lyridis and Mr. Ioannis Prousalidis for their recommendations and comments on several points of this study.

In addition I wish to thank the personnel of Maran Gas Maritime Inc. and especially the Fleet Technical Manager, Mr. Steve Mavrakis for the proper guidance he provided to me, for which I express my sincere gratitude. Thanks also go to the Technical Director, Mr. Andreas Spertos, to the Assistant Technical Manager Mr. Spyridon Gertsos and to the LNG fleet Manager, Captain Srdan Silic for the useful technical data they provided to me and for their important suggestions.

Also I would like to thank Mr. Christian Skoudal Loeth, Marine Installation MAN B&W Diesel A/S and Mr. Lars Zimmermann, Senior Sales Manager, Sales& Order Processing, MAN B&W Diesel A/S for their immediate response to my questions and the useful information they sent to me. For the same reason I wish to thank Mr. Giulio Tirelli, Project Engineer, Business Support/Ships, Ship Power, Solutions, Wärtsilä Finland and Mr. Vassilis Kalamakis ,Marine Sales, Wärtsilä Greece S.A.. Moreover I wish to thank Mr. Spiros A. Azzopardis, Sales Engineer, Rolls-Royce Marine Hellas for his suggestions.

Finally I am indebted to Dr. Nikolaos Ventikos and to the Ph.D. candidates George Dimopoulos and Panagiotis Zaxarioudakis for the economic and technical data they provided to me.

1.

INTRODUCTION

LNG carriers have been used to transport liquefied natural gas overseas on a commercial basis since the late 1960s. Over the years, there have been many improvements in the designs, but the main propulsion system is still the same. In all other sectors of commercial shipping, the steam turbine has been replaced by much more efficient Diesel engines, but LNG carriers stick with steam turbines. The main reason for this is the steam turbine propulsion system's unique capability to running on two cheap fuels simultaneously: Heavy Fuel Oil and Boil-off Gas. This feat, combined with a very high reliability, ensured the survival of the steam turbine.

The main drawback of the traditional steam turbine plant is its low thermal efficiency, and hence high fuel consumption. Also the lack of alternative usage for the boil-off gas has led to thinking that the boil-off gas is free. Alternative methods of utilising boil-off gas have forced changes in this thinking. Furthermore the natural boil-off quantity is decreasing in modern LNG carriers owing to advances in tank insulation technology and design. As a result, the natural boil-off is far from sufficient to fuel the propulsion power needed for the relatively high ship operating speeds.

Therefore forced boil-off gas or heavy fuel oil is needed to top up the fuel demand of the boilers, both of which increase operating costs. On a laden voyage typically around 50 % of the energy requirement comes from heavy fuel, and up to 80 % during ballast voyage.

Environmental aspects also need to be considered. The high fuel consumption of a steam turbine plant leads directly to high CO_2 emissions which will become an increasing liability in the future. Although NOx emissions of traditional LNG carriers are very low owing to the combustion characteristics of boilers, their SOx emissions are considerable because of the heavy fuel used to top up the energy requirement.

Among the other arguments often heard against steam plant are an increasing lack of competent steam engineers, poor manoeuvring characteristics, and limited propulsion redundancy.

Furthermore short-term contracts and even spot cargoes are becoming more common today owing to the increasing LNG demand and supply. Some LNG carriers have even been ordered without any shipment contract or route, which was previously unheard of in the LNG business. Thus ship operators are bound to look for newbuildings with more operational flexibility and efficiency to adapt to varying contractual situations. This primarily calls for a flexible and efficient propulsion plant able to accommodate different ship speeds and alternative operating profiles. Already there have been inquiries about ships that would normally operate at about 15 knots, but have to be capable of doing 19 knots on spot cargo trades.

These occasions in recent years stimulated the development of new techniques, represented by the boil-off-gas (BOG) reliquefaction plant, the dual fuel Diesel engine and the marine gas turbine, which have been put into practical use in quick succession.

In 2002, Chantiers de l'Atlantique in France received the first order from Gaz de France for a 74,000 cubic meter Diesel-electric driven LNG carrier, which was the first non steam turbine propelled LNG vessel in recent years[1]. The decision to select Diesel engine instead of the conventional steam turbine indicated that there are owners and/or charterers in the LNG shipping community who are willing to try new technology, which increases thermal efficiency of the propulsion plant.

Due to the small size of the LNG carrier ordered at Chantiers de l'Atlantique, its power requirements are too low to lend itself for gas turbine drive. However, larger vessels with propulsion power requirements between 24 and 30 MW, are ideally suited for the use of aero-derivative gas turbines.

The other possible candidates for the replacement of the traditional steam plant, such as slow speed Diesel with reliquefaction plant, slow speed gas-HFO Diesel engines, medium speed dual-fuel Diesel engines upgraded to burn HFO and other hybrid systems among the already proposed solutions are also attractive and promising alternatives.

The strong intention to improve transportation costs by introduction of the enlargement of cargo tank capacity and alternative propulsion systems stimulated many new LNG carrier projects with propulsion system other than the steam turbine, which have been ordered since 2004. The propulsion plant that was selected in each case was either twin slow speed Diesel with reliquefaction plant or medium speed dual-fuel Diesel electric.

Whatever propulsion plant is chosen, there has to be some way of handling the boil-off gas either by utilising it as fuel, or reliquefying it. The selection depends on the result of a feasibility study taking into account not only the operating profile of the ship but also oil price trends[2] and the availability of bunkers of the correct grade in the vicinity.

The challenge to shipowners for the selection of the optimum propulsion plant will increase as vessels are required to have, or be prepared for, emission control equipment.

The purpose of this diploma thesis is to evaluate the possible alternative propulsion systems for LNG carriers presenting the advantages and disadvantages of each one. Furthermore there is an effort to perform a detailed evaluation, of techno-economic aspect, on some of the most viable solutions according to the present technological development and the current market requirements. This study was based on a selected LNG carrier size and has taken into account the main technical elements (such as the configuration of the prime mover, the type of fuel used, the boil off gas handling, the transmission system, the propulsion power requirement, the electrical power coverage, the propulsion unit to be installed, etc.) and economic elements (such as the investment cost, the operating profile, the operating cost, economic factors: price of liquid fuel and LNG, etc.) that should be considered when attempting to evaluate propulsion alternatives different to the typical steam propulsion plant.

---

[1] In 1973 Moss Rosenberg built an exception to the steam turbine rule, the low pressure dual fuel low speed Diesel (7-cyl Sulzer RNDM90) driven 29000 m^3 LNG carrier *Venator*. In 1974 another non steam turbine vessel, constructed by Moss Rosenberg as well, entered service, the 29000 m^3 LNG/ethylene carrier *Lucian* driven by a regenerative heavy-duty marine gas turbine (GE MM5212R).

[2] The relative price of LNG versus fuel oil, considering of course the recently high oil prices, influences the selection of the propulsion system. Since the 1970s oil crisis, conversion of the propulsion system has been made in almost all merchant ships by the application of low-speed Diesel engine directly coupled with propeller. In the case of LNG carriers, however, the steam turbine propulsion system with dual fuel boiler continued to be used and is adopted almost in all such carriers until today, because it is one of the best methods of treating BOG safely and efficiently.

2.

LNG CARRIER PROPULSION PLANTS DESCRIPTION

2.1 Steam Turbine

2.1.1 General information-technological development

Since the emergence of a high-profile liquefied natural gas (LNG) trade in the early 1970s, steam turbines have retained a dominating grip on LNG tanker propulsion –despite being ousted during that time from all other mainstream commercial shipping sectors, including large passenger vessels, container ships, and tankers. Nevertheless, today the steam turbine's supremacy is being more seriously challenged by Diesel and gas turbine machinery in both mechanical and electric-drive configurations.

Stimulating the original choice of steam turbines for LNG tankers was the need for a high-power output, proven reliability, and ability of the associated boiler plant to burn low-grade fuel as well as cargo boil-off gas. Turbine maintenance was also relatively modest in cost.

Among the drawbacks – stronger lately due to increase of fuel price – is the comparative inefficiency of steam plant and hence high fuel consumption, which also translates directly to high carbon dioxide emissions. A declining population of competent seagoing steam engineers, poor manoeuvring characteristics, and limited propulsion redundancy are also cited by opponents proposing Diesel-based solutions.

Steam plant development has been muted, compared with impressive Diesel engine advances, and the number of designer/manufacturers of large steam turbines and boilers active in the marine market has dwindled to a couple of Japanese suppliers. Among the few specialists remaining to contest the niche is Kawasaki, which has a pedigree dating back to 1907, when it started producing steam turbines under technical tie-ups with Curtis Co (USA) and John Brown Co (UK).

Kawasaki's own-design K-, S- and H-series of the 1950s and 1960s, with entry steam pressure and temperature conditions ranging from 18 kg/cm^2/340^{o}C to 40 kg/cm^2/450^{o}C, gave way in the mid-1960s to the UA and UC types (60 kg/cm^2/510^{o}C). These non-reheat types were supplemented by the UR reheat design.

References were earned in the LNG carrier arena from the early 1980s with UC-400 and UC-450 turbines for 125,000 m^3 and 128,000 m^3 capacity tonnage - respectively with maximum ratings of 29.4 MW and 33 MW - built by Kawasaki Heavy Industries for Japanese and overseas owners.

Deliveries in the 1990s switched to the UA-type with outputs generally ranging from around 26.5 MW to 28.7 MW, but an 8825 kW version was supplied for a 19,100 m^3 carrier handed over by KHI in 1995 to Hiroshima Gas. The UA-type, a non-reheat two-cylinder cross-compound impulse/reaction design with high-pressure and low-pressure stages, can accept steam entry conditions of 62 kg/cm^2/525^{o}C. Design refinements have benefited turbine efficiency, while computer analysis has enhanced structural anti-vibratory performance.

A wide-ranging UA programme extends from the UA-120, with a maximum continuous rating of 8800 kW, to the UA-440 rated at 32.4 MW; a more powerful UA-500 design, suitable for engine powers of 36,775 kW has been offered since 2002 to target anticipated 200,000 m^3-plus LNG carriers [1]. This UA500 turbine set builds of the company’s extensive experience in this field, including perfection in 1997 of an advanced reduction gearbox capable of handling successfully outputs of 32,362 kW from the current turbine model, UA440 [2].UA installations have earned a high market share from Japanese, South Korean, and European newbuilding projects, references in the past years including the 145,000 m^3 *Energy Frontier*, whose UA-400 turbine with a maximum rating of 26.9 MW at 80 rev/min delivers a service speed of 19.5 knots [1].

In the new UA500 design, rotating parts inherit the basic specifications of their counterparts in the UC450 model, which is still operating successfully in three LNG tankers built approximately 20 years ago. High-load 3D blades are employed in the low-pressure turbine for the last stage, with fir-tree-type blade roots, and an integral shroud is fitted to reduce blade resonance stress [2].

Packaged plants are supplied to foster a reduction in overall machinery weight, an ergonomic engineroom arrangement, and ease of installation. The HP turbine and manoeuvring valve are sub-assembled on a common bed and the LP turbine is coupled with an underslung main condenser. Both assemblies are connected to a reduction gearset incorporating the main thrust bearing.

Kawasaki also manufactures the special double-reduction gearing associated with the turbines, whose high-pressure and low-pressure elements typically rotate at 5000 rev/min and 3300 rev/min respectively, a speed which must be reduced to 80 rev/min-90 rev/min for the propeller [1].

This tandem articulating gearbox design (double reduction with double helical gears) is said to offer very high accuracy and power density, capable of handling a maximum power output of 38,220 kW. By using ultra-hard components and carburised-quenching heat treatment for the pinion surfaces, the fatigue strength of the gears has been improved, while high –precision finishing of the teeth surfaces using ultra precision machinery should give enhanced gear accuracy.

What Kawasaki calls “ultra precision tooth-surface correcting technology” takes account of elastic and thermal deformation during operation, with a view to perfecting uniform tooth contact and reducing the impact of gear errors. Total weight of the new UA500 set is 380 tonnes, a substantial increase over the 280 tonnes of the UA440, and dimensions are slightly increased at 8600 mm length, 8500 mm width, and 6300 mm height. Additionally advanced technology is employed to improve turbine efficiency, using experience gained from land-based sets, and gearbox output speed to the propeller is reduced to 84 rev/min, compared with 90 rev/min for the UA440 design [2].

Another Japanese group, Mitsubishi, entered the steam turbine business a century ago and now offers the MS-2 and MR-2 series, which are respectively non-reheat and reheat-type two-cylinder cross-compound impulse-reaction designs. A range of models covers power demands beyond 44 MW, the five basic elements forming each package being matched to the specific requirement. Last years’ delivery references included the 137,000 m^3 *Pacific Notu*s, whose MS32-2 turbine delivers a service speed of 19.2 knots with an output of 21.32 MW at 81 rev/min. Mitsubishi also enjoys a healthy share of the main boiler market provided by LNG carriers, having developed advanced dual-fuel units and electronic control systems.

Opportunities for rival prime movers – Diesel engines and gas turbines - to enter the LNG arena have been boosted by developments in dual-fuel burning technology, the recent newbuilding order boom, and the interest of operators in securing higher operational flexibility with efficiency for varying contractual speed and deployment scenarios.

Recent breakthroughs by dual-fuel Diesel, low speed Diesel and gas engines at both ends of the LNG tanker propulsion spectrum as well as the marketing efforts of gas turbine suppliers must give cause for concern to those favouring the whiff of steam.

Options for enhancing the efficiency and flexibility of steam plant are limited, and only the residual conservatism of LNG tanker shipping can prevent the surrender of its last bastion [1].

2.1.2 Conventional steam turbine propulsion plant

The steam propulsion plant used in modern LNG's is very similar in outline to those used on earlier vessels. The plant usually comprises of two boilers supplying steam to high and low pressure turbines, which in turn drive a single screw via a gearbox. The steam also drives the electrical generators as well as powering many auxiliaries and provides the heat source to fuel tanks, air conditioning etc. The vessels are equipped with one or two Diesel generators, which are only for backup when maneuvering, in port and for cold starting purposes [3].

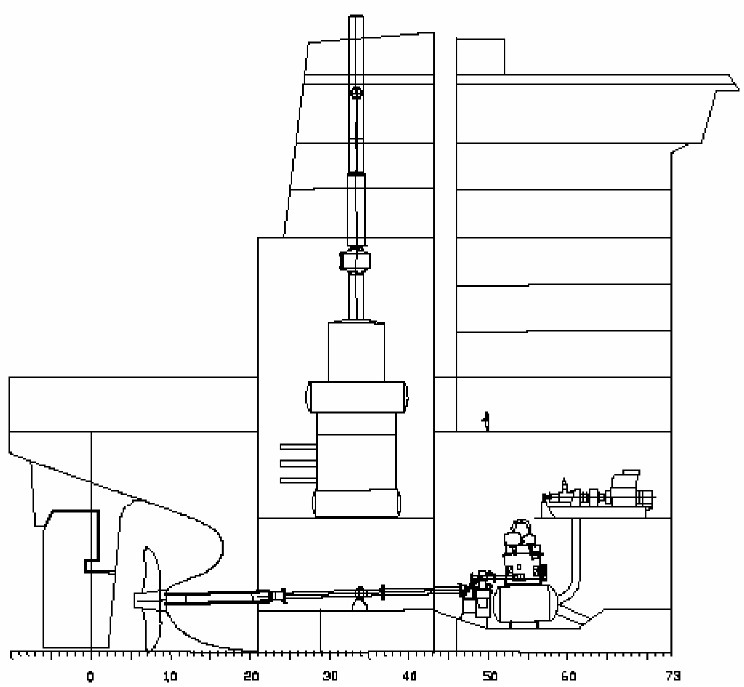


Fig. 2.1.1 Steam turbine propulsion-engine room configuration [5].

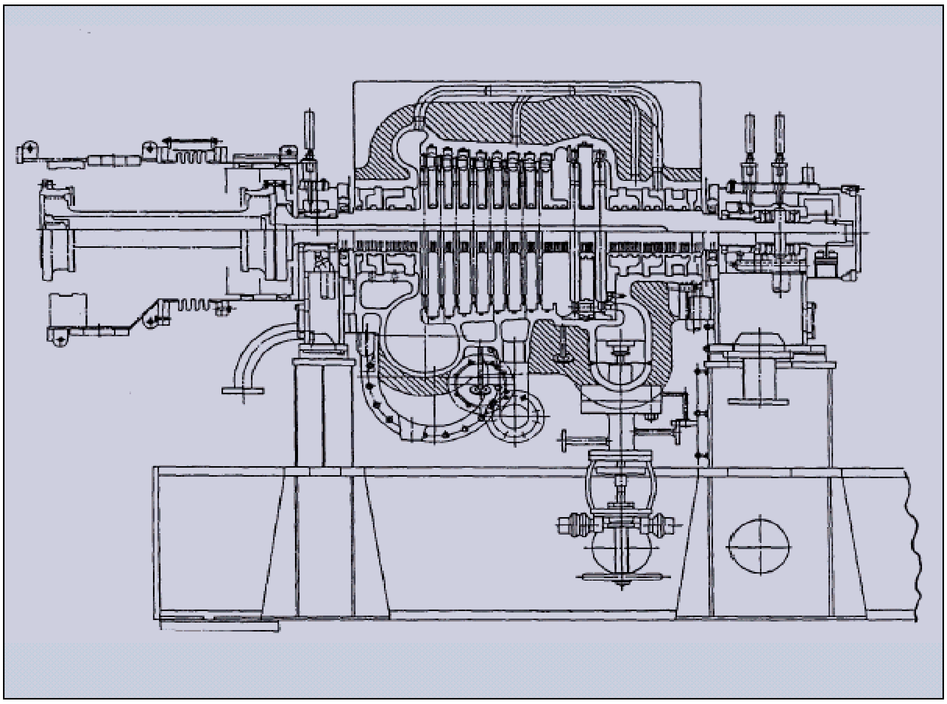


Fig. 2.1.2 The high-pressure section of a Kawasaki UA steam turbine [1].

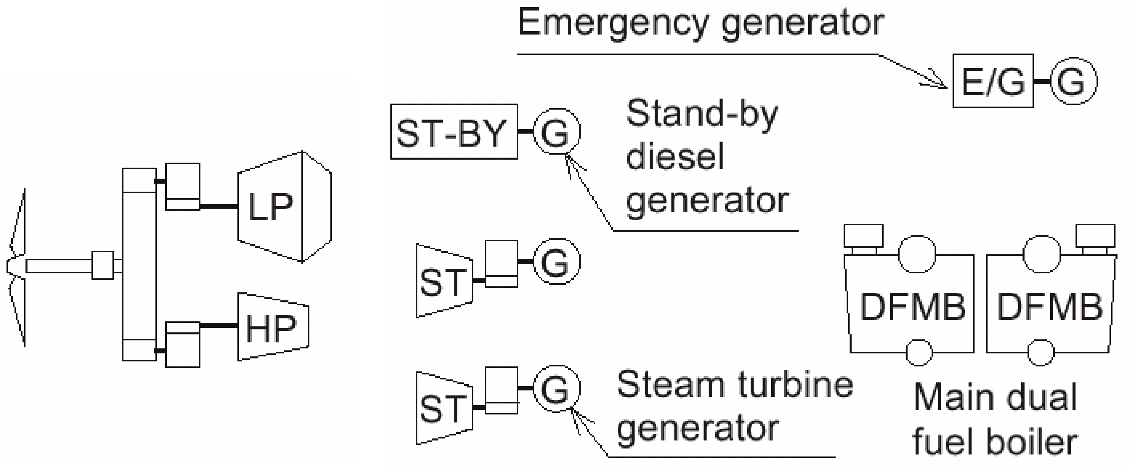


Fig. 2.1.3 Steam turbine propulsion system (High-efficiency plant) [14].

Conventional LNG Carrier

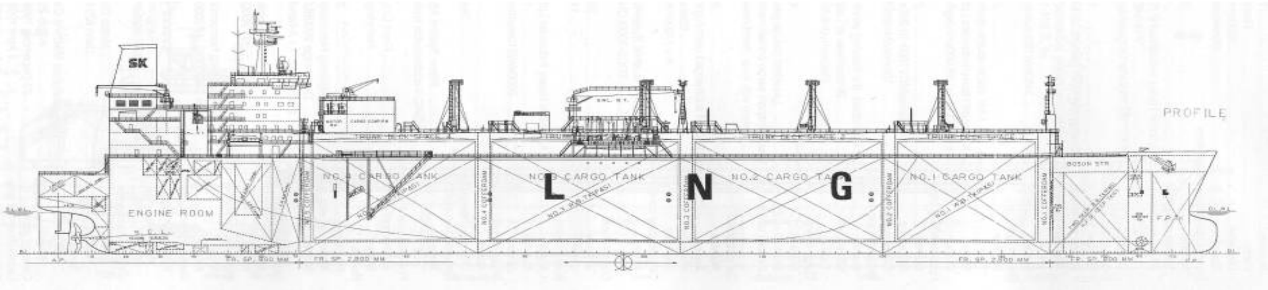


Fig. 2.1.4 Conventional LNGC profile plan for "SK Summit" [4].
Owner: SK Shipping Co. Korea. Builder: Daewoo HI, Korea. Delivery: 1999.
Dimensions: 277 x 43.4 x 11.3 m (L x B x D). Cargo capacity (100%):138,000 cubic meters.
Speed: 20.3 kn. Fuel consumption: 2,400 kg/h HFO + 3,950 kg/h BOG. Propulsion machinery: 1 Kawasaki UA-440 steam turbine, 29,830 kW.

SK Summit represents the current standard in LNG carriers, 138,000 cubic meter cargo capacity and a cruising speed of around 19 knots. As of November 2002, there are approximately 60 vessels rather similar to SK Summit on order, with about 25 options. SK Summit is therefore a great example to be used as a benchmark when determining the relative merits of alternative LNG carrier's propulsion systems. Prices for these vessels hover between USD 165M and 170M. Total project cost per vessel can reach USD 200M as a result of financing, delivery, project management, insurances, bank guarantees, etc. [4].

As we mentioned above for the LNG carrier propulsion system, there is a requirement not only for improved thermal efficiency but also for safe and efficient treatment of BOG. For efficient treatment of BOG, there are two methods; one is to use BOG as "fuel for various types of engines" and the other is to "save it by reliquefaction".

The second solution took place at the S/S LNG Jamal, built at Mitsubishi Heavy Industrie's Nagasaki Shipyard and put into service in November 2000.That is an LNG carrier equipped with the world's first LNGC on board reliquefaction system. Having successfully passed its overhaul inspection in first dry dock in August 2003, this system has the operation result for nearly four years. With the conventional type steam turbine adopted as its propulsion system, this carrier is operated using cheap heavy fuel oil, and saving BOG by reliquefaction on voyage with cargo loaded.

This solution, although has increased initial cost, offers the highest flexibility on the boil off gas handling (use as a propulsion fuel or reliquefy) and consequently on the fuel used for propulsion .The fuel cost depends on the unit cost (ratio) of LNG/fuel oil. Since the unit price ratio may fluctuate depending on the mode of LNG transaction (CIF, FOB, etc.) and the fuel oil market conditions, it is desirable to achieve fuel cost improvement over as wide a range as possible.

The reliquefaction process adopts the intermediate cooling system using the Brayton cycle, in which nitrogen is used as refrigerant. In this process, BOG is liquefied and subcooled in the pressurized condition, and is then returned to the tank. There is no consumable supply including refrigerant nitrogen, for the nitrogen is produced from the air on board. For compression of BOG, a system in which two units of centrifugal single-stage compressors (motor-driven) are adopted for the purpose of sharing it for boiler supply, and they can also be connected in series for boosting supply to reliquefaction. For compression of nitrogen, centrifugal, three-stage compression is adopted in which the 1st and 2nd stages are driven by a steam turbine and the 3rd stage is driven by a nitrogen expansion turbine for the purpose of the power recovery of expansion process (Fig. 2.1.5). Also, by development of a dedicated control device for reliquefaction system, automation of starting procedure and unmanned continuous operation during normal navigation was realized, leading to a reduction in work load and high skill of operators [14].

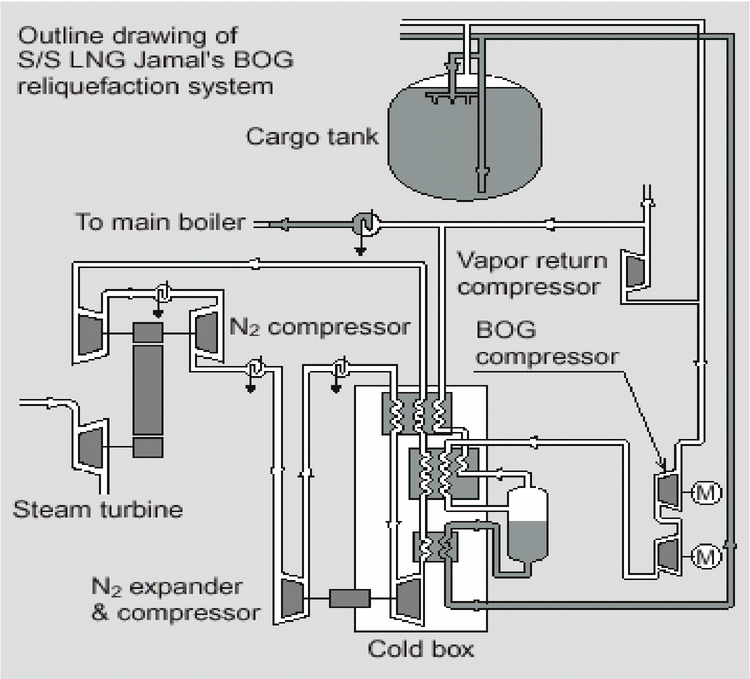


Fig. 2.1.5 Outline of LNG Jamal reliquefaction system [14].

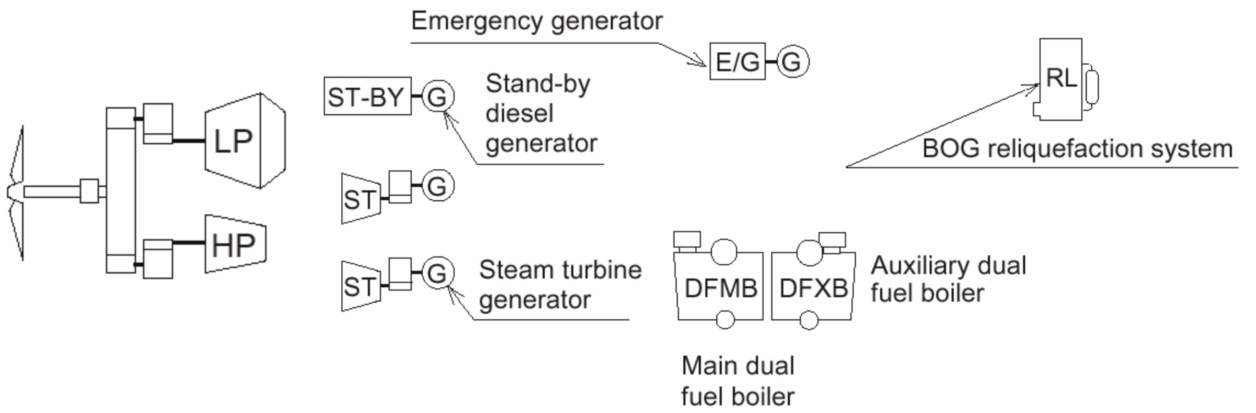


Fig. 2.1.6 Steam turbine propulsion system with BOG reliquefaction [14].

2.1.3 Advantages and drawbacks for a steam turbine propulsion plant installation

Advantages

I. Very easy and reliable method to utilize the BOG. The power requirements of a vessel in service exceed the energy available from the BOG, enabling complete utilization.

II. The ability of the associated boiler plant to burn low-grade fuel as well as cargo boil-off gas.
III. Very low lubricating oil consumption.
IV. High power output with proven high reliability.
V. Low turbine maintenance and also relatively modest in cost.
VI. Low vibration levels.

Disadvantages

I. Low efficiency of the turbine plant with the inevitable high fuel consumption.
II. A declining population of competent seagoing steam engineers creates the need to continue developing experienced crew, familiar with the operation and maintenance of a steam plant. The few shipping companies involved until recently in LNG shipping operation have managed to continue training their own staff, but the newer entrants to the market are going to find such experience difficult to come by.
III. Long delivery time for turbines and reduction gears and very limited production versus demand. Hence in case of failure, major delays and "off-hire" may be encountered, unless depot spares of the major components are maintained. This increases considerably the ship's capital cost and becomes more pronounced as the number of sister ships in the fleet is reducing.
IV. The comparative inefficiency of steam plant and hence high fuel consumption translates directly to high carbon dioxide emissions due to high exhaust gas volumes.
V. Larger engine room space requirements than for a motor ship.
VI. Heavy installation of high installation cost.
VII. Lower power per unit weight comparatively with other alternatives.
VIII. The layout offers limited propulsion redundancy.
IX. In case of low speeds or at anchor, the power requirements are much lower than the energy available from the BOG. The excess steam is "dumped" into the main condenser resulting in the loss of economic value of the boil-off.
X. Poor manoeuvring characteristics.

2.2 Gas Turbine

2.2.1 General information-technological development

Gas turbines are one of the serious alternatives to traditional steam power that are currently being examined by operators for new-generation LNG carriers.

Even though the gas turbine propulsion system has many advantages in power to weight ratio (gas turbines are light and virtually vibration-free), emission level, flexible machinery arrangement, efficiency and consequential cargo volume increase, it has not been adopted as a new propulsion system in an LNG carrier so far. As the GT propulsion system has some unique features and limitations compared with conventional marine propulsion systems, detailed technical and economic issues have to be solved in order to implement this power plant in an actual LNG carrier.

The GTs proposed for LNG propulsion are usually marinized aero engines of the latest generation with lower ratings compared to those used on aircraft. These changes promise to enhance reliability in the marine environment.

The primary fuel considered for the alternatives associated with the GT is gas, with MGO being considered only as a back-up fuel in case of emergency. The alternatives therefore are suitable for projects where the use of gas (boil off and forced) has been established by overall economic considerations, similar to the medium speed dual fuel (gas and MDO burning) electric alternative [3].

More complex cycles, exploiting intercooling and recuperation (ICR) technology, can achieve specific fuel consumption closely approaching the very flat curve characteristic of larger Diesel engines.

Also there are many heavy-duty but lightweight gas turbine designs which are able to burn lower grade fuels than aero-derived turbines, including selected heavy fuels and marine Diesel oils [5].

Further, the configuration options available with gas turbine are mainly based on electric propulsion. Although mechanical drive through reduction gear is possible, it is not considered a likely candidate for LNGs because it removes some of the advantages achieved with the gas turbine, like flexibility of installation, elimination of auxiliary electric power generators, etc.

Electricity generated by the gas turbine-driven alternators is delivered to the distribution network on a high-voltage main busbars. Power for the propulsion motor –or motors- is taken directly from these busbars and converted to provide a variable speed drive [3].

This system meets LNG carrier requirements under all operating conditions and provides redundancy for both propulsion and the safe burning of natural gas boil-off when not used for power production. To provide electrical power for loading, unloading and redundancy, one or two small gas turbine alternators are provided depending on vessel size and power requirement [5].

2.2.1.1 Marine aero-derivative gas turbines manufacturers

Aero-derivative gas turbines are, as the name indicates, derived from turbofan engines for airplanes. The gas turbine consists of two major parts: the gas generator and the free power turbine. The gas generator is the core of the jet engine, with the big fan in front removed. The free power turbine is mounted on the exhaust side of the gas generator. Its purpose is to convert the energy in the exhaust gas stream into a rotary movement, which can be used to drive a propeller, a waterjet or a generator. The term free power turbine indicated that the shafts in the gas generator and in the free power turbine are not fysically connected. They are aero-dynamically coupled, by way of the exhaust gasses escaping from the gas generator. For marine applications the compressor blades of the gas generator receive special coatings to make them more resistant to the effects of the salt in the intake air.

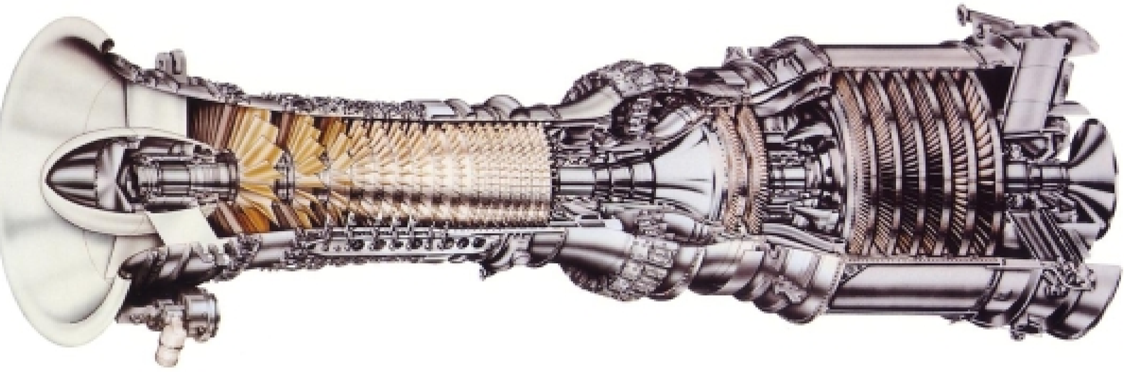


Fig. 2.2.1 Marine Aero-derivative gas turbine cross-section including power turbine [6].

Currently, there are three major manufacturers of aero-derivative gas turbines with output over 20 MW, suitable for marine propulsion: General Electric, Rolls Royce and Pratt & Whitney.

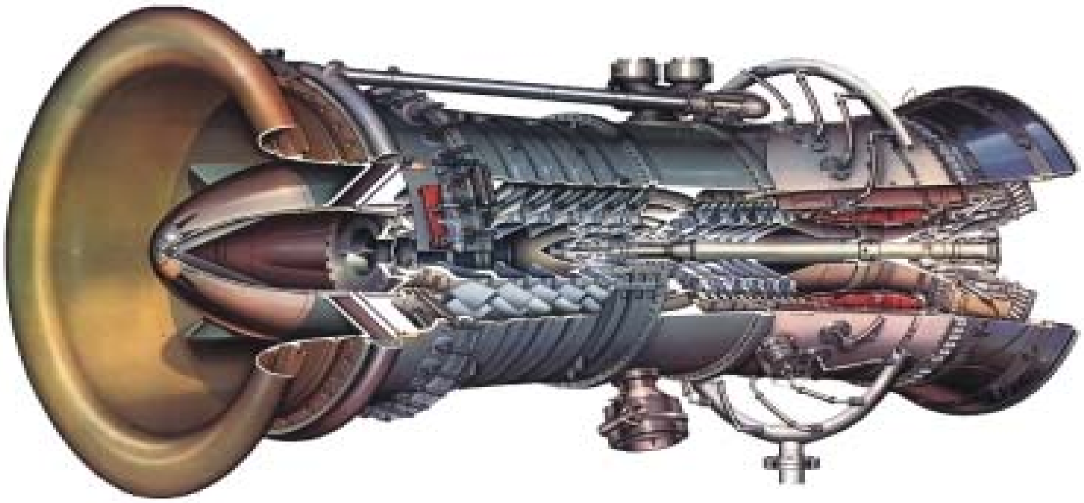


Fig. 2.2.2 Marine Aero-derivative gas generator cross-section [6].

In the mid 1960s, GE developed the TF-39 to power the Lockheed C-5A Galaxy air transport, ordered by the USAF. The TF-39 proves so sucessful that a commercial version designated CF-6 was developed almost immediately. To date the CF-6 series engine is the most successful commercial turbofan engine available on the market. The CF-6 is in use on the Airbus A300, A310, A330, Boeing 747 and 767. In the late 1960s the basic design of the TF-39 was marinized into the LM2500. This engine is the prime mover in countless naval vessels, and in the late 1990s the first fast ferries were fitted out with these engines. In the mid 1990s, development of an upgrated version, the LM2500+ started. In 1998, Royal Caribbean surprised the entire marine industry and ordered eight cruise vessels to be driven by LM2500+ gas turbine generators. In the follow-up to this success, GE scored a number of orders for cruise vessels.

Rolls Royce developed the RB211 turbofan for the Lockheed L-1011 Tristar widebody in the 1960. Development problems put Rolls Royce into state ownership. Now, the RB211 is a very successful turbofan engine for the Boeing 747 and 767 wide body aircraft. The RB211 is also doing very well in industrial and off-shore applications. So far, the RB211 has scored no orders in the commercial marine propulsion market despite its excellent reputation. All marketing efforts are concentrated on the MT30, which is now available for commercial applications.

Pratt & Whitney enjoyed initial success with the FT4 in a few marine applications such as the Seatrain vessels and GTS Finnjet in the 1970s. The FT8 development started in the mid 1980s. It is based on the JT8D aero engine, which is in use on the Boeing 727, 737, McDonnell-Douglas DC-9 and MD-80 mid range jet liners. The FT8 is a little lower in output and efficiency than the LM2500+ and the RB211. The FT8 has considerable success as industrial gas turbine, with more than 150 units sold. Currently, there are no FT8 units in commercial marine service and marketing efforts are limited [6].

2.2.1.2 Gas turbine myths and misunderstandings

In the marine community there are still a lot of myths and misunderstandings about gas turbines.

Myth: Gas turbines have very low torque and cannot be used in mechanical drive applications.

Fact: Gas turbines can develop a very high torque, because the gas generator is aerodynamically coupled to the free power turbine. This allows the gas generator to spin up even when the free power turbine is stationary because of the moment of inertia of the propeller. When the gas generator develops sufficient air flow, the torque of the free power turbine overcomes the inertia of propeller.

Myth: Gas turbines are very noisy.

Fact: This misunderstanding typically derives from experience with aircraft noise but there are significant differences between gas turbines installations on ships and aircrafts. Weight and volume restrictions limit the amount of noise reduction measures that can be adopted for an aero engine but shipboard gas turbine packages can be arranged to achieve substantially lower noise levels than typical marine Diesel installations.

Myth: Gas turbines are unable to take instant load application.

Fact: The design of the gas turbine, with the gas generator aero-dynamically coupled to the free power turbine, lends itself very well to instant application of heavy loads, which occur when a generator suddenly trips off-line. The speed of the free power turbine might drop momentarily, but the gas generator will generate sufficient airflow to correct free power turbine speed almost instantly.

Myth: Weight saved by Gas turbines is of negative value since it is low in the ship and reduces stability.

Fact: The weight of the gas turbine plant (both for a simple and for a combined cycle plant) is significantly lower than for steam plant or a Diesel-electric plant (by 600 to 1000 t or more) but this does not create a stability problem. A shorter engine room enables lower location of deadweight, especially fuel storage, and the low turbine machinery height makes it possible to slightly decrease the main deck height or draught of the vessel-both measures decreasing the vertical centre of gravity. The weight saving can be replaced by additional cargo carrying capacity or fresh water and/or fuel storage capacity, allowing a more flexible itinerary. If the weight is not replaced, the reduced ship displacement should result in a lower propulsion power requirement.

Myth: Gas turbines run on jet fuel only.

Fact: Commonly available residual fuels have high contents of Sulfur, Vanadium and alkali metals. The marine liquid fuel specifications of the gas turbine manufacturers have been compiled to ensure satisfactory hot section replacement intervals. Distillate fuels, such as MDO DMX and DMA (ISO-8217:1996(E), Category ISO-F) are acceptable, provided the Sulfur content is below 1.0 %. Higher Sulfur and alkali metals content will reduce hot section lifetime accordingly. Vanadium content is given as 0.5 ppm maximum to reach a satisfactory lifetime. Higher Vanadium content will accellerate high temperature corrosion of the turbine blades. The replacement cost of a prematurely worn hot section will definitely offset the gains of using non-compliant fuels. Also there are many heavy-duty marine gas turbine designs based on industrial heavy-duty but lightweight designs (such as ABB Stal's GT35 gas turbine) which are able to burn lower grade fuels than aero-derived turbines, including selected heavy fuels and marine Diesel oils [6].

2.2.1.3 Advantages of marine aero-derivative gas turbines

Operation:

- Gas turbines do not emit black smoke during transient loads;
- Gas turbines pick up load very rapidly, at a rate of about 1 MW per second;
- During start-up, operation and shut-down, the gas turbine is operated through the turbine control system, which controls fuel management, but also monitors turbine condition. If any parameter exceeds pre-set limits, the turbine control system will give alarm and reduce turbine load to avoid damage. In case of serious problems, the control system will shut down the engine.

Maintenance:

- Gas turbine control system monitors engine performance and condition "on-line";
- Modular gas turbine construction allows for rapid exchange of engine modules, avoiding lengthy on-site repairs;
- Gas turbine size and weight allows for a complete engine change-out on-site within hours, without dry-docking or extended stays in port;
- Gas turbine and spares can be air freighted worldwide.

Reliability and availability:

- Aero-derivative gas turbines provide the very high reliability (> 99.5%) and availability (97.5%) associated with aero engines;

Environment:

- Low NOx and SOx emissions;
- Low particulates emission;
- No visible smoke during transient loads;
- No fuel sludge from heavy fuel oils.

Noise and vibration:

- Gas turbines are rotary machines, inherently of low structure borne noise;
- Gas turbine packages feature an acoustic enclosure, reducing engine room noise levels and improving the quality of the working environment in the engine room;
- Resilient package mounting reduces structure borne noise even further;
- High pitched air borne noise is easily attenuated;
- Lower investment in air borne and structure borne noise insulation.

Vessel design:

- Low weight and compact dimension of gas turbine and ancillary systems allows design freedom in terms of location of engine room in the vessel;
- Smaller engine room leaves more space for revenue making purposes;
- Low weight allows the engine room to be moved away from the bottom of the vessel;
- Low noise and vibration levels improve crew and passenger comfort, allowing engine room spaces to be located closer to accommodation areas;

Propulsion plant design:

- Gas turbines have high exhaust gas mass flow and temperature, which makes exhaust gas heat recovery both technically and economically feasible.

Installation:

- Gas turbine, control system and ancillaries are packaged on skids, ready for installation on the building blocks in the shipyard, speeding up the construction process;
- Gas turbine package with ancillaries are factory tested, reducing commissioning time in the shipyard;
- Gas turbine packages and ancillaries are assembled in the factory by specialized personnel, avoiding assembly problems and delays in the shipyard;
- Gas turbines are air cooled, eliminating the need for elaborate high and low temperature cooling water systems;

- Gas turbine lube oil is not exposed to the combustion process, resulting in very low lube oil consumption and eliminating the need for extensive lube oil conditioning systems;
- Gas turbines usually operate on MGO, obviating the need for fuel bunker heating, fuel line tracing and fuel conditioning systems [6].

2.2.1.4 Disadvantages of marine aero-derivative gas turbines

Thermal efficiency:

- Gas turbine thermal efficiency is lower than the thermal efficiency of comparable Diesel engines. Thermal efficiency of aero derivative gas turbines in the 20 - 30 MW class ranges from 36.5 to 40 %.
- Gas turbine thermal efficiency is proportional to gas turbine output. Thermal efficiency of small gas turbines, in the 2 - 5 MW class, hardly exceeds 30%;

Liquid fuel quality restrictions:

- Gas turbines can operate on either gaseous fuel or liquid fuel or both simultaneously, without any restriction in the ratio between fuels. However there are some severe restrictions on the quality of the liquid fuel. Vanadium and sulfur content should be kept within the specified limits in order to avoid high temperature corrosion of the turbine blades, which leads to loss of engine performance. In practice, the fuel specifications completely rule out the use of any residual fuel and the cheaper distillates as well. ISO 8317-1996 Class F Marine Fuels DMA and DMX are suitable.

Initial investments:

- Initial investment for a gas turbine engine in the 20 - 30 MW class is approximately 15 – 20% higher than in Diesel engines of comparable output. For smaller gas turbines, especially derivatives of helicopter engines, the price difference is even higher;

All the above reasons might spell doom for many a marine gas turbine project. And rightly so, if the advantages do not offset the disadvantages of the use of gas turbines, the vessel will be an economic disaster. All kinds of projects traditionally featuring Diesels as prime movers were suddenly re-engined with gas turbines of all makes and sizes. None of them made it through the project phase. Many of these projects failed because of the low thermal efficiency of smaller gas turbines. Even projects involving large gas turbines failed, mainly because of the high specific fuel consumption of the gas turbine and high fuel cost. With residual fuels usually being between USD 100 and USD 200 per ton cheaper than MDO and Diesels being 20% more fuel efficient, single cycle gas turbines have a hard time competing [6].

2.2.1.5 Gas turbines for LNG carriers

Rolls-Royce has developed a range of MT30 based propulsion systems for LNG carriers that deliver increased cargo carrying capacity, operational flexibility and through life cost savings. These are modern and highly efficient integrated systems that provide a reduction in operating costs when compared with existing steam and other proposed alternatives.

The range of propulsion and power systems based on the MT30 meet all the requirements of large (145,000 m^3 - 250,000 m^3) LNG carriers. The power dense MT30 provides the potential to reduce engine room length by approximately 19 m compared with a similar steam turbine application. The additional space-saving provides the scope to increase cargo-carrying by up to 12% on a typical vessel.

The MT30 systems range includes both COGES and simple cycle depending on the customer requirements. The MT30 primarily burns boil-off gas otherwise lost from the cargo tanks [7].

Lloyd's Register Asia has recently completed the first full safety case of a gas turbine propulsion system for LNG carriers of 250,000 cubic metres and above for Rolls-Royce’s MT30 system (Fig.2.2.4). Carried out in conjunction with Daewoo Shipbuilding & Marine Engineering (DSME) and Rolls-Royce, this work was designed to fulfil the requirement of the oil majors involved in the QatarGas and RasGas projects that shipowners, yards and class ensure that proposed ship design concepts are as sound as practicable.

Gas turbine propulsion systems have been widely used on naval and cruise ships but are relatively new to LNG vessels, which have traditionally been powered by steam turbine engines. This safety case is the first of its kind to be completed within the major Korean shipyards and puts DSME and Rolls Royce in a leading position to offer gas turbine propulsion as a viable alternative for the large LNG carriers of the future.

Work began on the project in 2004 with detailed engineering drawing development by DSME and Rolls Royce. LR Asia provided a risk assessment methodology for evaluation of the gas turbine propulsion system and facilitated its execution with an early hazard identification (HAZID) study in December 2004. This was followed by a full safety case, combining a further HAZID study and a hazard and operability (HAZOP) study of the developed arrangements in April 2005.

Bearing in mind that the gas turbine would normally be fuelled by boil-off gas from the cargo tanks themselves, the safety case paid particular attention to the ship’s high-pressure gas supply system. The HAZOP study covered failure modes and the maintenance of propulsion and electrical power in the event of a gas turbine failure.

Also Lloyd’s Register (LR) has issued an ‘approval in principle’ of GE Energy’s LM2500-based gas turbine propulsion system for LNG tankers. The approval in principle, issued through LR North America, gives GE Energy a high level of confidence that the marine industry will embrace its gas turbine propulsion system design as a viable alternative to traditional propulsion methods for the next generation of large LNG tankers.

Based on years of hands-on experience with LNG ship technology, a consulting team of engineering and electrical design specialists from various parts of the LR Group performed a comprehensive study of the system’s suitability for use on LNG ships. The team helped to ensure that the system met the strict safety and reliability requirements of LR’s rules for ships for liquefied gases, which incorporate the International Maritime Organization’s International Gas Carrier Code. The project began in early 2005 and recently concluded with hazard identification (HAZID) workshops at the GE Energy factory in Houston [41].

Fig. 2.2.3 Rolls Royce MT30: 36 MW flat rated at 26°C, 42% thermal efficiency, 201 g/kWh on gas, Dual fuel capable [41].

Increasing LNG carrier cargo capacity

The current cargo capacity of 138,000 cubic meters, e.g., can be increased substantially when the engine room bulkhead and the aft cofferdam are moved further aft. Changing the overall length or the draft is not recommended, as some major LNG ports have size restrictions. Changing these parameters would impair the flexibility of the vessel. Gas turbine propulsion will allow a rearrangement of the engine room, since the gas turbine is much smaller than the steam turbine and its steam boilers.

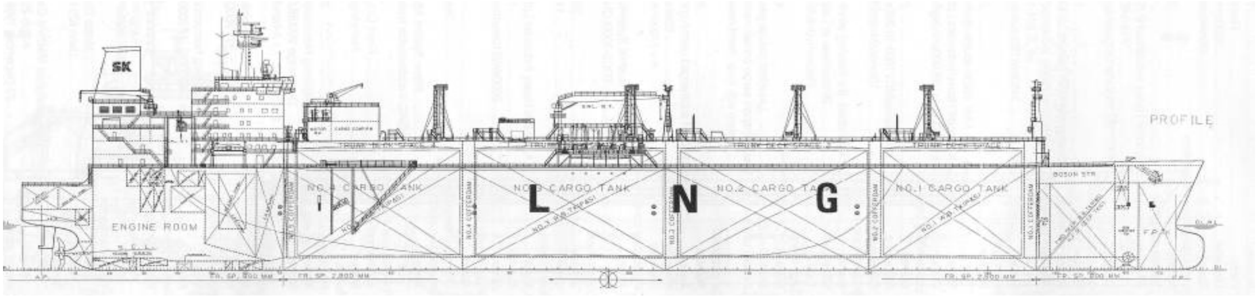


Fig. 2.2.4 Conventional LNGC profile plan [4].

Moving the ER bulkhead aft from frame 71 to frame 45, in the particular example, extends the cargo hold by 20.8 meter. If the gain in cargo hold length is distributed over the four cargo tanks, an increase of 19,000 cubic meters in cargo capacity can be realised. The advantage of this version of the LNG carrier is that it can accommodate both gas turbine electric and gas turbine mechanical drive. The hull form does not have to be changed, so the redesign costs are minimal [4].

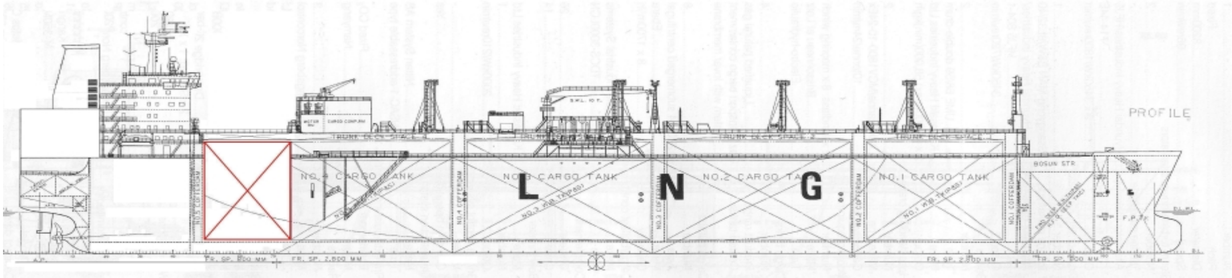


Fig. 2.2.5 Gas Turbine LNGC profile plan [4].

Gas turbine mechanical drive LNG carrier

The gas turbine mechanical drive power plant is the simplest and most efficient power plant available. The gas turbine mechanical drive power plant is very compact the gain in cargo capacity is approximately 19,000 cubic meters as mentioned above [4].

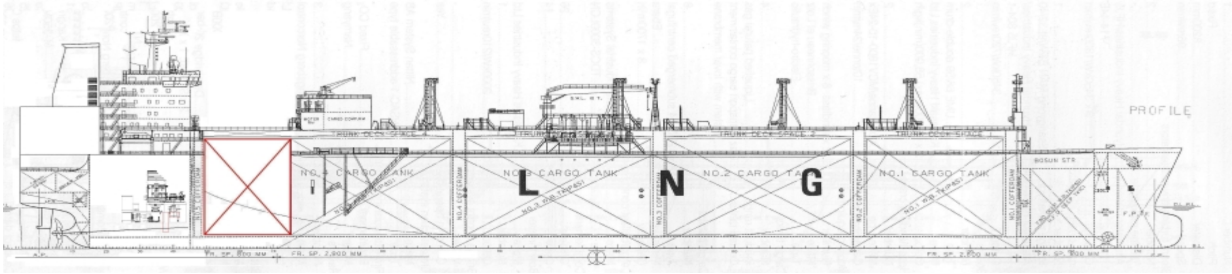


Fig. 2.2.6 Gas Turbine mechanical drive LNGC profile plan [4].

Gas turbine electric drive LNG carrier

The gas turbine electric drive power plant is the power plant that allows most flexibility in the design and layout of the vessel. The gas turbine drives the propeller shaft by way of an electric motor. This arrangement allows the gas turbine generator power plant to be located away from the tank top. In this case, the power plant is housed in the superstructure, located over the mooring winch deck. The engine room size can therefore be reduced substantially, increasing cargo capacity by approximately 19,000 cubic meter. The traditional LNG carrier hull can be maintained, to minimise redesign costs [4].

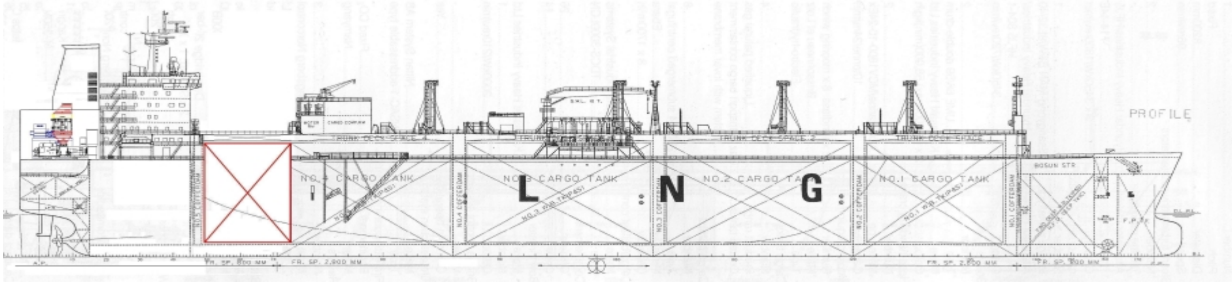


Fig. 2.2.7 Gas Turbine electric drive LNGC profile plan [4].

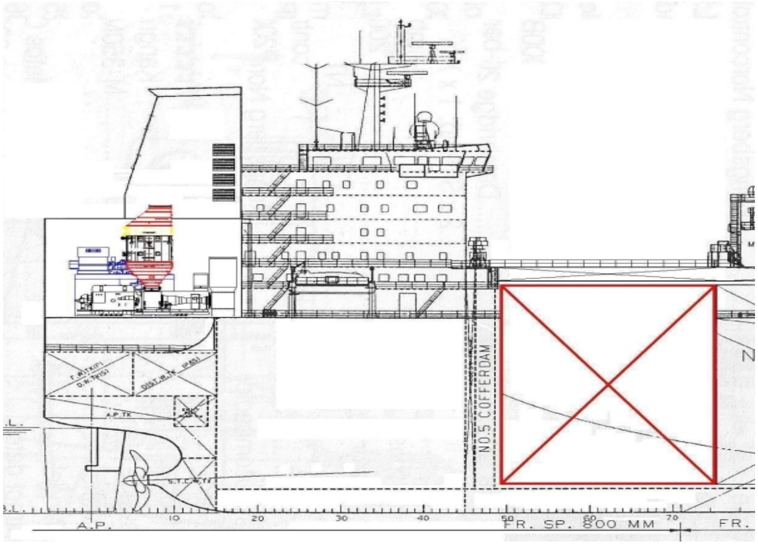


Fig. 2.2.8 Gas Turbine electric drive LNGC extra cargo capacity [4].

2.2.2 Typical gas turbine propulsion plant

Simple cycle usually consists of one main turbine and one auxiliary turbine in an electric drive power plant. Electricity generated by the gas turbine-driven alternators is delivered to the distribution network on a high-voltage main busbars. Power for the propulsion motor –or motors- is taken directly from these busbars and converted to provide a variable speed drive [3].

The gas turbine drives usually 1 FPP. A stand by Diesel generator is also installed.

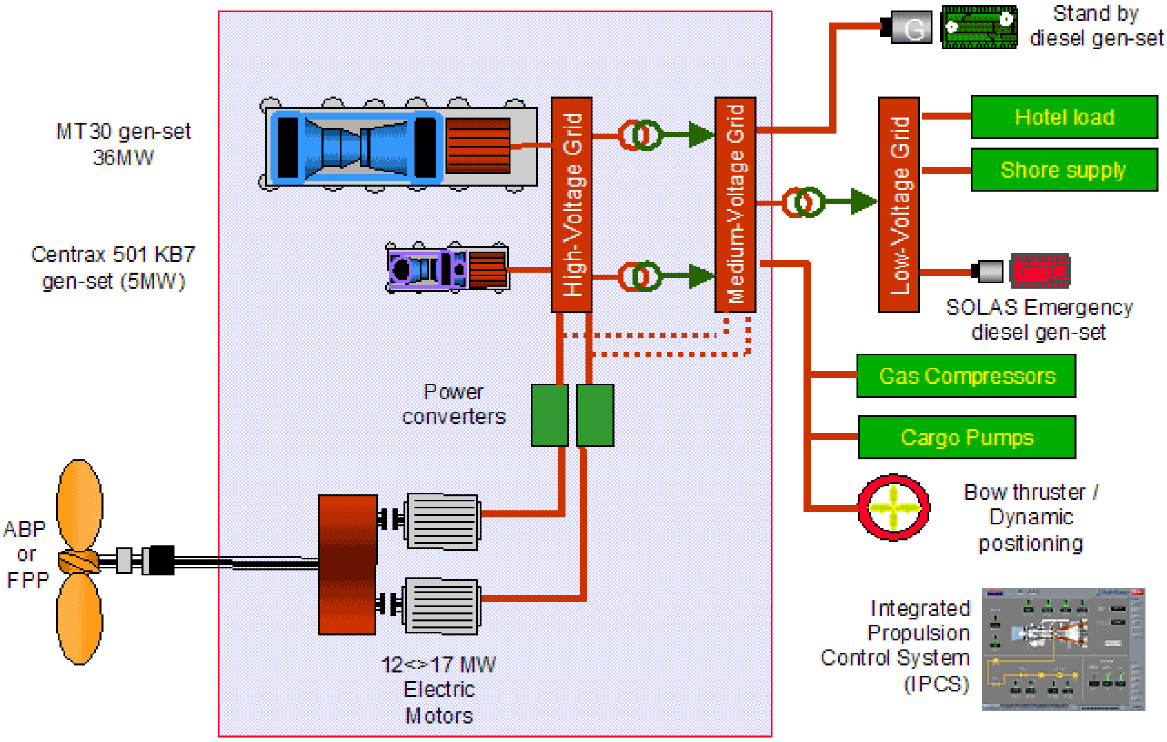


Fig. 2.2.9 Simple cycle Gas Turbine electric drive power plant [7].

2.2.3 Advantages and drawbacks for a gas turbine propulsion plant installation

Advantages

I. Increased thermal efficiency compared to steam turbines.
II. Increased cargo carrying capacity (up to 10 % more cargo capacity compared to a steam turbine vessel).
III. Low machinery weight and volume.
IV. Reduced installation and commissioning time in the shipyard through factory assembled and tested packages.
V. State of the art gas turbine with aero engine standards of reliability.
VI. Reduced installation costs.
VII. Low equipment cost.
VIII. Flexible modes of operation.
IX. Low equipment routine maintenance
X. No hull redesign cost.
XI. Design flexibility.
XII. Low engine noise and vibration.
XIII. Dual-fuel capability (simultaneous boil-off gas/MGO or MDO capability).
XIV. Simplified engine room arrangement, smaller cooling water system.
XV. Gas turbine lube oil is not exposed to the combustion process, resulting in very low lube oil consumption and eliminating the need for extensive lube oil conditioning systems.
XVI. Gas turbines operate on MGO or MDO, obviating the need for fuel bunker heating, fuel line tracing and fuel conditioning systems.
XVII. Lower fuel consumption than a steam plant.
XVIII. Easy maintenance and engine replacement.
XIX. Reduced crew members.
XX. Reduced emissions compared to traditional Diesel and steam turbine configurations (no selective catalytic reduction (SCR) or other special exhaust gas treatment systems are necessary to meet strict regulations).
XXI. FPP can be used without reversing gear in the case of electric propulsion
XXII. Improved Engine Management System (EMS), from aero engine's technology, which provides:
    i) Fully integrated alarm, monitoring and control functions by remotely mounted touch screen panels or through the direct integration into ship machinery control systems communicating with the EMS through a dual redundant databus.
    ii) The routine maintenance is limited to merely checking fluids and visual examination, as internal condition sensors enable the unit to be serviced on an 'on condition basis', avoiding unnecessary scheduled maintenance and only replacing what needs to be replaced.
    iii) Independent engine over-speed protection and an integral back-up power supply.
    iv) Simplified wiring, reduced number of connectors and main processors, power supplies located outside of the module.

Disadvantages

I. Gas turbine has to be located very near to the propeller shaft and a reduction gearbox, reversing gear is required for direct mechanical drive with a FPP.
II. Gas compressor required to supply gaseous fuel at 30 bar pressure to the gas turbine. Parasitic load can go up to 2.3 MWe.
III. In the case of electric drive, increased cost and complexity compared to mechanical drive.
IV. Energy conversion losses in the electric drive system for the case of electric propulsion.
V. Expensive back up fuel.
VI. Higher capital cost (the capital cost of an LNG carrier with gas turbine simple cycle for a 130,000 –150,000 m^3 LNGC is expected to increase by about 3% or higher, when compared with a steam turbine driven vessel).
VII. Lower redundancy compared to alternatives.
VIII. Relatively not common technology for commercial vessels.
IX. Specialized training of engineers is required.

2.3 Combined Gas and Steam Turbine

2.3.1 General information-technological development

With a combined cycle gas turbine power plant, a total rearrangement of the LNG carrier would yield even better results. Cargo capacity would increase by 24,000 cubic meter over the standard design, while the increase thermal efficiency of the combined cycle gas turbine power plant brings fuel cost down by 40%. Increased propulsion efficiency from the podded drive system would bring fuel consumption down even further. Newbuilding cost can be reduced because of the simplified construction of the aft ship, without complex curves around the propeller boss [4].

Gas turbine mechanical drive combined cycle LNG carrier

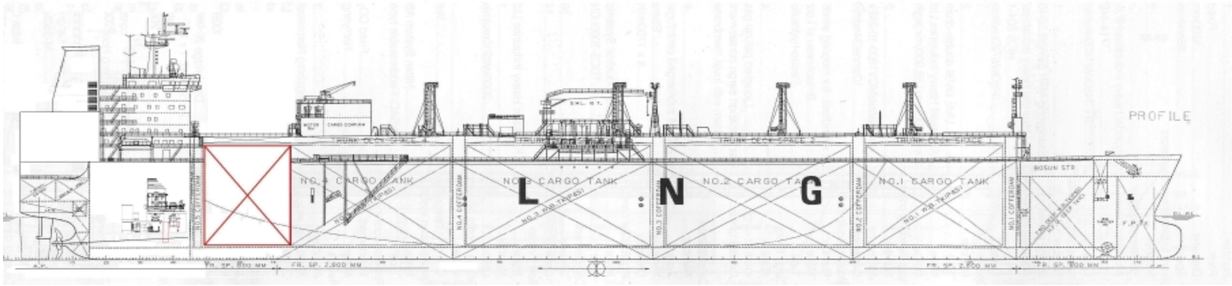


Fig. 2.3.1 Gas Turbine mechanical drive combined cycle LNGC profile plan [4].

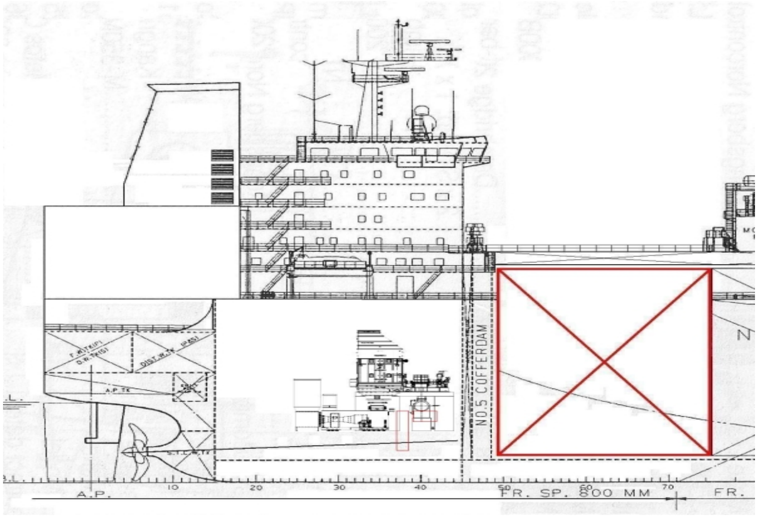


Fig. 2.3.2 Gas Turbine mechanical drive combined cycle extra cargo capacity [4].

Gas turbine mechanical drive combined cycle propulsion arrangement:

1 x Dual-fuel marine gas turbine mechanical drive package, output approximately 27 MW;
1 x Steam turbine generator, output approximately 10 MWe;
1 x Exhaust gas boiler with supplementary firing and duct firing capabilities;
1 x 10 MWe generator/electric motor;
1 x Twin in / single out vertical offset reduction gearbox;
1 x Hydraulic reversing gear;
1 x FPP.

The gas turbine directly drives the propeller shaft through a reduction gearbox. This arrangement avoids energy conversion losses as much as possible. As can be seen in the fuel consumption and thermal efficiency diagram of the Fig. 2.3.3, the thermal efficiency of the gas turbine mechanical drive power plant can reach 52 % in combined cycle operation. At operating conditions, the thermal efficiency is very near to 50 %. The high thermal efficiency of the power plant and the additional BOG, as a result of increased cargo capacity, eliminate the need for supplementary liquid fuel or forced vaporised gas during the loaded voyage.

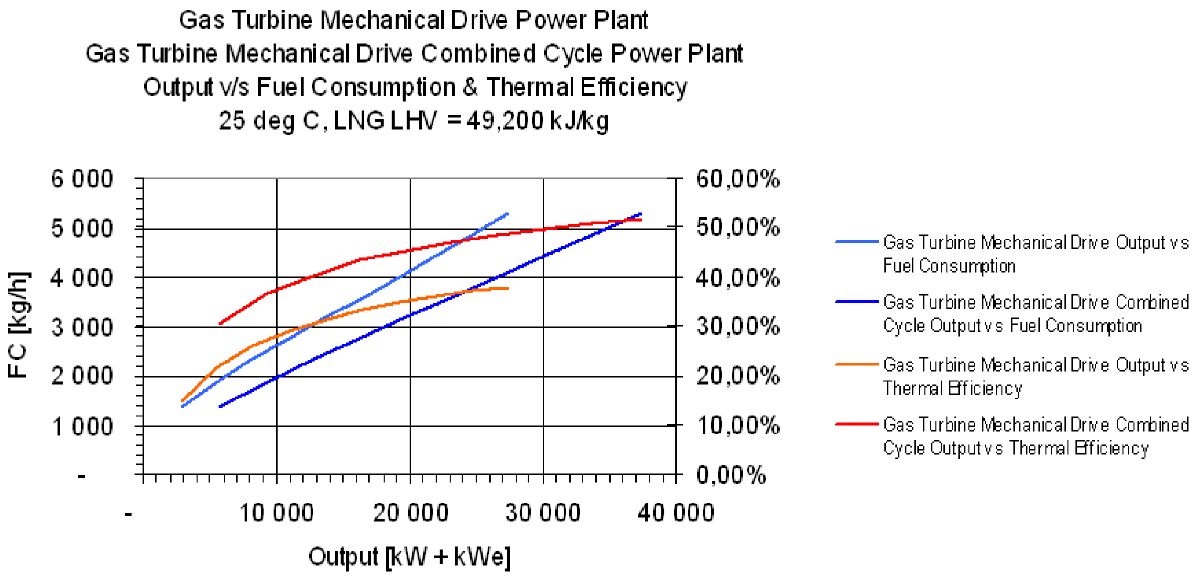


Fig. 2.3.3 Gas Turbine mechanical drive power plant vs Gas Turbine mechanical drive Combined cycle power plant [4].

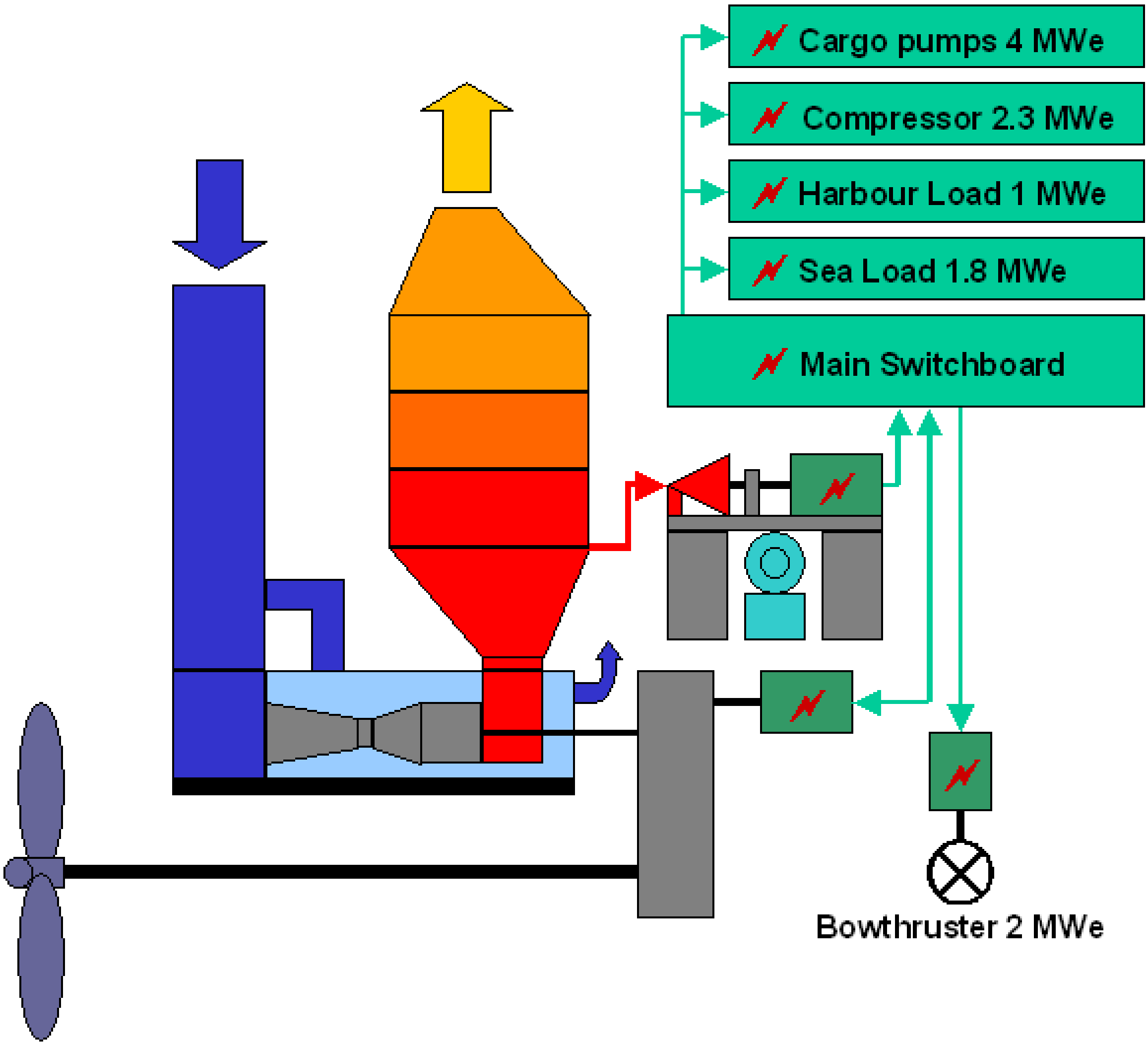


Fig. 2.3.4 Gas Turbine mechanical drive Combined cycle power plant [4].

The free power turbine of the gas turbine drives the input shaft of the reduction gearbox. The reduction gearbox reduces the input speed of 3600 RPM to the propeller shaft speed of 94 RPM. The exhaust gasses from the gas turbine raise steam in an exhaust gas boiler. This steam is used to produce power in a 10 MWe steam turbine generator. The steam turbine generator feeds the electric consumers from the main switchboard.

The PTO/PTI shaft of the gearbox is connected to a 10 MWe generator/electric motor. In generator mode, the generator feeds the main switchboard. In electric motor mode, the main switchboard feeds the electric motor to provide additional power to the propeller shaft [4].

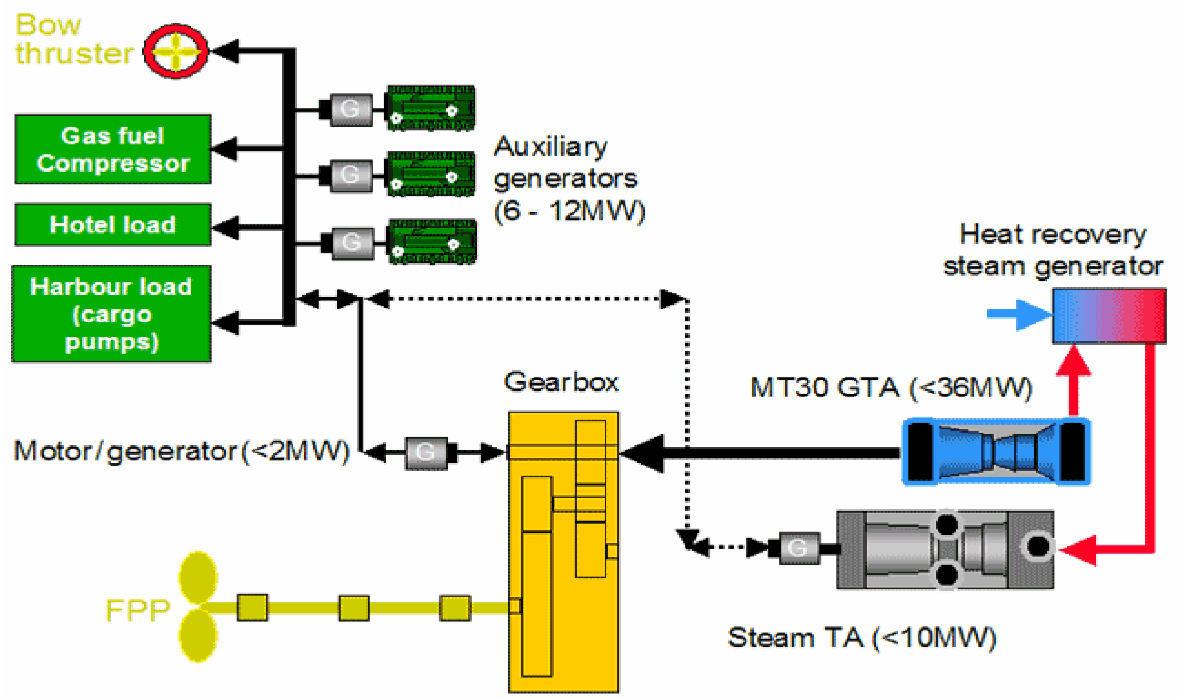


Fig. 2.3.5 Gas Turbine mechanical drive Combined cycle power plant [7].

Gas turbine electric drive combined cycle LNG carrier

The combined cycle gas turbine electric drive power plant is the power plant that allows most flexibility in the design and layout of the vessel. The gas turbine drives the propeller shaft by way of an electric motor. This arrangement allows the gas turbine generator power plant to be located away from the tank top. In this case, the power plant is housed in the superstructure, located over the mooring winch deck. The engine room size can therefore be reduced substantially, increasing cargo capacity by approximately 19,000 cubic meters. The traditional LNG carrier hull can be maintained, to minimise redesign costs.

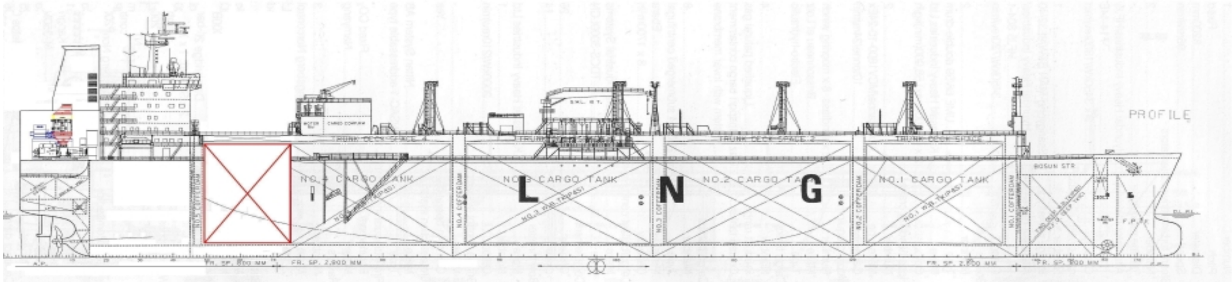


Fig. 2.3.6 Gas Turbine electric drive dombined cycle LNGC profile plan [4].

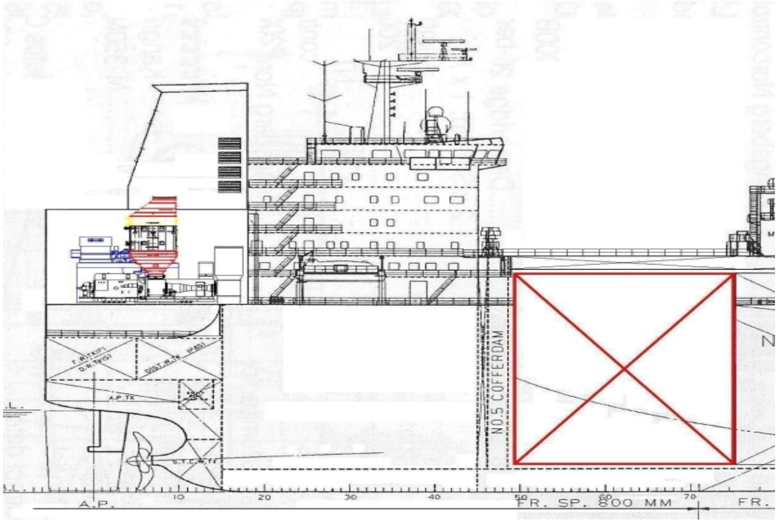


Fig. 2.3.7 Gas Turbine electric drive combined cycle extra cargo capacity [4].

Gas turbine electric drive combined cycle propulsion arrangement:

1 x Dual-fuel marine gas turbine generator, output 27 MWe;
1 x Steam turbine generator, output approximately 10 MWe;
1 x Exhaust gas boiler with supplementary firing and duct firing capabilities;
1 x Frequency controlled electric motor;
1 x FPP.

As can be seen in the fuel consumption and thermal efficiency diagram, the thermal efficiency of the gas turbine electric drive power plant exceeds 50 % in combined cycle operation. At operating conditions, the thermal efficiency is approximately 48 %.

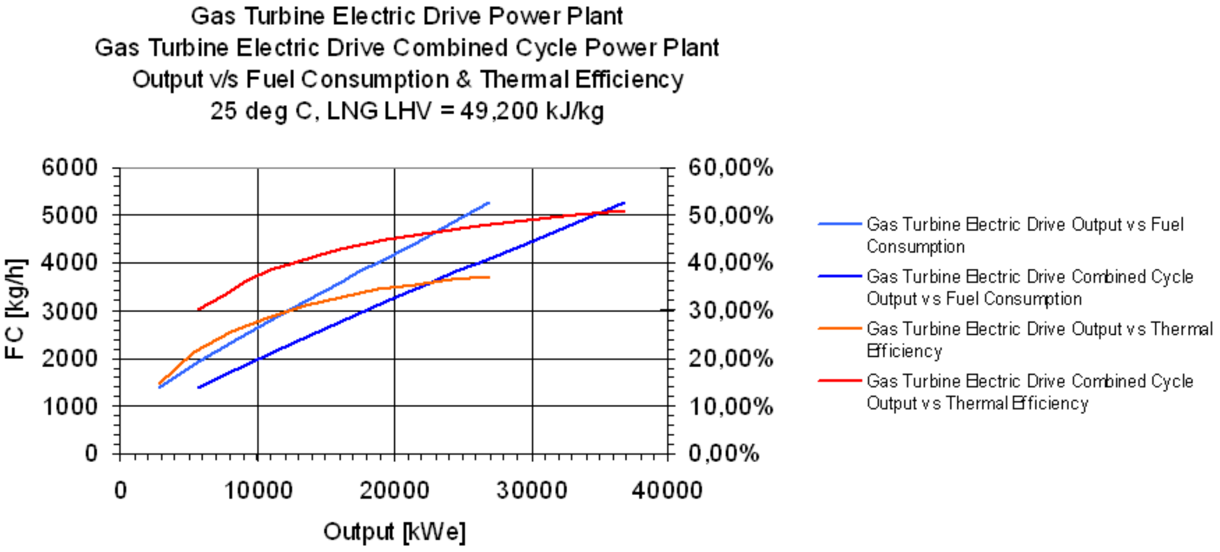


Fig. 2.3.8 Gas Turbine electric drive power plant vs Gas Turbine electric drive Combined cycle power plant [4].

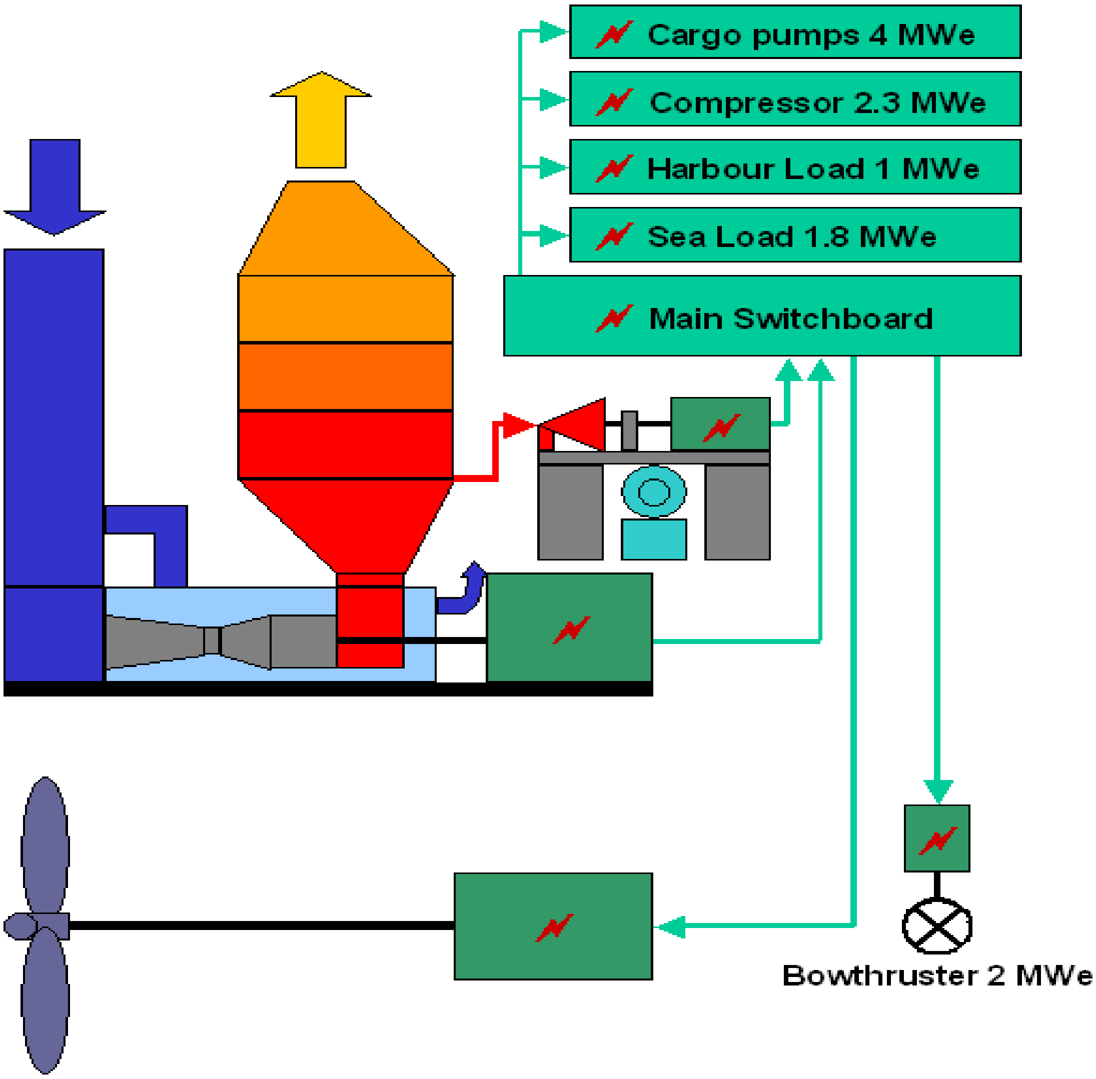


Fig. 2.3.9 Gas Turbine electric drive Combined cycle power plant [4].

The free power turbine of the gas turbine drives the generator. The generator feeds into the main switchboard. The main switchboard feeds all electric consumers. The propeller is driven by a frequency controlled electric motor. The exhaust gasses from the gas turbine raise steam in an exhaust gas boiler. This steam is used to produce power in a 10 MWe steam turbine generator. The steam turbine generator also feeds into the main switchboard [4].

Gas turbine electric podded drive combined cycle LNG carrier

The present LNG carrier is radically redesigned to exploit the full advantages of combined cycle gas turbine electric drive propulsion system. The engine room in the present design has been removed to make space for an extra cargo tank and MDO bunkers. The gas turbine generator, the steam turbine generator, the exhaust gas boiler, the condensers, the steam system and fuel handling systems have been moved to a dedicated superstructure on the main deck, over the mooring winch deck. Similar mooring deck arrangements can be found on cruise vessels and post-panamax container vessels.

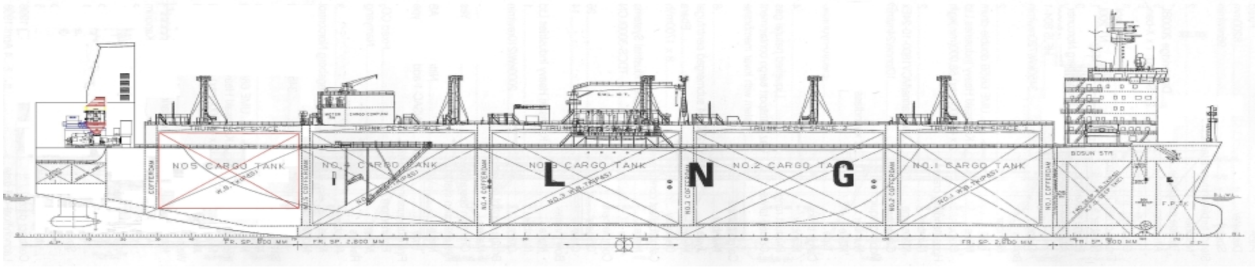


Fig. 2.3.10 Gas Turbine electric podded drive Combined cycle LNGC profile plan [4].

One or two podded drive propulsors are mounted beneath the hull to replace the FPP and the rudder. The podded drives place the main propulsion motors outside the vessel, saving space inside the vessel for revenue making purposes. Since there is no need to taper in the hull towards the stern boss, the parallel midship is extended to the transom. The keel gradually rises aft of frame 70 to provide a smooth flow of water to the podded drives. Without any taper, the hull frames are U-shaped and consequentially hull construction is much simpler and cheaper.

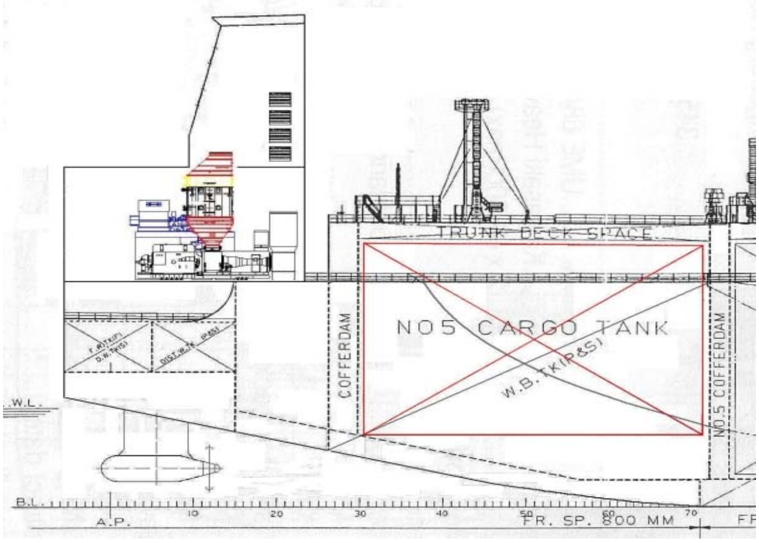


Fig. 2.3.11 Gas Turbine electric podded drive Combined cycle extra cargo capacity [4].

An extra cargo tank between frame 71 and 30 could increase cargo capacity by up to 24,000 cubic meters. Aft of cargo tank 5 between the cofferdam and the aft peak bulkhead MDO bunker can be located, with a total capacity of up to 5,200 cubic meters.

Gas turbine electric drive combined cycle propulsion arrangement:

1 x Dual-fuel marine gas turbine generator, output 27 MWe;
1 x Steam turbine generator, output approximately 10 MWe;
1 x Exhaust gas boiler with supplementary firing and duct firing capabilities;
1 x Frequency controlled electric motor;
1 (or 2) x Podded drive(s).

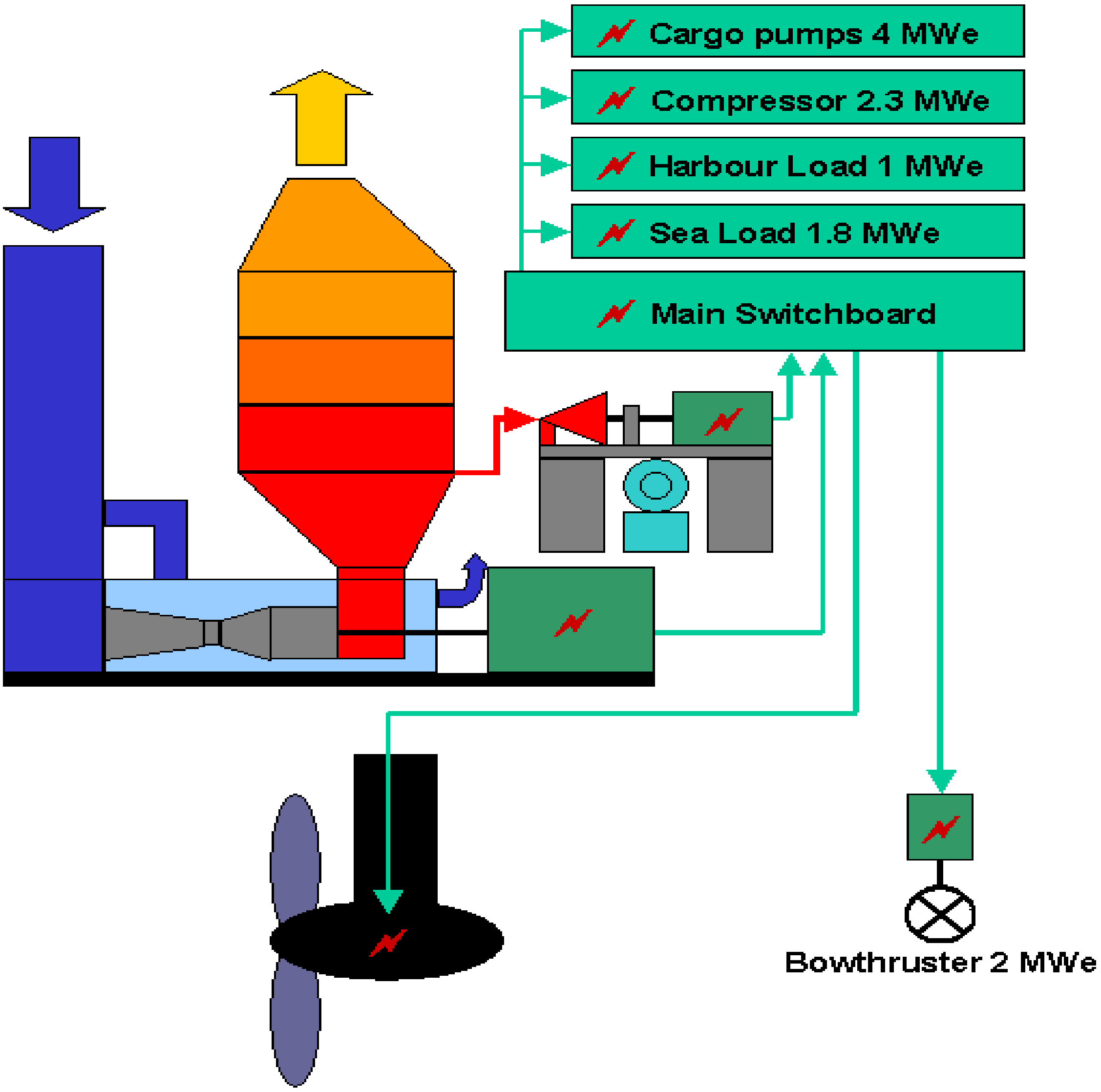


Fig. 2.3.12 Gas Turbine electric podded drive Combined cycle power plant [4].

The free power turbine of the gas turbine drives the generator. The generator feeds into the main switchboard. The main switchboard feeds all electric consumers. The propeller is driven by a frequency controlled electric motor. The exhaust gasses from the gas turbine raise steam in an exhaust gas boiler. This steam is used to produce power in a 10 MWe steam turbine generator. The steam turbine generator also feeds into the main switchboard [4].

2.3.2 Typical combined gas and steam turbine propulsion plant

Combined cycle has usually one main turbine and one auxiliary gas turbine with the addition of a heat recovery system which utilizes the energy in the main turbine exhaust gasses to add steam turbine driven electric generation into the propulsion/auxiliary power system. This configuration is promised to offer a 10% increase in overall efficiency compared to the simple cycle [3].

The most common proposal is the combined cycle gas turbine electric drive power plant. The gas turbine drives the propeller motor by way of an electric motor. 1 FPP is usually proposed. A stand by Diesel generator is also installed.

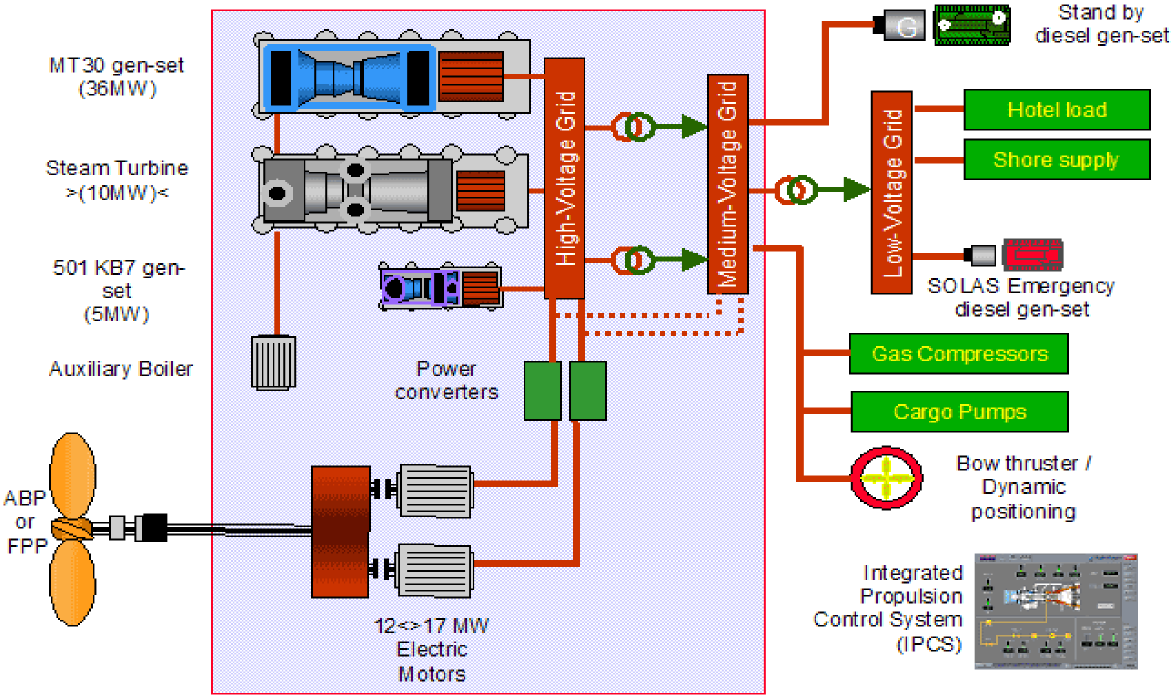


Fig. 2.3.13 Gas Turbine Combined cycle electric drive power plant single-screw [7].

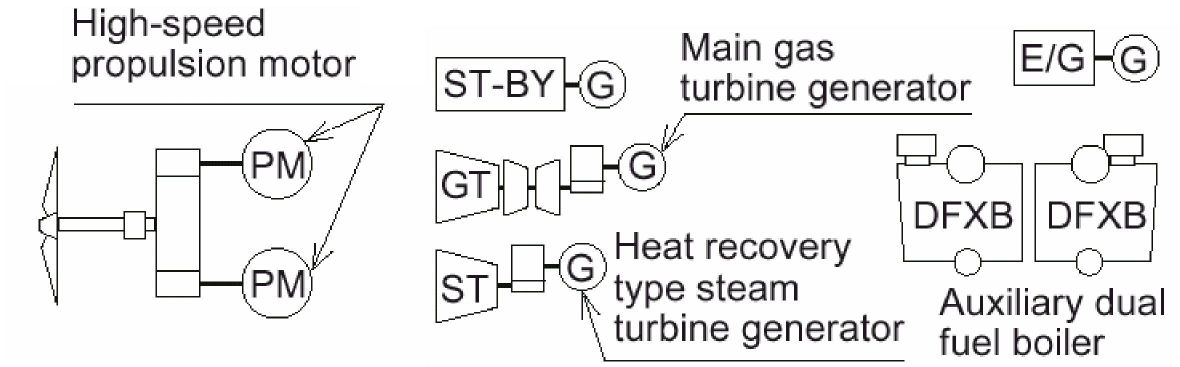


Fig. 2.3.14 Gas Turbine Combined cycle power plant single-screw [14].

In the Fig. 2.3.15 we can see the proposed components of an optimum propulsion plant for a 200,000m^3 LNG carrier with twin propellers based on a Rolls-Royce MT30 gas turbine operating on a combined gas/steam/electric (COGES) cycle [11].

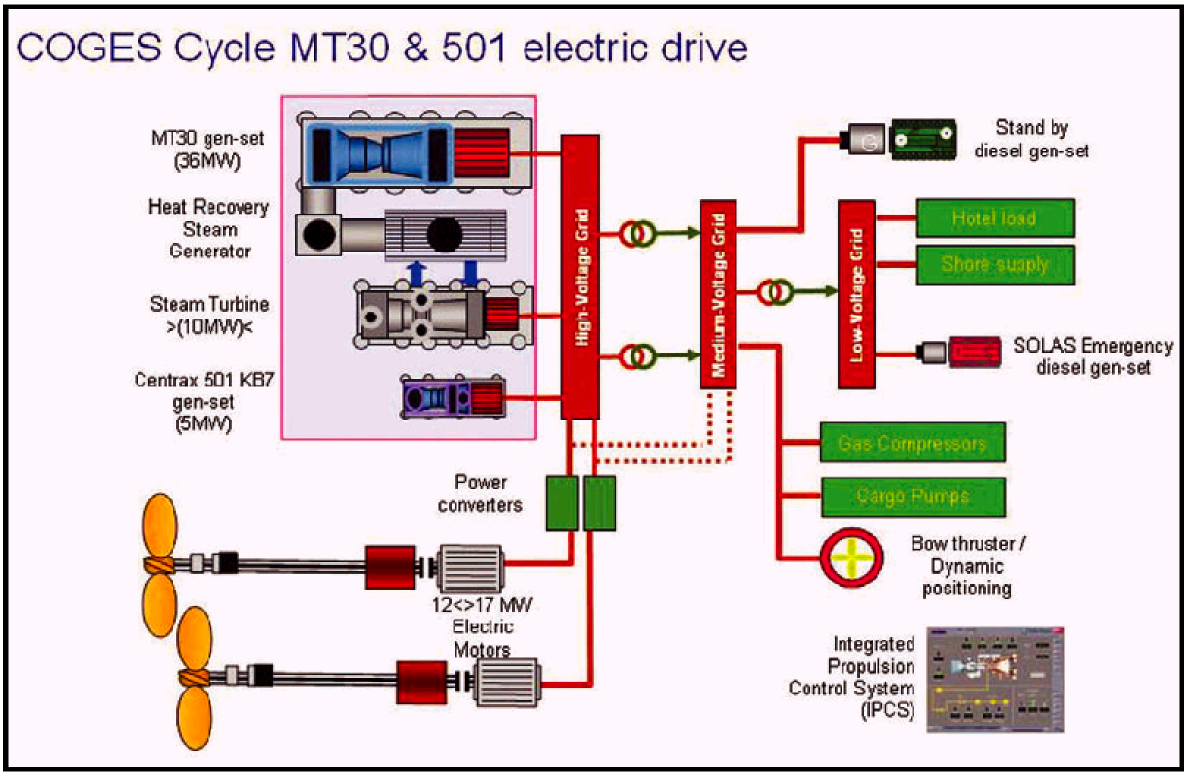


Fig. 2.3.15 Gas Turbine Combined cycle electric drive power plant twin-screw [11].

2.3.3 Advantages and drawbacks for a combined gas and steam turbine propulsion plant installation

<u>**Advantages**</u>

I. Increased thermal efficiency compared to steam turbines.
II. Increased cargo carrying capacity (for a 138,000 m^3 vessel, the increase in cargo carrying capacity is up to 13.8 % for mechanical or electric drive and 17.4 % for electric podded drive ,compared to a steam turbine vessel).
III. Low machinery weight and volume.
IV. Reduced installation and commissioning time in the shipyard through factory assembled and tested packages.
V. State of the art gas turbine with aero engine standards of reliability.
VI. Reduced installation costs.
VII. Low equipment cost.
VIII. Flexible modes of operation.
IX. Low equipment routine maintenance.
X. No hull redesign cost.
XI. Design flexibility.
XII. Propulsion and power generation redundancy.
XIII. Low engine noise and vibration.
XIV. Dual-fuel capability (simultaneous boil-off gas/MGO or MDO capability).
XV. Simplified engine room arrangement, smaller steam system, smaller cooling water system.

XVI. Gas turbine lube oil is not exposed to the combustion process, resulting in very low lube oil consumption and eliminating the need for extensive lube oil conditioning systems.
XVII. Gas turbines operate on MGO or MDO, obviating the need for fuel bunker heating, fuel line tracing and fuel conditioning systems.
XVIII. Lower fuel consumption than a steam plant.
XIX. Easy maintenance and engine change-out.
XX. Reduced crew members.
XXI. Reduced emissions compared to traditional Diesel and steam turbine configurations (no selective catalytic reduction (SCR) or other special exhaust gas treatment systems are necessary to meet strict regulations).
XXII. High availability.
XXIII. In the case of electric podded drive, increased propulsion efficiency through podded drives and increased manoeuvrability.
XXIV. FPP can be used without reversing gear in the case of electric propulsion (COGES).
XXIII. Improved Engine Management System (EMS), from aero engine's technology, which provides:
  i) Fully integrated alarm, monitoring and control functions by remotely mounted touch screen panels or through the direct integration into ship machinery control systems communicating with the EMS through a dual redundant databus.
  ii) The routine maintenance is limited to merely checking fluids and visual examination, as internal condition sensors enable the unit to be serviced on an 'on condition basis', avoiding unnecessary scheduled maintenance and only replacing what needs to be replaced.
  iii) Independent engine over-speed protection and an integral back-up power supply.
  v) Simplified wiring, reduced number of connectors and main processors, power supplies located outside of the module.

Disadvantages

I. Gas turbine has to be located very near to the propeller shaft and a reduction gearbox, reversing gear are required for direct mechanical drive with a FPP.
II. Gas compressor required to supply gaseous fuel at 30 bar pressure to the gas turbine. Parasitic load can go up to 2.3 MWe.
III. Expensive back up fuel.
IV. Higher capital cost (the capital cost of an LNG carrier with gas turbine combined cycle for a 130,000 –150,000 m^3 LNGC is expected to increase by about 5% or higher, when compared with a steam turbine driven vessel).
V. More complex and expensive than simple cycle.
VI. Relatively not common technology for commercial vessels.
VII. Specialized training of engineers is required.
VIII. In the case of electric drive increased cost and complexity compared to mechanical drive.
IX. At low loads the efficiency of the COGES plant is decreased dramatically and that causes a significantly increase in fuel consumption. The Diesel engines' tolerance to load changes is significantly better.

X. The efficiency of the combined cycle plant is directly related to the gas turbine size. The larger the output, generally, the more efficient the plant cycle is. So in smaller turbines it is difficult to attain efficiency close to 40%.

2.4 Slow Speed Diesel Engine

2.4.1 General information-technological development

LNG carriers represent the last stand for – in all other markets – practically extinct marine steam turbines. With efficiencies of only about 30%, versus the Diesel engines' more than 50%, and in combined systems even higher, Diesel engines are the propulsion system of choice in the marine industry.

This reason for the dominance of the Diesel engines is clearly demonstrated in the Fig. 2.4.1, showing the thermal efficiency of the various prime movers.

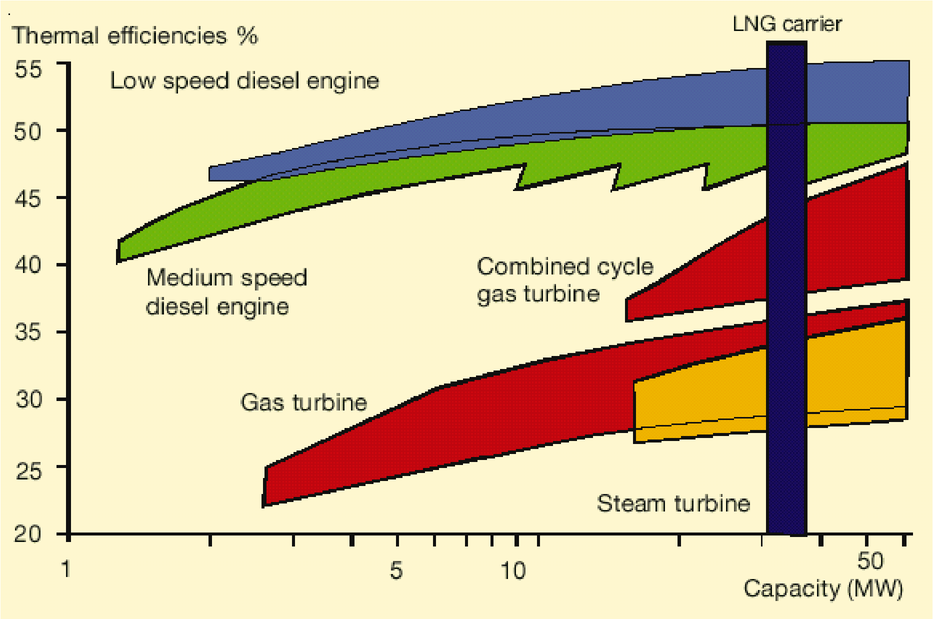


Fig. 2.4.1 Typical thermal efficiencies of prime movers [12].

As shown, steam turbine propulsion plants generally have a low efficiency and therefore need far more input energy than modern, fuel efficient Diesel engines. With efficiency and CO_2 emission being largely inversely proportional, many manufactures of slow speed Diesel engines as MAN B&W are proposing alternative propulsion concepts based on low speed Diesel engines with electronic control for modern LNG tankers.

HFO burning fuel efficient Low Speed two-stroke Diesel engines in single or twin propeller configuration, in combination with the reliquefaction of the Boil Off Gas (BOG), offer economic benefits for those trades where loss, i.e. consumption of cargo, is not accepted and the supply of the full amount of cargo is honoured.

However, LNG carriers are expensive ships, and the contractual supply of cargo is usually tied by strict charter party conditions. Therefore, the market has been hesitant to look at and accept other propulsion systems.

Now this has changed. With the market launch of electronically controlled low speed Diesels and reliable independent reliquefaction technology, all the traditional reasons not to leave the steam turbine have become invalid.

While reliquefaction is widely used in gas handling on land, it has been used on board ship so far only on LPG carriers. Recently, the technology for reliquefying LNG on board ship has been matured and commercialised. One Norwegian system, the Moss-RS Reliquefaction plant, is being offered for ships by Hamworthy KSE.

This patented system for reliquefying boil-off gas, establishes a solution for pumping LNG back to the tanks and selling more LNG to the buyers of gas. For a traditional size of LNG carrier, this company estimates that US$2-US$5 million can be saved annually by specifying such plant.

The boil-off gas reliquefaction concept is based on a closed nitrogen cycle extracting heat from the boil-off gas. Several novel features such as separation and removal of incondensable components have resulted in a compact system with low power consumption.

The LNG boil-off is compressed by the low duty (LD) compressor (BOG compressor), and sent directly to the so-called cold box. The cold box in which the boil-off is reliquefied is cooled by a closed refrigeration loop (Brayton cycle). Nitrogen is the working medium.Fig. 2.4.2 shows the standard Moss RS reliquefaction system.

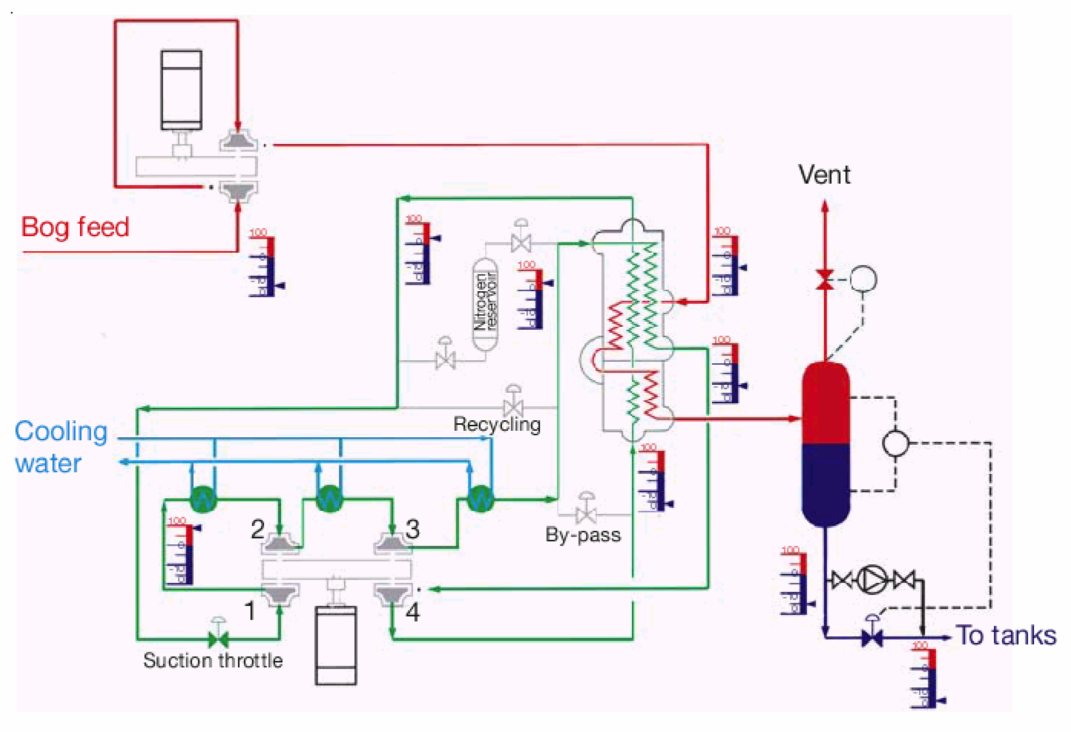


Fig. 2.4.2 Standard Moss RS reliquefaction system [12].

For a 149,000 m^3 carrier, the plant requires about 3.5 MW of electrical power. This converts to about 20% of the energy available in the recycled BOG being expended during the reliquefaction process or about 20 tons of fuel per day is consumed to cover the electrical demand for this reliquefaction plant.

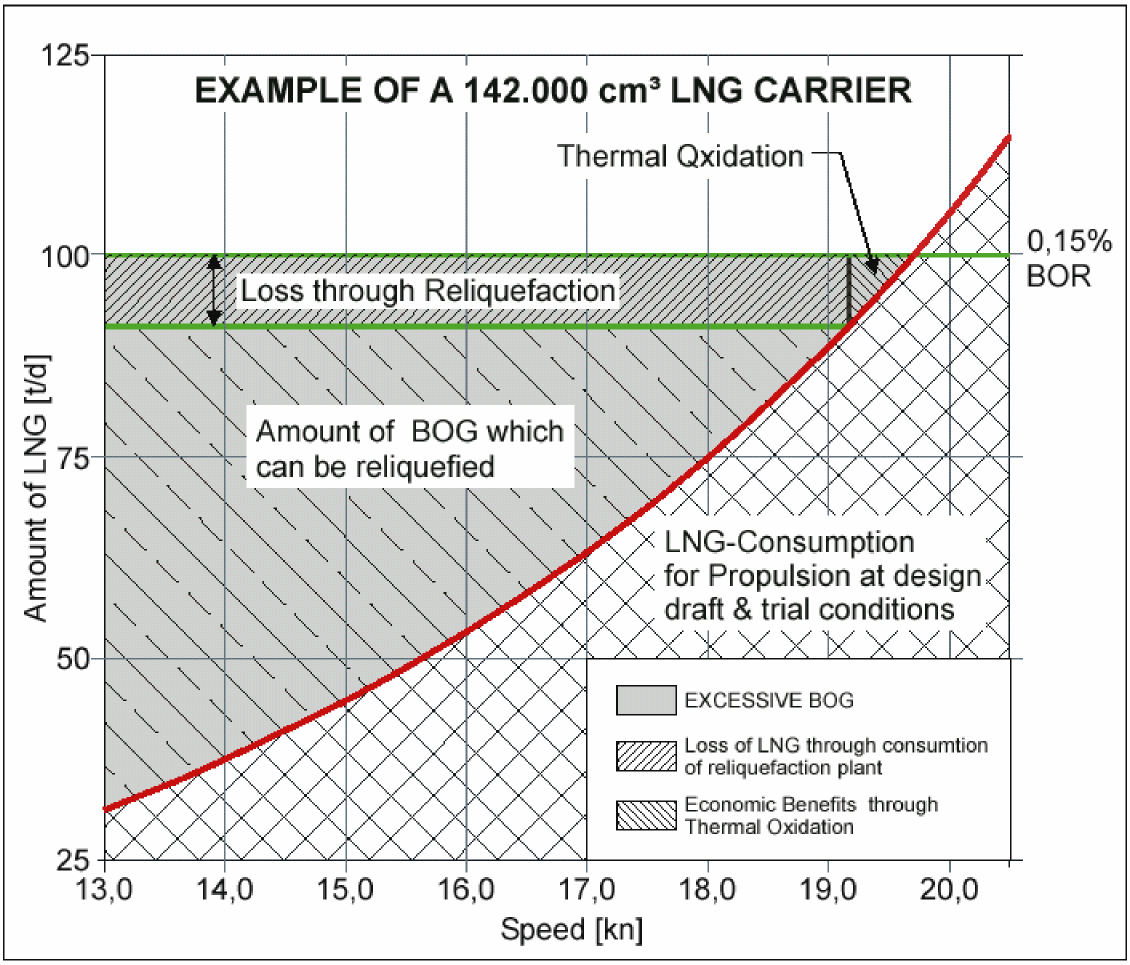


Fig. 2.4.3 Example for BOG reliquefaction viability [13].

LNG carriers, like oil tankers, are not permitted to immobilize their propulsion machinery while in port and close to port areas. Hence, redundancy is required.

For the steam ship, redundancy is considered fulfilled by having two boilers, whereas no redundancy is required for the single steam turbine, propeller shaft and propeller. The two boilers will have a steam-dumping condenser to be used for surplus steam when the turbine is not operating.

For Diesel engines, which require more maintenance on a routine basis than steam turbines, either a multi-engine configuration or an alternative power supply possibility for a single engine configuration is required. Immobilisation for carrying out maintenance work on a single configured two-stroke Diesel engine has so far been considered an obstacle on LNG carriers.

Shuttle tankers in the North Sea were originally equipped with twin low speed engines and twin propellers. This ensured that approximately half of the propulsion power is always available, and that one of the Diesel engines can be maintained without immobilising the vessel or compromising safety.

However, now single engine ships are widely used for this trade, as for chemical carriers and LPG vessels – a virtual proof of the inherent 'self redundancy' of such engines [12].

In any case, more redundancy could be achieved by installing a combined power take off, power take in (PTO / PTI) system (released by a Danish gear manufacturer Mekanord, for its 580HS and 650HS cp-gearboxes). The system has a PTI connected by gears and hydraulic clutch to the main pinion driving the propeller shaft.

At times of low power requirement, the system allows the main clutch to be disengaged and the main engine to be stopped. Power transmission to the propeller shaft comes from an auxiliary engine via an electric motor, the PTI, a PTI clutch, PTI gearwheels and the main pinion/gearwheel. The auxiliary engine can be operated at or near full load in this condition, providing efficiency and fuel economy compared to a conventional set up, where the main engine has to operate at much reduced load at times of low power requirement.

The system also provides emergency propulsion in the case of a main engine failure (the e-motor on the shaft line would be driven by the Diesel gensets which would allow the ship to sail at a safe manoeuvring speed). The availability of the PTI system corresponds to main engine ratings up to 3,500 kW at 800-1000 rev/min. This is a proven design which has been installed on several chemical tankers [13].

The International Association of (marine) Classification Societies' ((IACS) redundancy requirement for a reliquefaction plant for LNG carriers is fulfilled if one of the following options is installed:

Alternative 1: A spare capacity at least equal to the largest single reliquefaction unit should be fitted.
Alternative 2: Auxiliary boiler(s) capable of burning the boil-off vapours and disposing of the generated steam via a steam dumping system
Alternative 3: Gas Oxidiser, i.e. burning the boil-off gas in a separate burner unit positioned in the vessel's stack
Alternative 4: Controlled venting to the atmosphere of cargo vapours, if permitted by the authorities in question
Alternative 5: Two 100% reliquefaction plants with one cold box, comprising the following:
Two BOG-compressor units (two-stage centrifugal compressor)
Two N_2-compressor/expander units (three-stage integrated gear centrifugal compressor with one expander stage)
One cold box
One LNG phase separator
One LNG forced return pump
Auxiliary systems

Which one to operate of the two BOG-compressor units and N2-compressor/expander units can be freely chosen by operating the applicable valves. Changeover of equipment is done manually, and must be done only when the machinery is shut down. Simultaneous parallel operation of the equipment will not be possible.

Redundant low speed engine propulsion concepts, as outlined above, ensure that sufficient power is available for safe navigation and, for the twin engine concept with completely separated engine rooms, even an additional margin towards any damage is obtained.

For LNG carriers, a twin engine configuration is proposed to alleviate any possible doubt on reliability and redundancy.

As mentioned above, one of the main supporters of this propulsion option is MAN B&W. The low speed engine programme is developed in Denmark and manufactured by a family of licensees at major shipbuilding centres of the world. Single unit powers range from 2,000 HP to well over 100,000 HP, all for direct coupled installation at propeller speeds from 250 RPM down to 60 RPM for the largest propellers.

The power requirement for an LNG carrier calls for some 40,000 HP, typically two of 60 or 70 cm bore units. Also the introduction of electronically controlled camshaft-less low speed Diesel engines is now gaining momentum.

Camshaft-controlled Diesel engines have been the state of the art ever since the birth of reciprocating machinery and have been refined and developed ever since. However, a mechanical cam is fixed once made and, in spite of various mechanical and hydraulic add-on devices like VIT, etc., timing control possibilities are limited with mechanical cams. Not least fuel injection pressure control and variation over the load range have limitations with a cam-controlled engine. Therefore, the main purpose of changing to electronic control is to ensure fuel injection timing and rate, as well as the exhaust valve timing and operation, exactly when and as desired.

Especially with respect to the fuel injection rate, the control system has been so designed that it is possible to maintain a rather high injection pressure also at low load, without the limitation of the camshaft-controlled engine, where this would result in too high pressure at high load. The ‘cam angle, inclination and length are electronically variable. In addition, the ME engine features electronic control of the cylinder lube oil feed, by having their proprietary Alpha Lubricators integrated in the system. With the Alpha Lubrication system, about 0.3 g/bHPh cyl.oil can be saved, compared with engines with mechanical lubricators.

The electronic control of the engine fuel injection and exhaust valves improves low-load operation, engine acceleration, and gives better engine balance and load control, leading to longer times between overhauls, also by implementation of enhanced diagnostics systems. It will give lower fuel consumption, lower cylinder oil consumption and, not least, better emission characteristics, particularly with regard to visible smoke and NOx[1].

For the ME engines, the electronic control system has been made complete. Hence, the ME engine features fully integrated control of all functions like the governor, start and reversing, fuel, exhaust and starting valves, as well as cylinder oil feeding.

When installing an electronically controlled two-stroke engine using HFO and a reliquefaction plant on LNG/LPG carriers,CO_2 and SOx will be reduced and, at the same time, there will be a remarkable reduction in operational costs, as the boil-off gas will be regained as gas and put back into the tanks.

Also reduced speed of vessels close to shore could reduce emissions by approx. 20% per 10% reduction of speed.

With an electronically controlled engine, the fuel injection and exhaust gas valve activation is fully programmable, so that the optimum reduction of exhaust emission levels can be met at all engine loads.

With turbo generator and turbo-compound system plants, the prime mover concept can reduce the plant’s consumption of fuel and, beneficially, achieve a reduction of emissions.The concept utilises the high-efficiency air flow from the turbochargers for a power take-off or power take-in system [12].

The next generation of emission control systems, involves systems integrated into the engines, where NOx is reduced by operating with water in the engine intake air, also called the HAM “Humid Air Motor” principle, and the use of EGR (exhaust gas recirculation).

These methods, so far, look very promising, and a reduction of NOx of up to50% and a reduction of particulates and HC seems achievable, even though final tests and production maturing still need to be taken care of.

The reduction of the sulphur content in HFO is so far the most efficient method to reduce SOx, and this reduction has therefore been the reason for a lot of considerations from

---

[1] See also at the Appendix C about exhaust gas emissions from ships with Heavy Fuel burning Diesel engines.

the Industry. The oil companies may need to change their equipment to low-sulphur fuel production, and the shipowners could face considerably higher fuel costs.

The technique for removing SOx from engine exhaust gas on ships has proved to be very expensive and complicated and does not seem to be a viable solution with the systems being used today.

Another consideration for ships in service is the operation on different fuels with different sulphur levels. Ships were previously designed for HFO operation only, with relatively small tanks for distillates. If two fuel grades are to be used, there will be a change-over situation when operators change from one emission zone to another, e.g.4.5% sulphur to 1.5% sulphur, which is the limit in the low-sulphur restricted areas [18].

2.4.2 Typical slow speed Diesel propulsion plant

Based on the technology described in the foregoing, the machinery to replace the steam turbine and boilers in a typical 145,000 m^3 LNGC is therefore the following:

2 x approx. 20,000 HP low speed fuel burning ME-type Diesel engines[2] which drive two FPP.

The bridge and engine room control system shall be able to handle operation with both one (emergency) and two (normal) engines.

In the case of operation on two engines, the control system must be able to handle both individual control and simultaneous control of the engines. Simultaneous control consists of equality in power distribution, order for reversing, start of engines and stop of engines. The control system shall, in case of failure on one of the engines, be able to ensure continuous operation with only one engine without jeopardizing manoeuvrability or safety of the ship or engines.

In the event of an emergency situation, with one engine out of service, the actual propeller curve for the working engine will be conceived as 'heavy' up to 5-10%.

In the case of FP propellers, it is presumed that, in most cases, the shaft is declutched from the engines and the propeller wind-milling, while the engine can be repaired, alternatively that a shaft brake is applied.

In the case of CP propellers, it is presumed that the propeller is at zero pitch and the shaft brake is active. If engine repair or overhaul is to take place during sailing, declutching is necessary.

In either case, the working engine will have to accept the 'heavy propeller', i.e. higher torque, which basically calls for changed engine timing.

With the ME engine concept, this can be done by push button only, activating "single engine running mode". This can be pre-programmed into the software just as the so-called "economy mode" and "low NOx emission mode". Hence, the operating engine in case of non-availability of the other engine will be readily optimised for the purpose, and full mobility of the vessel ensured.

As per calculation, a speed of 75% of the design speed of the vessel can be obtained with a single engine in operation.

The vessels are equipped with two 100% reliquefaction plants with one cold box (the most common proposal), comprising the following:

- Two BOG-compressor units (two-stage centrifugal compressor)

---

[2] A twin (instead of a single engine + an alternative power supply) configuration is proposed to alleviate any possible doubt on reliability and redundancy.

- Two N_2-compressor/expander units
- (Three-stage integrated gear centrifugal compressor with one expander stage)
- One cold box
- One LNG phase separator
- One LNG forced return pump
- Auxiliary systems

Which one to operate of the two BOG-compressor units and N2-compressor/expander units can be freely chosen by operating the applicable valves. Changeover of equipment is done manually, and must be done only when the machinery is shut down. Simultaneous parallel operation of the equipment will not be possible [12].

Also 4 Diesel electrical generators are installed to cover the overall electrical demand.

A propulsion system based on two slow speed Diesel engines directly coupled with two FPP and steam turbine generators with an exhaust gas boiler for the electric power coverage, is a solution proposed by Mitsubishi Heavy Industries. A BOG reliquefaction plant offers the necessary redundancy (Fig. 2.4.7).

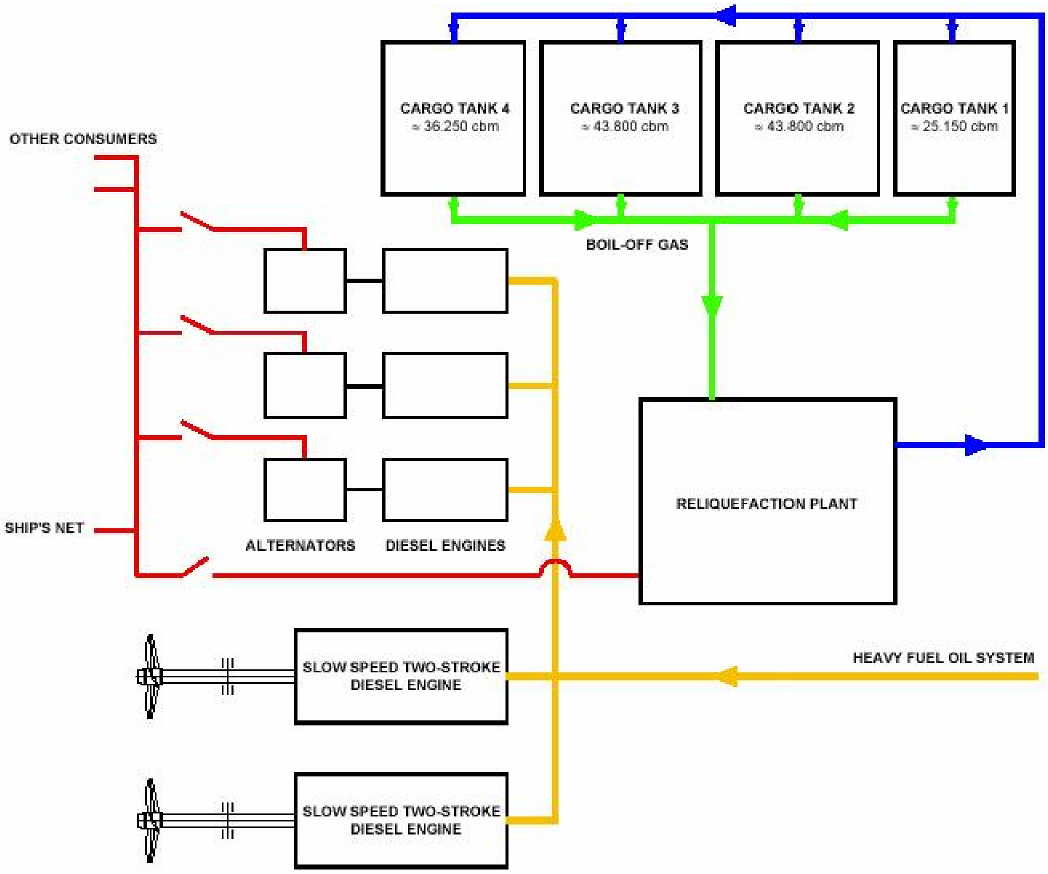


Fig. 2.4.4 Diagram of two slow speed Diesel engines with reliquefaction [13].

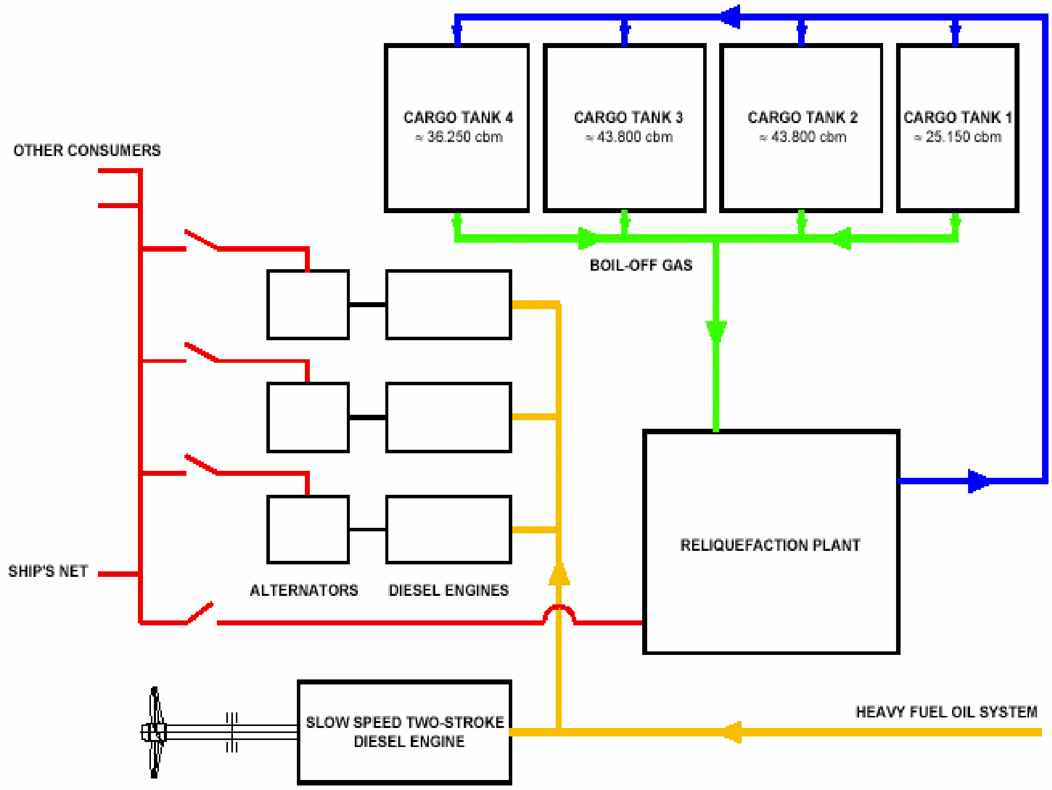


Fig. 2.4.5 Diagram of one slow speed Diesel engine with reliquefaction [13].

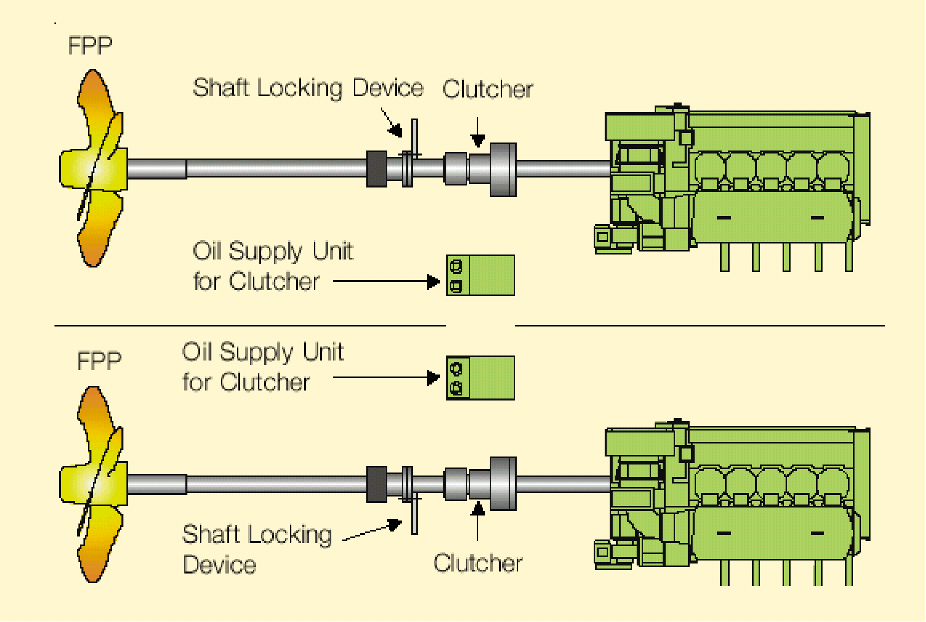


Fig. 2.4.6 Twin-engine configuration [12].

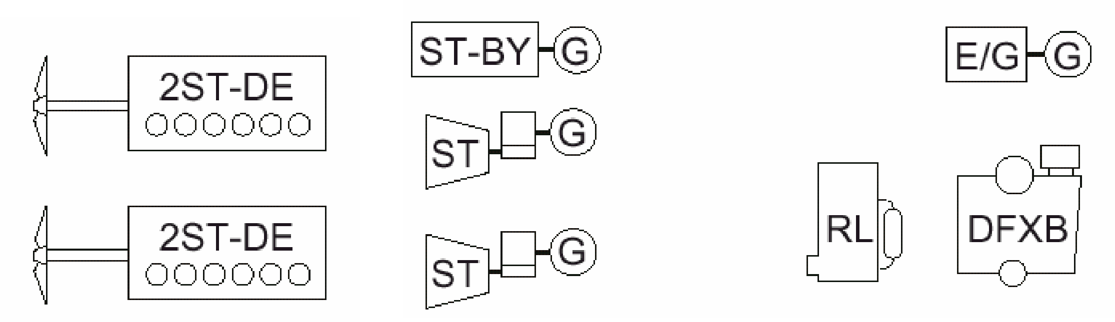


Fig. 2.4.7 Propulsion system directly coupled with Diesel engine + Steam turbine generators + BOG reliquefaction plant [14].

2.4.3 Advantages and drawbacks for a slow speed Diesel propulsion plant installation

Advantages

I. High overall fuel efficiency - up to 50% - (about 60% higher than for the steam plants) resulting in lower energy consumption and thus lower operating cost compared to steam plants.
II. Smaller Engine room required hence more cargo space for a given vessel compared to steam propulsion. (For a 138,000 m^3 vessel the increase in cargo carrying capacity is of the order of 6,000 m^3 when compared with a steam turbine vessel).
III. The amount of LNG delivered is higher as the BOG is reliquified.
IV. Reduced 'heel'[3] required for ballast voyage because the cargo tank temperature can be maintained by spraying *reliquified* LNG back into the cargo tanks.
V. The amount of CO_2 released can be reduced by approximately 60,000 mt/ship/year compared to a steam ship for a 150,000 m^3 LNG carrier (reduction of about 30%) because of the higher thermal efficiency of the slow speed Diesel.
VI. In the case of a design using twin Diesel engines, with separate engine rooms, there is full propulsion redundancy and added safety margins against floods and fires in the engine room.
VII. The reliquefaction plant ensures that all cargo handling takes place on the deck, avoiding gas entering the engine room. This makes cargo and engine room operations simpler and safer.
VIII. The reliquefaction plant and the separation between the cargo and the engine room, reduces the constraints on the propulsion plant design and the type of fuel.
IX. The nitrogen in the LNG boil-off gas (BOG) is not reliquefied; this results in reduced nitrogen in the tanks during the voyage, better control of tank pressure and lower power requirement for the RS system.
X. The reliquefaction system is prefabricated on skids for easy installation and hook-up.

---

[3] 'Heel' is the small amount of LNG cargo (around 1-2 % of a ships capacity) retained on board to keep the tanks and pipelines cold ready for loading the next cargo. It can be circulated through the cargo pumps and lines, and sprayed into the cargo tanks to cool them further before arrival at the loading berth.

XI. The reliquefaction system has automatic capacity control and can be stopped when the cargo pumps are in operation. This eliminates the need for extra generator capacity.
XII. No-or limited- increase in cargo-handling machinery space.
XIII. No extra personnel are required for operation and maintenance of the reliquefaction plant.
XIV. Availability of engineers experienced with this type of propulsion system.
XV. The design, installation and operation of a Diesel plant will be well known to shipyard and owner (Most all shipyards that today build LNG carriers have much more experience of installing Diesel engines than steam turbines and boilers, which adds to the advantage of Diesels).
XVI. The benefit of Diesel engine propulsion of LNG carriers is calculated to be up to approx.US$3.0 million per vessel per year. Especially the LNG selling price has a positive impact on the advantage of Diesel engine propulsion. The benefit gained in operating costs and the additional income from the sale of LNG by Diesel engine propulsion and reliquefaction will, in all cases, be sufficient to justify even large differences in investment costs.
XVII. In the case of an electronically controlled engine:
  i) Lower SOCK and better performance parameters at any load thanks to electronically controlled variable timing of fuel injection and exhaust valves at any load.
  ii) Control system offers more precise timing and thereby better engine balance and less noise with equalized thermal load in and between cylinders, minimising the risk of premature need for overhaul.
  iii) Improved emission characteristics, with lower NOx and smokeless operation.
  iv) Lower RPM possible for manoeuvring.
  v) Better acceleration, astern and crash stop performance.
  vi) System comprising performance, adequate monitoring and diagnostics of engine for longer time between overhauls.

Disadvantages

I. The readily available and clean BOG is not utilized for the propulsion of the vessel.
II. The reliquefaction plants require a substantial amount of electric power (3,5-5 MW) to operate and are costly, heavy and have only been applied in the marine environment on a very limited scale (at present there is experiences only from one shipboard LNG re-liquefaction plant (NYK)).
III. Higher NOx and SOx emissions compared to alternatives burning LNG instead of HFO (without additional equipment like SCR units or direct water injection, NOx emissions are substantial; as an inevitable consequence of using HFO as a fuel, SOx emissions are high too).
IV. Less redundancy than existing steam systems in the single engine layout.
V. Diesel engines require more maintenance on a routine basis than steam turbines.
VI. Higher lub oil consumption compared to steam turbine which adds to the operating cost.
VII. A system comprising the traditional steam plant is estimated to cost around US$20 million. The capital cost of an LNG carrier with slow speed Diesel and reliquefaction plant for a 130,000 –150,000 m^3 LNGC is expected to increase by about 0-1% when compared with a steam turbine driven vessel, twin engine installation gives obviously the higher difference.The twin-screw solution proposed does represent

added cost on the hull side at some shipyards. This could be up to US$5 million although the total cost is still comparable to that of the steam plant.

2.5 Medium Speed Diesel Engine

2.5.1 General information-technological development

Propulsion with medium-speed Diesel engines would naturally be a multi-engine installation, inherently offering some redundancy. The installation could be based on a single- or twin-screw arrangement.

A single-screw, twin four-stroke Diesel engine option would require a moderate-sized gearbox, couplings and a CP propeller. Continuous low-load operation on heavy fuel oil is not desirable, and therefore a PTO and shaft generator would probably not be feasible owing to the low load in port for the running of one of the main engines for electrical cargo pumps. Therefore, adequate auxiliary generator capacity would have to be installed to cover the power requirement of all electric consumers.

A twin-screw Diesel-mechanical medium-speed solution could have two engines (with single-in/-out gearboxes) or four engines (with twin-in/single-out gearboxes). In the case of a four-engine arrangement with smaller engines than in the twin-engine option above, one main engine could drive a primary shaft generator suitable for cargo operation, which could lead to reduced installed auxiliary generator capacity.

A propulsion system based on heavy-fuel engines will naturally require reliquefaction plant to take care of the boil-off gas [16].

A engine rated close to 19 MW, as those designated for LNG carriers in a twin engine configuration, emits a total of 136 tons of exhaust gases per operating hour (full load). As illustrated by Fig. 2.5.1, the majority of the constituents of the exhaust gases are harmless compounds frequently abundant in the atmosphere. The greenhouse gas CO_2 amounts to approximately 6 vol-%, a low amount as a direct result of the high overall efficiency of Diesel engines.

Only 0.35 vol-% in case of a high sulphur heavy fuel oil (HFO) with 4 % S are real pollutants (Fig. 2.5.2) with about equal amounts of sulphur oxides (SOx) and nitrogen oxides (NOx) and minor amounts of carbon monoxides (CO), hydrocarbons (HC) and particulate matters (PM).

The percentages in Fig. 2.5.1 refer to unregulated engines where emphasis has been placed on achieving lowest fuel consumption rates. With low sulphur fuels SOx can be easily halved, however at the penalty of a higher fuel price. With such fuels (2 % S), burnt in a NOx-optimised engine complying with IMO’s NOx limiting curve, the pollutant fraction amounts to 455 kg/h at full load. This corresponds to 0.3 % of the total exhaust gas flow [19].

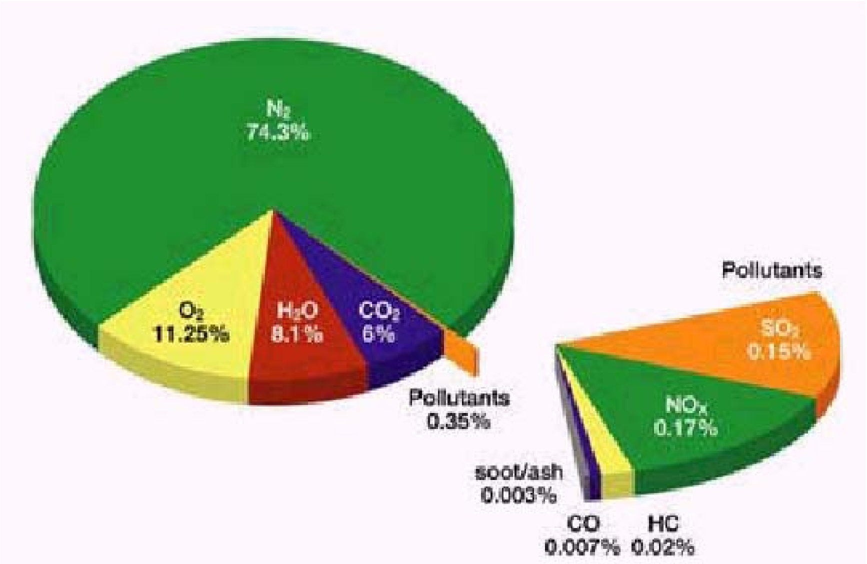


Fig. 2 .5.1 Exhaust gas emissions of medium-speed Diesel engines (HFO with 4% sulphur) [19].

2.5.2 Typical medium speed Diesel engine propulsion plant

Two main engines and mechanical drive through gearbox with 3-4 gensets for the electric power coverage is a possible configuration although electric propulsion offers by far the most flexible alternatives for machinery arrangement. It is also easy to build the required level of redundancy into the system with divided engine rooms and ancillary systems.

With electric propulsion, there is no need for separate auxiliary generator sets, so the total installed power can be reduced. With electric cargo pumps, one generator set should be sufficient to handle the power demand for cargo operations.

Single-screw electric propulsion with a fixed pitch (FP) propeller may be selected if appropriate redundancy is built into the electric drive system. More than one electric motor can be used for the propeller shaft either in tandem, or coupled separately through a gearbox. The electric motors can also be double wound for additional redundancy.

Twin-screw propulsion can be configured either with podded drives or FP propellers driven by electric motors. Another possibility would be to utilise a single FP propeller complemented by a podded drive replacing the rudder. Using the 'contra-rotating propeller principle' with the podded drive immediately abaft the main propeller, a considerable propulsive efficiency gain is possible. The main propeller would cater for approximately half the required propulsive power. The other half would be provided by the podded drive [16].

So, the most common proposal is Diesel-electric propulsion with one or two shaft lines or two azimuthing thrusters and 2 reliquefaction plants.

2.5.3 Advantages and drawbacks for a medium speed Diesel engine propulsion plant installation

Advantages

I. High propulsion redundancy, especially on a twin propeller configuration.
II. Higher availability of experienced crew comparing to steam turbine.

III. Auxiliary Electric power demand is covered by the propulsion engines eliminating the need for additional auxiliary gen sets.
IV. Increased cargo capacity compared to the steam propulsion option.
V. Higher efficiency compared to steam propulsion.
VI. The amount of LNG delivered is higher as the BOG is reliquified.
VII. The reliquefaction plant ensures that all cargo handling takes place on the deck, avoiding gas entering the engine room. This makes cargo and engine room operations simpler and safer.

Disadvantages

I. Higher capital cost due to the reliquefaction plant which is of the order of $10million for 2x100% units.
II. Higher NOx and SOx emissions compared to alternative burning LNG instead of HFO.
III. The readily available and clean BOG is not utilized for the propulsion of the vessel.
IV. Higher maintenance as a result of more moving parts, higher speed and more cylinders in a particular installation.
V. In the case of electric propulsion, about 4% efficiency loss in the electric power generation process.

2.6 Slow Speed Gas-Diesel Engine

2.6.1 General information-technological development

The slow speed Diesel with dual gas and heavy fuel oil burning capability, propulsion option for LNG carriers is now a realized solution. Recent technical development has made it possible for manufactures to offer this option of dual fuel operation for LNG carriers but this alternative has not yet been thoroughly tested.There is one land based installation on a power plant having a slow speed Diesel in operation on natural gas only. While this tests the ability of the engine to operate only on gas, it does not test the ability to operate with a mix of two fuels, HFO and gas.

Gas-Diesel engines act according to the Diesel principle and can virtually burn any possible mixture of gas and liquid fuel, with only a few restrictions to the quality of the gas. As the mixture of gas and liquid fuel is injected into the combustion chamber during air compression, the required injection pressure is high. For two-stroke gas-Diesel engines, a gas pressure of around 250 bar is required.

Fuel burning options available with this type of engine are, the ‘dual fuel mode’ with minimum pilot oil amount, the ‘specified gas mode’ with the injection of fixed gas amount and the ‘fuel oil mode’.

The system focuses around a high pressure reciprocating compressor supplying the engine with the main gas injection, while ignition is ensured by pilot oil injection. The fuel injection timing on dual fuel engines is either mechanically or electronically controlled. In the electronically controlled version (like MAN B&W ME-GI engines) it can be user-defined and is subject to greater control and flexibility, thereby allowing the dual fuel concept to be further optimised [12].

The efficiency of the slow speed Gas Injection dual fuel engines is the same as an ordinary slow speed Diesel engine, due the Diesel cycle. The system efficiency will be higher than that of other gas consuming propulsion systems,including dual fuel medium speed Diesel electric, even considering the compressor power.The higher efficiency reduces the amount of energy required for propulsion and brings it much closer to the amount of energy available from the boil off gas. Therefore the supplementary fuel oil requirement is drastically reduced, or even eliminated, compared to that of a steam turbine installation.

However the gas supply must be compressed to about 300 bar, to facilitate injection into the cylinder. This requires considerable energy, expensive and maintenance intensive compressors and it also raises safety concerns.

Full redundancy as required by International Association of Classification Societies (IACS) can be met with one compressor, one reliquefaction unit or one oxidizer as discussed later for the slow speed Diesel engine [5].

Emissions of gas-Diesel engine installations are generally lower than those of steam turbine and Diesel engine installations as a result of higher efficiency and cleaner fuel, respectively.

The other basic elements of a slow speed Gas Injection dual fuel engine is generally the same as an ordinary slow speed Diesel engine either mechanically or electronically controlled, as also discussed later [12].

Also MAN B&W Diesel is closely cooperating with major Korean shipyards, Samsung, Daewoo and Hyundai, on the use of ME-GI engines for LNG carriers. Work is now being finalised on the Hazid/Hazop (Hazard identification Studies/Hazard and Operability Studies) safety study for the entire gas supply system from LNG tanks including vapourizer gas compressors and oxidizers, as well as internal gas system on the electronically controlled ME-GI dual fuel low-speed MAN B&W Diesel engines. Det Norske Veritas (DNV) chaired the first Hazid/Hazop meeting in June 2005. This meeting was held in connection with the total gas supply system and was initiated by Hyundai.

Apart from DNV, there were representatives from Hyundai, MAN B&W Diesel, and a compressor supplier, Burkhardt Compression AG, at the meeting. The high-pressure gas injection concept for the engine itself has already been evaluated and accepted by major classification societies. A mechanically controlled MC-GI engine has been working for several years as a power plant in Japan, confirming gas burning ability and performance[40].

2.6.2 Typical slow speed gas-Diesel engine propulsion plant

Based on the technology described in the foregoing, the machinery to replace the steam turbine and boilers in a typical 145,000 m^3 LNG carrier is therefore 2 approx.20,000 HP low speed Gas Injection Diesel engines driving either two FPP (the most common option) or two CPP, with a clutch and brake on each shaft so that one propeller could continue operating in the event of failure of the other. A twin (instead of a single engine + an alternative power supply) configuration is usually proposed to alleviate any possible doubt on reliability and redundancy [27].

With the MAN B&W ME-GI engine, the configuration shown in Fig. 2.6.1, comprising one reliquefaction unit, one high pressure compressor and one oxidizer, will comply with redundancy requirements and offer full fuel flexibility [12].

The bridge and engine room control system shall be able to handle operation with both one (emergency) and two (normal) engines. Also 4 Diesel electrical generators are installed to cover the overall electrical demand [5].

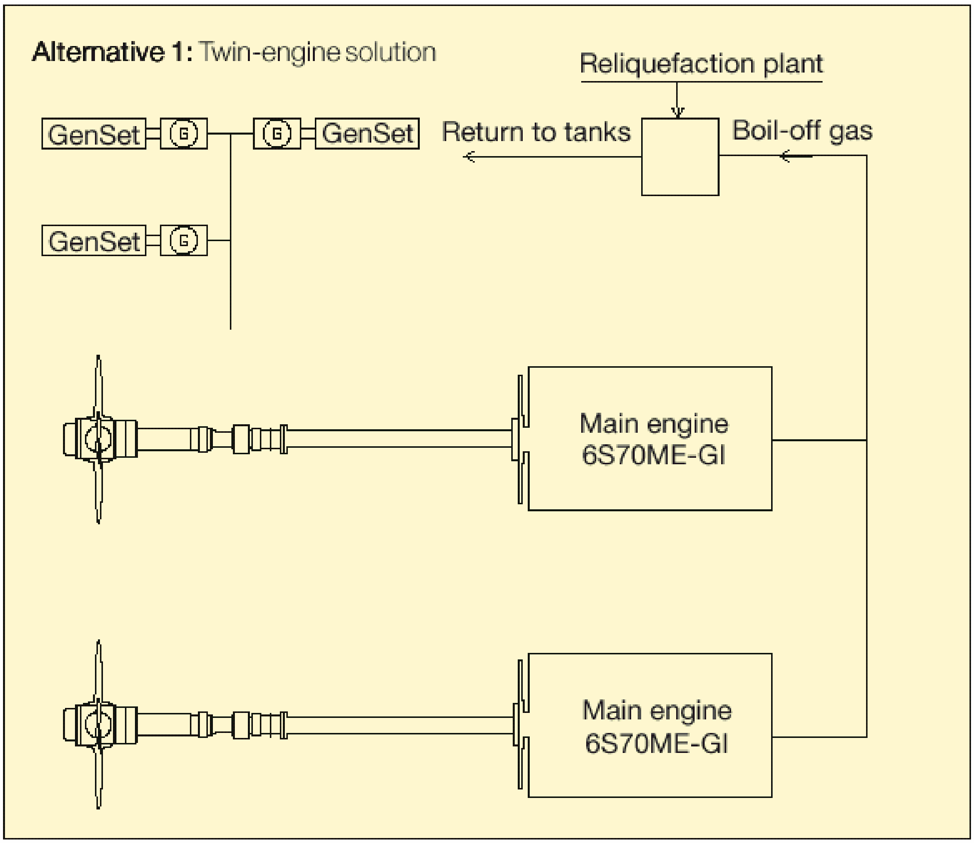


Fig. 2.6.1 Twin-engine propulsion system [12].

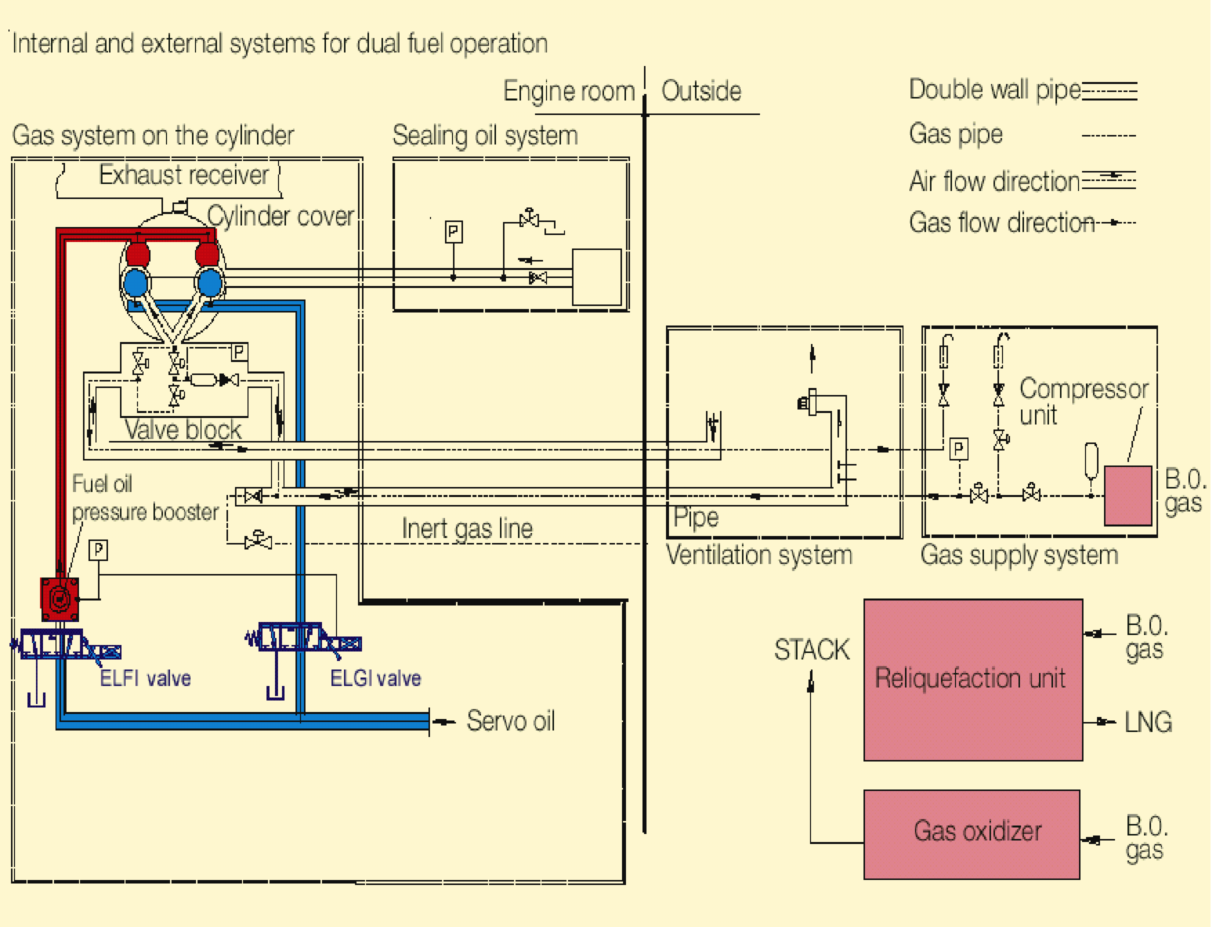


Fig. 2.6.2 ME-GI engine and gas handling units [12].

2.6.3 Advantages and drawbacks for a slow speed gas-Diesel propulsion plant installation

Advantages

I. High overall fuel efficiency - up to 50% - (about 60% higher than for the steam plants) resulting in lower energy consumption and thus lower operating cost compared to steam plants.

II. The higher efficiency reduces the amount of energy required for propulsion and brings it much closer to the amount of energy available from the boil off gas. Therefore the supplementary fuel oil requirement is drastically reduced, or even eliminated, compared to that of a steam turbine installation.

III. High flexibility on the available fuel (HFO and gas) and engine load.

IV. Smaller Engine room required hence more cargo space for a given vessel compared to steam propulsion.

V. Availability of engineers experienced with this type of propulsion system.

VI. The design, installation and operation of a Diesel plant will be well known to shipyard and owner.

VII. In the case of a design using twin Diesel engines, with separate engine rooms, there is full propulsion redundancy and added safety margins against floods and fires in the engine room.

VIII. The system efficiency will be higher than that of other gas consuming propulsion system, incl. dual fuel Diesel electric even considering the compressor power.

IX. The capital cost of a vessel with dual fuel slow speed Diesel installation is about 3% lower when compared to a steam turbine driven vessel.

X. In the case of an electronically controlled engine:
  i) Lower SFOC and better performance parameters at any load thanks to electronically controlled variable timing of fuel injection and exhaust valves at any load.
  ii) Appropriate fuel injection pressure and rate shaping at any load.
  iii) Improved emission characteristics, with lower NOx and smokeless operation.
  iv) Easy change of operating mode during operation.
  v) Simplicity of mechanical system with well-proven traditional fuel injection technology familiar to any crew.
  vi) Control system with more precise timing, giving better engine balance with equalized thermal load in and between cylinders
  vii) Lower RPM possible for manoeuvring.
  viii) Better acceleration, astern and crash stop performance.
  ix) System comprising performance, adequate monitoring and diagnostics of engine for longer time between overhauls.

Disadvantages

I. The gas supply must be compressed to about 300 bar, to facilitate injection into the cylinder. This requires considerable energy (the parasitic energy consumption of the high-pressure fuel gas compressor is approximately 6 % of the engine power).

II. Expensive and maintenance intensive compressors (gas compressor required to supply gaseous fuel at 300 bar pressure to the gas-Diesel engine).

III. The complex control system required.

IV. The shipping industry’s reluctance to have high-pressure gas systems on board because this raises many safety concerns.

V. Excess BOG, at low speeds or at anchor, is sent to the oxidizer which results in the loss of economic value of the boil off.

VI. Higher NOx and SOx emissions as the engines burn HFO.

VII. Less redundancy than existing steam systems in the single engine layout.

VIII. Diesel engines require more maintenance on a routine basis than steam turbines.

IX. Higher lub oil consumption compared to steam turbine which adds to the operating cost.

2.7 Medium Speed Dual Fuel Diesel Engine

2.7.1 Gas-HFO engine alternatives

2.7.1.1 General information-technological development

Dual fuel engine burning BOG and/or HFO

Gas-Diesel engines act according to the Diesel principle and can virtually burn any possible mixture of gas and liquid fuel, with only a few restrictions to the quality of the gas. As the mixture of gas and liquid fuel is injected into the combustion chamber during air compression, the required injection pressure is high. For four-stroke gas-Diesel engines, a gas pressure of around 350 bar is required.

Wärtsilä brought its first four-stroke gas-Diesel engine, the Wärtsilä 32GD, with an output of 410 kilowatt per cylinder, to the market in 1987. The larger Wärtsilä 46GD, with an output of 975 kilowatt per cylinder, was introduced in 1991 [5].

As boil-off gas is generated at atmospheric pressure, large gas compressors are required to boost the gas pressure to the appropriate level. These compressors require a substantial amount of electric power to operate and are costly and heavy. Additionally, the presence of high-pressure gas in the engine room is a major safety concern, especially on LNG carriers.

Emissions of gas-Diesel engine installations are generally lower than those of steam turbine and Diesel engine installations as a result of higher efficiency and cleaner fuel, respectively.

Although no such engine is now available in the market , its introduction in the near future, as promised by a leading manufacturer, will offer the most economically attractive layout, since the plant will be able to produce the required power by utilizing either gas only or HFO only or a combination of gas and HFO without installing excess power.

Obviously, the highest flexibility is obtained if a reliquefaction plant is installed as a primary means of dealing with the BOG. Such a configuration will give complete freedom on the boil off gas handling (use as a propulsion fuel or reliquefy) and consequently on the fuel used for propulsion.

The configuration will allow optimum adoption to the relative prices of gas and HFO and to different vessel operating profiles and speeds. It seems therefore ideal for spot trade ships [3].

Dual fuel engine burning BOG and/or MDO, HFO

The combination of dual-fuel engine technology and electric propulsion system is said to give the LNG market a machinery concept that offers significant benefits compared to classical steam turbine installations and other currently emerging alternative machinery concepts for LNG carriers.

The recent introduction of heavy fuel oil as fuel for the engine’s Diesel mode further enhances fuel flexibility and provides ship operators the highest degree of control over operating costs under fluctuating gas and liquid fuel prices [15].

The Wärtsilä 50DF for example is a four-stroke dual-fuel engine. The engine can alternatively run either on natural gas or marine Diesel fuel (MDF) and can, with certain modifications, also run on HFO [22].

The possibility to use HFO on the Wärtsilä 50DF was introduced during last year in order to offer ship operators ultimate fuel flexibility on DF-electric machinery installations. LNG carrier newbuilding projects currently under discussion can make use of this option.The pilot fuel will remain MDO.

2.7.1.2 Typical gas-HFO engine propulsion plant

Dual fuel engine burning BOG and/or HFO

A suitable number (typically four) of gas/HFO burning engines (Wärtsilä – SULZER GD –series) in case of a Diesel electric propulsion with two electric motors and a single shaftline is usually proposed. The four Diesels provide electrical power for the main propulsion motors and the other electrical consumers. This gives a high flexibility between different operating modes [13].

The direct mechanical drive is also possible but usually the electric propulsion concept is preffered because you don't need to have additional gensets.

The need to have a back up means of dealing with the boil off gas is normally handled by the installation of an oxidiser. The oxidiser burns the amount of BOG which exceeds the propulsion requirements. Separately, a reliquefaction plant can be installed as a primary means of dealing with the BOG [3].

Dual fuel engine burning BOG and/or MDO, HFO

A suitable number (typically four) of gas/MDO upgraded to burn HFO engines (such as Wärtsilä 50 DF series, available on 50DF engines that will enter production after 1/08/05) in case of a Diesel electric propulsion with two electric motors and a single shafline is usually proposed. The four Diesels provide electrical power for the main propulsion motors and the other electrical consumers. This gives a high flexibility between different operating modes [13].

2.7.1.3 Advantages and drawbacks for a gas-HFO engine propulsion plant installation

Advantages

I. High propulsion redundancy, especially on a twin propeller configuration.
II. Higher availability of experienced crew comparing to steam turbine.
III. High flexibility on the available fuel and engine load.
IV. Auxiliary Electric power demand is covered by the propulsion engines eliminating the need for additional auxiliary gen sets.
V. Increased cargo capacity, compared to the steam propulsion option for a given ship size, because of the shorter engine room length and possibly because of the reduced size of bunker tanks.
VI. Higher efficiency compared to steam propulsion.
VII. The provision of usually four or even more prime movers facilitates voyage maintenance with no or little available power reduction.

Disadvantages

I. Added complication due to the handling of gas in the engine room, however low pressure gas is supplied into the engine room similar to the existing steam turbine design.
II. Higher capital cost, by about 3-5% for a 130,000-150,000 m^3 vessel, compared with a steam turbine driven vessel.

III. The possibly installation of a reliquefaction plant will increase the capital cost by another 5%.
IV. Higher maintenance as a result of more moving parts, higher speed and more cylinders in a particular installation.
V. In the case of electric propulsion, about 4% efficiency loss in the electric power generation process.
VI. At low speeds or at anchor, the power requirement is much lower that energy available from the BOG. Excess BOG is sent to the oxidiser which results in the loss of economic value of the boil off.

2.7.2 Gas-MDO engine alternatives

2.7.2.1 General information-technological development

Low-pressure dual-fuel technology is only available on four-stroke engines. The first Wärtsilä dual-fuel engine, the Wärtsilä 32DF, was brought to the market in 1996. This engine, with a power of up to 350 kilowatt per cylinder, is available in six- and nine-cylinder inline and twelve- and eighteen-cylinder Vee-form configurations.

The larger Wärtsilä 50DF was launched in 1998. This engine is available in six-, eight- and nine-cylinder inline and twelve-, sixteen- and eighteen-cylinder Vee-form configurations. With an output of 950 kilowatt per cylinder, it delivers between 6 to 17 MW at full load [5].

The Wärtsilä 50DF is designed to give the same output regardless of whether it is running on natural gas or on MDF. The engine operates with gas or MDF. The engine operates according to the lean-burn principle: the mixture of air and gas in the cylinder is lean, which means that there is more air than needed for complete combustion. Lean combustion increases engine efficiency by raising the compression ratio and reducing peak temperatures, and therefore also reducing NOx emissions. A higher output is reached while avoiding knocking or preignition of gas in the cylinders.

Combustion of the lean air-fuel mixture is initiated by injecting a small amount of MDF (pilot fuel) into the cylinder. The pilot fuel is ignited in a conventional Diesel process, providing a high-efficiency ignition source for the main charge.

The fuel oil system on the engine has been divided into two subsystems: one for pilot fuel oil and one for the main Diesel oil for back-up fuel operation. The equipment used for Diesel operation is similar to the conventional Diesel engine, with camshaft-driven injection pumps at each cylinder. The engine is equipped with a twin-needle injection valve, one main needle used during Diesel mode and one for pilot fuel oil. The pilot fuel is elevated to the required pressure by one common pump unit, including filters, pressure regulator and an engine-driven radial piston-type pump. The pilot fuel is distributed through common-rail type piping and injected at approximately 900 bar pressure into cylinders. Pilot fuel injection timing and duration are electronically controlled.

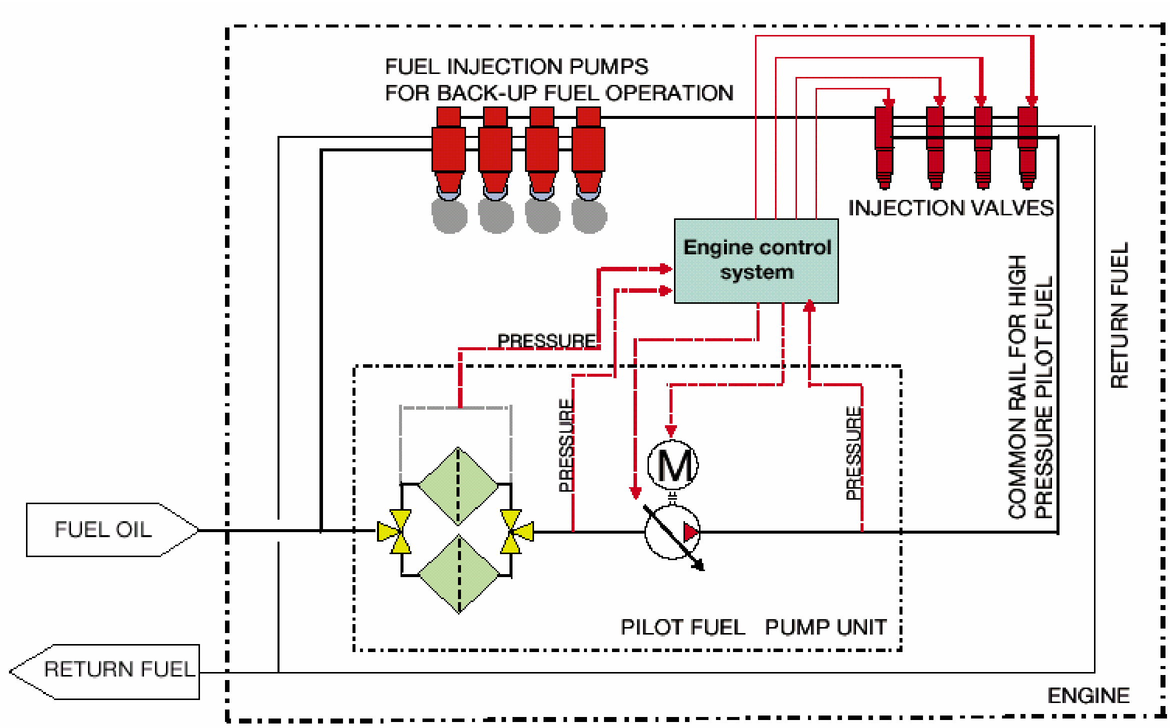


Fig. 2.7.2.1 Engine fuel oil system [22].

When running the engine in gas mode, the pilot fuel amounts to less than 1% of full-load consumption. The fuel gas system feeding the engine with fuel includes filters and the necessary shut-off and venting valves to ensure safe and trouble-free gas supply. The natural gas is supplied to the engine through a gas valve unit. The fuel gas feed pressure to the engine is controlled by a pressure regulating valve located on the gas valve unit. The fuel gas pressure is dependent on engine load and the fuel gas calorific value (lower heating value). On full engine load, the gas pressure on the engine is about 4 bar(g) when operating on a gas with LHV 36 MJ/Nm 3 ; for lower LHV the gas pressure has to be increased. On the engine, the electronically actuated and controlled gas admission valves give exactly the correct amount of gas to each cylinder. This enables reliable performance without shutdowns, knocking or misfiring.

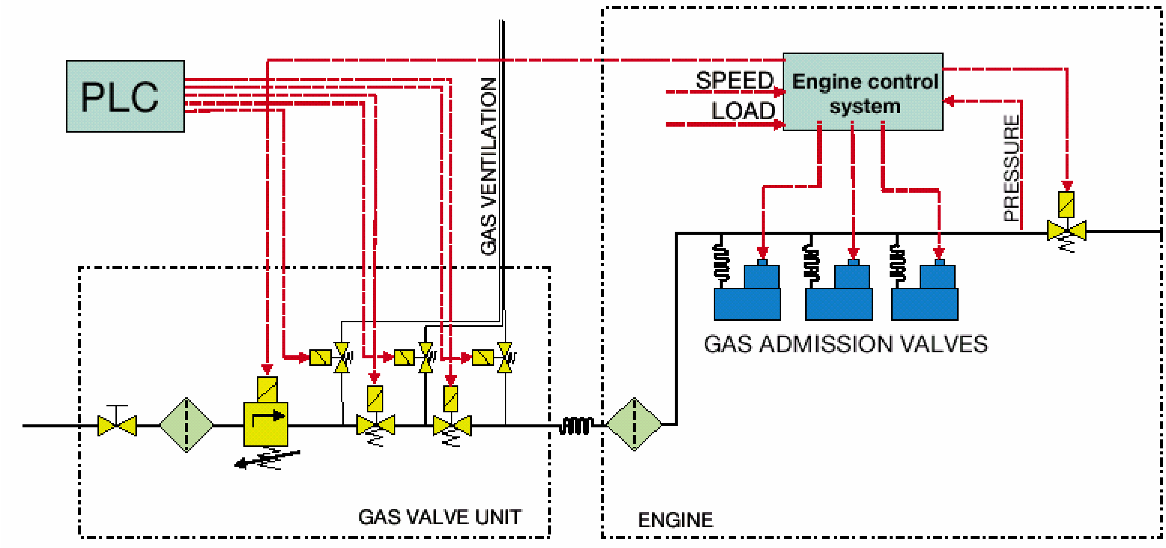


Fig. 2.7.2.2 Fuel gas system [22].

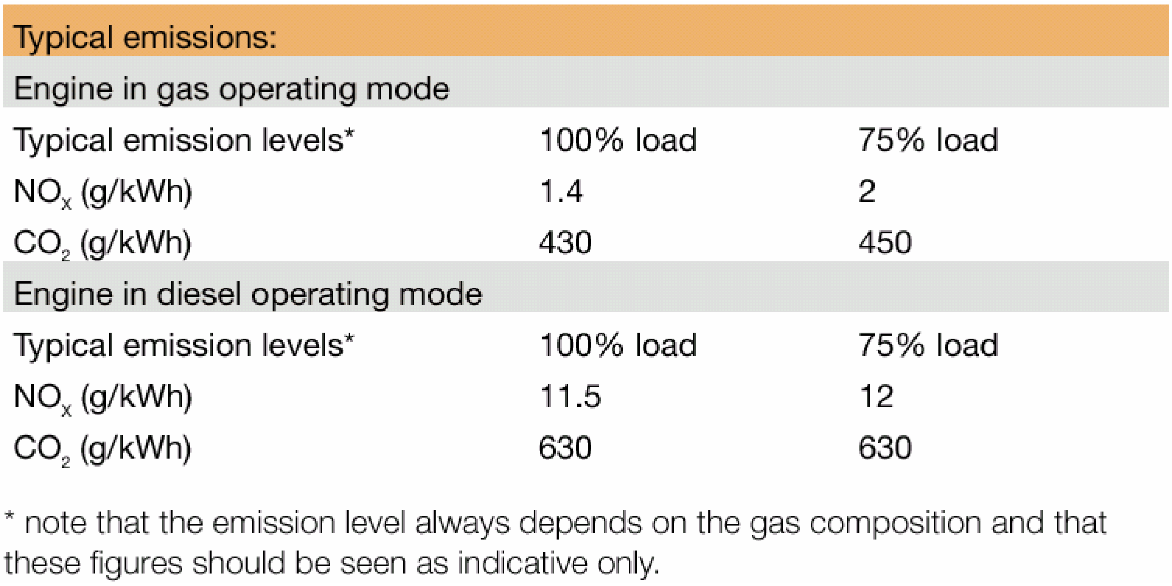
The Wärtsilä 50DF engine is designed for generating electrical power for ship propulsion. The dual-fuel engine operates on natural gas as main fuel, and on Diesel as backup fuel. The Wärtsilä 50DF engine can be switched from gas operation to backup fuel operation at any load. The switchover is instant and the engine has the capability to operate on backup fuel if needed, without interrupting power generation. Fuel oil is always circulating through the engine, ensuring sufficient fuel supply for pilot fuel and for quick switchover to backup fuel operation. The engine can be switched from backup fuel operation to gas operation at loads up to 80% of full load [22].

The dual fuel engine is basically a normal 4 stroke Diesel which can utilize natural gas as fuel. The gas is injected into the air intake and a small amount of Diesel is added in the combustion chamber to ignite the gas/air mixture. The engine is also capable of only running on MDO, switching from gas to Diesel mode is possible within one revolution of the engine.

The system is extremely environment friendly. When using LNG as fuel there is very little NOx, no SOx and no particle emissions.The reduction of CO_2 emissions totals approximately 100,000 mt per year compared to a standard steam-driven LNG carrier [13].

More specifically, in the Wärtsilä 50DF engine, the air-fuel ratio is very high. Since the same specific heat quantity released by combustion is used to heat up a larger mass of air, the maximum temperature and consequently NOx formation are lower.

The engine has a thermal efficiency of 47%, higher than for any other gas engine. This, and the clean fuel used, gives engine extremely low CO_2 emissions.



Typical emissions:		
Engine in gas operating mode		
Typical emission levels*	100% load	75% load
NO_x (g/kWh)	1.4	2
CO_2 (g/kWh)	430	450
Engine in diesel operating mode		
Typical emission levels*	100% load	75% load
NO_x (g/kWh)	11.5	12
CO_2 (g/kWh)	630	630

* note that the emission level always depends on the gas composition and that these figures should be seen as indicative only.

Fig. 2.7.2.3 Dual-fuel engine exhaust emissions [22].

The engine is controlled by a sophisticated engine control system, a fully integrated engine management system designed for harsh environments. It ensures maximum engine performance and safety by monitoring and controlling vital engine functions such as temperatures and pressures through the numerous sensors mounted on the engine [22].

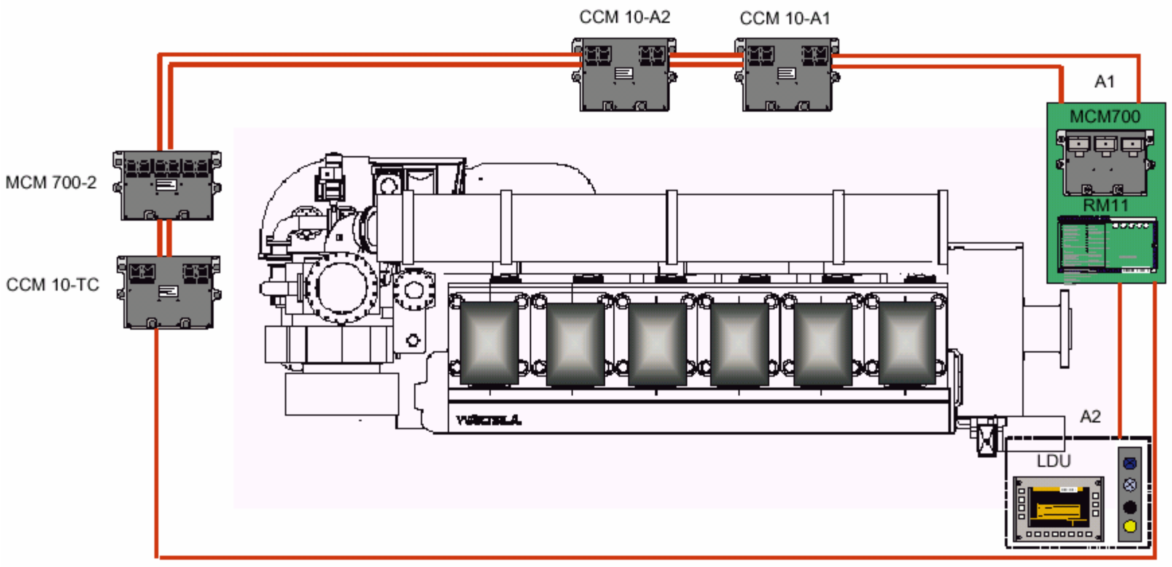


Fig. 2.7.2.4 Engine control modules [22].

All options with medium speed engines are almost exclusively considered in combination with electric propulsion. The engines operate as generator sets and deliver the propulsion power to the propeller through either medium speed electric propulsion motor(s) with reduction gear or directly through low speed electric propulsion motor(s).Single and twin screw configurations as well as azipod options are also available to suit to particular ship design depending on the level of propulsion redundancy, maneuverability and draft characteristics required [22].

To enhance the redundancy of the propulsion plant, the main engine rooms and casings are divided with a fire-resistant bulkhead. The main engine rooms are under diminished air pressure [16].

Medium speed dual fuel engines have been installed in both offshore and onshore power plant applications for many years. In the case of onshore installations, natural gas is utilized and for offshore installations generally process gas is used as fuel for power generation.

Dual fuel engines proposed for LNG vessels are developed upon these same principles. The engine, as mentioned above, is capable of burning either gas with marine Diesel oil as pilot fuel for injection, or marine Diesel oil. It is capable of changing over instantly between the two modes of operation whenever required with stepless power output.

During the gas operation mode, the engines operate on Otto cycle, gas is introduced into the cylinder during the air suction cycle at low pressure. Gas injection sub-system is normally located directly on the engine and its basic function is to provide timely and accurate delivery of the gas fuel into the cylinder, gas is delivered through an electronically actuated control valve leading to the engine air inlet ducting. Knocking sensors adjust combustion timing based on the gas quality.

When the engine is switched to the MDO mode, then it operates under the normal Diesel cycle.It should be mentioned that large bore medium speed engines operating on gas have not been tested in service yet.

Diesel electric option is more beneficial the smaller the ship size, according to a recent cost analysis of electric propulsion and steam turbine for a 74,000 m^3 vessel build for Gaz de France.For ship sizes of 138,000 m^3 and above we haven’t the same economic benefits as the steam plant cost represents a smaller proportion of the overall build cost.

However as the electric propulsion option is more commonly employed to LNG carriers the economies of scale building help drive the comparative cost of electric propulsion down.

High total efficiency

Recent studies suggest that the most beneficial solution, both economically and environmentally, for topping up the energy available from boil-off gas is to use forced boil-off instead of Diesel fuel oil. This solution, in combination with DF-electric propulsion, is economically very attractive in both installation and operating costs. Recent evaluations in the industry have calculated annual savings in total operating costs of between 2.2 and 2.8 million USD compared with a traditional steam turbine LNG carrier.

As the dual-fuel engine is operated on low-pressure gas, below five bar at the engine inlet, the fuel gas compressor package is essentially similar (only two-stage instead of single-stage) to that already used in the current steam-powered fleet. The main difference is that the total efficiency of the DF-electric plant is well above 40 % compared to less than 30 % for the steam plant. The difference is even greater in part-load operation [16].

Operating economy

As dual-fuel engines have the ability to run on both gas and MDO, the choice of fuel is up to operator. Several independent studies have however confirmed that forcing additional boil-off gas to complement the natural boil-off gas is the way to profit most from the potential of the dual-fuel-electric solution. Firstly, forced boil-off gas is cheaper than alternative fuels. Secondly, it is lighter than alternative fuels. Fuel ‘bunkers’ weight is thus reduced, and at a given displacement, the ship will be able to carry more cargo weight. Carrying more cargo volume is enabled by the fact that the dual-fuel-electric solution saves engine room space (Fig. 2.7.2.14). Even when using a small part of the cargo as fuel, a dual-fuel-electric LNG carrier will deliver more cargo to the unloading port in this way.

The efficiency of the propulsion machinery of a dual-fuel- electric LNG carrier is approximately 41% and the efficiency of the electric power generation machinery is around 44%, compared to 29% and 25% respectively for a steam turbine installation [5].

Environmental friendliness

When exclusively using natural and forced boil-off gas as fuel, the dual-fuel electric solution shows unrivalled emission values. All other machinery alternatives suffer from the use of HFO, either used uniquely or in combination with natural boil-off gas [5].

Safety

A ‘Safety Concept’ for dual-fuel-electric machinery on board LNG carriers has been developed by Wärtsilä to make sure that the safety of the installation complies with class and at least matches the safety of steam turbine installations. The recent introduction of double-wall gas piping on the Wärtsilä 50DF will further increase the safety of the solution. With several potential customers and class, safety studies including hazard identification, FMEA and hazardous operations studies, have been conducted to further validate the safety of the solution [5].

LR Asia completes LNG safety case

Lloyd’s Register Asia has completed the first safety case in Korea for dual-fuel electric propulsion in association with Daewoo Shipbuilding (DSME) and Wärtsilä. The system is for the new large LNG tanker designs of 200,000 cubic metres and above being put forward by Korean yards. Lloyd’s Register Asia has worked with DSME and Wärtsilä to help to ensure that the technology is properly qualified for installation on board the next generation of LNG tankers.

The safety case methodology involves two key elements, i.e. a hazard identification study, which identifies critical issues and looks at engine room arrangements and layout, and a hazard operability study, which looks at ship systems including, for example, a detailed examination of piping and instrumentation diagrams from a safety and operability point of view. It is essentially a method of evaluating the safety and integrity of an installation, a system or a product through a formal process of risk assessment which can give stakeholders confidence in a new technology or design [39].

Maintainability

Case studies for various customers have shown that the required maintenance on dual-fuel-electric installations can easily be carried out without affecting the ship’s operational performance. Maintenance of dual-fuel-electric installations is more costly than of steam turbine installation, but does no harm to the ship’s operating economy [5].

Crew availability

Dual-fuel-electric installations can be operated and maintained by Diesel engine crews. There is no need for crew members with exceptional skills or experience.

Also the dual-fuel-electric installation provides excellent propulsion characteristics for navigation in ice, due to the availability of full propeller torque at zero speed and excellent manoeuvring characteristics. Dual-fuel-electric installations can easily cope with the power requirements of dynamic positioning systems. This might become a valuable feature, as an increasing amount of offshore LNG terminals is envisaged [5].

Market introduction

Wärtsilä dual-fuel engines have already collected a vast number of running hours in installations on land and at sea without any significant problems.

The first dual-fuel-electric ships running on LNG, *Viking Energy* and *Stril Pioner*, are in operation since 2002 and the first dual-fuel-electric LNG carrier, *Gaz de France Energy*, will be in operation in the near future.

Eleven more Wärtsilä dual-fuel engines are in service at sea, and twelve more engines are about to follow [5].

Petrojarl I

Off shore Norway, two eighteen-cylinder Wärtsilä 32DF engines, with an aggregate power of 12 MW, are running on natural gas from the Glitne oil and gas field on board Petroleum Geo-Services' FPSO Petrojarl I.

Sendje Ceiba

One eighteen-cylinder Wärtsilä 32DF dual-fuel engine, rated at 6 MW, is running on natural gas from the Ceiba oil and gas field off shore Equatorial Guineaon board Bergesen's FPSO Sendje Ceiba.

Viking Energy and **Stril Pioneer**

The platform supply vessel Viking Energy, delivered to Eidesvik of Norway by Kleven Verft of Norway in 2002, is equipped with four six-cylinder Wärtsilä 32DF dual-fuel engines. These engines, with a combined output of 8 MW, are driving two azimuthing thrusters through an electric drive. Added to the fact that Viking Energy is the first ship to apply dual-fuel-electric machinery, it is also the first ship running on LNG. Using hot water vaporizers, natural gas is forced to boil off from a 220 m^3 insulated LNG fuel tank underneath the ship's deck.

Viking Energy's sister ship, Stril Pioner was delivered to Simon Møkster of Norway by the same shipyard during the same year. Both ships are on charter to Statoil and are stationed in the port of Bergen in Norway [5].

Gaz de France Energy

In February 2002, the French utility Gaz de France placed on order for a 74,130 m^3 dual-fuel-electric LNG carrier at the French shipyard Chantiers de l'Atlantique.

Four six-cylinder Wärtsilä 50DF dual-fuel engines, with an aggregate power of 22.8 MW, will power the ship to a service speed of 17.5 knots. Natural boil-off gas complemented by forced boil-off gas will serve as fuel in normal operating conditions. In case no gas is available, the engines will run on MDO.

Gaz de France Energy will primarily trade between Algeria and France.

Provalys

In September 2003, Gaz de France ordered a second DF-electric LNG carrier at Chantiers de l'Atlantique. This ship, Provalys, will have a cargo capacity of 153,500 m^3 and upon delivery at the end of 2005 be the largest LNG carrier afloat.

On this ship, three twelve- and one six-cylinder Wärtsilä 50DF dual-fuel engines, with a combined output of 39.9 MW, will generate the required electric power to give the ship a service speed of 19 knots. These engines are currently in production at Wärtsilä Italia in Trieste.

Also in Provalys, forced boil-off gas will complement the natural boil-off gas in normal operation conditions, while MDO will serve as fuel when no gas is available.

The ship will primarily trade between Egypt and France, and Norway and France.

In July 2004, a joint-venture of NYK of Japan (60%) and Gaz de France (40%) ordered a sister ship to Provalys at Chantiers de l'Atlantique, which is scheduled for delivery at the end of 2006 [5].

In 2005 Wärtsilä has received a major order to supply twenty-four Wärtsilä 50DF dual-fuel engines to Samsung Heavy Industries of Korea. These engines will power a series of six 155,000 m^3 dual-fuel-electric LNG carriers. Four of these ships were ordered by A.P. Moller of Denmark, while Kawasaki Kisen Kaisha ("K" Line) of Japan ordered the other two. The delivery of the first ship in this newbuilding series is scheduled for early 2008. Each ship will be equipped with three twelve-cylinder and one six-cylinder Wärtsilä 50DF dual-fuel engines, delivering a total power of 39.9MW. The delivery of these engines from Wärtsilä's engine factory in Trieste, Italy, will commence in January 2007.

Another four LNG carriers ordered by BP at Hyundai Heavy Industries will feature dual-fuel engines. Each ship will be equipped with two twelve-cylinder and two nine-cylinder Wärtsilä 50DF dual-fuel engines, delivering a total power of 39.9 MW.

Fifty-two Wärtsilä 50DF dual-fuel engines have so far been ordered for application in thirteen dual-fuel-electric LNG carriers.

Additionally there are many LNG carrier projects under discussion which are considered to be equipped with dual-fuel Diesel engines. So it is certain that more dual–fuel Diesel electric LNG carriers will be ordered in the near future.

The dual-fuel-electric machinery concept for LNG carriers combines multiple dual-fuel generating sets with electric propulsion and offers a very significant improvement compared to the traditional steam turbine installation in terms of operating economy, exhaust gas emissions and redundancy. At the same time, it keeps aspects like safety, reliability and maintainability at an appropriate level [39].

Dual-fuel-electric machinery is presently being evaluated by ship owners and shipyards around the world for a vast number of LNG carrier newbuilding projects. The cargo capacities of the envisaged ships are ranging from the conventional 150,000 m^3 to 200,000 and even 250,000 $m^{3.}$ Port-to-port sailing distances are ranging from several days to several weeks. In addition, dual-fuel engines are under consideration for application in various kinds of offshore installations, including floating liquefaction units, as well as floating regasification units [5].

2.7.2.2 Typical gas-MDO engine propulsion plant

The number and size of the dual-fuel generating sets depends on the ship size and speed, but also on the envisaged operating philosophy.

An LNG carrier with a cargo capacity of some 150,000 m^3 will typically require one six- and three twelve-cylinder Wärtsilä 50DF engines. An LNG carrier with a cargo capacity of 200,000 m^3 will typically require two six- and four nine-cylinder engines, and a ship of 250,000 m^3 cargo capacity will do with two six- and four twelve-cylinder Wärtsilä 50DF dual-fuel engines.

The generated electric power is fed to an electric drive fairly similar to those used on contemporary cruise ships. Two 'high-speed' electric propulsion motors drive a fixed-pitch propeller through a reduction gear. Twin 'low-speed' electric motors mounted on the same shaft can be selected to drive the propeller without assistance of a gearbox alternatively. For the larger ships, twin-screw arrangements can be selected without significantly increasing the complexity of the machinery installation [5].

Diesel electric propulsion with 4 dual fuel gas/MDO burning engines, two electric motors and a single shafline is usually proposed. The four Diesels provide electrical power for the main propulsion motors and the other electrical consumers. This gives a high flexibility between different operating modes. The total power installed is less than for any other propulsion alternative because of this flexibility.

As the Diesels are producing electricity, an in-line arrangement of shaft/gearbox/engine is not necessary. So the Diesels can be arranged on a higher deck, thus reducing engine room space demand. The layout offers multiple redundancy, apart from the shafting and the gearbox. Even in the event that two Diesels should fail, or one electric motor is out of use, the ship would be able to sail at about 75% of its design speed.

An LNGC of about 145,000 m^3 with Diesel-electric propulsion will be able to take about 5000 m^3 more cargo than a steam-driven ship with same overall dimensions.

The need to have a back up means of dealing with the boil off gas, during long periods of low-load operation, is normally handled by the installation of an oxidiser. The oxidiser burns the amount of BOG which exceeds the propulsion requirements.

However the Diesel-electric version allows a higher redundancy, increased flexibility as well as greater cargo capacity. A Diesel-electric ship fitted with a reliquefaction plant seems to be the most promising solution for current and future demands to LNG carrier propulsion, especially considering the reduced emissions of NOx, SOx and CO$_2$ and future trading and fuel choice flexibility [13].

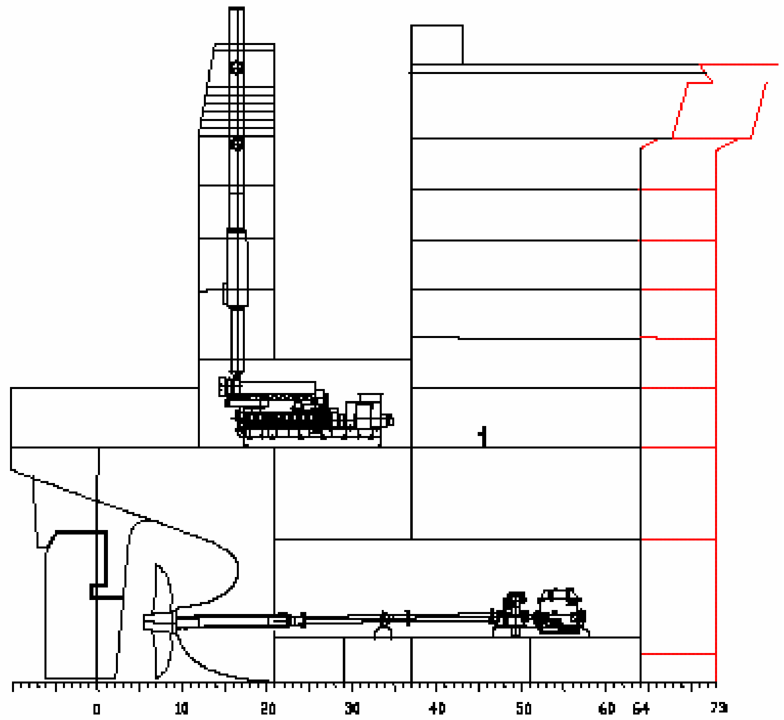


Fig. 2.7.2.5 Dual-fuel-electric machinery [5].

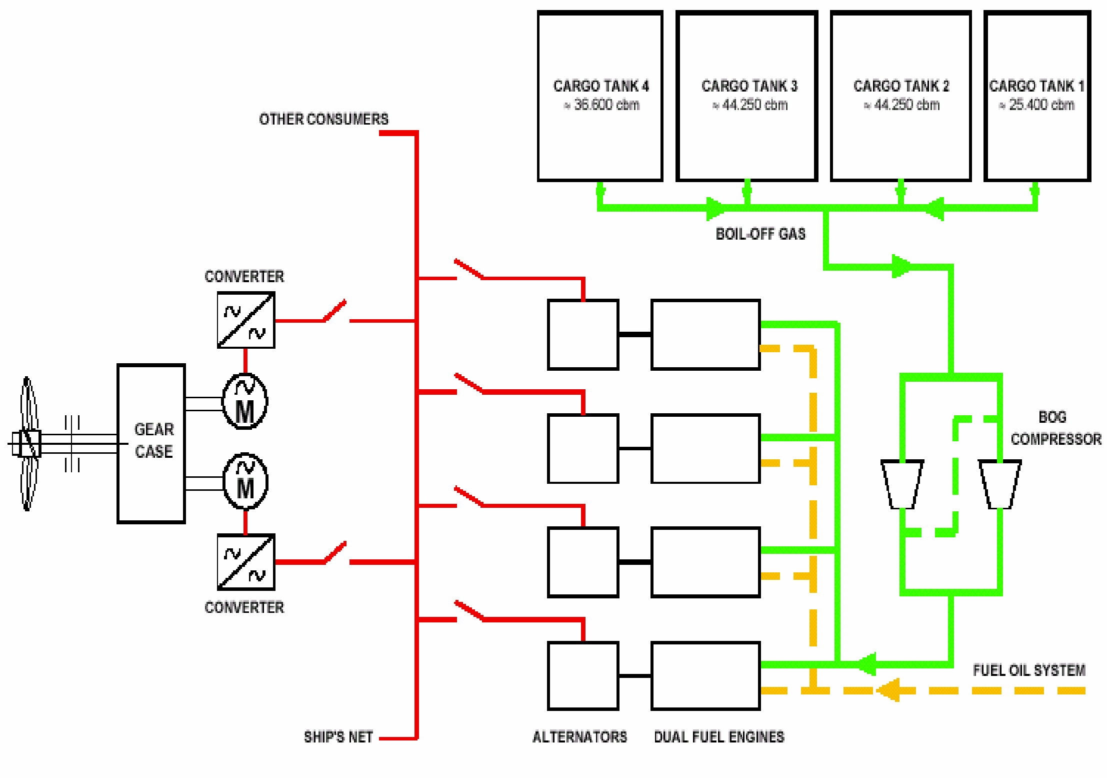


Fig. 2.7.2.6 Diagram of Diesel-Electric Propulsion [13].

A proposed machinery arrangement, for a 150,000 m³ LNG carrier, by Wärtsilä is shown at Fig.2.7.2.7.

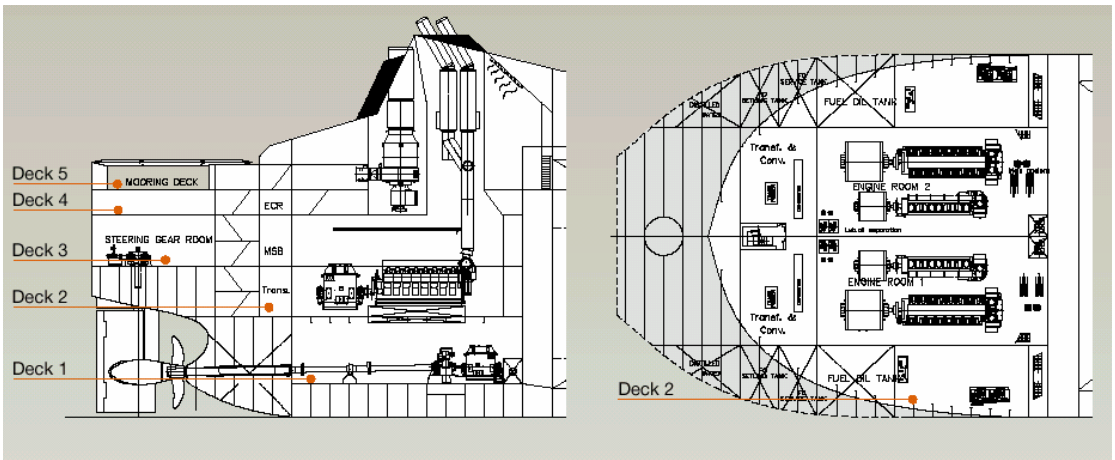


Fig. 2.7.2.7 Machinery arrangement of Wärtsilä dual-fuel electric (DF-E) configuration [20].

According to Wärtsilä the machinery is of the dual-fuel electric (DF-E) type and consists of two Wärtsilä 16V50DF and two 9L50DF generating sets, giving a total installed power of 47.5 MW. The engines use liquefied natural gas (LNG) as primary fuel and marine Diesel oil (MDO) as pilot and back-up fuel.

The engine room, as well as the whole electrical system, is divided into two compartments (Fig.2.7.2.9) to add redundancy (Emergency Shut Down (ESD) protected machinery space according to the International Gas Code (IGC) rules). Fuel handling and fuel pipes are fitted in the front part of the engine room while all the electrical equipment is in the aft part of the engine spaces. This arrangement results in short cabling and piping routes and further increases the safety aspects in the design. No extra auxiliary engines are needed since the generating sets cover the vessel's total electrical need. The funnel structure includes fresh air intakes, exhaust pipes with silencers and an oxidizer, where the surplus boil-off gas is burned.

The propulsion train is placed below the generating sets on deck 1, which is an efficient way to take advantage of the tapered deck space down aft. The electrical propulsion motor power is 37 MW enabling a service speed of 21.5 kn (85% MCR, 20% sea margin). If one of the engine rooms is out of operation the vessel can still attain a speed of 17.5 kn.

Finally the vessel is fitted with a single Lips FP-propeller and a Lips Efficiency Rudder in order to reduce fuel consumption, noise and vibration levels, and also the risk of cavitation on the propeller blades. The manoeuvring characteristics are further improved with a bow thruster [20].

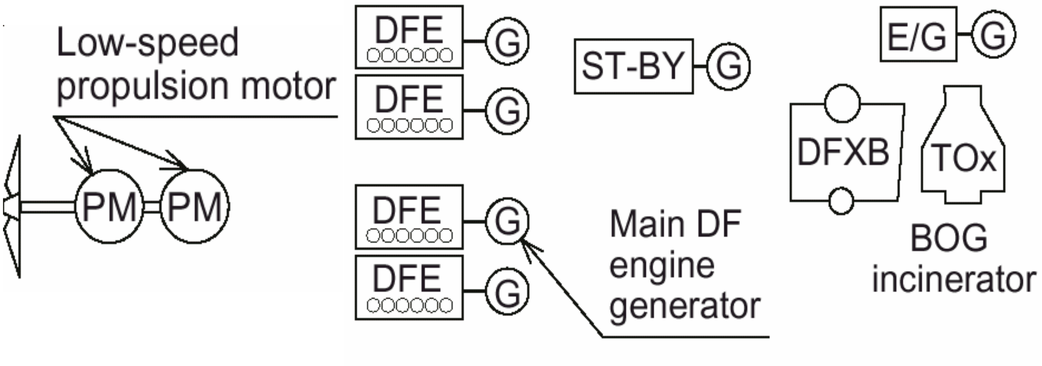


Fig. 2.7.2.8 Electrical propulsion DF engine plant [14].

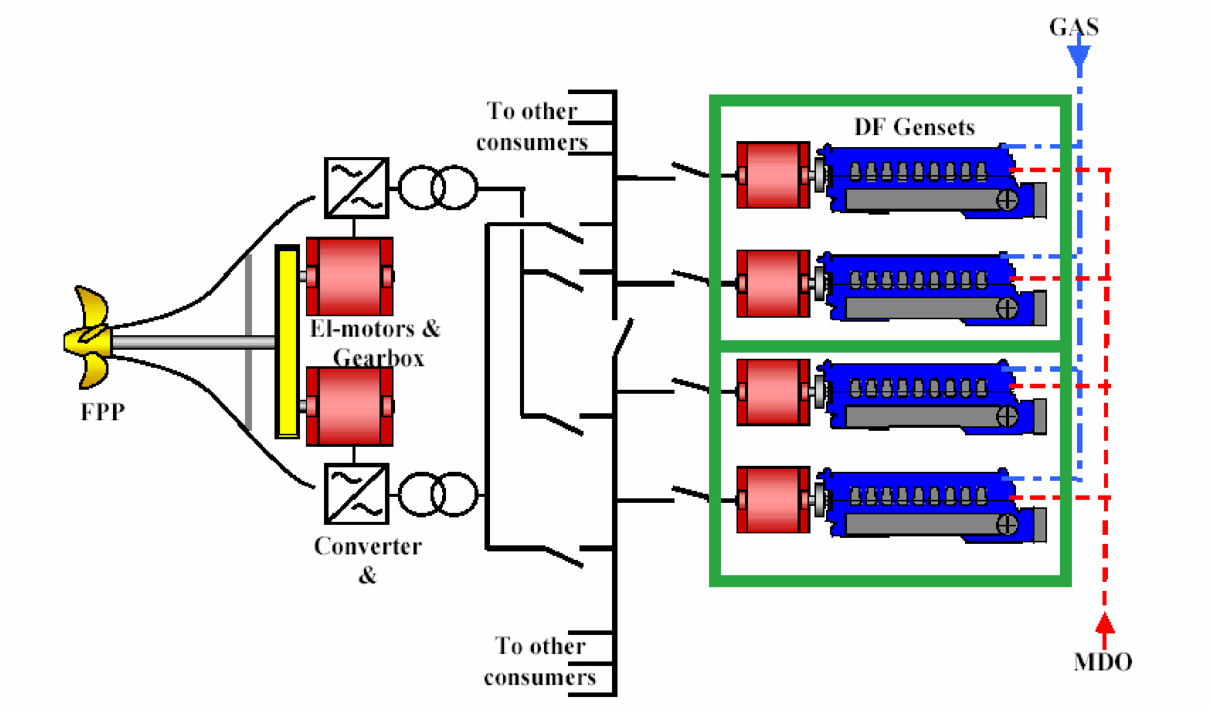


Fig. 2.7.2.9 Electrical propulsion DF engine plant with separated (ESD protected) engine rooms [20].

2.7.2.3 Advantages and drawbacks for a gas-MDO engine propulsion plant installation

Advantages

I. The system is extremely environment friendly. When using LNG as fuel there is very little NOx, no SOx and no particle emissions. The reduction of CO_2 emissions totals approximately 100,000 mt per year compared to a standard steam-driven LNG carrier.

II. The four Diesels provide electrical power for the main propulsion motors and the other electrical consumers so the total power installed is less than for any other propulsion alternative because of this flexibility.

III. As the Diesels are producing electricity, an in-line arrangement of shaft/gearbox/engine is not necessary. So the Diesels can be arranged on a higher deck, thus reducing engine room space demand.

IV. A Diesel-electric ship fitted with a reliquefaction plant seems to be the most promising solution for current and future demands to LNG carrier propulsion, especially considering the reduced emissions of NOx, SOx and CO_2 and future trading and higher fuel choice flexibility.

V. High fuel choice flexibility.

VI. Higher availability of experienced crew comparing to steam turbine.

VII. Increased cargo carrying capacity, compared to steam propulsion option, because of the shorter engine room length and possibly because of the reduced size of bunker fuel tanks. An LNGC of about 145,000 m^3 with Diesel-electric propulsion will be able to take about 5000 m^3 more cargo than a steam-driven ship with same overall dimensions.

VIII. High propulsion redundancy.

IX. The engine control system offers the following advantages:
  i) Easy maintenance and high reliability thanks to rugged engine-dedicated connectors and prefabricated cable harness.
  ii) Easy interfacing with external systems via a databus.
  iii) Reduced cabling on and around the engine.
  iv) High flexibility and easy customizing.
  v) Digital signals - free from electromagnetic disturbance.
  vi) Built-in diagnostics.

Disadvantages

I. Higher initial costs (The investment cost of an LNG carrier with medium speed dual fuel(GAS/MDO) Diesel electric propulsion for a 130,000-150,000 m^3 LNG is expected to increase by about 3-5% when compared with steam turbine driven vessel. The installation of a reliquefaction plant will increase the capital cost by another 5%.
II. Small efficiency loss (about 4-5%) in the electric power generation process.
III. Higher maintenance as a result of more moving parts, higher speed and more cylinders in a particular installation.
IV. Added complication due to the handling of gas in the engine room, however low pressure gas is supplied into the engine room, similar to the existing steam turbine design.
V. When the the energy available from the BOG exceeds the power requirement then the excess BOG is sent to the oxidiser which results in the loss of economic value of the boil off.
VI. Limitations on satisfactory engine operation while burning gas based on the gas composition (max 22% Nitrogen and minimum 78% Methane).

2.8 Combined HFO Medium Speed Diesel and Medium Speed Dual Fuel (Gas-MDO)

2.8.1 General information-technological development

A combination of dual fuel (gas/MDO as analyzed above) burning engines and HFO burning engines (typically two and two) is another possible configuration for the propulsion of LNGC.

This layout is suitable when gas cannot be predicted with confidence to be the primary fuel over the vessels service life. In this case when gas is not available or the price difference between gas and HFO triggers the choice of HFO, the installation can produce the propulsion and auxiliary power requirement by operating only the HFO burning engines. Obviously higher installed power is required if the normal power demand needs to be available either only gas or only HFO is available [3].

Also this arrangement is based on the desire not to install any reliquefaction plant and instead to use natural boil-off gas only as fuel (without forced boil-off gas) and top up the remaining energy requirement with heavy fuel.

Furthermore, since the energy price of LNG compared to heavy fuel is about the same, it is logical to use BOG-burning engines if only to keep the propulsion power plant simple, not to mention the environmental benefits gas fuel can offer [16].

2.8.2 Typical medium speed Diesel and medium speed dual fuel engine propulsion plant

The most common proposal is an electric propulsion system based on the combination of heavy fuel burning generator sets and dual fuel (gas/MDO) burning generator sets (typically two and two). The four Diesels provide electrical power for the main propulsion motors and the other electrical consumers.

2.8.3 Advantages and drawbacks for a medium speed Diesel and a medium speed dual fuel engine propulsion plant installation

Advantages

I. The system is environment friendly when using LNG as fuel.
II. High fuel choice and engine load flexibility.
III. Auxiliary Electric power demand is covered by the propulsion engines eliminating the need for additional auxiliary gen sets.
IV. Higher availability of experienced crew comparing to steam turbine.
V. Increased cargo carrying capacity compared to steam propulsion option.
VI. High propulsion redundancy.

Disadvantages

I. Higher initial costs.
II. Higher installed power is required if the normal power demand needs to be available when either only gas or only HFO is available.
III. Small efficiency loss (about 4%) in the electric power generation process.
IV. Higher maintenance as a result of more moving parts, higher speed and more cylinders in a particular installation.
V. Added complication due to the handling of gas in the engine room, however low pressure gas is supplied into the engine room similar to the existing steam turbine design.
VI. Added complications due to two types of engines are installed.
VI. Higher NOx and SOx emissions when HFO engines are used.

2.9 Medium Speed Gas-only Engine

2.9.1 General information-technological development

Until today, just a handful of vessels are using natural gas as fuel using medium speed gas engines.

LNG carriers have used the boil off gas as fuel for steam turbines and recently for dual-fuel (BOG/MDO or HFO) engines but haven't used gas-only engines yet.

Designed and manufactured at Rolls-Royce's Bergen facility in Norway, the K and B series of gas-fuelled engines were recently introduced to the marine market in order to meet the increasingly tough low emission targets. The starting point for the development of these engines was the exhaust gas emissions issue which has become one of the most important controlling factors for all future engine developments.

A number of manufactures offer dual-fuel engines but, while these appear attractive, they always need to burn Diesel fuel with the optimum ratio being 95% gas and 5% Diesel. In addition, the dual-fuel units rely on compression ignition creating high pressure and temperature in the cylinder. This can cause the gas to self-ignite (knocking) so a compromise must be sought to avoid knocking at high load, miss-firing at low load and problematic transient engine operation.

Bergen introduced the KV-G type gas engine in 1991 for the land power industry and has built up a good reputation by steadily developing the engine range to the current 200 kW per cylinder at 43% efficiency. This gas fuelled Otto 'cycle' engine is now available to the marine industry for direct mechanical drive, as a gas electric drive or genset. The K series is produced with cylinder configurations of 6, 8 or 9 cylinders in line and V12, V14 or V18 to give a power range from 1MW to 4MW.

The success of the K engine led RR to introduce a significantly larger and more powerful engine, the new B35:40V gas fired engine which will be available in 12V, 16V and 20V cylinder versions, with power ratings from 4.5 to 8.5 MW.

By suitable development of a strong ignition source, the pre-chamber and the gas-air mixture in the cylinder can be leaned out, giving much improved engine performance. Efficiency is increased, emissions are reduced, particularly NOx, and the specific power of the engine can be significantly increased because the knock limit is extended.

Fast and complete combustion is achieved by means of two ABB turbochargers, mounted back-to-back with one exhaust outlet. A mechanically operated gas valve comprising admission and flow-valves, is set into the inlet port of each cylinder. The valves inject gas into the inlet stream while the special inlet port design, flame deck layout, piston bowl and the engine control system ensures a homogenous and lean mixture of air and gas for quick and complete combustion under all operating conditions.

The advanced electronic engine control system ensures that operating parameters of the engine are adjusted and optimised in relation to each other. The engine has been optimised with regard to process parameters, turbocharger type and excess ratio in such a way as to maintain a high exhaust temperature thus maximizing waste heat recovery.

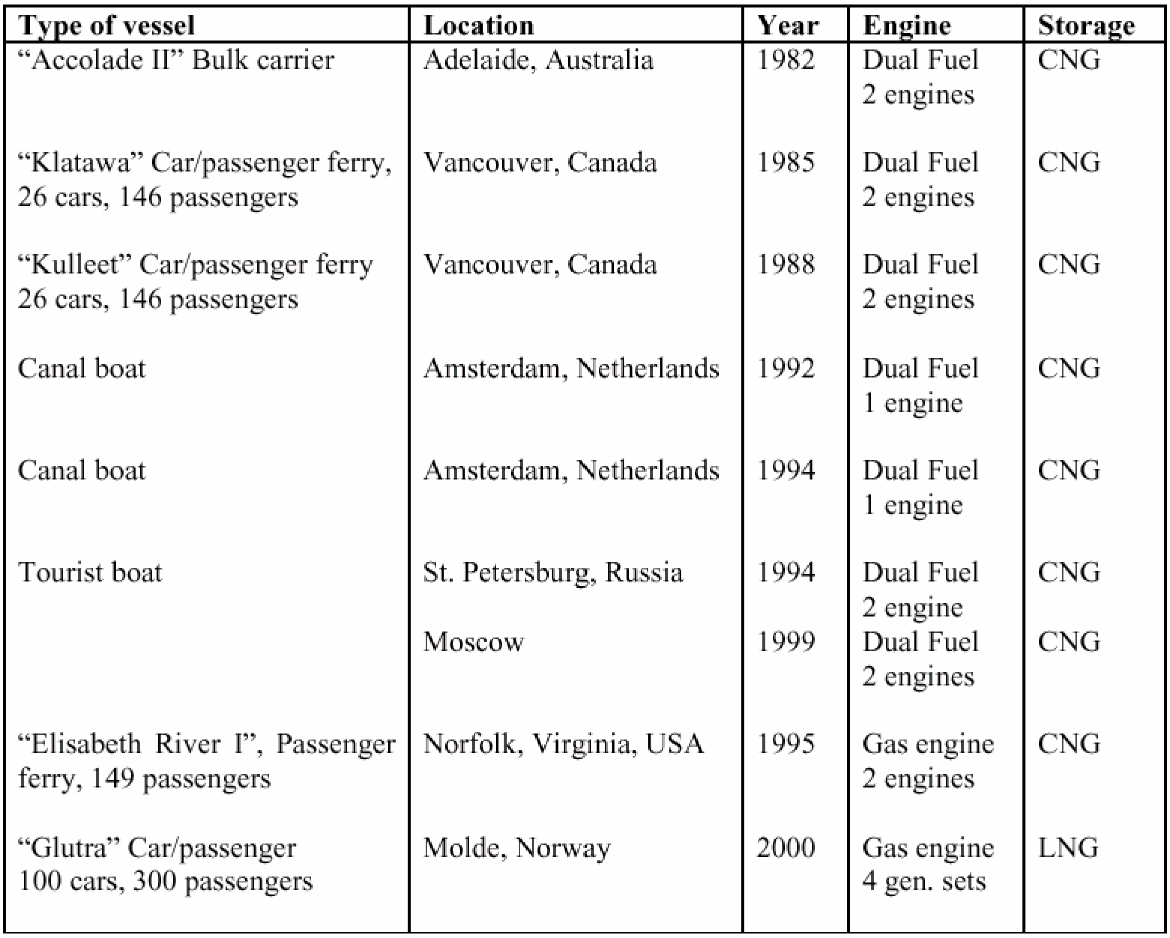
The manufacturer claims that the gas-only engine delivers optimum performance throughout the whole operating range without having to compromise between efficiency, performance and low emissions. It also simplifies the design, provides a wide operating range with no low-load limitations and enables crash-stopping without 'choking' the engine.

Due to the simple design of the gas engines and their relatively low running speed, the intervals between overhauls can be longer giving lower service costs. The robust construction of the engine is based on a number of advanced features such as nodular cast iron structure, six studs per cylinder head and latest bearing and valve materials. In addition, there are fewer parts subject to wear while the generous sizing of parts offers larger wear margins.

With the growing availability of LNG world-wide, the opportunities for gas engines is expanding especially with certain ship types including FPSO vessels, shuttle tankers, offshore support vessels, ferries and of course LNG carriers. Particularly at LNG carriers there is available fuel for the gas engines from the cargo boil off gas and this is a clear advantage toward the adoption of this type of engine for the propulsion of these vessels.

Another gas engine manufacturer is Mitsubishi with its GS-series gas engines [29]. The list in the Table 2.9.1 is covering some of the first ships and boats powered by natural gas burning engines.

Table 2.9.1 Ships and boats powered by natural gas from 1982 until 2000 [21].



Type of vessel	**Location**	**Year**	**Engine**	**Storage**
"Accolade II" Bulk carrier	Adelaide, Australia	1982	Dual Fuel 2 engines	CNG
"Klatawa" Car/passenger ferry, 26 cars, 146 passengers	Vancouver, Canada	1985	Dual Fuel 2 engines	CNG
"Kulleet" Car/passenger ferry 26 cars, 146 passengers	Vancouver, Canada	1988	Dual Fuel 2 engines	CNG
Canal boat	Amsterdam, Netherlands	1992	Dual Fuel 1 engine	CNG
Canal boat	Amsterdam, Netherlands	1994	Dual Fuel 1 engine	CNG
Tourist boat	St. Petersburg, Russia	1994	Dual Fuel 2 engine	CNG
	Moscow	1999	Dual Fuel 2 engines	CNG
"Elisabeth River I", Passenger ferry, 149 passengers	Norfolk, Virginia, USA	1995	Gas engine 2 engines	CNG
"Glutra" Car/passenger 100 cars, 300 passengers	Molde, Norway	2000	Gas engine 4 gen. sets	LNG

It has now been 5 years since the first LNG fuelled ferry in the world, called Glutra, started its shuttle transport of people and cars across a fjord on the west coast of Norway. In the years since the Glutra ferry project started we have seen much new movement and growing interest in the use of gas fuelled reciprocating internal combustion engines for ships propulsion. Two supply vessels equipped with dual fuel engines have gained almost two years of experience, running on LNG almost all of this time, and two LNG tankers are also running with gas engine installations now. There have been some very interesting projects involving gas fuelled engines on ships during the last years, and even more new projects will come in the future. The Glutra car ferry is the first LNG fuelled ferry in the world, finished in January 2000. The four engine rooms each holding one gas engine are located above the car deck on one side, while the vacuum insulated gas tanks with liquid gas are located in the centre below the car deck. The operational experience with this vessel has been very good, much due to the redundancy built into the design. The engine emissions have been measured, showing poor efficiency and high emissions at low loads, however with a gas electric configuration like this, engines can be run on higher loads, so this is not a big problem. Five new gas ferries will be built in the Aker Yards for delivery from August till December in 2006; these will have the gas engine room spaces as well as the gas tanks located below the car deck.

The two supply vessels running on LNG, Viking Energy and Stril Pioneer are each equipped with four dual fuel gas engines, located in two engine rooms below deck level. The LNG tank is located aft of the engine rooms. The vessels were delivered in 2003, and have been operating on gas almost every day since they where finished, and have good experience. Also the workers on the platforms served by the supply vessels embrace the clean air they experience when the gas fuelled vessels operate at the platform, and wish for nothing but gas fuelled supply vessels from now on.

The LNG market is a very interesting one when it comes to the use of gas engines, and for the first time in many years gas carriers are actually built with other propulsion solutions than dual fuel steam boilers. This also includes gas fuelled engine solutions. On the small Pioneer Knutsen (1100 m^3) LNG carrier, ordered in 2002 by Knutsen OAS to the Dutch yard Scheepswerf Bijlsma, two pure gas engines are combined with two Diesels, located in separate spaces. On the Gaz de France Energy four dual fuel engines are installed in two engine room spaces. In the larger LNG vessel also to be built to Gaz de France, Provalys, four DF engines will also be used, three of them with higher power output. More LNG vessels with DF engines are ordered in Hyundai, Korea by BP and other ship operators.

DNV rules for classification of gas fuelled engine installations in ships were introduced already in January 2001, and they are applicable to all ship types, including LNG tankers. The rules set requirements to location of tanks, to piping installations, engine room installations, as well as to the gas engine itself [30].

2.9.2 Typical medium speed gas engine propulsion plant

As we haven't medium speed gas-only engine's installations on board of seagoing LNG vessels so far, we use as an example an existing Norwegian ferry the natural gas powered ferry "Glutra".

Financed by the Norwegian Directorate of Public Roads, the car ferry with a capacity of 100 private cars was designed for operation on natural gas, based on a new set of Norwegian safety standards for gas fuelled passenger ships.

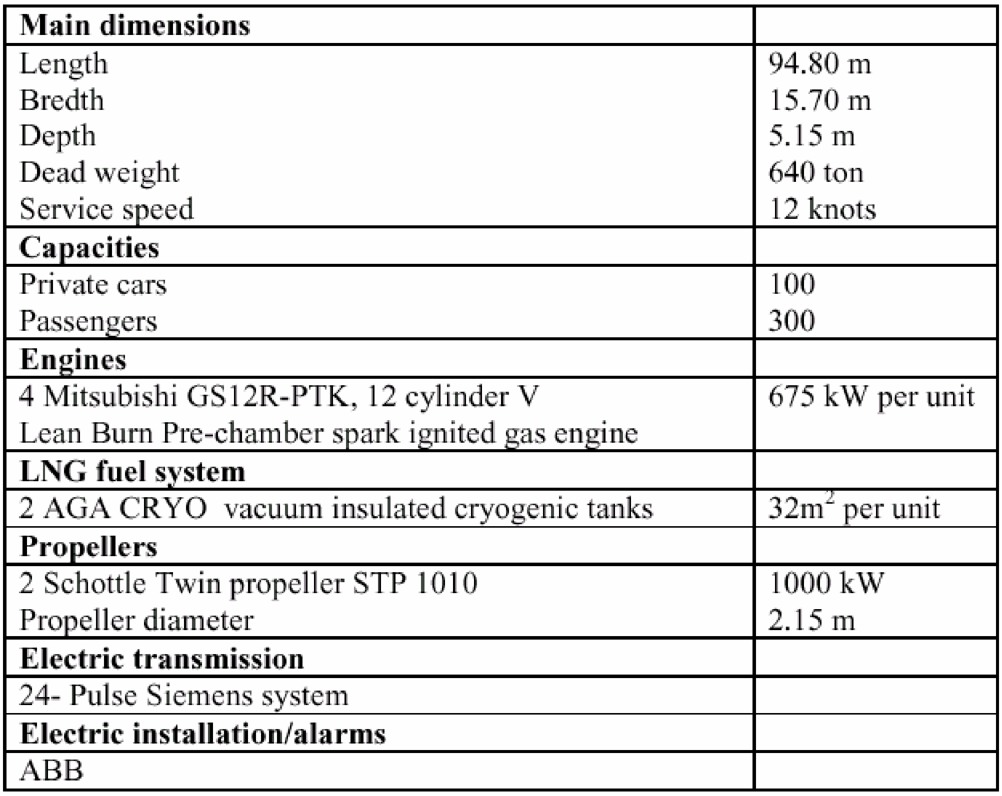
The ferry is propelled by four gas engine generator sets giving power to two electric driven compass thrusters, one in each end of the ship.

Four generator sets, 675 kW each, were put in separate engine rooms above the main deck. This was at the same time an elegant way to meet the strict requirement regarding consequences of an explosion in the engine room. An explosion analysis showed that in the worst case the two-sashed door of the engine room would burst and immediately release the pressure without affect the other engine rooms. The engine rooms are arranged two and two, with the main switchboard for the electric power, separating them.

In normal operation two engines give sufficient power for propulsion and other energy consumers. The third generator set is backup or may be added to increase speed or higher energy demand due to weather conditions. The fourth generator set could then be available for maintenance. By this arrangement the ferry could be in operation 365 days a year in a period of 2-3 years.

Glutra has been in operation for more than half a year without any kind of interruptions. The ferry company is satisfied in all respect [21].

Table 2.9.2 Specifications of the LNG ferry M/F Glutra [21].



Main dimensions	
Length Bredth Depth Dead weight Service speed	94.80 m 15.70 m 5.15 m 640 ton 12 knots
Capacities	
Private cars Passengers	100 300
Engines	
4 Mitsubishi GS12R-PTK, 12 cylinder V Lean Burn Pre-chamber spark ignited gas engine	675 kW per unit
LNG fuel system	
2 AGA CRYO vacuum insulated cryogenic tanks	$32m^2$ per unit
Propellers	
2 Schottle Twin propeller STP 1010 Propeller diameter	1000 kW 2.15 m
Electric transmission	
24- Pulse Siemens system	
Electric installation/alarms	
ABB	

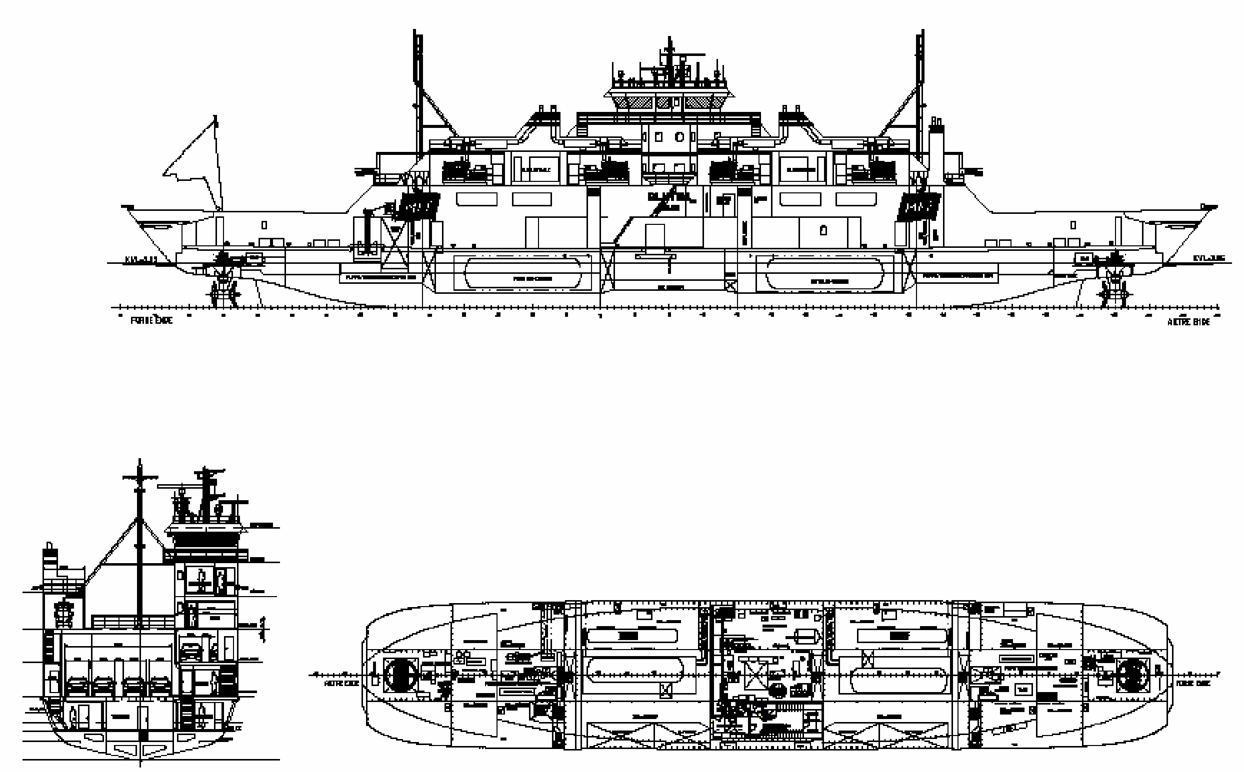


Fig. 2.9.1 LNG ferry Glutra - General arrangement [21].

Based on the Norwegian ferry configuration, four medium speed spark ignited gas – only engines (Rolls-Royce Bergen B-series gas engine or Mitsubishi GS-series gas engine) using electric transmission with a sufficient number of MDO or HFO medium speed Diesel engines only as a back up is a viable propulsion solution for many vessel types and of course for LNG carries which can use the boil off gas as fuel.

This option becomes competitive particularly for LNG carriers when oil prices are high.

2.9.3 Advantages and drawbacks for a medium speed gas engine propulsion plant installation

Advantages

I. The system is environment friendly because LNG is used as fuel.
II. Auxiliary Electric power demand is covered by the propulsion engines eliminating the need for additional auxiliary gen sets.
III. Increased cargo carrying capacity compared to steam propulsion option.
IV. Higher efficiency compared to steam propulsion.
V. Cost savings when oil prices are higher than LNG price.

Disadvantages

I. Higher initial costs.
II. Small efficiency loss (about 4%) in the electric power generation process.

III. Higher maintenance as a result of more moving parts, higher speed and more cylinders in a particular installation.
IV. Added complication due to the handling of gas in the engine room, however low pressure gas is supplied into the engine room similar to the existing steam turbine design.

2.10 Combined Slow Speed Diesel and Medium Speed Dual Fuel

2.10.1 General information-technological development

The CRP POD system proposed by Mitsubishi Heavy Industries is considered to be suitable propulsion for next generation LNG carriers.

The propulsion plant in the HYBRID LNG system consists of a low-speed Diesel engine which drives a FPP and an electrical propulsion plant with dual- fuel medium speed Diesel engines which drive the POD propeller.

The ratio of power share between the Diesel engine and POD is determined by the manoeuvring around coastal and portal area (low-steaming navigation), with POD alone taken as the basic requirement and in consideration of additional propulsive force during ocean going navigation [14].

The need to have a back up means of dealing with the boil off gas is normally handled by the installation of an oxidiser. The oxidiser burns the amount of BOG which exceeds the propulsion requirements.

Obviously, the highest flexibility is obtained if a reliquefaction plant is installed as a primary means of dealing with the BOG. Such a configuration will give complete freedom on the boil off gas handling (use as a propulsion fuel or reliquefy) and consequently on the fuel used for propulsion.

Hybrid BOG treatment plant

The auxiliary power system in the HYBRID LNG system can treat BOG in a safe and efficient manner by adjusting the quantity of BOG to be reliquefied and that to be fired, thus adapting to the circumstances in combination with the reliquefaction system. The cogeneration system, in which waste heat from the main engine and the heat generated upon partial combustion of BOG are utilized, supplies electric power to POD and liquefying power, which are the main unit of power consumption. In case of LNG carriers, the liquefying power is considerably higher than any other ship service power (3 to 5 MW when the entire quantity of BOG is liquefied in a 135,000 to 200,000 m^3 hull form). Since existing marine (commercial) techniques are applied to this system, including the reliquefaction system, dependence on the skill of crew members is considered to be less than in other alternative propulsion systems [14].

2.10.2 Typical slow speed Diesel and medium speed dual fuel Diesel engine propulsion plant

A typical slow speed Diesel and Medium speed Dual fuel Diesel engine propulsion plant consists of one slow speed Diesel with a FPP and 2 or 3 dual-fuel medium speed Diesel engines driving the POD propeller and offering the necessary electrical power in an electrical propulsion system [14].

A thermal oxidiser or a reliquefaction plant offer redundancy for the excess BOG treatment.

The need to have a back up means of dealing with the boil off gas is normally handled by the installation of an oxidiser. The oxidiser burns the amount of BOG which exceeds the propulsion requirements.

Obviously, the highest flexibility is obtained if a reliquefaction plant is installed as a primary means of dealing with the BOG. Such a configuration will give complete freedom on the boil off gas handling (use as a propulsion fuel or reliquefy) and consequently on the fuel used for propulsion.

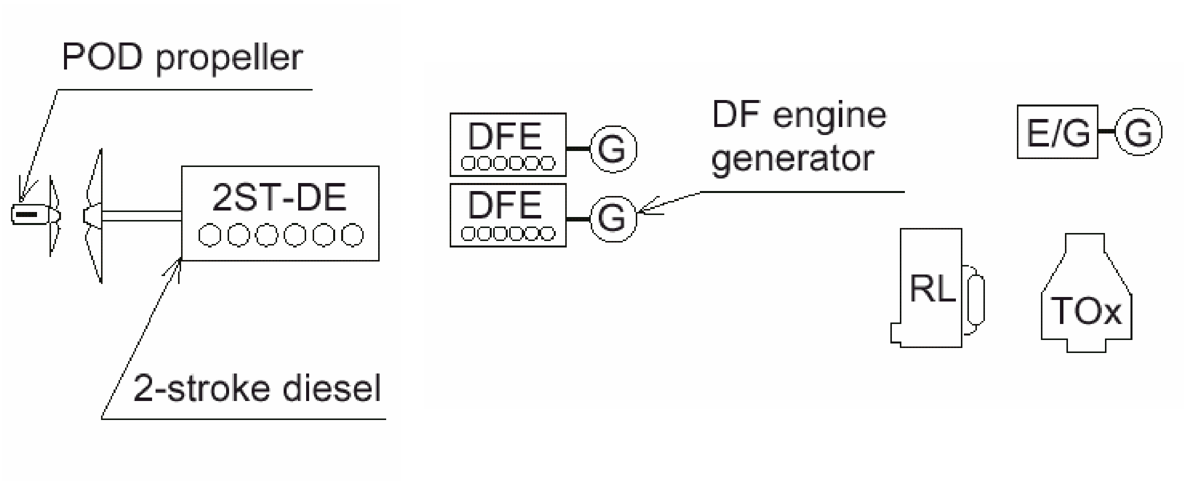


Fig. 2.10.1 Hybrid propulsion system [14].

2.10.3 Advantages and drawbacks for a slow speed Diesel and a medium speed dual fuel Diesel engine propulsion plant installation

Advantages

I. Higher efficiency compared to a steam propulsion plant resulting in lower energy consumption.
II. High fuel choice and engine load flexibility especially if a reliquefaction plant is installed.
III. Auxiliary Electric power demand is covered by the dual-fuel propulsion engines eliminating the need for additional auxiliary gen sets.
IV. Higher availability of experienced crew comparing to steam turbine.
V. The system is environment friendly when using LNG as fuel.
VI. Increased cargo carrying capacity compared to steam propulsion option.
VII. High propulsion redundancy.
VIII. In the case of an electronically controlled engine:
    vii) Lower SFOC and better performance parameters at any load thanks to electronically controlled variable timing of fuel injection and exhaust valves at any load.

viii) Control system offers more precise timing and thereby better engine balance and less noise with equalized thermal load in and between cylinders, minimising the risk of premature need for overhaul.
ix) Improved emission characteristics, with lower NOx and smokeless operation.
x) Lower RPM possible for manoeuvring.
xi) Better acceleration, astern and crash stop performance.
xii) System comprising performance, adequate monitoring and diagnostics of engine for longer time between overhauls.

Disadvantages

I. Higher installed power is required if the normal power demand needs to be available either only gas or only HFO is available.
II. Diesel engines require more maintenance on a routine basis than steam turbines.
III. Higher lub oil consumption compared to steam turbine which adds to the operating cost.
IV. Added complication due to the handling of gas in the engine room, however low pressure gas is supplied into the engine room similar to the existing steam turbine design.
V. Added complications due to two types of engines are installed.
VII. Higher NOx and SOx emissions when low speed engine is used.
VIII. Higher lub oil consumption compared to steam turbine which adds to the operating cost.
IX. Higher initial cost.

2.11 Combined Medium Speed Diesel and Gas Turbine (CODAG OR CODLAG)

2.11.1 General information-technological development

Gas turbines have been used within CODAG (combined Diesel and gas) configurations in many cruise ships. This propulsion system is also a possible, but less promising alternative for LNG carriers.

Another proposed arrangement is a combined Diesel-electric and gas turbine (CODLAG) system, if the greater complexity is acceptable.

The aim is to use Diesel power (Diesel-mechanical or Diesel-electric) during normal operation and the turbine for short period transit runs or in environmentally-sensitive areas, burning mostly BOG. Since gas turbine deployment is not continuous it is not feasible to apply any type of heat recovery systems to the turbine.

For the excess BOG treatment there are two possible scenarios. The first is to operate the gas turbine continuously, with or without the Diesel engines, when the BOG rate is enough for the propulsion requirements (full load) and use an oxidiser when BOG isn’t enough. The oxidiser can also be used if the amount of BOG exceeds the propulsion requirements.

The second possible solution is to install a reliquefaction plant as a primary means of dealing with the BOG. Obviously this arrangement offers higher flexibility between different operating modes and gives complete freedom on the boil off gas handling (use as a propulsion fuel or reliquefy) and consequently on the fuel used for propulsion.

The main advantages of a CODLAG concept are compactness, good fuel economy under normal operation and an attractive first-cost for the machinery. Also this concept offers significant space and weight savings and low emission levels.

A disadvantage of this simple-cycle gas turbine-based system is that the machinery can only operate efficiently in limited operating profiles. CODLAG systems are valid if the operational profile includes a clear ‘booster’ speed element (ship in spot market). The concept is essentially conventional Diesel-electric during normal operation, with the gas turbine engaged for only short periods. Another disadvantage is that there is always a risk of a situation where the Diesel power is insufficient and the gas turbine must run at low load. In addition the system has significant complexity, two different types of power source call for different sets of full auxiliary systems. This is the major drawback of both CODAG and CODLAG systems: the simplicity of a pure gas turbine-based plant is lost due the introduction of two different engine types with associated ancillaries, spares, maintenance routines and operational characteristics. Another drawback is fuel cost.

Energy management must be carefully considered during the design phase of a ship. It is important to focus on total energy efficiency and not just on energy for propulsion. Only a careful evaluation of all energy flows (not just mechanical) allows an assessment of how the different options should be blended when seeking optimum production and use of energy [28].

2.11.2 Typical medium speed Diesel and gas turbine propulsion plant

This propulsion concept consists of a combination of medium speed Diesel-electric engine employing a gas turbine to feed off the BOG (CODLAG system).

The configuration can employ one or two FPP, CRP propeller or one/two POD propellers.

Although mechanical drive through reduction gear (CODAG system) is also possible, it is not considered a likely candidate for LNG carriers because it removes some of the advantages achieved with electric propulsion, like elimination of auxiliary electric power generators, flexibility of installation etc.

The need to have a back up means of dealing with the boil off gas is normally handled by the installation of an oxidiser. The oxidiser burns the amount of BOG which exceeds the propulsion requirements. Highest flexibility is obtained if a reliquefaction plant is installed as a primary means of dealing with the BOG.

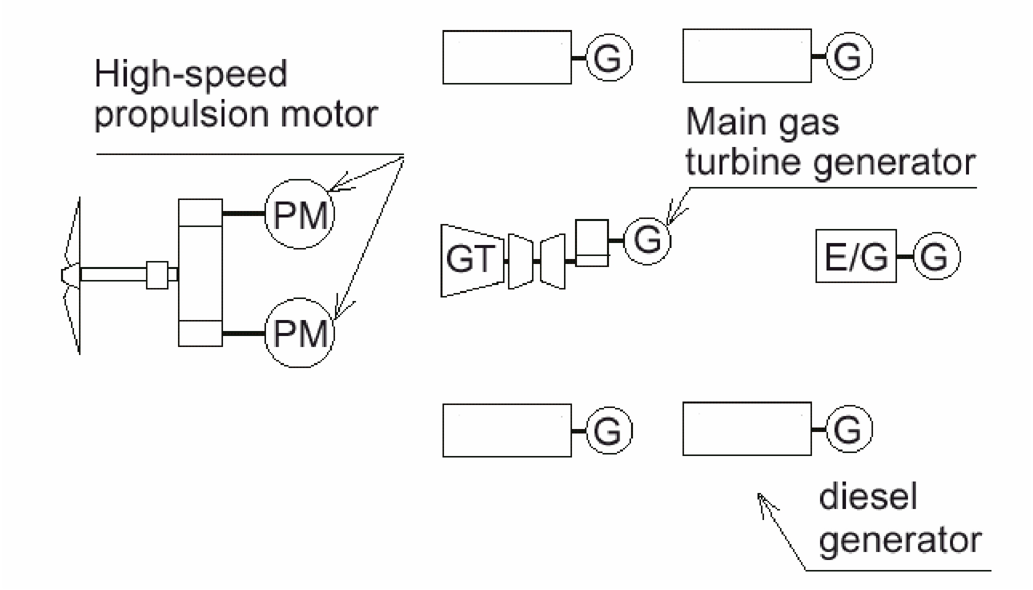


Fig. 2.11.1 The CODLAG single-screw concept [28].

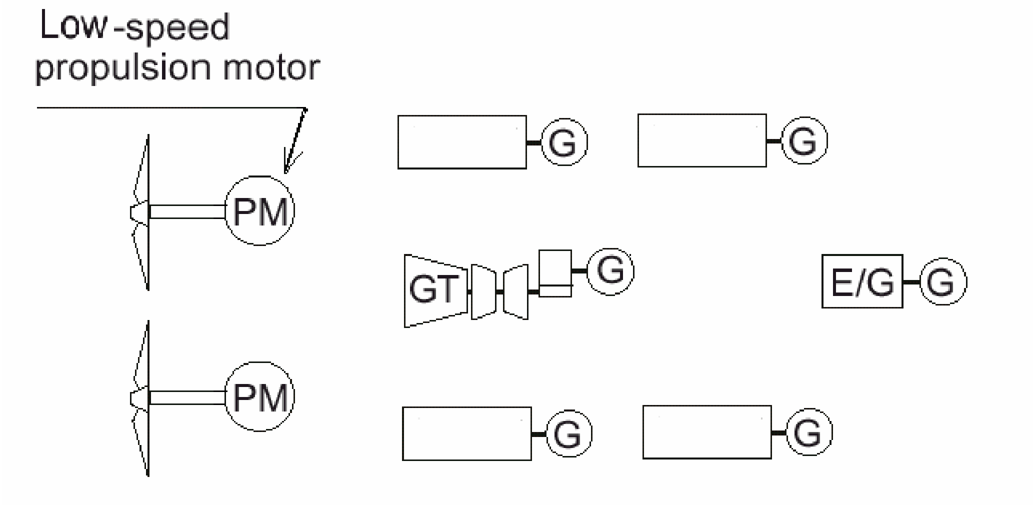


Fig. 2.11.2 The CODLAG twin-screw concept [28].

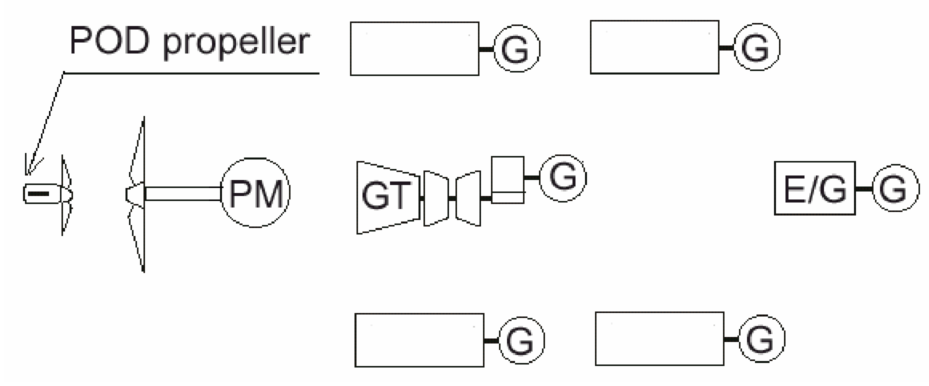


Fig. 2.11.3 The CODLAG CRP concept [28].

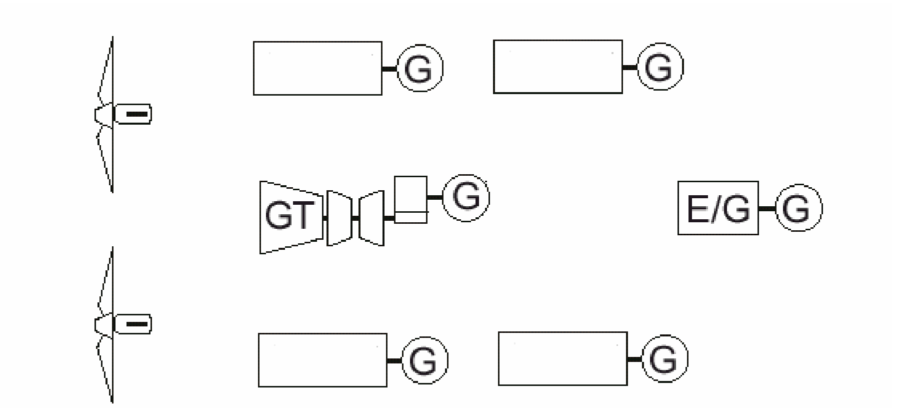


Fig. 2.11.4 The CODLAG twin-POD concept [28].

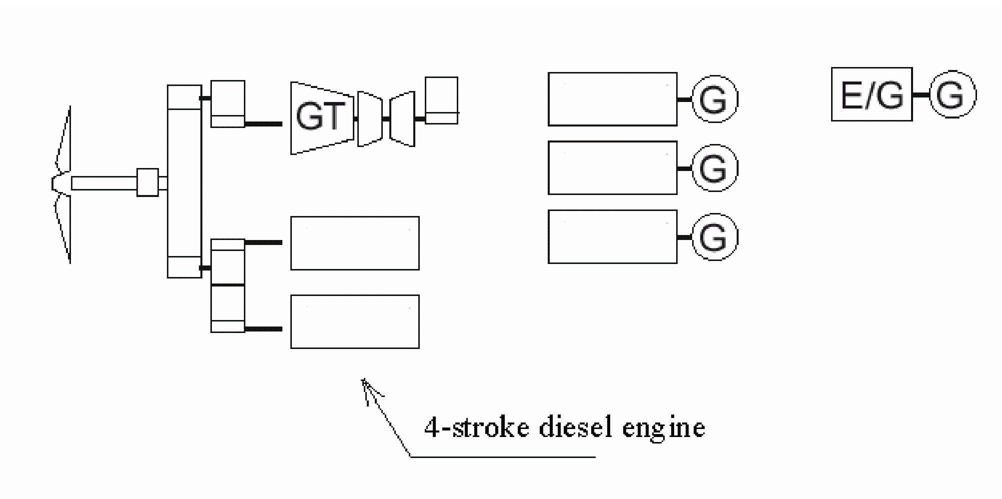


Fig. 2.11.5 The CODAG concept [28].

2.11.3 Advantages and drawbacks for a medium speed Diesel and a gas turbine propulsion plant installation

Advantages

I. Increased thermal efficiency and lowest energy conversion losses compared to steam turbines.
II. High fuel choice and engine load flexibility especially if a reliquefaction plant is installed.
III. Significant space and weight savings resulting in increased cargo carrying capacity compared to steam propulsion option.
IV. Higher availability of experienced crew comparing to steam turbine.
V. The system is environment friendly when using LNG as fuel.
VI. High propulsion redundancy, especially on a twin propeller configuration.
VII. State of the art gas turbine with aero engine standards of reliability and easier maintenance and engine change-out.
VIII. Dual-fuel capability for the gas turbine (simultaneous boil-off gas/MGO capability).
IX. In the CODLAG arrangement, auxiliary electric power demand is covered by the propulsion engines eliminating the need for additional auxiliary gen sets.
X. FPP can be used without reversing gear in the case of electric propulsion

Disadvantages

I. Added complication due to the introduction of two different types of engines with associated ancillaries, spares, maintenance routines and operational characteristics. Another drawback is fuel cost.
II. Gas turbine has to be located very near to the propeller shaft and a reduction gearbox, reversing gear are required for direct mechanical drive with a FPP.
III. Gas compressor required to supply gaseous fuel at 30 bar pressure to the gas turbine.
IV. In the case of electric drive increased cost and complexity compared to mechanical drive.
V. Energy conversion losses in the electric drive system for the case of electric propulsion.
VI. Expensive back up fuel for the gas turbine.
VII. Specialized training of engineers is required.
VIII. Higher NOx and SOx emissions when Diesel engines are employed.
IX. Diesel engines require more maintenance on a routine basis than steam turbines.
X. Higher lub oil consumption compared to steam turbine which adds to the operating cost.

2.12 Combined Slow Speed Diesel and Steam Turbine

2.12.1 General information-technological development

A HYBRID LNG system proposed originally by Mitsubishi Heavy Industries, Ltd. (MHI) is a system in which a slow speed Diesel engine propulsion plant, driving a FPP and steam turbine generators driving a POD propeller, as well as reliquefaction system and gas combustion system are combined in the propulsion plant and BOG treating plant, respectively.

The CRP POD system (Fig. 2.12.1) is considered to be a suitable propulsion system for high-speed vessels and high-powered ships such as next-generation high-speed container ships and LNG carriers. This system can achieve high power, fuel cost improvement and high manoeuvrability with comparative ease.

The propulsion plant in the HYBRID LNG system consists of a low-speed Diesel engine and electrical propulsion plant.

Optimization of liquefaction plant by peak shaving

The quantity of BOG shows significant fluctuations during a voyage (Fig. 2.12.1). In cases where a large quantity of BOG is generated temporarily, the HYBRID LNG system utilizes BOG in excess of the liquefying capacity as boiler fuel (heat source) [14].

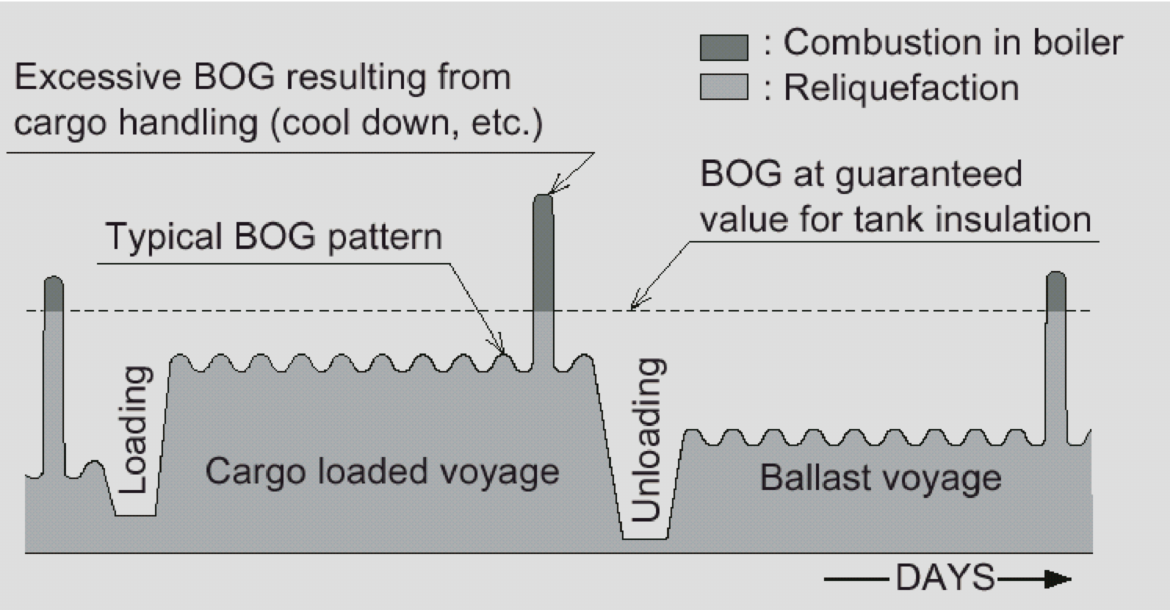


Fig. 2.12.1 BOG generating patterns and peak shaving of liquefaction [14].
The capacity of the reliquefaction system is designed with natural boil-off
(guaranteed value for tank insulation) used as reference, and temporarily
generated excessive BOG is used as boiler fuel.

Environmental protection measures

In recent years, there has been a marked tendency toward compulsory use of low-sulfur fuel and intensified control of emissions of nitrogen oxides (NOx) from engines, particularly in the coastal areas of Europe and West Coast of the USA**.** LNG is a clean fuel having no sulfur content and is lower in price than marine Diesel oil and low-sulfur heavy oil. LNG carriers with HYBRID LNG system are operated mainly by Diesel engines during navigation at sea, but cruise with POD at low steaming during coastal and portal navigation, while BOG is used as boiler fuel and excessive BOG is saved by reliquefaction.

This system requires neither excessive gas treatment nor use of expensive marine Diesel oil and low-sulfur heavy oil, and achieves zero emission of sulfur oxides (SOx). Moreover, the gas combustion process in the boiler has a very low NOx emission rate as compared with that of internal combustion engines (Fig. 2.12.2) [14].

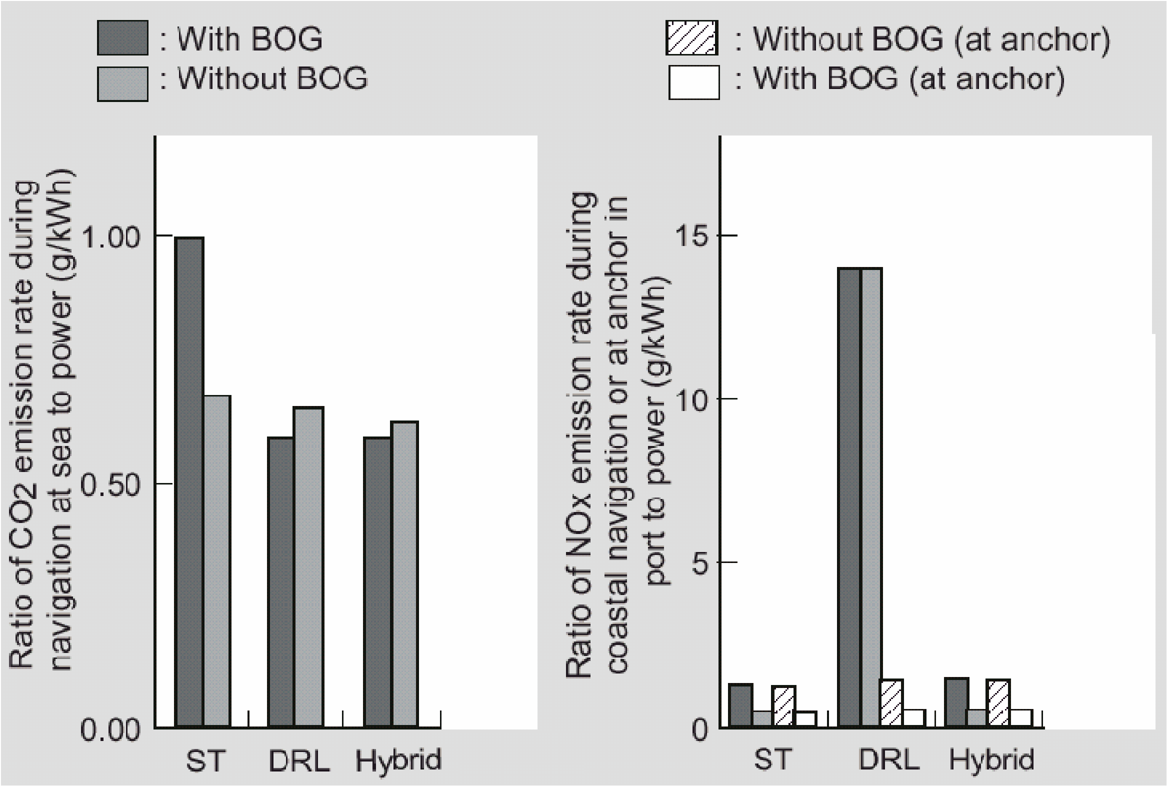


Fig. 2.12.2 CO_2 and NOx emission rates from Steam turbine, Slow speed Diesel engine and the Hybrid (slow speed Diesel and steam turbine) system [14].

2.12.2 Typical slow speed Diesel and steam turbine propulsion plant

A typical slow speed Diesel and steam turbine propulsion plant consists of one Slow speed Diesel driving a FPP and 2 or 3 steam turbine generators driving the POD propeller and offering the necessary electrical power in an electrical propulsion system [14].

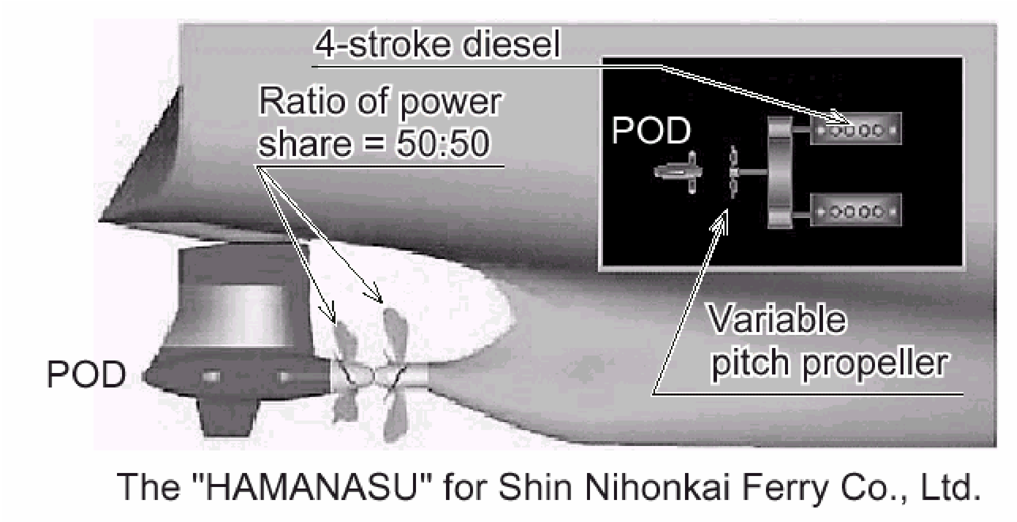


Fig. 2.12.3 Hybrid propulsion system adopted for ferry boats [14].

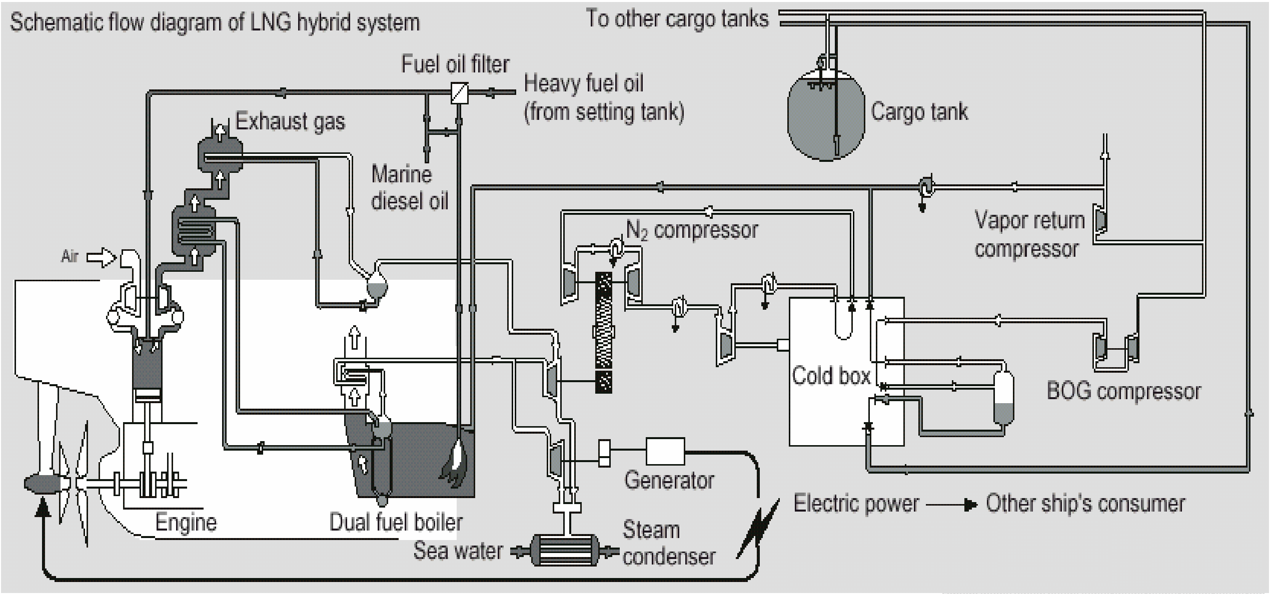


Fig.2.12.4 Outline of hybrid system [14].

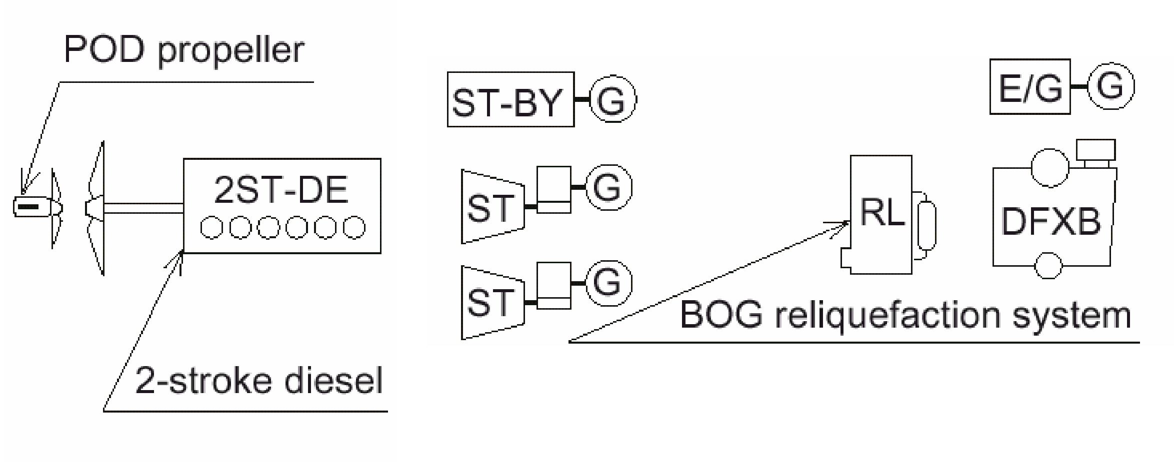


Fig. 2.12.5 Hybrid propulsion system [14].

2.12.3 Advantages and drawbacks for a slow speed Diesel and a steam turbine propulsion plant installation

Advantages

I. The steam turbine utilization provides a very easy and reliable method to utilize the BOG. The quantity of BOG shows significant fluctuations during a voyage. In cases where a large quantity of BOG is generated temporarily, the HYBRID LNG system utilizes BOG in excess of the liquefying capacity as boiler fuel (heat source).

II. Low turbine maintenance and also relatively modest in cost.

III. High overall fuel efficiency for the slow speed Diesel - up to 50% - resulting in low energy consumption and thus low operating cost.

IV. Optimization of liquefaction plant by peak shaving. The reliquefaction system is optimized by shaving of liquefaction to natural BOG on voyage with cargo loaded, thus enabling high-efficiency operation at most period of voyages.

V. The HYBRID LNG system provides complete freedom on the boil off gas handling (use as a propulsion fuel or reliquefy) and consequently on the fuel used for propulsion.Since the unit price ratio may fluctuate depending on the mode of LNG transaction (CIF, FOB, etc.) and the fuel oil market conditions, it is desirable to achieve fuel cost improvement over as wide a range as possible.

VI. The nitrogen in the LNG boil-off gas (BOG) is not reliquefied; this results in reduced nitrogen in the tanks during the voyage, better control of tank pressure and lower power requirement for the RS system.

VII. LNG carriers with HYBRID LNG system are operated mainly by the slow speed Diesel engine during navigation at sea, so the amount of CO_2 released can be reduced significantly compared to a steam propulsion plant burning either BOG or HFO, because of the higher thermal efficiency of the slow speed Diesel.

VIII. LNG carriers with HYBRID LNG system use the POD at low steaming during coastal and portal navigation, while BOG is used as boiler fuel and excessive BOG is saved by reliquefaction. This system achieves zero emission of sulfur oxides (SOx) and moreover, the gas combustion process in the boiler has a very low NOx emission rate as compared with that of internal combustion engines, and that compromises with the IMO’s emission control regulations (MARPOL Annex) and the regional restrictions especially in the coastal areas of Europe and West Coast of the USA.

Disadvantages

I. Low efficiency of the steam turbine plant with the inevitable high fuel consumption.
II. Added complication due to the introduction of two different types of engines with associated ancillaries, spares, maintenance routines and operational characteristics.
III. A declining population of competent seagoing steam engineers creates the need to continue developing experienced crew, familiar with the operation and maintenance of a steam plant.
IV. Long delivery time for turbines and reduction gears and very limited production versus demand.
V. The comparative inefficiency of steam plant and hence high fuel consumption translates directly to high carbon dioxide emissions due to high exhaust gas volumes.
VI. Poor manoeuvring characteristics.
X. The reliquefaction plants require a substantial amount of electric power to operate and are costly, heavy and have only been applied in the marine environment on a very limited scale.
XI. Higher NOx and SOx emissions compared to alternatives burning LNG instead of HFO (without additional equipment like SCR units or direct water injection, NOx emissions are substantial; as an inevitable consequence of using HFO as a fuel, SOx emissions are high too).
XII. Diesel engines require more maintenance on a routine basis than steam turbines.
XIII. Higher lub oil consumption compared to steam turbine which adds to the operating cost.

2.13 Combined HFO Medium Speed Diesel and Medium Speed Gas Engine

2.13.1 General information-technological development

An electric propulsion system based on a combination of heavy fuel burning generator sets and gas burning generator sets has been proposed as well. This is based on the desire not to install any reliquefaction plant and instead to use natural boil-off gas only as fuel (without forced boil-off gas) and to top up the remaining energy requirement with heavy fuel. However, to cater for the wide variation in boil-off gas energy available, the total installed engine power would be high, perhaps up to 65 % greater than with a single type of engine. Furthermore, since the energy price of LNG compared to heavy fuel is about the same, it is logical to use gas-burning engines if only to keep the propulsion power plant simple, not to mention the environmental benefits gas fuel can offer [16].

2.13.2 Typical HFO medium peed Diesel and medium speed gas engine propulsion plant

As mentioned at the paragraph 2.9.2, on the small Pioneer Knutsen (1100 m^3) LNG carrier two pure gas engines are combined with two Diesels, located in separate spaces.

This vessel, designed by Conoship and manufactured at the Dutch yard Bijlsma will use boil-off LNG from the cargo as its main fuel for two gas engines in combination with two Diesel engines in an Diesel-electric propulsion arrangement.

The four engines, each of equal output, are split over two spaces on two levels - two on the main deck and two on the tanktop - to meet Det Norske Veritas class requirements. Each drives an alternator to supply current to a pair 900kW frequency-controlled motors, which drive azimuthing propellers. During normal sailing, cargo boil-off is expected to be sufficient to power the gas engines, but if required, the cargo can be heated to obtain more boil-off, and two extra compressors are mounted on top of the cargo tanks for pumping gas to the machinery rooms. Approximately 84m^3 of fuel oil is carried for the Diesel engines [24].

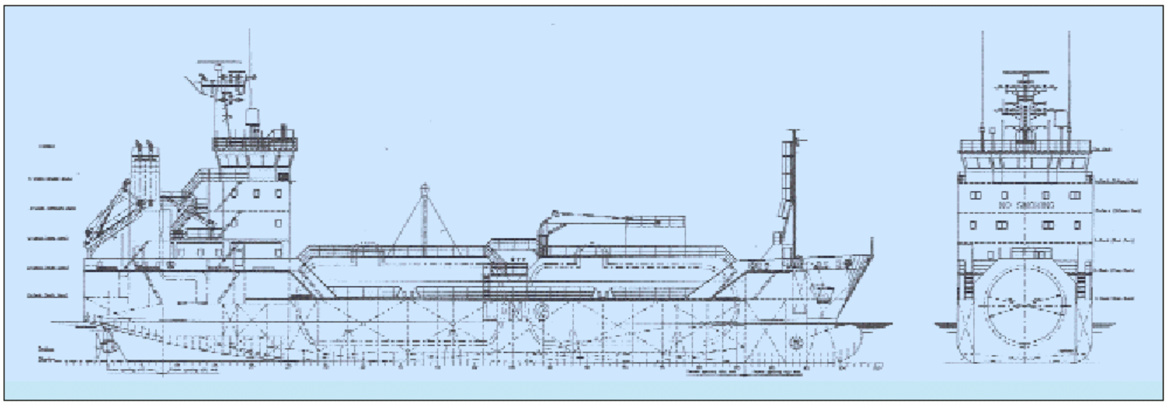


Fig. 2.13.1 Profile and cross-section of a small LNG tanker. Apart from the modest capacity (1100m ^{3}), the design is notable for a Diesel-electric propulsion plant, with two pure gas engines principally planned to burn cargo boil-off and two Diesel engines [24].

The most common proposal is an electric propulsion system based on the combination of heavy fuel burning generator sets and gas burning generator sets (typically two and two). The four Diesels provide electrical power for the main propulsion motors and the other electrical consumers.

2.13.3 Advantages and drawbacks for a HFO medium speed Diesel and medium speed gas engine propulsion plant installation

Advantages

VI. The system is environment friendly when using LNG as fuel.
VII. High fuel choice and engine load flexibility.
VIII. Auxiliary Electric power demand is covered by the propulsion engines eliminating the need for additional auxiliary gen sets.
IX. Higher availability of experienced crew comparing to steam turbine.
X. Increased cargo carrying capacity compared to steam propulsion option.
XI. High propulsion redundancy.
XII. Higher efficiency compared to steam propulsion.

Disadvantages

V. Higher initial costs.
VI. Higher installed power is required if the normal power demand needs to be available either only gas or only HFO is available.
VII. Small efficiency loss (about 4%) in the electric power generation process.

VIII. Higher maintenance as a result of more moving parts, higher speed and more cylinders in a particular installation.
IX. Added complication due to the handling of gas in the engine room, however low pressure gas is supplied into the engine room similar to the existing steam turbine design.
X. Added complications due to two types of engines are installed.
XI. Higher NOx and SOx emissions when HFO engines are used.

2.14 Compressed Natural Gas (CNG) Engine

2.14.1 General information-technological development

In a unique research project the Japanese ‘Ship and Ocean Foundation’ (SOF),has, since 1998, been developing an engine that utilizes reformed fuel from compressed natural gas (CNG) and an accompanying system for increasing thermal efficiency.

Using a catalytic NG reforming unit and a CO_2 separator, this revolutionary engine system boasts a thermal efficiency better than 70% and a dramatic emission reduction with CO_2 reduced to less than a half of their present level while NOx and SOx are reduced to almost zero.

The main objective of the programme is to turn natural gas into a viable alternative primary energy resource that can be used in place of oil. Energy from reformed exhaust gas is used to drive a gas turbine in combination with an electric generator and steam turbine.

As the exhaust gas passes through a two-part process, i.e. a CNG fuel catalytic converter and a reformation unit, almost all the CNG is reformed into carbon monoxide (CO) and hydrogen (H_2). These gases are then heated by the hot exhaust gas in a heat exchanger with elements made of porous metals. The calorific value of reformed fuel increases by about 30% in the converter.

The research is also aimed at developing a complete ‘CNG reformation engine system’ which integrates a highly efficient heat exchanger, with steam and exhaust turbines.

Achieving 60% thermal efficiency in a Diesel engine has long been a goal of engine technologists. A study in 2003, which involved research into the combustion process through experimental engine differential simulation, showed that a thermal efficiency of 57,5% is attainable. The development of auxiliary devices such as compact reformation converter and heat exchanger has also reached the stage for preparing the system for practical operation.

It is planned that the CNG reformation engine will be fitted with a 200 kVA output dynamo. This unit is adaptable to a wide range of applications including electricity generation, and vessel and automobile propulsion.

The reformed CNG fuel engine has the potential to reduce CO_2 emissions to 50% of existing engines, NOx to below 10ppm and SOx to zero. It is hoped that a decentralized hybrid engine system combining generator and electric motor will encourage further development of electric ship propulsion systems and other environmentally friendly innovations.

On a practical note, a hybrid engine system will allow ship crews to continue operating a vessel even in the case of a single engine failure [17].

The reformed CNG fuel engine system consists of a gas engine, a heat exchanger, a turbo generator that operates using exhaust gas and steam, and a fuel reformation unit. The level of development for each component is as follows:

Heat exchanger

By taking advantage of porous metals, the heat exchanger has been reduced in size from a cylinder (diameter 800mm x height 1500mm) to a block (400mm x 420mm x 810mm), which is significantly more compact than conventional units. Experimental trials indicate that this size reduction makes heat transfer smoother, and that thermal efficiency (effectiveness) was five times higher than for a conventional unit. The tests have been concluded, and development work is approximately 90% complete with only minor modifications and fine-tuning remaining.

Turbo generator & steam turbine

These units are still in an early stage of development. Although existing prototypes are functioning, research is continuing into further improving their effectiveness.

Fuel reformation unit

Modules for the absorption and separation of CO_2 have been completed, and development work is approximately 90% accomplished.

Natural gas engine

Design and experimental trials of a single-cylinder engine have been completed. Development work on an adiabatic engine, a pre-combustion chamber engine and CNG combustion system, which together form the system core, is approximately 90% complete.

Each of the major system components can be applied independently, in a wide range of uses. The rapid progress of the programme means the completion of a 6-cylinder prototype engine can be expected within the next year. It is hoped this will lead to the construction of a 200 kW engine of 3x3x2 m size based on the same engineering principles that will offer similar levels of thermal efficiency. Being much more compact, the thermal efficiency of the reformed CNG fuel engine system compares favourably with that promised by a fuel cell (SOFC) system [17].

2.14.2 Typical CNG engine propulsion plant

As we haven't CNG Engine System installations on board of seagoing LNG or other vessels so far, we will make an assumption of a possible future propulsion plant based on the present data without any further details.

The reformed CNG fuel engine system consists of a gas engine, a heat exchanger, a turbo generator that operates using exhaust gas and steam, and a fuel reformation unit.

This hybrid engine system combining a gas turbine in combination with an electric generator and steam turbine is basically an electric propulsion system which can drive either one/two FPP or one/two CPP or azimuth thrusters.

The number of CNG engines installed for propulsion and electric power needs, depends on the power output of each engine. These engines will be under construction in the future.

The need to have a back up means of dealing with the boil off gas is normally handled by the installation of an oxidiser. The oxidiser burns the amount of BOG which exceeds the propulsion requirements. Obviously, the highest flexibility is obtained if a reliquefaction plant is installed as a primary means of dealing with the extra BOG.

Diesel-generators maybe installed for electric power coverage or as an emergency power source.

2.14.3 Advantages and drawbacks for a CNG engine propulsion plant installation

Advantages

I. Reduced CO_2 emissions to 50% of existing engines, NOx to below 10ppm and SOx to zero.
II. Low turbine maintenance and also relatively modest in cost.
III. High thermal efficiency for the - up to 60% - resulting in low energy consumption and thus low operating cost.

Disadvantages

I. This technology is on the verge of being realized, but the last stages of development will need to be conducted on a wider, more global scale in order to get ready to be employed on ships.
II. High investment costs (at least for a 10-20 years period).

2.15 Fuel Cells (Hybrid Systems)

2.15.1 General information-technological development

A fuel cell generates electricity from continuously supplied streams of fuel and oxidant. The two streams do not mix or burn but produce electricity by electrochemical reactions similar to a conventional battery. The details of the chemical reactions depend on the type of fuel cell, but in all types an electrically charged ion is transferred through an electrolyte which physically separates the fuel and oxidant streams. The fuel cell thus provides an elegant means of converting the chemical energy of the fuel directly into electrical energy.

No FC-System has been tested on board of seagoing merchant vessels so far. The current status of marine FC development is as follows:

- The most relevant marine application is the HDW/Siemens 250 kW hydrogen/oxygen PEM-FC System installed in HDW U-212 & U-214 class submarines. Currently more than 10 submarines are on order. HDW is working on a Methanol reformer for the next generation of submarine FC-Systems.

- Developments for civil marine applications are known from HDW and MTU Friedrichshafen.

- A consortium around STN-Bremen is developing a remote operated vehicle (ROV) which will use a PE-FC developed by ZSW in Stuttgart. The project supported by the German Ministry of Research named DeepC has finished with the test of a technology demonstrator in 2003.

- The US Marine Administration (MARAD) supports the development of a power barge for the power supply of the hotel load for ships during port operation. In a first phase of the two-phase project a test installation had been run with two 200 kW PA-FC. The shiploads were simulated during the tests. In phase two the erection of a demonstrator including is intended.

- The US Office of Naval Research (ONR) proposed a demonstration project to develop a 625 kW MCFC system using Diesel oil as fuel. In 2001 the R&D phase was announced to last 6 years ending with a demonstrator.

- In Iceland the government is intending to substitute fossil fuel by hydrogen produced from geothermal energy available in Iceland at low cost. Projects with buses using hydrogen as fuel are running. The fishery fleet is one of the major fossil fuel consumers in Iceland. It is proposed to use FC technology instead of Diesel engines for fishing vessel power supply.

- The European Commission (EC) is supporting a pilot study named FCSHIP. The Project has started in June 2002. More than 20 companies and institutions including the Fincantieri yard, engine manufacturer MTU, the research companies SINTEF and MARINTEK and the class societies DNV, GL, LR and RINA are participating. The project is co-ordinated by the Norwegian Ship Owner's Association (NSA). It is intended to define the basis for the development of FC-Systems for merchant ships. Transfer of experiences from land based projects to marine applications, measurement of real life load requirements, definition of basic safety and operational requirements, a conceptual ship design for a passenger ship and the assessment of infrastructure requirements are main topics.

- The Public Road Administration in Norway has initiated many projects about fuel cells for ships. The most promising is a case study for fuel cell installation on board an existing ferry the natural gas powered ferry "Glutra" [8].

- Rolls-Royce has experience in the system integration of several different types of fuel cells and believes the Solid-Oxide Fuel Cell is the best for stationary power generation applications while retaining the capability of being developed subsequently for various transportation, military and marine applications [9].

- Aker Kvaerner, Norske Shell and Statkraft are to cooperate in the development of large fuel cells driven by natural gas. Natural gas is seen by energy companies as a critical commodity- it is clean burning (i.e. has low emissions),there are abundant reserves and it currently offers the most economical way of producing hydrogen for fuel cells, a power source of the future. The three Norwegian companies have set themselves the goal of becoming the first operators in the world to commercialize fuel cells producing 10-20 MW. A project team comprising representatives of the three companies will conduct a pilot study on the potential of fuel cell technology. This is intended to show whether there is a technical and commercial basis to continue the venture. The current belief is that investments of about NKr 1 billion ($ 127 million) are required to realize a large fuel cell before 2010 [10].

Fuel cell technology is on its way to find a market in the power supply sector. All manufacturers announce competitive systems for the second half of this decade. At the moment a large number of pilot applications are either running or under design.

For merchant ships, including LNG vessels, pilot projects can be expected in the next years.

In a short term (a 10-20 years period) the fuel cell technology is not an alternative for merchant shipping due to:

- high investment costs
- facilities for a large scale production of hydrogen are not existing (should be combined with CO_2 depositing in large offshore structures)
- a not existing distribution network for hydrogen
- cheap fossil fuels
- safety.

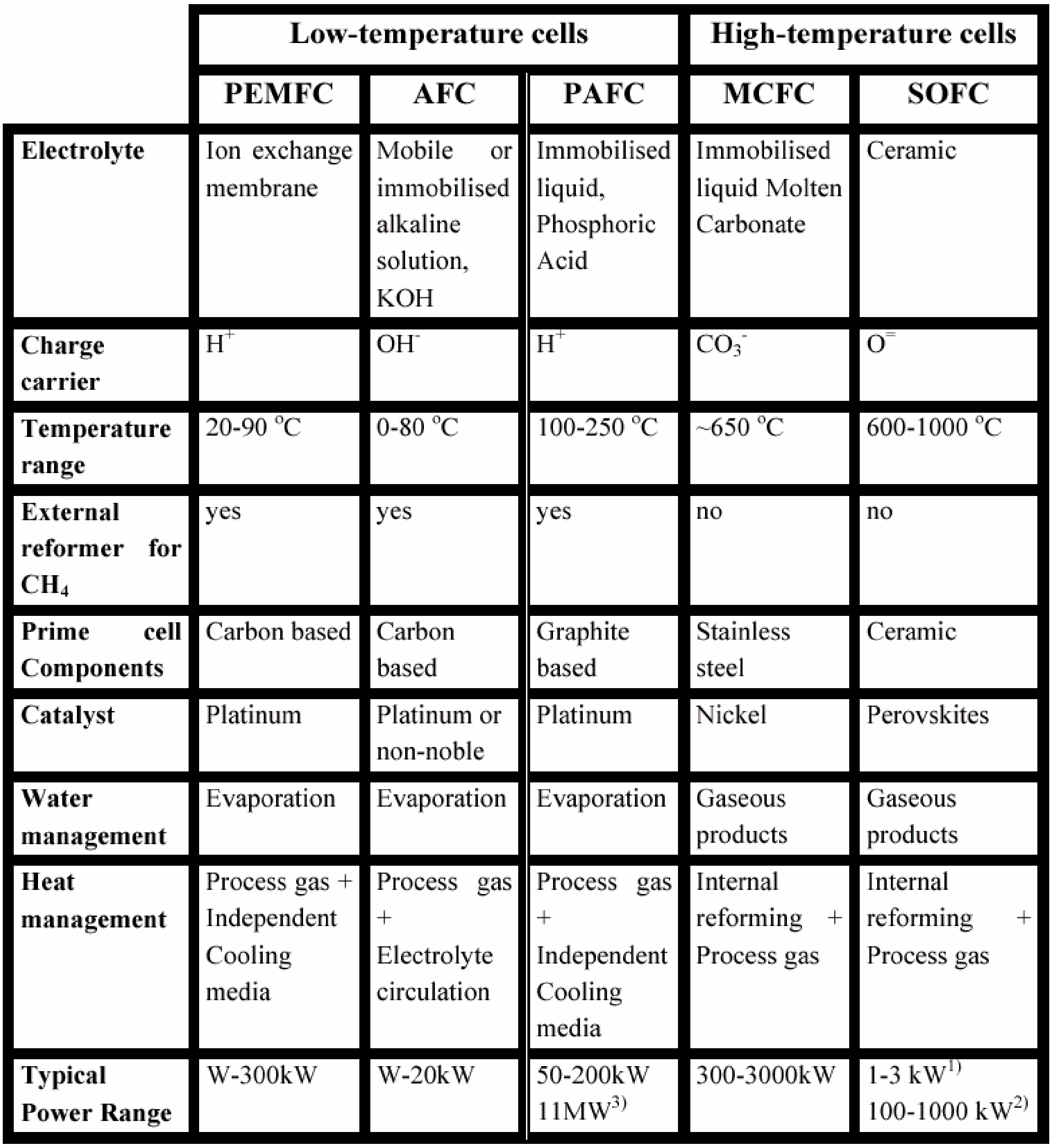
In a short term use of natural gas is a good solution for many ship operators. The investment cost is a little bit higher (5-15%), but the life cycle cost is lower. In addition use of natural gas reduces the NOx emission by 90% compared to marine Diesel oil and no emission of particulates and HC [8].

Characteristics of fuel cell types

As we mentioned above, fuel cells (FCs) convert chemical energy in a fuel (usually hydrogen gas) directly into electricity in an electrochemical process. The FCs are named after the type of electrolyte separating the anode from the cathode. The PEM fuel cell uses a polymer membrane, the AFC an alkaline (KOH) solution, the SOFC a solid oxide, the PAFC a phosphoric acid immobilised solution and the MCFC molten carbonate salt as electrolyte. This large variety of materials results in highly different operation ranges and system components.

In the Table 2.15.1 we can see which are the key parameters for the 5 main fuel cell system types [8].

Table 2.15.1 Key parameters for the 5 main fuel cell system types [8] [1] [2] [3].



	Low-temperature cells			High-temperature cells	
	PEMFC	**AFC**	**PAFC**	**MCFC**	**SOFC**
Electrolyte	Ion exchange membrane	Mobile or immobilised alkaline solution, KOH	Immobilised liquid, Phosphoric Acid	Immobilised liquid Molten Carbonate	Ceramic
Charge carrier	H^+	OH^-	H^+	CO_3^-	$O^=$
Temperature range	20-90 °C	0-80 °C	100-250 °C	~650 °C	600-1000 °C
External reformer for CH_4	yes	yes	yes	no	no
Prime cell Components	Carbon based	Carbon based	Graphite based	Stainless steel	Ceramic
Catalyst	Platinum	Platinum or non-noble	Platinum	Nickel	Perovskites
Water management	Evaporation	Evaporation	Evaporation	Gaseous products	Gaseous products
Heat management	Process gas + Independent Cooling media	Process gas + Electrolyte circulation	Process gas + Independent Cooling media	Internal reforming + Process gas	Internal reforming + Process gas
Typical Power Range	W-300kW	W-20kW	50-200kW 11MW3)	300-3000kW	1-3 kW1) 100-1000 kW2)

---

[1] The new generation flat plate SOFCs developed for combined heat and power (CHP) for residential applications and APUs for automobiles (typically operating at 600-800 °C).

[2] The tubular SOFCs developed by SIEMENS Westinghouse for stationary power production (800-1000 °C).

[3] A stationary PAFC power plant was built and ready in January 1991 at Tokyo Electric Power Company (TEPCO) in Tokyo, Japan. The plant was rated at 11MWe.

Technological evaluation of the FC types and their feasibility

Due to many advantages with respect to emission and efficiency, FCs have been developed into a number of different types covering widely different markets and applications in the range from W to MW.

As shown in Table 2.14.1, the five FC types have different characteristics. The large difference in the operation temperature should be noted (0-1000 ^{o}C). Classically, FCs are divided into two categories, low temperature fuel cells (0-250 ^{o}C) and high temperature fuel cells (600 – 1000 ^{o}C).

Low temperature fuel cell systems will need high purity H_2 that dictate the incorporation of a reformer as well as a gas clean-up system to remove CO from the synthesis gas (H_2, CO and CO_2). Such systems have been developed with success but the systems are voluminous and so far costly due to the complexity and the use of noble metal catalysts.

From a technical point of view, the high temperature FC technologies are better suited for a NG-fuelled ship application. This is due to their ability to convert NG directly or operate on partly reformed fuels.

- SOFCs have originally been developed for large stationary applications (>100kWe). However, due to recent developments of flat plate cells that tolerate lower temperatures, a new market is opening for the SOFC in the kW range. These cells are meant for residential applications and as Auxiliary Power Unit (APU) in e.g., passenger cars, the latter demanding high power densities. These small-scale flat plate SOFCs might eventually reach the 50kW$_e$ size, but it is expected that this will take 2-3 years. This makes the SOFC interesting for our application in the medium term perspective. The development of the flat plate cells is still in the prototype stage and a full range of products is not anticipated before 2006.

- MCFCs have been demonstrated for large power units (300 kW and upwards) only. The technology is not considered viable for small-scale applications. For MCFC some large-scale development programmes have been carried out for FCs used in naval ships. As for all military applications, cost is not an issue.

- PAFCs have been market ready for almost 10 years. The high price is linked to the use of porous Teflon bonded carbon electrodes with high catalyst loading. Only noble metal catalysts can be used in these cells. It is believed that, in the long run, the PAFC will not be able to compete with the other FC systems.

The PAFC is past the prototype development stage and a full range of products are commercially available. US Department of Defence (DoD) has more than ½ million operation hours on PAFC systems [International Fuel Cells are leading this development technologically and are able to deliver systems based on 200 kW$_e$ units running on natural gas.

In Japan there are PAFC developers, which provide systems with high reliability. Four different PAFC systems (FP50 and FP100 from FUJI Electric, PC25 C from Toshiba and MP200 from Mitsubishi) have been evaluated by Tokyo Gas. Tokyo Gas still operates the world’s largest fuel cell system, a 10 MW PAFC-plant (originally rated at 11 MW). A total of >800.000 operating hours are obtained on PAFC-systems. Some units have operated for more than 8000 hours per year.

FUJI Electric's technology has shown the best availability (>99%) compared to the late versions of the PC25 at around 95%. In average the availability of the power from these PAFC-units has exceeded 90% since mid 1998 except for the early versions of the PC25 C-unit. The performance degradation was only 10% within the 40.000hours of operation. The power was delivered at a very high quality (Voltage ±1% and Frequency ±0.01%). In the cases of system shutdown, the reason was primarily related to the auxiliary system components.

- PEMFCs have in recent years been developed and high performance at low noble metal loading has been demonstrated. Further cost reduction is also anticipated with increased mass manufacturing, reduced material costs and lower catalyst loading.

The development of the PEMFC technology is led by North American companies such as Ballard Power Systems and Plug Power, but a large and increasing number of companies are involved. The systems have shown very high power density and are currently the most studied fuel cell system.

- AFCs are mainly considered for smaller power applications. Some large units have been produced (for military and aerospace applications) at very high costs using pure hydrogen / oxygen and noble catalysts.

As a low cost system the AFCs are attaining renewed interest. A few (5-10) companies are involved in AFC development. The European company ZeTek Power was leading the development, however, due to the uncertainty of this company the technological advancement has been somewhat set back [8].

Fuel cell system requirements for marine applications

Marine applications introduce a set of requirements for fuel cell (FC) systems. These reflect the special conditions experienced at sea (such as movement due to waves, saline air etc.) and the need to be compatible with the conventional power systems on board the vessel. The latter puts certain restraints to the FC system with regard to power quality and dynamics. Further, any installation should be in compliance with current regulations.

System requirements

- Total FC system shall fit in a 20-foot container.

- The container shall be installed above main deck.

On Diesel electric ships the main engines normally are situated below main deck, but due to application of natural gas as fuel an alternative design must been chosen. In these ships the main engines are situated on the boat deck (above main deck). This arrangement has been developed to comply with existing regulations from The Norwegian Maritime Directorate (NMD) for gas operation.

It is likely that a fuel cell installation on board will have to meet the same regulations.So the fuel cells and auxiliary systems should be installed above main deck.

- The prime fuel for the system is Natural Gas (NG) and the power output shall be AC electricity (see Power requirements below).
- If needed, any installation (e.g., reformer) for converting NG to Hydrogen will be considered a part of the system.

- The system shall be self-sufficient with respect to internal water management, cooling etc.
- The fuel cell system shall not rely on supply of electricity or any other form of support from the main propulsion or existing power generation system.
- A small backup/buffer system (battery) shall maintain the system operation or facilitate shut-down procedures in accordance with safety requirements and regulations.
- The system shall sustain harsh seawater conditions including high air salinity and humidity
- The dynamics of the FC-system shall be in compliance with the demand of the auxiliary systems components and if needed a buffer system should be included.
- The electrical power shall be 230Volt AC, 50 Hz.

Fuel storage - general arrangement

Fuel storage on an existing ship design has to comply with existing regulations from NMD. Alternative fuel storage for fuel cell application is:

- Metal hydrids
- Liquified H_2, (LH_2)
- Compressed H_2, (CH_2)
- Other H_2 carriers as natural gas, methanol, etc.

Fuel processing and transfer system – general arrangement

The fuel transfer system connects the fuel storage tank to the fuel cell system, and shall comply with existing regulations from NMD. Main components in this system are: piping, valves, alarm system, shut-off system, inert gas system, etc. The piping shall go through existing casing for pipes if the storage is below main deck.

A double piping system is required for transfer of gaseous fuel. In case of leakage, the double pipe system shall be vented to the top of a mast beam above highest point on the ship. In all spaces and voids, which may be exposed to gas leakage, a gas detection and alarm system is required.

If natural gas is chosen as the H_2 carrier, the original natural gas piping system on board will be used. This system will supply natural gas at a delivery pressure of app. 4 bar to the fuel cell system.

Fuel processing system

A natural gas processing system (reformer) may be required unless MCFC or SOFC will be used. This unit should be specified together with the fuel cell.

Refuelling system

In general the refuelling system shall be easy to operate and no needs for specific operations shall be required. The refuelling system is dependent on the fuel storage system. During refuelling no spill of ignitable gas is allowed.

Safety

All safety measures shall be included in a fuel cell installation to ensure safe operation. This includes operational procedures, design and auxiliary system as inert gas system [8].

Criteria for selection of FC type

The following criteria for the selection of a fuel cell (FC) system for a specific ship type have been reviewed and are listed below:

a) Safety
The current stringent regulations for all marine systems should not by any means be compromised. The safety should be ensured through regulations and products that are subject to approval from authorities. The inherent level of safety for each FC-type should be considered.

b) System efficiency
Reduction in emissions is the rational for the whole project and hence the second most important criteria. System efficiency is the key to reduced emission and pollution. Efficient fuel utilization is linked to the environmental effect, especially through CO_2-emissions. It should also be remembered that fuel cells eliminate the NOx emissions.

c) System costs
The present cost of the system is crucial for the realisation of a demonstration project. The total operation cost including operation (fuel) and maintenance (labour and spare-parts) should be considered. In cases where there is a trend towards substantial system cost reductions this should be taken into account upon FC-type selection. A slow degradation rate of the system with time is required (i.e., long life-time[4]). High complexity of the system will increase the installation costs and also influence the maintenance cost of the system. In addition, increased fuel utilisation will reduce operation cost.

d) Future technology improvement potential
Future technological breakthroughs are hard to predict. Still these are important for a correct choice of FC system. Due to the characteristic features of the respective fuel cell types, they have different potentials for improvements with respect to e.g., cost reduction, efficiency improvements etc. Each technology's potential for improvements should therefore be identified and considered.

e) Start up / transient response
A short start up time is favourable. The transient response time upon load changes for a power system is closely linked to operation safety of the whole ship. Delays in response may be problematic in critical situations. An adequate system should therefore be able to react without delays that compromise safety or reduces the comfort.

f) Power supply reliability
The reliability of a FC-system may be revealed through extensive testing (like for the PAFC) or through warranties from the suppliers. The complexity of a system, however, generally influences the reliability through the number of components that may fail. A

---

[4] For a Norwegian coastal ferry project, for example, assuming 18 hours operation time per day the yearly operation time is 6570 hours. A typical criterion used when considering FC-system life-time is a 10% performance degradation (reduction) at nominal power output. The lifetime of the system should be as high as possible (preferably more than 3 years normal operation). Maintenance of the system should preferably be performed at the same time and with the same time intervals as the ship maintenance is taking place (usually every year).

pressurised system is inherently less reliable than an atmospheric system, but exhibit an increased power density. Direct conversion of NG to electricity is advantageous because the reformer is eliminated. Reliability is closely linked to safety, and safety requirements might dictate a certain degree of reliability.

g) Power density
Incorporation of a FC-system in a ship should be held against the future possibility of using FC's for the main propulsion system of the vessel. Power density (kW/liter and kW/kg) is not only important with respect to the space and volume available on board the ship. High Power density may be the key to reduced FC stack cost because it reduces the amount of materials needed.

h) Technology availability
Different FC types have reached different levels of development. The availability (and delivery time) of FC stacks and auxiliary components needed to assemble a system may dictate the selection of a FC technology that in the long term perspective may be inferior to others. Therefore, availability is crucial especially if the demonstration project should be realised in a short-term perspective. The present and future power range of available products should be evaluated. As indicated many of the criteria listed above are highly interrelated. It is considered inadequate and unfeasible to give each criterion a certain weight and based on that, provide a total score for each technology and supplier. Therefore, it is important to hold each FC type and supplier against each criterion, and make an overall evaluation as to which types are viable and which suppliers are found capable of delivery [8].

2.15.2 Typical fuel cell propulsion plant

As we haven't FC-System installations on board of seagoing LNG vessels so far, we use as an example a case study for a fuel cell installation on board an existing Norwegian ferry the natural gas powered ferry "Glutra".

Installation

The drawings below indicate where a PEM fuel cell has to be installed on board the Norwegian ferry “Glutra”, and how it is connected to the existing machinery systems. The fuel cell container also includes a reformer and an air pre-treatment system.

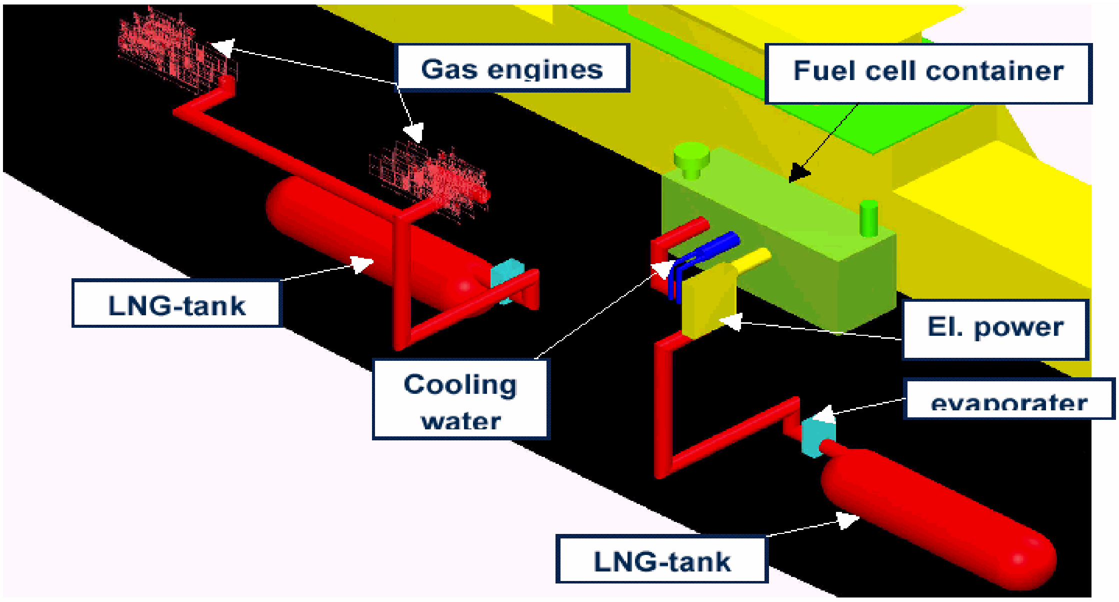


Fig. 2.15.1 A PEM fuel cell installation on board “Glutra” [8].

Another fuel cell installation is based on the European project FCSHIP. Two case ships have been defined.

Case ship 1 is a large passenger ferry operating between the Norwegian port of Oslo and the German port of Kiel. Based on this ship, a case ship analysis has been carried out using high or low temperature fuel cells for the supply of auxiliary power on board the ship; the main propulsion is supplied by conventional ship engines. Three different fuels are considered for the fuel cells of case ship 1: low sulfur Diesel (car Diesel), liquefied natural gas (LNG) and liquid hydrogen (LH_2). Hydrogen will be used in a low-temperature PEM fuel cell, car Diesel and LNG will be used in high-temperature fuel cells (MCFC – molten carbonate fuel cell or SOFC – solid oxide fuel cell). The electricity output for auxiliary power in case ship 1 is about 2 MW (2 generator sets with 1,080 kW each).

Case ship 2 is a small commuter ferry operating in the Dutch city of Amsterdam. In the case ship 2 analysis PEM fuel cells supply the power for propulsion and for the auxiliary electricity consumption. Compressed gaseous hydrogen (CGH_2) is stored on board the ship for the supply of the fuel cell. The total installed power of case ship 2 (two engines) which has to be replaced by the PEMFC power train is approximately 400 kW.

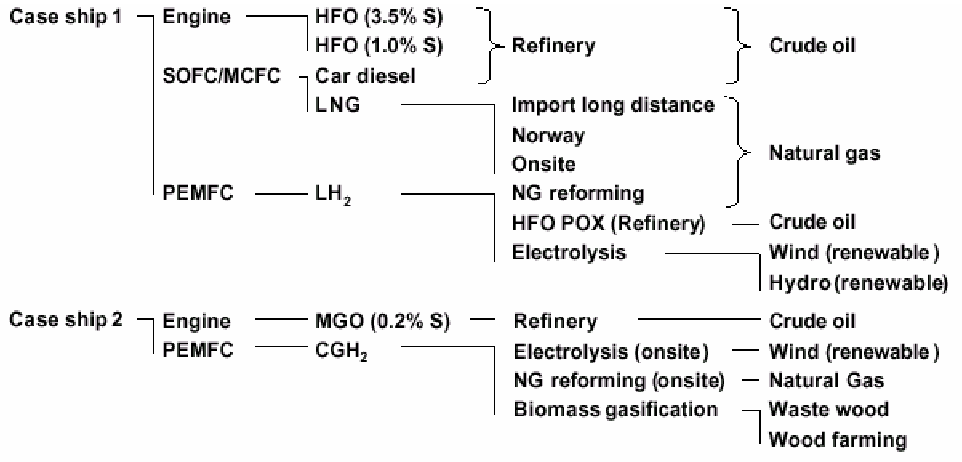


Fig. 2.15.2 Fuels and fuel supply paths [23].

Efficiency

Based on studies within the FCSHIP project, the efficiencies of the conventional engines and of the fuel cell systems for auxiliary power supply of case ship 1 are assumed to be 43.3% for the HFO powered engine, 41.8% for a car Diesel powered MCFC, 47.8% for an LNG powered SOFC or MCFC, and 50% for a hydrogen powered PEM fuel cell. For the lower power rating of case ship 2 and the duty cycle including many transients and part load phases, the efficiency of the Diesel engine based on measurements on the existing ferry is 27% on average, while the efficiency of the hydrogen PEM fuel cell is assumed to be 50%.

Economics

Ship fuels are exempt from taxes. Therefore, conventional ship fuels are extremely sensitive to variations in crude oil prices. In real terms of 1995, annual average crude oil prices over the last three decades have ranged from 12 to 69 US-$ per barrel. Reducing the sulfur content of heavy fuel oil from the average 2.5% in the EU to 1.0% would entail additional costs of 50 to 90 EUR per ton.

At oil prices of 20-25$/bbl, only liquefied natural gas supplied to a large ship (case ship 1) is in the range of cost competitiveness to conventional or reduced-sulfur ship fuels. At historically high oil prices, fossil-based hydrogen and eventually renewable hydrogen become cost competitive.

Liquefied natural gas fuel is close to competitiveness with conventional fuels at oil prices of 20-25 $/bbl, depending on the LNG supply path. Depending on the efficiency advantage of fuel cells compared to conventional engines, LNG becomes competitive.

Fossil hydrogen based on natural gas or heavy fuel oil becomes competitive in large ships (case ship 1) at historically high oil prices.

Natural gas based hydrogen supplied to a small ship (case ship 2) comes close to competitiveness at historically high oil prices. Here, further cost reductions are required. These may be achieved by supplying multiple ships on the same spot leading to economies of scale in the hydrogen production and supply facility.

Renewable comes close to competitiveness in a large-scale scenario at historically high oil prices in large ships (case ship 1). Renewable hydrogen supplied to a small ship (case ship 2) comes close to competitiveness at historically high oil prices. Here, further cost reductions are required. These may be achieved by supplying multiple ships on the same spot leading to economies of scale in the hydrogen production and supply facility, and eliminating/ reducing the need for expensive hydrogen pipelines.

Emissions

Fuel cells reduce pollutant emissions (SO_2, NOx, particulate matter etc.) drastically and independently of the fuel chosen. Only SO_2 emissions of a small ship (case ship 2) are notreduced by natural gas derived hydrogen, if the European electricity mix is used for auxiliary power and for hydrogen compression as assumed here. Using for example the German electricity mix would reduce SO2 emissions by more than a factor of two.

Greenhouse gas emissions can be reduced using natural gas fuel for high temperature fuel cells by 25% to 40% in the on board power supply of a large ship (case ship 1). In this application, natural gas derived hydrogen does not reduce GHG emissions. GHG emissions are reduced to almost zero by using renewable hydrogen. Because of the significantly higher efficiency of the fuel cell compared to the conventional engine in a small ship (case ship 2), even natural gas derived hydrogen reduces GHG emissions by 20%. GHG emissions are reduced to almost zero by using renewable hydrogen [23].

The advantages of fuel cells on commercial ships are clear: high fuel-saving potential, reduced toxic emissions, low operating costs, noiseless and clean propulsion.

In 1995, HDW together with Ballard already investigated the use of fuel cells on board commercial ships including suitable fuels in a joint study. According to this study, fuel cells are particularly suited for:

- emergency power supply,
  e.g. passenger ships, ferries
- energy generation, in particular environmentally friendly in highly polluted ports,
  e.g. container ships
- energy generation / driving power for ships with specific noise reduction requirements
  e.g. passenger ships, research vessels
- driving power on ships with hydrogen or methane 'boil of'
  e.g. LH_2 carriers, LNG carriers.

In order to demonstrate the possible applications of the fuel cell technology on board ships, HDW Fuel Cell Systems (HFCS) is going to launch its own maritime fuel cell plant with a power output of 160 kWel soon.

The Fuel cell plant for maritime applications (FCMA) has been integrated into a 20 ft. standard container so that it can be installed easily on board ships. Fig. 2.15.3 shows a model of the plant. Besides four fuel cell modules of 40 kW each, which are operated with hydrogen the container also includes all the processing and electrical engineering systems for control and monitoring, as well as an inverter which permits the generated electrical energy to be fed into the ship's mains. The electrical engineering systems have been designed flexibly so that it is possible to use the ship's mains in order to operate the plant with different voltages and line frequencies. It is also possible to operate the container ashore and feed the energy into the local mains network (e.g. for port power supply) [34].

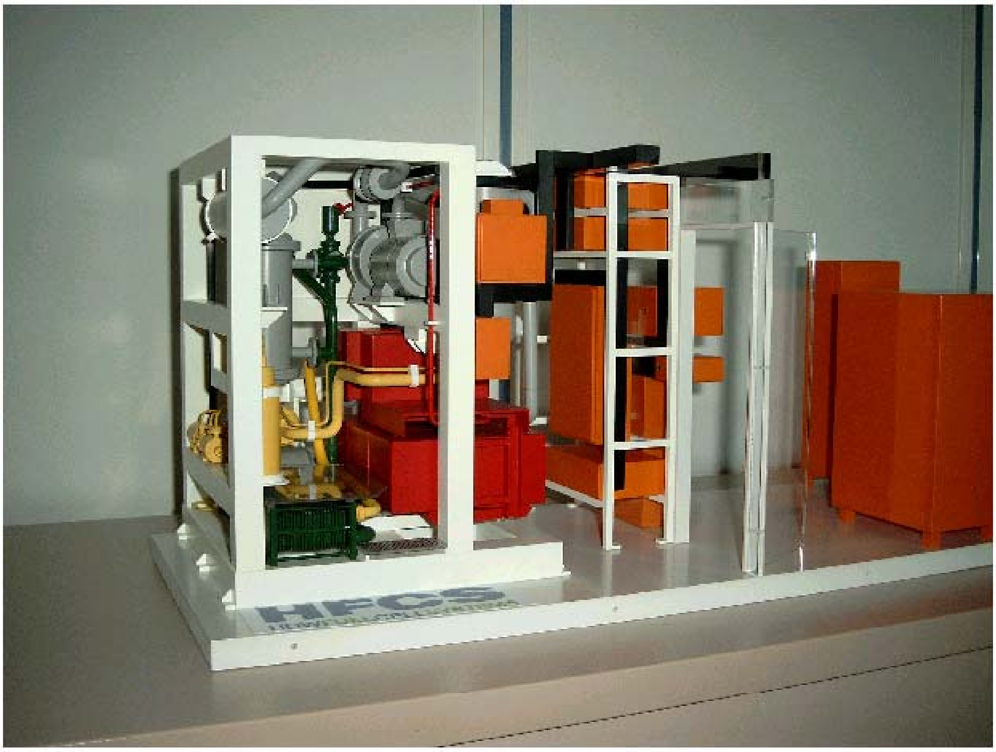


Fig. 2.15.3 Model of the containerised 160 kW_{el} HFCS fuel cell plant for maritime applications [34].

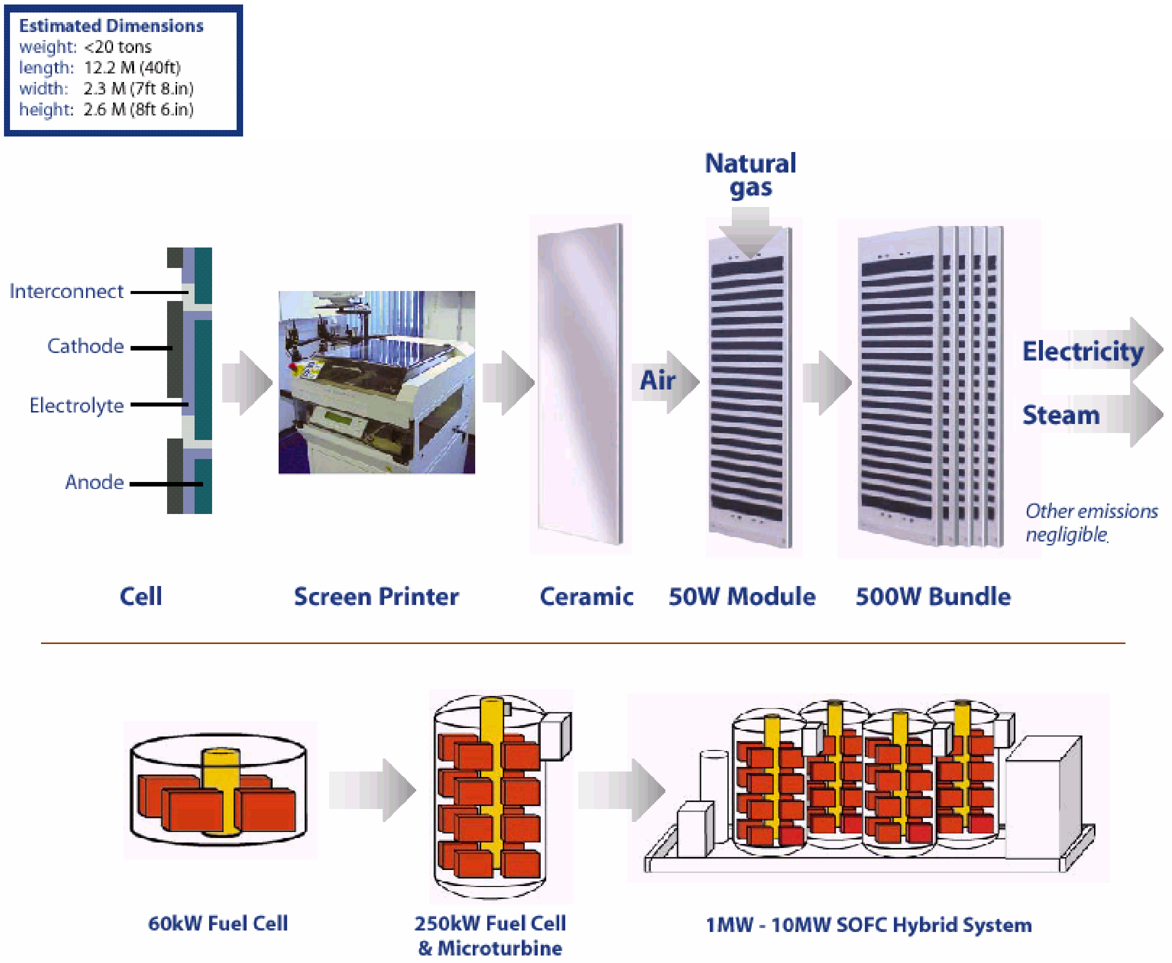


Fig. 2.15.4 Rolls-Royce Solid-Oxide Fuel Cell System [9].

2.15.3 Advantages and drawbacks for a fuel cell propulsion plant installation

Advantages

I. Increased fuel flexibility. The system can be configured to use existing hydrocarbon-based fuels, i.e. natural gas and liquid fuels, and alternative fuels such as coal gas and bio-mass.
II. Negligible air emissions, i.e. SOx, NOx, CO_2 and particulate matter and additionally the system can be entirely recycled at the end of its useful life.
III. Minimal noise and vibration profile.
IV. The system uses commercial-grade materials, has few components and is low in weight.
V. The fuel cell is produced by screen-printing on low cost "bathroom ceramic" type materials using proven production processes and minimal exotic materials.
VI. Considering efficiency, power density and future cost estimates the PEMFC is considered as the best technology.
VII. When fuel flexibility is considered the SOFC is the best technology due to the possibility to convert natural gas directly to electricity.

VIII. The use of natural gas is a good solution for many ship operators. The investment cost is a little bit higher (5-15%), but the life cycle cost is lower. In addition use of natural gas reduces the NOx emission by 90% compared to marine Diesel oil and no emission of particulates and HC.

Disadvantages

I. High investment costs (at least for a 10-20 years period).
II. Increased size for increased power output.
III. The salt damage and the reliability under operating conditions which are proper to ships must further be verified.
IV. Facilities for a large scale production of hydrogen does not exist (should be combined with CO_2 depositing in large offshore structures).
V. A not existing distribution network for hydrogen.
VI. Safety aspects must be examined.
VII. To put the fuel cell into practical use several problems such as the reliability and service life of power generation equipment must be solved.

3.

LNG CARRIER PROPULSION PLANTS EVALUATION

3.1 General Comments

According to Chapter 2 there are enough proposals for the propulsion of a LNG carrier from the conservative and tested steam turbine solution until more innovative, although not tested yet, ideas such as fuel cells hybrid systems. Each one of the proposed solutions has both advantages and disadvantages which are related to economic savings, environmental impact and safety issues.

Since 2004 many LNG carrier projects with propulsion other than steam turbine have been under construction. The preferred solutions so far include medium speed dual-fuel Diesel-electric installations and direct drive slow speed Diesel and reliquefaction plant installations.

At this point we must mention the need to save energy and the exploitation of alternative energy resources to avoid an over-dependence on oil. This also motivates the shipping industry forward to improvement of more efficient energy-saving systems such as combined cycle systems, hybrid systems using alternative fuels (e.g. LNG, CNG, LH_2, etc.).

The Table A.1 in the Appendix A presents all the propulsion alternatives mentioned in this paper including details about the possible configurations of the prime mover, the type of fuel used and the fuel treatment needed before use, the BOG handling, the transmission systems, the electrical power coverage for all on board power arrangements (heating, cooling, lighting, ventilation, kitchen, laundry etc.), the emergency power coverage, the possible additional equipment depending on the selected prime mover and finally the propulsion unit to be installed.

3.2 Technical and Economic Evaluation of the Propulsion Alternatives. Study on a 150,000 m³ LNG Carrier

This chapter deals with an evaluation (of techno-economic aspect) of the LNG carrier's propulsion plants presently under consideration.

The most attractive and applicable solutions according to Chapter 2 are:

1. Steam turbine Direct Drive.
2. Medium Speed Dual Fuel Diesel (GAS/MDO) Electric Drive.
3. Slow speed Diesel Direct Drive.
4. Gas turbine Electric Drive.
5. Combined Gas and Steam turbine Electric Drive (COGES).
6. Combined Medium Speed Diesel and Gas Turbine (CODLAG).
7. Slow Speed Gas-HFO Diesel Engine Direct Drive.
8. Combination of HFO Medium Speed Diesel Engine and Medium Speed Dual Fuel Diesel (GAS/MDO) Electric Drive.
9. Medium Speed Dual Fuel Diesel (GAS/HFO) Electric Drive.
10. Combination of HFO Medium Speed Diesel and Medium Speed Gas only Engine Electric Drive.

The detailed evaluation is limited to the first five propulsion alternatives, which by the author's opinion are some of the most viable solutions according to the present technological development and the current market requirements concerning the following:

- Economic aspects (delivered cargo capacity, operating cost and additional income compared to steam vessels).
- Safety issues against gas hazards in machinery spaces (safe operation with high pressure gas supply in the engine room, separated engine room departments, emergency shut down, gas supply piping jacketing, etc.).
- Overall simplicity of the selected alternative for easy installation and maintainability.
- Reliability and Redundancy of the selected alternative.
- Emission restrictions.

The actual outcome of the evaluation will depend on the specific project, i.e. voyage profile, service speed, size of the vessel, economic factors: price of HFO and LNG, as well as of the boil-off rate.

According to the assumptions of the present study the most important data of the technical and economic analysis are presented in the following paragraphs.

The basic data for this study were obtained from shipping companies, engine manufactures and various revelant published papers.

3.2.1 Technical evaluation

3.2.1.1 Main particulars of the vessel

A 150,000 m^3 LNG carrier was used for the technical and economic evaluation. The main dimensions of the vessel are kept the same for all the alternatives. However, as analysed in Chapter 2, the differences in the size and weight of each alternative allow different cargo capacities due to variations in the engine room space demand. The engine room length is shortened as far as possible, in order for the cargo carrying capacity to be maximised.

Hull (aftbody) and propeller modifications due to the different propulsion plant could reduce the resistance of the vessel and as a result less propulsion power maybe needed. This is not analyzed in this paper.

The approximate Principal Particulars for all the alternatives are the following:

Length overall:	291.50 m
Length between perpendiculars:	280.00 m
Breath moulded:	43.00 m
Depth to maindeck:	27.00 m
Cargo tank capacity (Steam Turbine (Single Screw)):	150,000 (*147,750) m^3
Cargo tank capacity (Dual-fuel-electric (Single Screw)):	156,700 (*154,350) m^3
Cargo tank capacity (Two-stroke Diesel + Reliquefaction (Twin Screw)):	156,300 (*153,956) m^3
Cargo tank capacity (Simple-cycle Gas Turbine-electric (Single Screw)):	165,000 (*162,525) m^3
Cargo tank capacity (Combined-cycle Gas Turbine-electric (Single Screw)):	165,000 (*162,525) m^3
Draught design (Steam / DF diesel electric):	12.00 m
Draught (Two-stroke+ Reliquefaction plant):	12.1 m
Draught (Simple Gas Turbine/COGES):	12.00 m

Speed at design draught: 20 kn
Service speed laden voyage: 20 kn
Service speed ballast voyage: 20 kn

(*) at 98,5% maximum filling ratio.
Cargo capacity at 100% filling level, for the steam turbine vessel: 150,000 m^3
Heel[1] for each one of the four cargo tanks is assumed to be: 500 m^3
Boil off rate is assumed to be: 0.12%.

3.2.1.2 Technical description

The following propulsion options are evaluated in the present thesis:

- **Steam Turbine**
- **Medium Speed Dual fuel (GAS/MDO) Diesel Engine**
- **Slow Speed Diesel Engine**
- **Gas Turbine**
- **Combined Gas and Steam Turbine**

- **Steam Turbine (Single Screw)**

- Steam turbine system with boil-off gas and add-on heavy fuel oil (1 main steam turbine, 2 dual fuel boilers).
- 2 Turbo generators for electrical power production.
- 1 stand by genset.
- Mechanical drive through reduction gear and 1 FPP.
- 1 bow thruster.

- **Dual-fuel-electric (Single Screw)**

- 4 medium speed dual-fuel (GAS/MDO) Diesel generator engines.
- 1 emergency gas oxidizer system.
- Electric propulsion system with 2 propulsion motors and 1 FPP.
- 1 bow thruster.

- **Two-stroke Diesel + Reliquefaction (Twin Screw)**

- Twin HFO-burning two-stroke diesel engines driving 2 FPP.
- 1 Reliquefaction plant for LNG.
- 1 stand by (back up) Reliquefaction plant.
- 3 HFO Gensets for electrical power production.
- 1 bow thruster.

---

[1] As mentioned in the section 2.4, 'Heel' is the small amount of LNG cargo (around 1-2 % of a ship's capacity) retained on board to keep the tanks and pipelines cold ready for loading the next cargo. It can be circulated through the cargo pumps and lines, and sprayed into the cargo tanks to cool them further before arrival at the loading berth.

Note:

A twin engine/twin screw solution was selected in order to increase the redundancy and the reliability of this alternative compared to the steam turbine. Of course a single screw/single engine solution, as of the most merchant ships installations, is reliable especially in combination with a PTO/PTI mechanism, as mentioned in subsection 2.4.1 of the Chapter 2 and also it is less expensive. In addition a further decrease in the initial cost can be achived if one auxiliary boiler is installed instead of a second reliquefaction plant, for burning of the excess BOG even if there is no need for useful heat.

- **Simple-cycle Gas Turbine-electric (Single Screw)**

- Gas turbine system with boil-off gas and add-on MGO (1 main gas turbine genset, 1 auxiliary gas turbine genset).
- 1 emergency gas oxidizer system.
- Electric propulsion system with 2 propulsion motors and 1 FPP.
- 1 stand by genset.
- 1 bow thruster.

- **Combined-cycle Gas and Steam Turbine-electric (Single Screw)**

- Combined Gas and Steam turbine system with boil-off gas and add-on MGO (1 gas turbine genset, 1 steam turbine genset).
- 1 exhaust gas boiler.
- 1 dual fuel auxiliary boiler.
- 1 emergency gas oxidizer system.
- Electric propulsion system with 2 propulsion motors and 1 FPP.
- 1 stand by genset.
- 1 bow thruster.

Note:

An auxiliary gas turbine genset was not installed because the power requirements of the selected size vessel are covered with the main gas turbine and the steam turbine genset in combination with a dual fuel auxiliary boiler. For larger vessels an auxiliary gas turbine genset maybe needed.

A stand-by diesel generator for the steam turbine and gas turbine propulsion systems was installed in order to increase the systems' redundancy.

All systems were also equipped with an emergency diesel generator. All the small four-stroke generator sets were assumed to burn MDO.

In the present study it was assumed that no forced BOG will be used for the extra energy needs.

If the ship is on a trade where it has to sail at a lower speed, then there will be an excess in boil off which will be reliquified or burnt in the gas oxidizer systems.

The medium speed dual-fuel Diesel generator engines were assumed to utilize MDO as add-on when boil-off gas is not available. In 2005 these engines were modified in order to be able to burn HFO as well. As the HFO price is substancially lower than the MDO price, an additional savings can be achieved with this propulsion system. However, this possibility is not taken into consideration in this study.

Gas turbines were assumed to burn MGO as add-on when boil-off gas is not available. However a medium grade intermediate fuel oil (MDO or lower grade fuel oil) could be used in the turbine modules to create additional income from the lower price compared to the MGO. The combustion byproducts associated with this type of fuel oil can be filtered out and their detrimental effects reduced. Water washing and fuel treatment chemicals are some of the options available for the on board treatment of fuels. With these treatments available, the gas turbine modules may be able to make a transition to heavier fuels although the time for hot end overhaul and full overhaul would normally decrease. However, this possibility is not taken into consideration in this study too.

Also with the gas turbine application, there was a substantial decrease in necessary vessel auxiliary machinery. With the decreased amount of machinery there would be a decreased cost associated with breakdowns, maintenance and crew costs as well, but there were not enough available data to analyze these issues.

3.2.1.3 Propulsion plant efficiencies

The total propulsion plant efficiencies as analyzed in the Table B4 in the Appendix B are the follwing:

Steam Turbine: 30%.
Medium Speed Dual fuel (GAS/MDO) Diesel Engine: 43%.
Slow Speed Diesel Engine: 48%.
Gas Turbine: 33%.
Combined Gas and Steam Turbine: 40%.

Note:

The Diesel engines maintain their high efficiency at lower loads. On the other hand the efficiency of the gas turbine plants is more sensitive on load variations and generally decreases at part loads.

3.2.1.4 Energy analysis under various conditions of operation

The power demands of each alternative were calculated separately for 3 conditions:

- ✓ Loaded conditions
- ✓ Ballast conditions
- ✓ Port (Manoeuvring, Loading, Unloading, Waiting & Bunkering, etc.)

The main propulsor power requirements were based on actual numbers. The electric loads were estimated based on the size of the vessel and on the specific electric needs of each of the propulsion concepts. Bow thruster requirements were estimated based on the vessel's size.

The propulsion and electrical power requirements are shown at the Table B3 in Appendix B.

All these loads were estimated based on certain conditions:

- ❖ The engines will be selected in order to give an engine load of close to 85% while running at service speed.
- ❖ The power demand was calculated with a sea margin of 20%.
- ❖ The propulsion power demand at ballast condition was assumed to be by 4% lower than the propulsion power demand at fully loaded condition.
- ❖ The electric power consumption for each condition was the sum of the ship's service power and the electric power demand for the other electric power consumers. The electric power demand for all onboard power arrangements (heating, cooling, lighting, ventilation, kitchen, laundry etc.) and the emergency power needed is

considered the same for equal sized LNGC. In the Table B3 in Appendix B there are the electrical power consumers in detail[2] for each alternative.

- The propulsion transmission losses and the electric losses for electricity generation were calculated according to Table B4, which gives the efficiency of the engines.

In reality all loads would vary depending on conditions (sea state, main engine maintenance, hull and propeller roughness, etc.).

3.2.1.5 Remarks on the calculations

The data in Table B3, of the power needs of each alternative, were calculated according to the following equations:

Fuel Energy needed for propulsion and electric generation: E
D: Delivered power demand (kW)
SEC: Specific energy consumption (kJ/kWh)

$$E = D \times SEC \times 10^{-6} \text{ (GJ/h)} \qquad (1)$$

Available energy in BOG: A
EBOG: Energy in BOG (methane) (GJ/day or GJ/kg)

$$A = EBOG \times \frac{1}{24} \text{ (GJ/h)} \qquad (2)$$

Available Energy in Exhaust Gases: AE

$$P_{s0} = 60 \text{ bar}, T_{s0} = 426\,^{o}C \Rightarrow h_{s0} = 3{,}245.06 \text{ kJ/kg}, s_{s0} = 6.64078 \text{ kJ/kgK} \qquad (3)$$

$$s_{1'} = s_{s0} = 6.64078 \text{ kJ/kgK}, Ps_{1'} = 0.05 \text{ bar} \Rightarrow hs_{1'} = 2{,}025 \text{ kJ/kg} \qquad (4)$$

$$\eta_T = 0.85$$

$$\eta_T = \frac{h_{s0} - h_{s1}}{h_{so} - h_{s1'}} \Rightarrow h_{s1} = 2{,}208.009 \text{ kJ/kg} \qquad (5)$$

$$T^*_{s2} = 32.9\,^{o}C + 1\,^{o}C = 33.9\,^{o}C, \qquad (6)$$

$1\,^{o}C$ *increase for 1 pump.*

$$P_{s2} = 0.05 \text{ bar}, T^*_{s2} = 33.9\,^{o}C \Rightarrow h_{s2} = 141.96 \text{ kJ/kg} \qquad (7)$$

$$\eta_B = 0.95$$

---

[2] Reliquefaction plant: The Reliquefaction plant requires approximately 10,5-11% of the main engine power. The low duty (LD) compressors, installed in the cargo machinery room, are provided to compress the LNG vapour, produced by natural boil-off and forced vaporization, to a sufficient pressure to be used in the boilers or in the combustion chamber as fuel.
Steam Turbine: Compressing less than 1,5 bar needed so the required power for the main engine's compressor is appriximately 0,4% of the main engine power.
Dual Fuel Diesel: Low Pressure (5 bar) Gas Compressors require approximately 1,1%-2% of the main engine power.
Gas Turbine: High Pressure (20-25 bar) Gas Compressors require approximately 4-5% of the main engine power.

$$c_{pg} = 1.15 \, {}^{kJ}\!/_{kgK}$$

$$\overset{\bullet}{m}_4 = 113 \, {}^{kg}\!/_{s}$$

$$T_4 = 466 \; {}^{o}C$$

$$T_5 = 160 \; {}^{o}C$$

$$\overset{\bullet}{m}_{s0} \times (h_{so} - h_{s2}) = \eta_{\mathrm{B}} \times \overset{\bullet}{m}_4 \times c_{pg} \times (T_4 - T_5) \Rightarrow \overset{\bullet}{m}_{s0} = 12.174 \, {}^{kg}\!/_{s} = 43{,}826.4 \, {}^{kg}\!/_{h} \qquad (8)$$

$$\eta_G = 0.95$$

$$\overset{\bullet}{W}_G = \eta_G \times \overset{\bullet}{m}_{s0} \times (h_{s0} - h_{s1}) = 43{,}177{,}701.35 \, kJ/h = 43.2 \, GJ/h = AE \qquad (9)$$

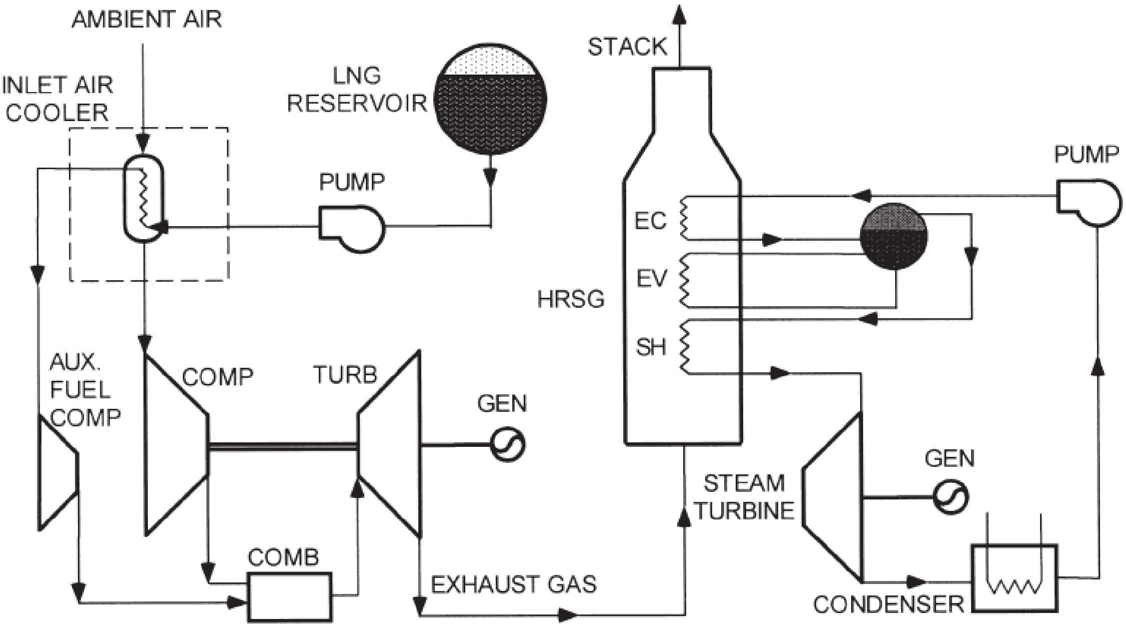


Fig. 3.1 A simplified flow diagram of the combined cycle power plant.

Extra energy needed from fuel oil: EX
E: Fuel Energy needed for propulsion and electric generation (GJ/h)
A: Available energy in BOG (GJ/h)
AE: Available Energy in Exhaust Gases (GJ/h)

$$EX = E - A - AE \;\; (GJ/h) \qquad (10)$$

Corresponding mass flow rate for fuel (HFO/MDO/MGO equivalent): EQ
EX: Extra energy needed from fuel oil
LHVO:LHV of liquid fuel oil (kJ/kg)

$$EQ = {}^{EX}\!/_{LHVO} \;\; (t/h) \qquad (11)$$

Delivered power for propulsion: P_{engine}

η_i *: propulsion transmission losses as shown in Table B4, i=1, 2 ,3 ,4 ,5*

For steam turbine vessel :

$\eta_1 = \eta_{gearbox} \times \eta_{shafting}$

For dual fuel-electric vessel:

$\eta_2 = \eta_{gearbox} \times \eta_{shafting} \times \eta_{\substack{electric\\motors}} \times \eta_{\substack{transfere\\\&cpnversion}} \times \eta_{alternators}$

For two stroke Diesel vessel:

$\eta_3 = \eta_{shafting}$

For gas turbine vessel:

$\eta_4 = \eta_{gearbox} \times \eta_{shafting} \times \eta_{\substack{electric\\motors}} \times \eta_{\substack{transfere\\\&cpnversion}} \times \eta_{alternators}$

For COGES vessel:

$\eta_5 = \eta_{gearbox} \times \eta_{shafting} \times \eta_{\substack{electric\\motors}} \times \eta_{\substack{transfere\\\&cpnversion}} \times \eta_{alternators}$

$$P_{engine} = \frac{P_{propeller}}{\eta_i} \quad (kW) \qquad (12)$$

Delivered power for electric generation: $P_{generator}$

η_j *: electric generation losses as shown in Table B4, j=6, 7, 8, 9, 10*

For steam turbine vessel :

$\eta_6 = \eta_{alternators}$

For dual fuel-electric vessel:

$\eta_7 = \eta_{alternators}$

For two stroke Diesel vessel:

$\eta_8 = \eta_{alternators}$

For gas turbine vessel:

$\eta_9 = \eta_{alternators}$

For COGES vessel:

$\eta_{10} = \eta_{alternators}$

$$P_{generator} = \frac{P_{electric}}{\eta_j} \quad (kW) \qquad (13)$$

Power consumption of the Reliquefaction plant and of the gas compressors for the main engines: PC

SPC: Specific power consumption (W/kg/h)

V: Volume of BOG (methane) (m^3/day)

AD: Average LNG density (methane) (kg/m^3)

$$PC = SPC \times V \times AD \times 1/24 \times 10^{-3} \quad (kW) \qquad (14)$$

Specific energy consumption:
LHVO: LHV of liquid fuel oil (kJ/kg)
SFC: Specific fuel oil consumption (g/kWh)

$$SEC = LHVO \times SFC \times 10^{-3} \text{ (kJ/kWh)} \qquad (15)$$

Notes:

Dual fuel electric: From full power down to approx. 8 MW, the specific fuel consumption is almost constant at a mean level of 190 g/kWh.

Two stroke Diesel: The specific fuel consumption is almost constant (flat fuel consumption line).

Gas turbine: When the turbines have to operate at part load then the specific fuel consumption rates are higher.

The most important data of the technical analysis are presented in the following tables in Appendix B:

Power Needs: Table B3
Plant efficiencies: Table B4
Basic Data for the machinery: Table B5

3.2.2 Economic evaluation

3.2.2.1 Investment cost for the machinery

The initial cost of the ship's machinery was difficult to estimate because of the novelty and complexity of the propulsion concepts proposed to replace the traditional steam turbine. However an indication could be gained by comparing published data from feasibility studies for future or recently under construction vessels, with alternative propulsion systems.

In the initial cost the following machinery items weren't included:

i. Main and Emergency cargo pumps cost, ballast pumps, fire pumps, feed water pumps, fuel and lub oil supply pumps cost.
ii. Ancillary piping cost.
iii. Air conditioning and refrigeration plant cost.
iv. Gas and fire detection and fire-fighting equipment cost.
v. Extra safety equipment cost (double-wall gas piping, extra engine room arrangements, fire-resistant bulkheads, etc.).
vi. Other cost for cargo handling (HD Cargo Compressors, Main heaters, Vaporiser, Inert gas system unit, Nitrogen gas generators)[3].
vii. Electric Power Distribution network cost [4](High-voltage main busbars or Medium Voltage switchboard systems).

Also in the initial cost were not included:

viii. Navigation Equipment cost.
ix. Steel building cost.

---

[3] See data for this equipment in Appendix A.

[4] In the last years the power plant for the cargo handling system has been changed from a 440 V system to a medium voltage system (3.3 kV or 6.6 kV) or a high-voltage system (11 kV) due to increased installed power for the cargo pumps as the ship sizes have increased. This increases also the initial cost but no data were available for an analytical calculation.

x. Outfitting cost.
xi. Other building cost except the installation cost for the machinery items which were included in this study.

Regarding the installation cost of the machinery this was estimated roughly because there were no available data. The installation cost can vary a lot from project to project, depending on when, where, how many and of course which type of engine will be installed.

The installation cost was different for each alternative because of the following:

i) Differences in size and compactness of the main engines (prefabrication and modular constuction).
ii) Different auxiliaries (mechanical, electrical and electronic equipment) (boilers, gearboxes, gen-sets, propulsion motors, alternators, transformers, frequency converters, cables etc.).
iii) Different additional equipment (thermal oxidisers, exhaust gas boilers, reliquefaction plants, gas compressors, etc.).
iv) Different ancillary systems (fuel oil, lub oil, cooling water, gas treatment , etc.) and piping required.
v) Different safety equipment (double-wall gas piping, engine room arrangements , fire-resistant bulkheads).
vi) Different shaftline length and configuration, associated equipment (bearings, propeller, etc.).

The initial and installation cost are shown in Table B2 in Appendix B.

3.2.2.2 Residual value

The expected residual value of the propulsion equipment, after a 30- year service life is assumed to be 3% of the initial investement.

3.2.2.3 Possible roots

A 6,500 nautical miles distance root was selected for the current study. It was decided not to examine different trade distances scenarios - short and medium distances of 500 and 2,000 nm in conjunction with the selected long trade distance of 6,500 nm - in the present study.

3.2.2.4 Voyage profile

The selected voyage profile is shown in Table 3.1.

Table 3.1 Voyage profile.

Distance (Pilot-Pilot) (nm)	6500
Service speed laden voyage (kn)	20
Service speed ballast voyage (kn)	20
Loaded voyage (hours)	325
Ballast voyage (hours)	325
Manoeuvring (hours)	6
Reserve (waiting, bunkering etc.) (hours)	24
Loading time (hours)	12
Unloading time (hours)	12
Time per round-trip (hours)	704
Round-trips per year for steam vessel	12
Round-trips per year for dual -fuel vessel	12
Round-trips per year for two-stroke vessel	12
Round-trips per year for gas turbine vessel	12
Round-trips per year for coges vessel	12

Notes:

Service per year: 355 days

The number of round-trips per year remains the same for all the alternatives because the time saved from better maoeuvring is compensated from the increased time for loading and unloading due to the increased cargo delivered.

Time for loading and unloading was calculated based on a given number and power of cargo pumps (main cargo pumps per tank : 2 x 1700 m^3/h , tanks : 4) assumed the same for all the alternatives. The maoeuvring time is based on information provided by a shipping company.

3.2.2.5 Operating cost

The operating costs were calculated separately for 3 conditions:

- ✓ Loaded conditions
- ✓ Ballast conditions
- ✓ Port (Manoeuvring, Loading, Unloading, Waiting & Bunkering, etc.)

The analysis included fuel oil, lubricating oil and maintenance costs for both propulsion and electricity production under various operating conditions. The crew salaries were also included. The availability and the number of crew members needed for the selected propulsion plant configuration have been considered.

The lub oil for the steam and gas turbine applications and the pilot fuel needed for each propulsion system was difficult to estimate because there were not enough available data for all the alternatives , so they were not considered in this study.

An annual increase for the fuel (BOG FOB, HFO, MDO, MGO) prices and lub oil prices of a=0,8% was assumed, based on historically data for the long term fuel oil price fluctuation during the last 30 years (1974-2004), which is the same period with the assumed ship's operating life. The same annual increase was assumed for the NG CIF price also. In addition it was assumed a b=2% annual increase for the crew salaries. The average inflation was assumed zero. The maintenance cost was assumed constant.

The number of the bridge, deck, auxiliary deck, catering personnel was assumed the same for all the alternatives and only the number of crew members needed for the selected propulsion plant was changed (engine room and auxiliary engine room personnel).

The composition of the crew was based on Greek legislation for safety manning [48] and the salaries on the ATOMOS IV 2002, which contained data for Greek and Spanish flag [46] and Maran Gas Inc. salaries for East European personnel [51]. Cost for the crew training was not included. All the data for the crew salaries are contained in Table B6 in Appendix B.

Other runnig costs such as insurance and port fees have not been considered, because no data were available for the alternatives to the steam turbine.

It must be considered that 3 (2-stroke Diesel, simple gas turbine and combined cycle gas turbine propulsion systems) of the 5 propulsion concepts presented in this research have not yet applied in LNG vessels and thus it is difficult to obtain real data.

So in the operating costs the following were not included:

i. Port fees.
ii. Provision cost.
iii. Insurance cost for the machinery, the ship and the cargo.
iv. Emission penalty (increased port dues for ships with high emissions).
v. Taxes.
vi. Loan payback.
vii. Managerial cost.
viii. Other expences.

For each of the 5 possibilities (the steam basis and four alternatives), the operating costs are indicated in the tables in Appendix B. The calculations were based on the basic data contained in Table B1.

3.2.2.6 Company's policy

3.2.2.6.1 Long time charter

If the ship is chartered, then the revenues are calculated according to the current charter rates, which are unknown especially for those alternatives that have not entered in the market yet.

In the following there is an attempt to make calculations for a chartered vessel from the operator/owner point of view only with data that were included from the beginning in this study. Reasonable assumptions, historical and statistical data were used to relate variable parameters between the different alternatives.

The daily charter rate is a function of the price of the ship, the cost of financing, and operating costs. There is no set market for LNG tanker rates, as there is for crude oil tanker rates. Charter rates vary widely from as low as US$ 27,000 per day to as high as US$ 150,000. The average rate for long-term charters is between US$ 55,000 and US$ 65,000

So the charter price for a 150,000 m^3 steam turbine LNG carrier and a 30 years contract was assumed to be 55,000 US$/day.

To perform a study on the charter rates of the different alternatives the following were considered:

As mentioned above, the charter rate depends on the following:

I. Shipping cost (initial cost (loan payback), salaries, maintenance, lub oil cost).
II. Desirable profit.
III. Safety margin for unpredicted damages.
IV. Competition/Negotiations.
V. Cargo capacity.

If we assume the same desirable profit and safety margin for the owner, then each of the alternatives has different charter rate from the steam vessel because of the following

Directly to the operator:

a. It has different initial cost.
b. It has different operational cost for the owner/operator (crew salaries, maintenance, lub oil cost).

Indirectly:

c. It has different operational cost for the charterer (fuel cost).
d. It delivers different cargo capacities.

So we worked as follows:

a. For the different initial cost the following assumption was made:

AI:Additional Initial cost of each alternative (US$)
N: Cycle life of the investment (years)
RT: Round trips per year

$$CRD_a = \frac{AI}{N \times RT} \quad \text{(US\$/trip)} \qquad (16)$$

, where CRD$_i$, i= a, b, c, d is the charter rate difference for each parameter.

b. For the different operational cost for the owner/operator (crew salaries, maintenance, lub oil cost) the following assumption was made:
The mean square (MS) of the maintenance cost difference (MCd) , the lub oil cost difference (LCd) and the crew cost difference (CCd) were added to the charter rate.

$$CRD_b = MS(MCd + LCd + CCd) \quad \textit{(US\$/trip)} \qquad (17)$$

c. For the different operational cost for the charterer (fuel cost) the following assumption was made:
The mean square (MS) of the fuel cost difference was added to the charter rate.

$$CRD_c = MS(FCd) \quad \textit{(US\$/trip)} \qquad (18)$$

d. For the extra delivered cargo (EDC) a 11 US$/m^3/trip increase to the charter rate was assumed, based on :

- statistics for various ships' cargo capacities and long time contracts
- the selected charter rate for the steam vessel
- data from shipping companies

$$CRD_d = EDC \times 11 \quad \textit{(US\$/trip)} \qquad (19)$$

The mean square (MS) was calculated for 30 years of operation.

Of course the charter rate is negotiable and it is not possible to predict it and also this study doesn't include all the relative parameters for the shipping cost (e.g. hull construction first cost, port fees, insurance cost, managerial cost etc.) as those are not the main purpose of this thesis. So the results are for comparison reasons only and should not be considered as exact numbers.

The charter rates with the above assumptions were the following (Case 0):
Steam turbine vessel: 55,000 US$/day
Medium speed dual fuel vessel: 64,272 US$/day
Slow speed Diesel vessel: 76,667 US$/day
Gas turbine vessel: 54,887 US$/day
Combined gas and steam turbine vessel: 70,673 US$/day
as calculated according to the Eqs. (16) – (19).

So for each alternative the following were calculated:

Operator

For the operator:

Income = Time charter rate

Expences = Operating cost

Operating cost = Maintenance cost + Lub oil cost + Crew salaries

Profit = Income – Operating cost

Charterer

Assuming the same charter rates as those calculated in the previous paragraph, the same study was performed from the charterer point of view.

Income = Delivered LNG quantity x LNG CIF price

Expences = Cost for LNG + Transportation Cost

Cost for LNG = Loaded LNG x LNG FOB price

Transportation Cost = Fuel oil cost + Time charter + Port fees

or if we consume LNG as fuel:

Cost for LNG = Delivered LNG quantity x LNG FOB price

Transportation Cost = Gas fuel cost (calculated with the LNG FOB price) + Fuel oil cost + Time charter + Port fees ,
Port fees were not included in the present study so the final equations are the following:

Cost for LNG = Delivered LNG quantity x LNG FOB price

Transportation Cost = Gas fuel cost + Fuel oil cost + Time charter

Expences = (Delivered LNG quantity x LNG FOB price) + Gas fuel cost + Fuel oil cost + Time charter

Profit = Income – Expences

3.2.2.6.2 Spot Market

If the ship enters the Spot Market, then the revenues are calculated according to the current spot rates. For the assumed 30 years operational life of the vessel, it is very difficult to make a realistic assumption for the spot rates because there is a great fluctuation depending on many parameters. So for this scenario, calculations related to the spot market have not been performed.

3.2.2.6.3 LNG producing and trading

Natural gas company

Here, the case of a Natural Gas Company which produces or purchases natural gas and uses its own ships for the LNG transportation is examined. So for the purpose of a complete comparison, all costs were calculated together (in other words all the costs are covered from the owner/operator, who is at the same time the charterer).

Income = Delivered LNG quantity x LNG CIF price

Expences = Cost for LNG + Total operating cost

Cost for LNG (represents the drilling and production cost or the purchasing cost of LNG at the source) = Delivered LNG quantity x LNG FOB price

Total Operating cost = Gas fuel cost + Fuel oil cost + Lub oil cost + Maintenance cost + Crew salaries

Expences = (Delivered LNG quantity x LNG FOB price) + Gas fuel cost + Fuel oil cost + Lub oil cost + Maintenance cost + Crew salaries

Profit = Income – Expences

3.2.2.6.4 Additional revenue

An evaluation of the savings on operating costs and the additional income from selling the delivered LNG shows the substantial economic benefits that can be obtained by each alternative.

Value of extra LNG delivered compared to steam vessel = Extra LNG quantity x LNG CIF price

Operating cost difference compared to steam vessel = Total Operating cost for the alternative – Total Operating cost for the steam vessel

Total Operating cost = Gas fuel cost + Fuel oil cost + Lub oil cost + Maintenance cost + Crew salaries

Profit = Value of extra LNG – Operating cost difference

As mentioned above the results are for comparison reasons only and must not be considered as exact numbers. That's because in this study was included only a part of the ship's cost and only those concerning the machinery. Additionally, for the charter rate and for the relation between the oil prices (for the purposes of the sensitivity analysis) reasonable assumptions were made.

3.2.2.7 Remarks on the calculations

The data in Table B1 were calculated according to the following equations:

Initial Fuel/Oil Prices:

HFO price:	*331.5*	*USD/t*	
MDO price:	$DO = HF \times 1.8$	*USD/t*	*(20)*
MGO price:	$FO = HF \times 1.9$	*USD/t*	*(21)*
LNG FOB price:	$NGF = HF \times 0.48$	*USD/t*	*(22)*
LNG CIF price:	$NGC = HF \times 1.1$	*USD/t*	*(23)*
Lub oil for four-stroke engine gen-sets price:	$LO = HF \times 4$	*USD/t*	*(24)*
Cylinder L.O. for two-stroke engines price:	$CO = HF \times 5.3$	*USD/t*	*(25)*
System oil for two-stroke engines price:	$SO = HF \times 4$	*USD/t*	*(26)*

It was assumed, for the purposes of a sensitivity analysis that all the fuel oil, gas and oil prices would depend on the HFO price in linear fashion.

The parameters used came from historically mean square values of the related fuel and oil prices.

Lower heating values:

HFO:	40,400 kJ/kg
MDO:	42,700 kJ/kg
MGO:	42,700 kJ/kg
LNG:	49,700 kJ/kg

Time for Loaded, Ballast voyage: $t = \frac{s}{u}$ *(hours)* *(27)*

s: Distance (nm)
u: Service speed (kn)

Time per round trip: $T = t_1 + t_2 + t_3 + t_4 + t_5 + t_6$ *(hours)* *(28)*

t_1: *Loaded voyage time (h)*
t_2: *Ballast voyage time (h)*
t_3: *Manoeuvring time (h)*
t_4: *Reserve time (h)*
t_5: *Loading time (h)*
t_6: *Unloading time (h)*

Round trips per year: $RT = \dfrac{365 * 24}{T}$ (29)

Basic data for BOG rates:

Volume of BOG (methane): V
BOR: Boil-off rate ($\%\!/\!_{day}$)
C: Cargo capacity (m^3)
ML: Maximum loading (%)
$V = BOR \times C \times ML$ (m^3/day) (30)

Mass of BOG (methane): M
AD: Average LNG density (methane) (kg/m^3)
$M = V \times AD$ (kg/day) (31)

Energy in BOG (methane): EBOG
M: Mass of BOG (methane)
LHVG: LHV of BOG (methane) (kJ/kg)
$EBOG = M \times LHVG \times 10^{-6}$ (GJ/kg) (32)

Used or Reliquefied LNG: LoR
V : Volume of BOG (methane)
H: Hours per trip for each condition (h)
$LoR = V \times H \times 1\!/\!_{24}$ (m^3/per trip) (33)

Delivered cargo: DC
C: Cargo capacity (m^3)
TL: Total used or lost LNG per trip (m^3)
HE: Minimum level of LNG for cargo tank cooling (heel) (m^3)
$DC = C - TL - HE$ (m^3) (34)

Revenue difference :

Value of Used or Reliquefied LNG : VLoR
Vo: Volume of total used or Reliquefied cargo (m^3/trip)
AD: Average LNG density (methane) (kg/m^3)
NGC: LNG CIF price (US$/ton)
$VLoR = Vo \times AD \times NGC \times 10^{-3}$ (US$/trip) (35)

Revenues from selling the delivered cargo capacity: R
DC: Delivered cargo
AD: Average LNG density (methane) (kg/m^3)
NGC: LNG CIF price (US$/ton)
$R = DC \times AD \times NGC \times 10^{-3}$ (US$/trip) (36)

The most important data of the economic analysis are presented in tables:
Basic data : data from Table B1,

Initial cost for the machinery : data from Table B2,
in Appendix B.

3.2.3 Cost-benefit analysis

The economic evaluation results are presented in the following tables. The Tables 3.2, 3.3 and 3.4 show the final summary of the operating costs at loaded condition, ballast condition and at port for the first year of operation (Case 0). Table 3.5 presents the total investment and operating cost for each alternative.

In Table 3.6 there is a comparison of the propulsion alternatives mentioned above, which was based on the main elements that should be considered when attempting to evaluate propulsion alternatives different to the typical steam propulsion plant. In Figures 3.2, 3.3 and 3.4 the results of the Table 3.5 are visualized.

The criterion for the economic evaluation was the Net Present Value of each investment.

$$NPV = -I + \sum_{t=0}^{N} \frac{R_t - C_t}{(1+i)^t} + \frac{SV_N}{(1+i)^N} \qquad (37)$$

NPV: Net Present Value
I: initial cost
R_t: annual revenues
C_t: annual operating cost
N: cycle life of the investment
i: market interest rate
SV_N: salvage value of the investment at the end of N years

The NPV analysis was estimated for 10, 20, 30 years of operation and for 3 market interest rates rates: 6%, 8%, 10%.

Tables B9-B12 in Appendix B show the NPV results for each of the examined cases (Owner/Operator, Charterer, NG company, Additional income).

Comments on the results

As can be seen from Tables 3.5 and 3.6 and from the corresponding Figures 3.2-3.4 the steam turbine vessel has the lowest initial cost. The Diesel alternative solutions have an additional initial cost between 1 and 2 million US$. The twin-screw two stroke Diesel solution proposed may represent added cost on the hull side at some shipyards. This could be up to US$ 3-4 million, but the hull building cost was not included in the present study. On the other hand gas turbines in a simple or combined cycle have an additional initial cost between 6 and 7 million US$.

Of course these numbers are indicative only because the precise initial cost required for the machinery is something, which is negotiated between the licensee, the shipyard and the ship-owner in each project. For the above reason and also for future initial cost variation due to the continual technological development, a sensitivity analysis with different initial cost assumptions was performed in the following paragraph.

The installation cost (for the main engine and the auxiliaries, the shaftline, the propeller, the rudder, etc.) was estimated roughly because there were no available data. This can vary a lot from project to project, depending on when, where, how many and of course which type of engine will be installed. For the current study an indicative cost between

400,000 and 600,000 US$ was used, assuming that the heavier and less compact solutions such as the two-stroke Diesel and the steam turbine require the higher installation cost.

Regarding the operating cost this consists of the fuel and lub oil cost, the maintenance cost and the crew salaries. For the fuel and lub oil cost the calculations were made according to the HFO (IFO 380) price (Rotterdam 13/5/06) and the corresponding fuel oil (MDO DMB, MGO DMA), LNG (both FOB and CIF) and Lubricating oil (System oil, Cylinder oil) prices. So the results in Tables 3.5 and 3.6 are strictly connected to the above numbers which are shown in Table B1.

The maintenance cost includes spare parts and man-hours and therefore the selected specific maintenance cost (US$/MWh) prices are subject to differences depending on hourly wages and so on.

Finally the crew salaries were based on the ATOMOS IV 2002, which contained data for Greek and Spanish flag, and Maran Gas Inc. salaries for East European personnel.

As can be seen from Tables 3.5 and 3.6, the two stroke Diesel solution has the lowest operating cost and the combined gas and steam turbine vessel follows with a very small difference of about 140,000 US$/year. The operating cost for the medium speed dual fuel-electric vessel is 1,75-1,89 million US$/year higher than the two previous alternatives, but still more cost efficient compared to the steam turbine vessel for about 420,000 US$/year. The simple cycle gas turbine has the highest operating cost. This represents a significant added cost of 2,8 million US$/year compared to the steam turbine vessel and 5 million US$/year approximately, compared to the two stroke Diesel and COGES solutions.

For possible different results through differences in the fuel and oil prices, a sensitivity analysis was performed in the following paragraph.

NPV results for the five alternative solutions, for each of the examined cases, as mentioned in the subsection 3.2.2.6 :

For the Owner/Operator:

The NPV results for 10, 20 and 30 years of operation and for the three interest rates show that the most beneficial vessel is the one equipped with the slow speed Diesel and follows the vessel with the combined gas and steam turbine. The vessel with the medium speed dual fuel engine is more beneficial than the steam turbine vessel. The gas turbine vessel is less beneficial than all the other alternatives including the steam turbine vessel as a result of the reduced charter rate received from the operator according to the assumptions of the present study.

For the Charterer:

The NPV results for 10, 20 and 30 years of operation and for the three interest rates show that all the alternatives are more profitable than the steam turbine vessel. The first more beneficial vessel is the gas turbine vessel, the second, with a small diferrence from the first, is the combined gas and steam turbine vessel and the third is the vessel with the slow speed Diesel. The vessel with the medium speed dual fuel engine is again more beneficial than the steam turbine vessel but less beneficial than the other alternatives solutions.

For the gas turbine vessel it should be mentioned that this alternative is more profitable because the charterer pays a reduced time charter compared with the other alternatives (assumed by the previous charter rate calculations). So in this case we can see that the increased fuel cost is compensated for by the comparative advantage of the reduced charter rate and finally the gas turbine is the most profitable.

NG company:

Again for all the years of operation and for all the interest rates the steam turbine vessel seems to be the less profitable. More profitable vessel in this case is the combined gas and steam turbine vessel and then the slow speed Diesel vessel although with a small advance compared to the gas turbine vessel. The medium speed dual fuel vessel is for one more time less profitable than the other alternatives but far more profitable than the steam turbine.

Additional income:

The ΔNPV was calculated instead of the NPV, in order to avoid the negative values of the first two alternatives and have a better measure for the comparison.

The results show that the more profitable solution is the combined gas and steam turbine vessel. The second is the gas turbine vessel and has a big difference from the first. The slow speed Diesel vessel follows with a substantial difference from the second. The medium speed dual fuel vessel is more profitable than the steam turbine vessel but not than the other alternatives.

TABLE 3.2 Fuel, Lub oil and Maintenance cost at Loaded condition.

Propulsion Plant	Fuel (Both gas and fuel oil) and Lub Oil Cost for Prime Mover at service condition (US$/yr)	Fuel and Lub Oil Cost for Gen-Sets at service condition (US$/yr)	Maintenance Cost for Prime Mover (US$/yr)	Maintenance Cost for Auxiliaries (US$/yr)	**Overall cost at loaded condition (US$/yr)**
Steam Turbine Direct Drive (Single Screw)	8480403,32	697163,161	46500,9276	3430,64985	9227498,06
Medium Speed Dual Fuel Diesel (GAS/MDO) Electric Drive (Single Screw)	7724673,23	0	398953,844	0	8123627,08
Slow Speed Diesel Direct Drive (Twin Screw)	7505972,63	1322086,22	149616,735	68152,0064	9045827,59
Gas Turbine Electric Drive (Single Screw)	9290725,69	0	340344,495	0	9631070,18
Combined Gas and Steam Turbine Electric Drive (Single Screw) (COGES)	6805547,05	0	292691,506	9530,5977	7107769,15

TABLE 3.3 Fuel, Lub oil and Maintenance cost at Ballast condition.

Propulsion Plant	Fuel (Both gas and fuel oil) and Lub Oil Cost for Prime Mover at service condition (US$/yr)	Fuel and Lub Oil Cost for Gen-Sets at service condition (US$/yr)	Maintenance Cost for Prime Mover (US$/yr)	Maintenance Cost for Auxiliaries (US$/yr)	**Overall cost at ballast condition (US$/yr)**
Steam Turbine Direct Drive (Single Screw)	9673799,57	616890,291	44640,8905	3035,63743	10338366,4
Medium Speed Dual Fuel Diesel (GAS/MDO) Electric Drive (Single Screw)	10730256,4	0	379526,517	0	11109782,9
Slow Speed Diesel Direct Drive (Twin Screw)	7221247,92	840333,044	143632,065	43318,1907	8248531,22
Gas Turbine Electric Drive (Single Screw)	12470255,2	0	320213,577	0	12790468,8
Combined Gas and Steam Turbine Electric Drive (Single Screw) (COGES)	10054109,3	0	273884,283	9265,85887	10337259,5

TABLE 3.4 Fuel, Lub oil and Maintenance cost at Port.

Propulsion Plant	Fuel (Both gas and fuel oil) and Lub Oil Cost for Prime Mover at port (US$/yr)	Fuel and Lub Oil Cost for Gen-Set at port (US$/yr)	Maintenance Cost for Prime Mover (US$/yr)	Maintenance Cost for Auxiliaries (US$/yr)	**Overall cost at port (US$/yr)**
Steam Turbine Direct Drive (Single Screw)	10297,5409	145084,306	103,896104	892,021143	156377,764
Medium Speed Dual Fuel Diesel (GAS/MDO) Electric Drive (Single Screw)	14458,3327	147532,655	1604,37438	4853,16659	168448,528
Slow Speed Diesel Direct Drive (Twin Screw)	23064,2696	186994,269	334,285714	9639,33703	220032,162
Gas Turbine Electric Drive (Single Screw)	16506,692	172504,029	1458,25493	4529,41063	194998,387
Combined Gas and Steam Turbine Electric Drive (Single Screw) (COGES)	16506,692	138334,857	1458,25493	905,882126	157205,686

TABLE 3.5 Quantitative analysis of the propulsion alternatives.

Propulsion Plant	Purchase Cost for the prime mover and for the propulsion unit (main propulsion unit + bow thrusters) (million US$)	Purchase Cost for the gen-sets (million US$)	Purchase Cost for the BOG handling equipment and for the possible additional equipment (million US$)	Overall Purchase Cost for each alternative (million US$)	Overall Installation Cost for each alternative (million US$)	**Overall investment for the machinery (million US$)**	Fuel cost+Lub oil cost+Maintenance cost for all conditions (million US$/yr)	Cost for Crew salaries (million US$/yr)	**Overall Operating cost at service condition (million US$/yr)**
Steam Turbine Direct Drive (Single Screw)	16,80	3,20	0,00	20,00	0,50	20,50	19,72	1,25	20,97
Medium Speed Dual Fuel Diesel (GAS/MDO) Electric Drive (Single Screw)	20,65	0,50	0,50	21,65	0,45	22,10	19,40	1,15	20,55
Slow Speed Diesel Direct Drive (Twin Screw)	9,6	3,2	8	20,8	0,6	21,4	17,51	1,15	18,66
Gas Turbine Electric Drive (Single Screw)	23,95	1,40	0,50	25,85	0,40	26,25	22,62	1,15	23,77
Combined Gas and Steam Turbine Electric Drive (Single Screw) (COGES)	23,65	1,40	1,50	26,55	0,43	26,98	17,60	1,19	18,80

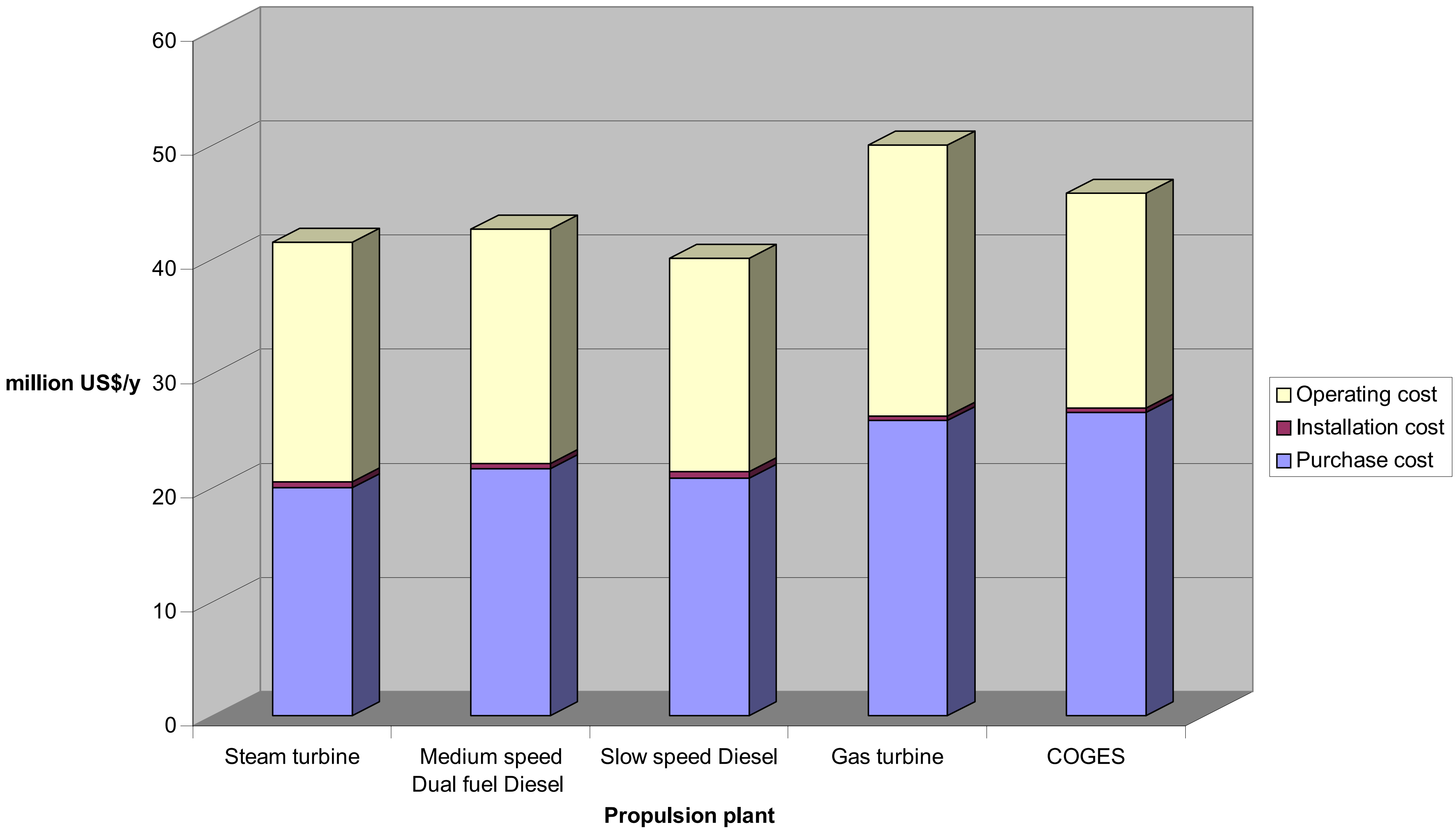


Fig. 3.2 Cost Distribution for years 0 and 1 (Case 0).

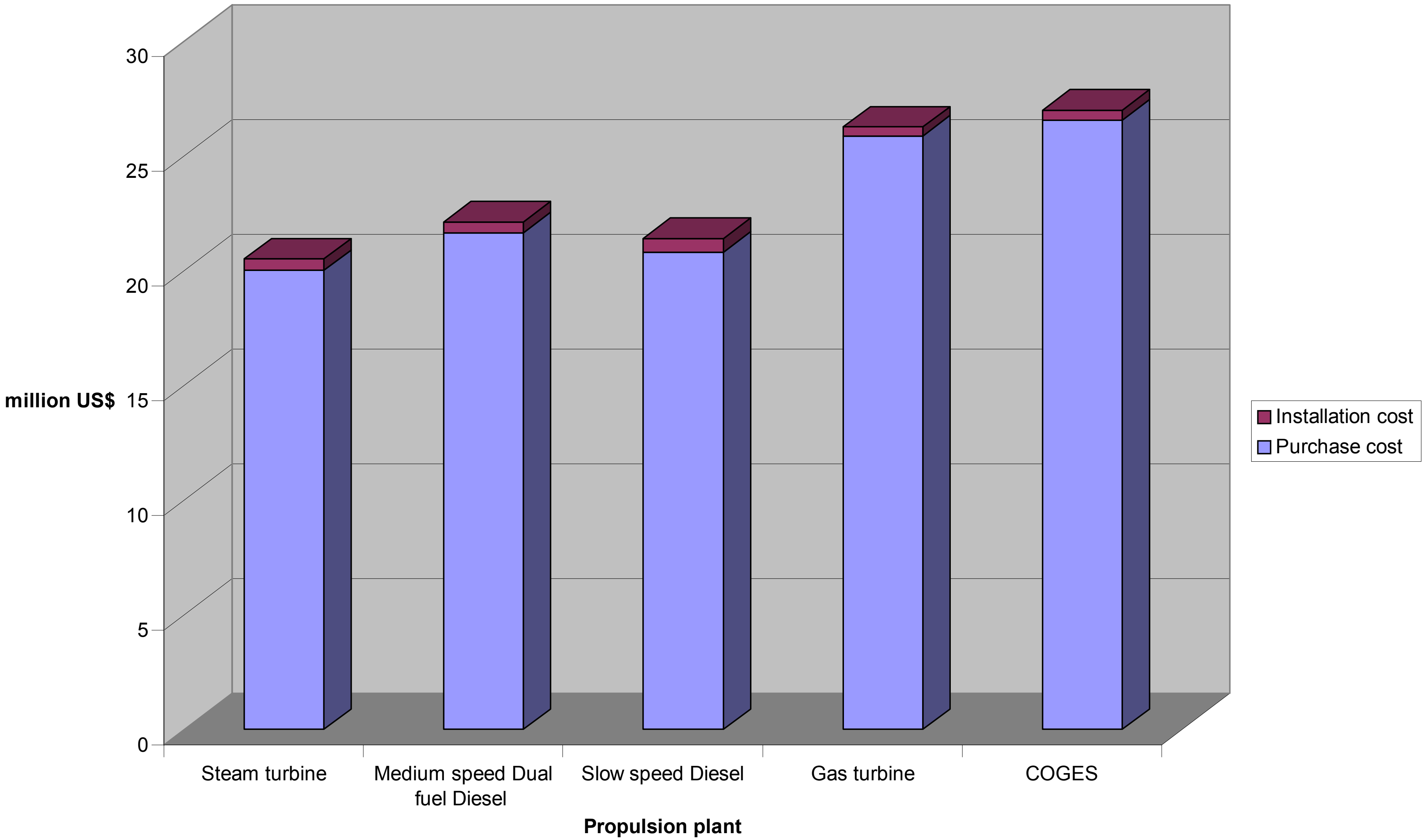


Fig. 3.3 Initial Cost

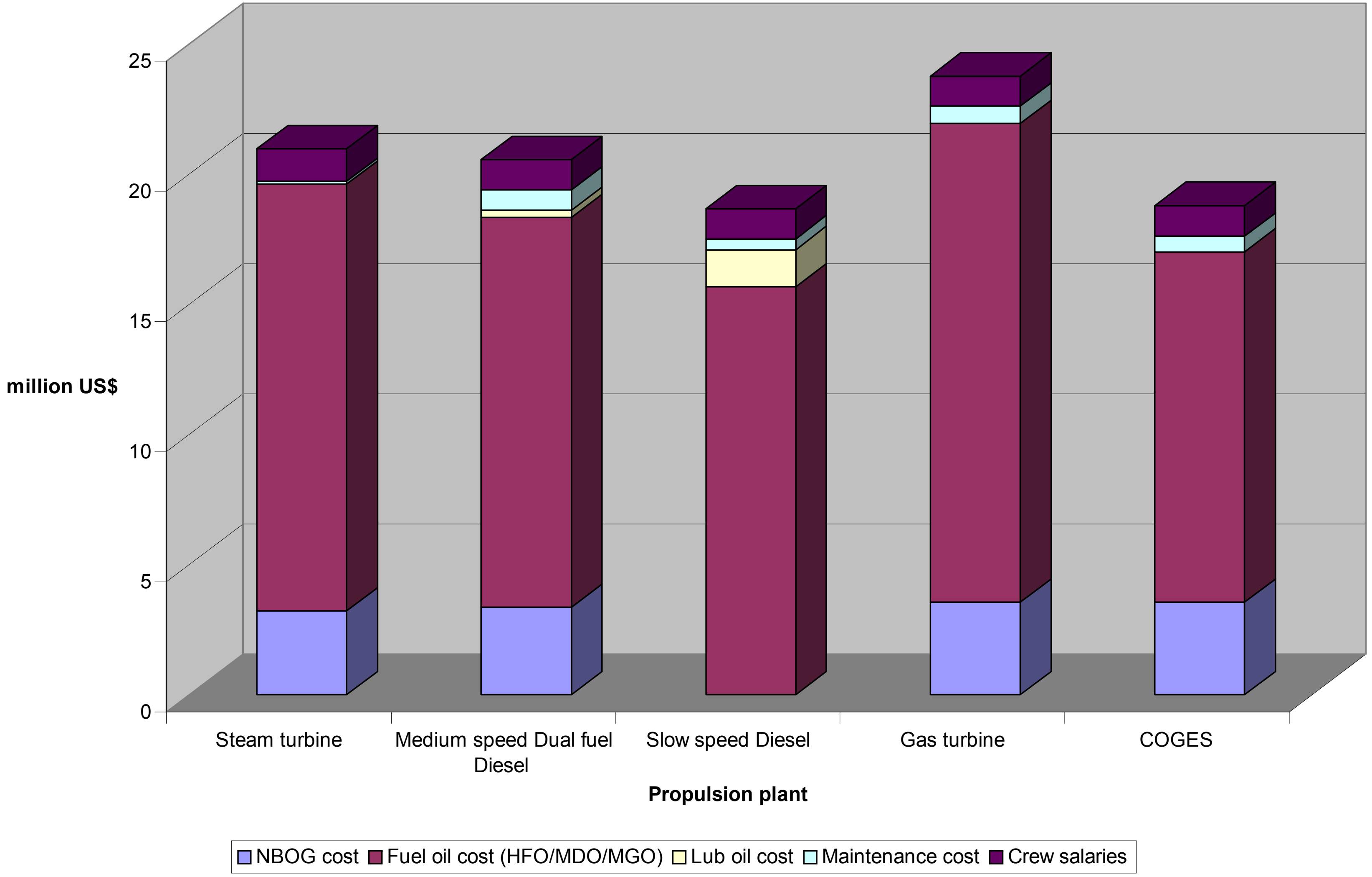


Fig. 3.4 Operating expences per year (year 1).

TABLE 3.6 Propulsion Alternatives Comparison.

Propulsion Plant	Initial cost (million US$)	Operating cost (million US$/yr)	Propulsion Efficiency (%)	Additional Cargo Capacity compared to the traditional steam turbine vessel (100% full) (m^3)	Emissions (Environmental friendliness of the selected alternative)	Manoeuvrability, Engine noise and Vibration Levels of the selected alternative	Reliability/ Safety	Overall simplicity of the selected alternative for installation and maitenance reasons	Crew availability
Steam Turbine Direct Drive (Single Screw)	20,5	20,97	30%	0	⇔	⇔	⇔	⇔	⇔
Medium Speed Dual Fuel Diesel (GAS/MDO) Electric Drive (Single Screw)	22,1	20,55	43%	6700	⇧	⇧	⇩	⇧	⇧
Slow Speed Diesel Direct Drive (Twin Screw)	21,4	18,66	48%	6300	⇩	⇩	⇩	⇩	⇧
Gas Turbine Electric Drive (Single Screw)	26,25	23,77	33%	15000	⇧	⇧	⇩	⇧	⇩
Combined Gas and Steam Turbine Electric Drive (Single Screw) (COGES)	26,98	18,80	40%	15000	⇧	⇧	⇩	⇩	⇩

⇔: indicates no effect
⇧: indicates positive effect
⇩: indicates negative effect

3.2.4 Sensitivity Analysis

In this paragraph there are the data and the results from the two sensitivity analyses performed in this study for the case of LNG producing and trading (NG company) which is the more representative of the examined cases in the paragraph 3.2.2.

Sensitivity analysis No 1

The input data for the first sensitivity analysis calculations were:

- 4 different prices for LNG (FOB, CIF)
- 4 different prices for liquid fuels (HFO, MDO, MGO)
- 4 different prices for lubricating oils (Cylinder oil 2-x, System oil 2-x, Lubrication oil 4-x)

all related with the HFO price with the Eqs. (20) – (26).

HFO price variation according to the parameter f : f = 50%, 100%, 150%, 200%

$\text{HFO price} = \text{Basis HFO price} \times f$ *USD/t*

Basis HFO price : *331.5 USD/t*

CASE 0 : $\text{HFO price} = \text{Basis HFO price} \times 100\%$

CASE 1.1: $\text{HFO price} = \text{Basis HFO price} \times 50\%$

CASE 1.2: $\text{HFO price} = \text{Basis HFO price} \times 150\%$

CASE 1.3: $\text{HFO price} = \text{Basis HFO price} \times 200\%$

N = 20 years

Market interest rate: i= 6%, 8%,10%

The fuel prices used in Table B1 in Appendix B are initial values.

The Figures 3.5, 3.6 and 3.7 show the results of the first sensitivity analysis for the three interest rates.

Sensitivity analysis No 2

A second sensitivity analysis is performed for the Initial cost.

Initial cost = Basis Initial cost x d , d= 60%, 80%, 100%, 120%, 140%

CASE 0 : $\text{Initial cost} = \text{Basis Initial cost} \times 100\%$

CASE 2.1: $\text{Initial cost} = \text{Basis Initial cost} \times 60\%$

CASE 2.2: $\text{Initial cost} = \text{Basis Initial cost} \times 80\%$

CASE 2.3: $\text{Initial cost} = \text{Basis Initial cost} \times 120\%$

CASE 2.4: $\text{Initial cost} = \text{Basis Initial cost} \times 140\%$

N = 20 years

Market interest rate: i= 6%, 8%,10%

The Initial costs in Table B2 in Appendix B are initial values.

The Figures 3.8, 3.9 and 3.10 show the results of the second sensitivity analysis for the three interest rates.

Comments on the results

Sensitivity analysis No 1

The Figures 3.5-3.7 show that for the three interest rates the NPV_{20} is greater for the combined gas and steam turbine installation. Then follow the slow speed Diesel installation, the medium speed Diesel, the steam turbine and the less profitable seems to be the gas turbine intallation.

Sensitivity analysis No 2

The figures 3.8-3.10 show that for the three interest rates the NPV_{20} is greater for the combined gas and steam turbine installation. Then follow the slow speed Diesel with a very small difference from the gas turbine installation. Finally the medium speed Diesel installation has greater NPV_{20} than the steam turbine installation but no than the other alternatives.

Note: These results must be evaluated only concerning the basic assumptions of the present study.

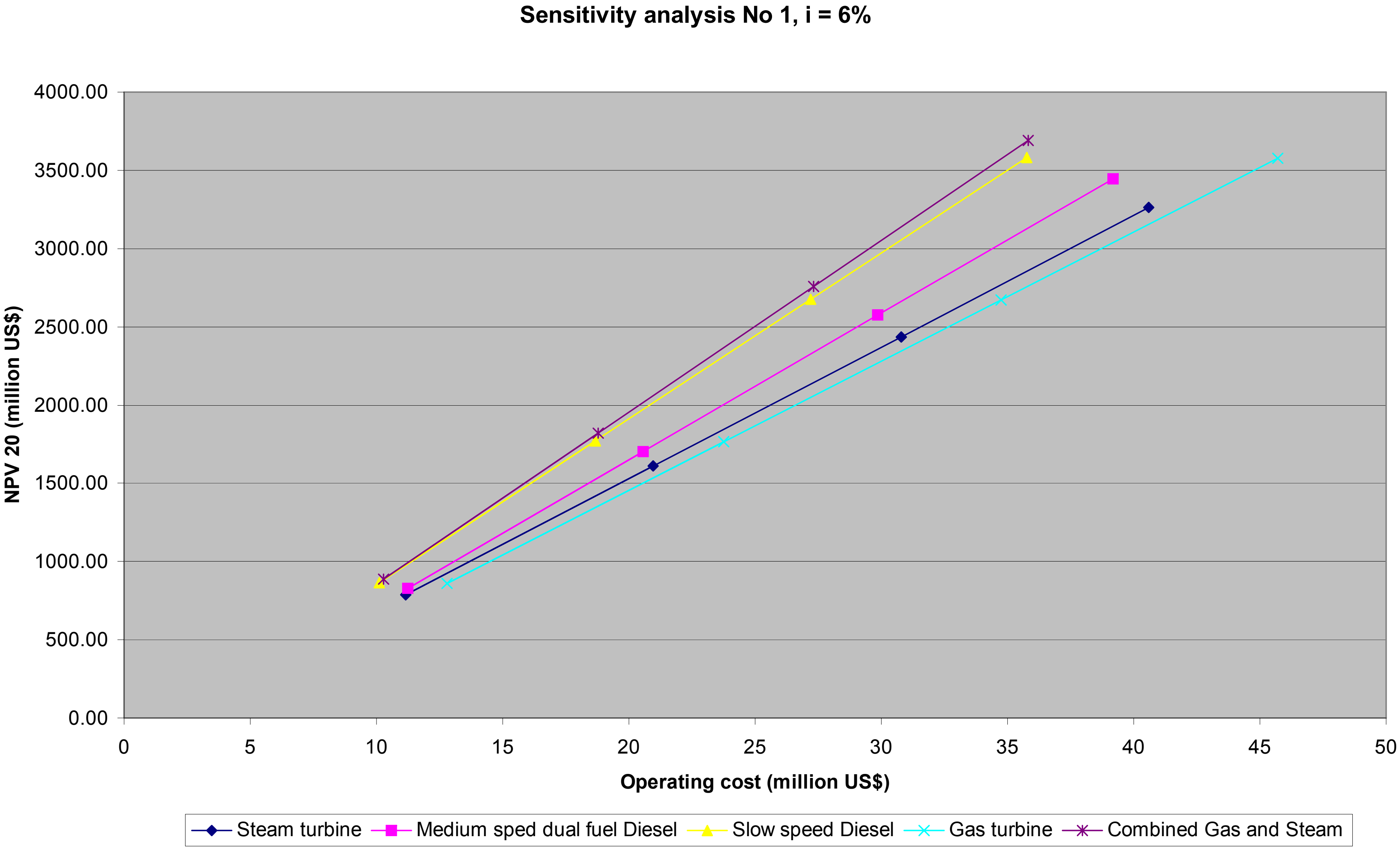


Fig. 3.5 Sensitivity analysis No 1, results for i=6%.

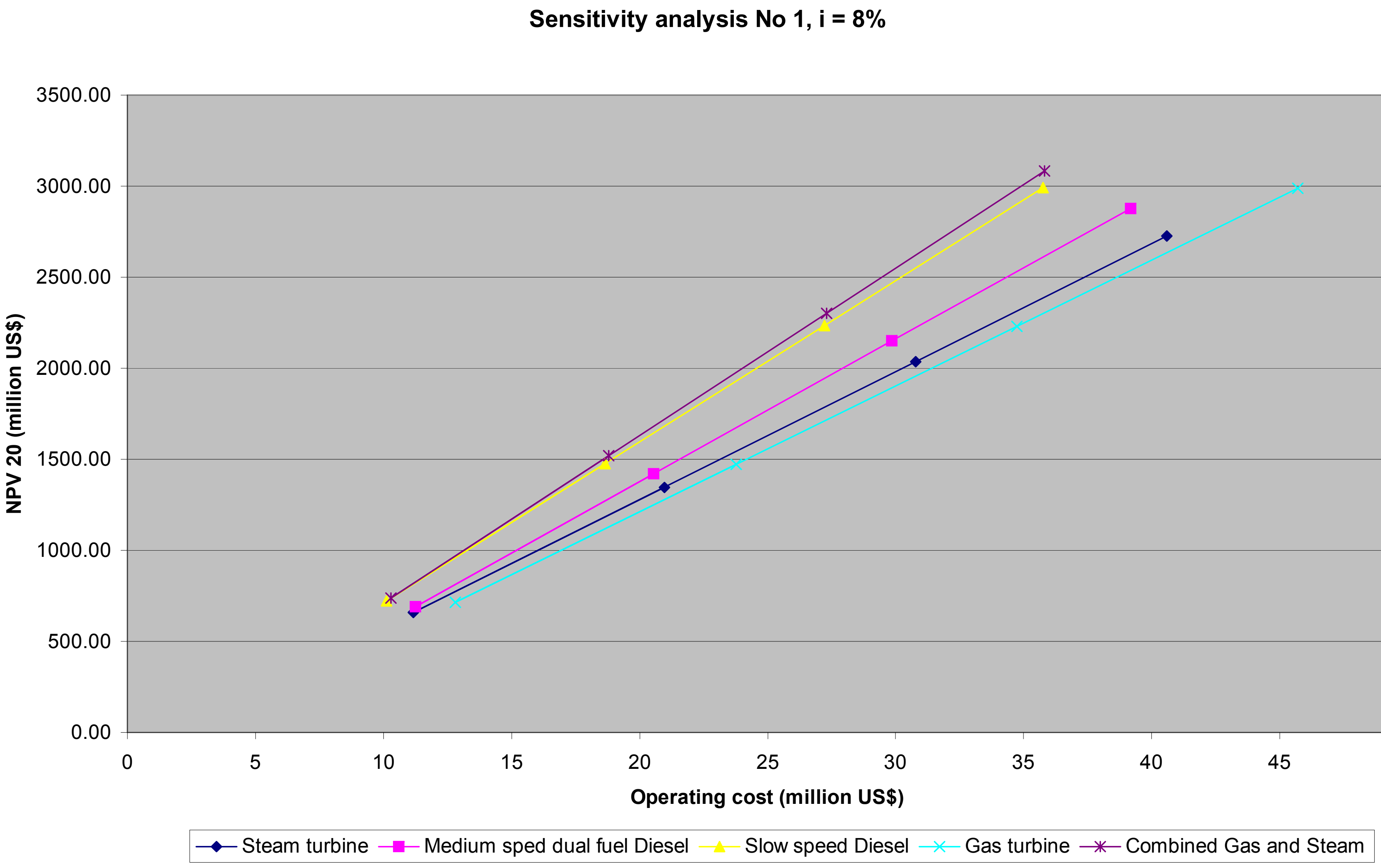


Fig. 3.6 Sensitivity analysis No 1, results for i=8%

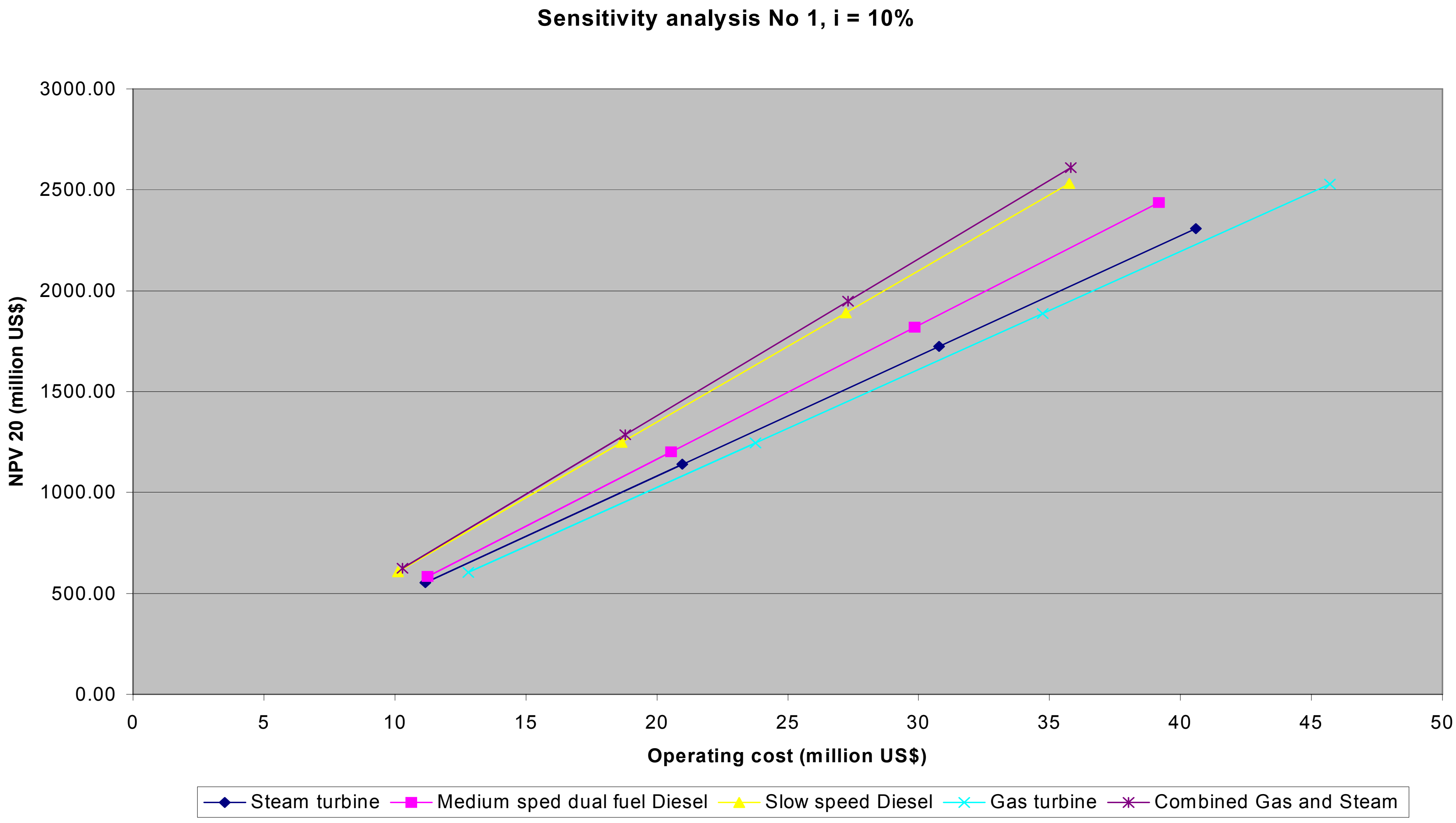


Fig. 3.7 Sensitivity analysis No 1, results for i=10%.

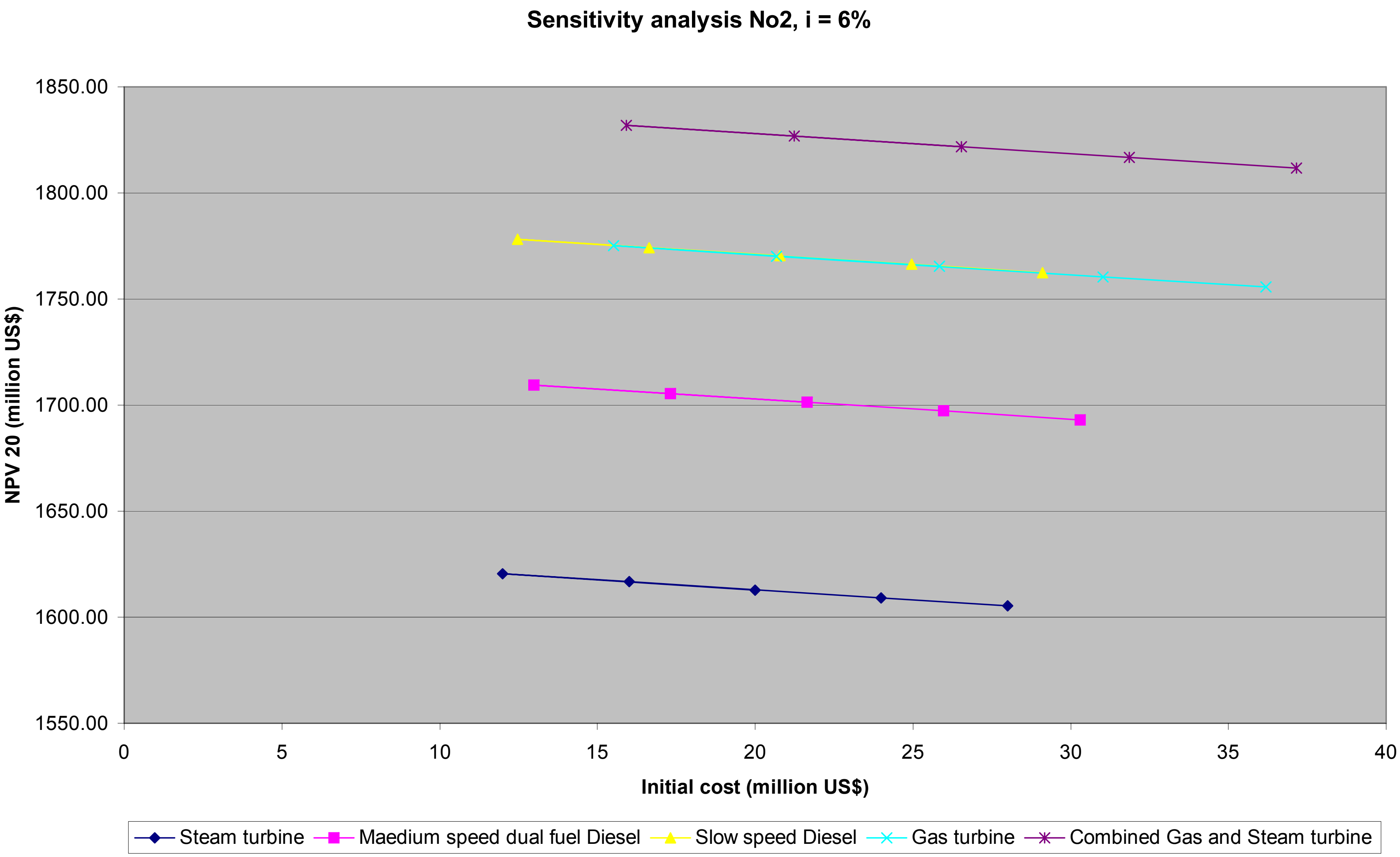


Fig. 3.8 Sensitivity analysis No 2, results for i=6%.

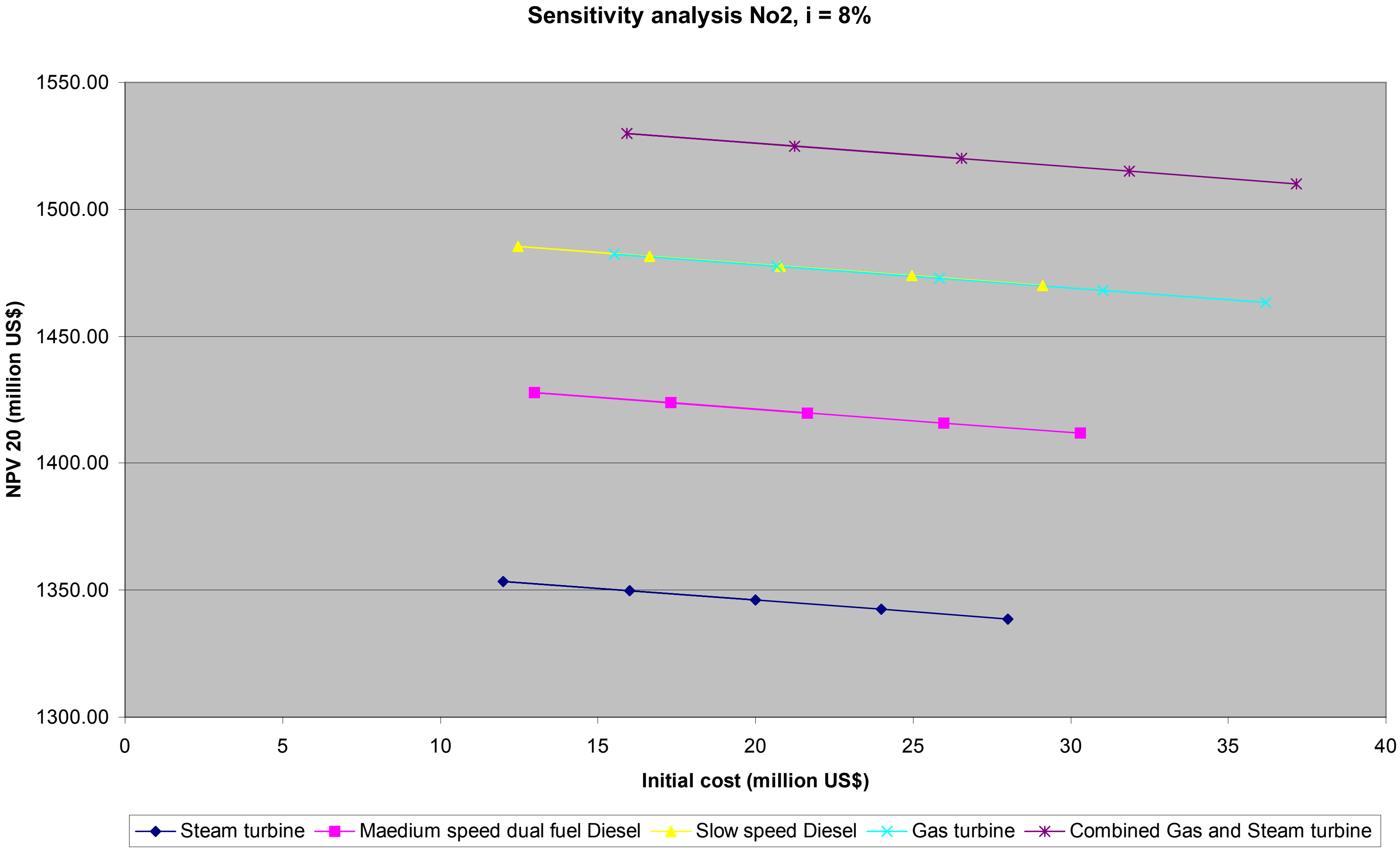


Fig. 3.9 Sensitivity analysis No 2, results for i=8%.

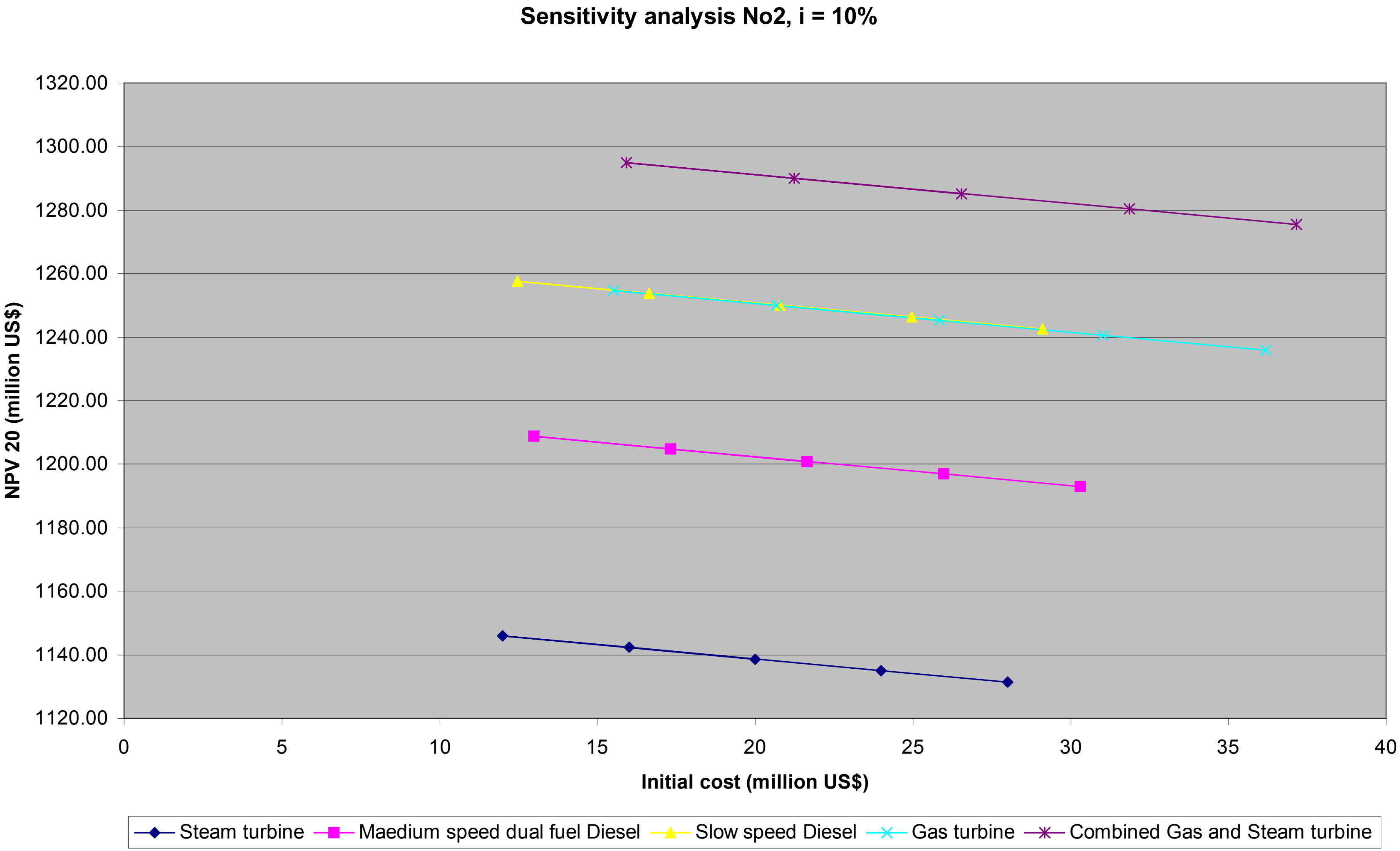


Fig. 3.10 Sensitivity analysis No 2, results for i=10%.

3.3 Environmental Considerations Concerning the Evaluated Propulsion Plants

3.3.1 Exhaust emissions from the evaluated propulsion plants

The annual exhaust gas emissions expected for the 5 alternatives are shown in Table B8 in Appendix B.

For the calculation of the exhaust emissions from the evaluated propulsion plants data from engine manufacturers' measurements and from the Table C7 of the TECHNE's proposed emission factors used for the European Commission's MEET project (Ref. 54) were used.

The calculations were based on the prime mover's exhaust emissions at loaded and ballast condition . Afortunately for the steam turbo gensets and for the small HFO Diesels there were no available data.

Also there were no available data for the exhaust emissions from the possible incineration of the excess BOG. However for the present study and for the selected operating profile there is only a small amount of excess BOG to be burnt on the oxidisers instead of used as fuel.

Note that the emission level always depends on the load (100%, 85%, 75% MCR or lower). These figures are typical emission levels for 85% load.

Also the emission level depends on the exact gas composition (less nitrogen content in ballast voyage[1]), in gas operating mode. So these figures should be seen as indicative only.

The results show that each of the alternatives produces mainly the following exhaust emissions : NOx, SOx and CO_2 (CO, HC and Particulates were not considered because there were not enough available data), whose quantity was categorized using the words high, substantial, low, negligible and zero.

Steam Turbine (Single Screw): BOG: substantial CO_2, low NOx, zero SOx.
HFO: high CO_2, low NOx, high SOx.

Dual-fuel-electric (Single Screw): BOG: substantial CO_2, low NOx, zero SOx.
MDO: high CO_2, substantial NOx, low SOx.

Two-stroke Diesel (Twin Screw): HFO: high CO_2, high NOx, high SOx.

Simple-cycle Gas Turbine-electric (Single Screw) & Combined-cycle Gas and Steam Turbine-electric (Single Screw): BOG: substantial CO_2, low NOx, zero SOx.
MGO: substantial CO_2, low NOx, negligible SOx.

The NOx emissions are higher for the 2-stroke Diesel plant. The SOx emissions are significantly high for both the steam plant and the 2-stroke Diesel plant. The CO_2 emissions are significantly high for all the alternative solutions.

The results are shown in Figures 3.11, 3.12 and 3.13.

---

[1] Loaded voyage: Average Nitrogen content in Natural BOG: 8%, BOG LHV(not only methane): 42,8 MJ/kg
Ballast voyage: Average Nitrogen content in Natural BOG: 0%, BOG LHV(not only methane): 49,2 MJ/kg

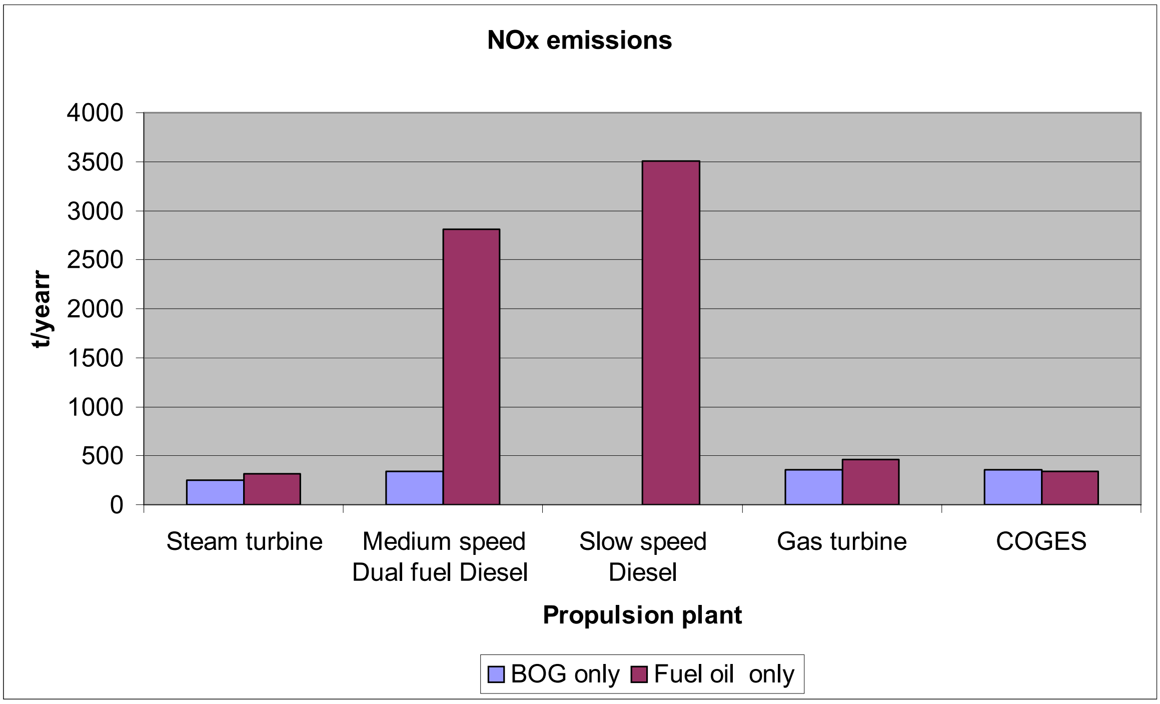


Fig. 3.11 NOx emissions from each alternative.

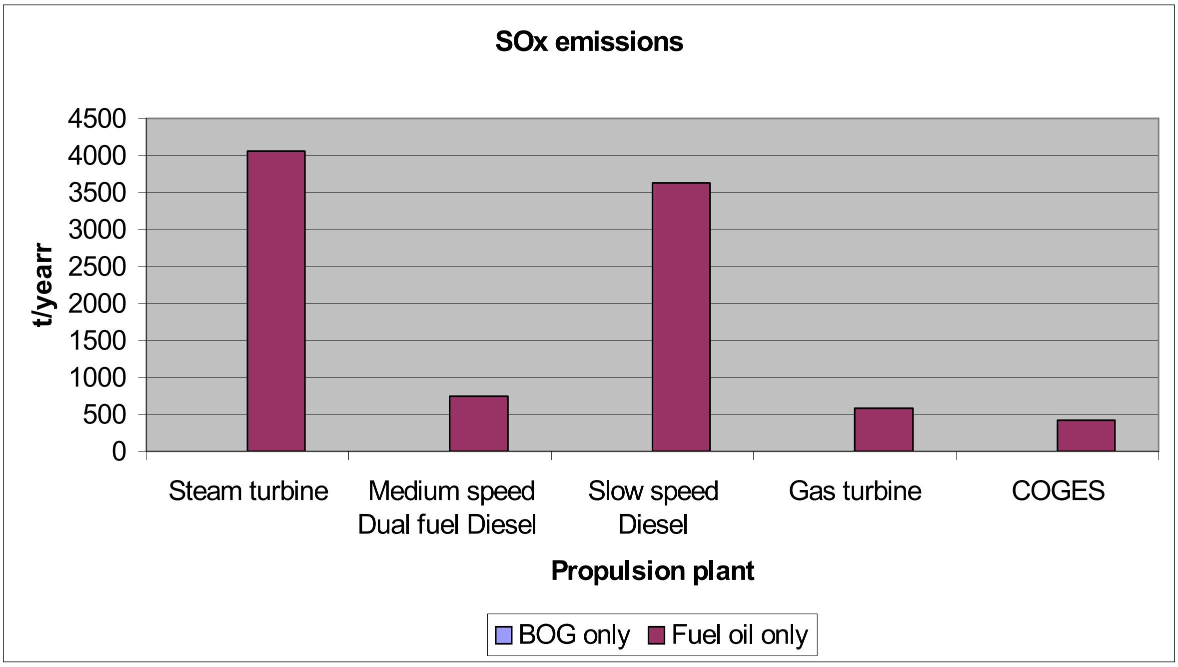


Fig. 3.12 SOx emissions from each alternative.

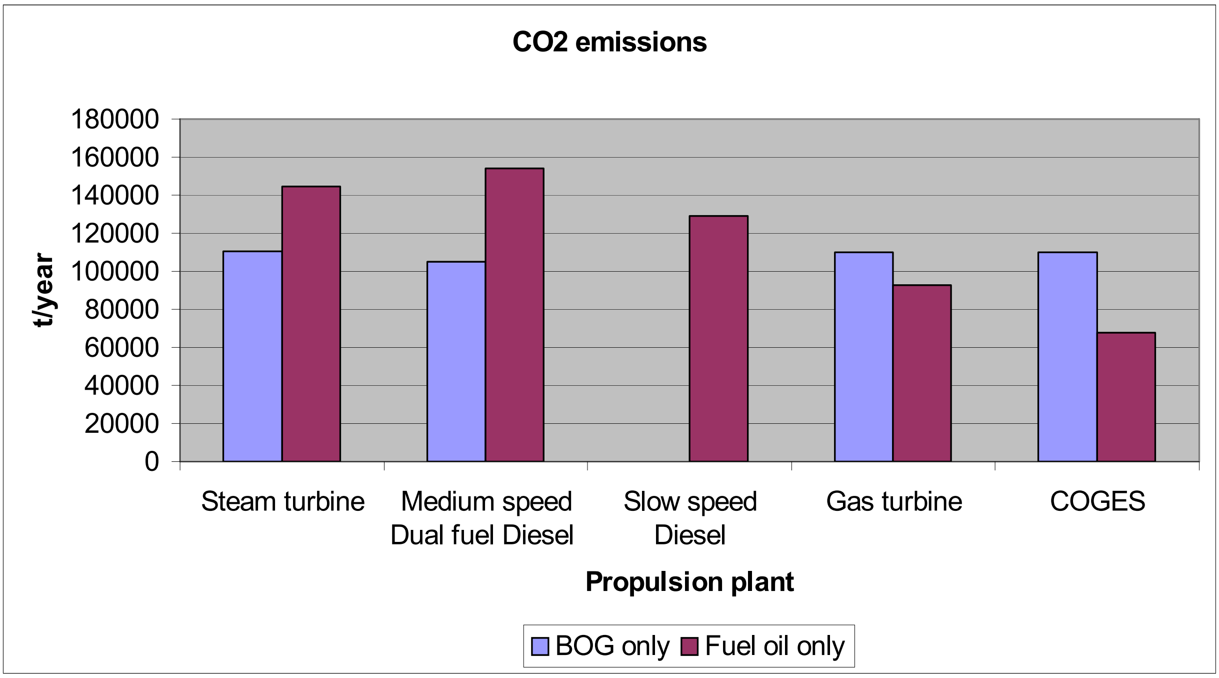


Fig. 3.13 CO_2 emissions from each alternative.

3.3.2 Latest Emission Control Regulations

The IMO Annex VI of MARPOL 73/78 Regulations for the Prevention of Air Pollution from Ships has been in effect since May 2005.

The NOx controls as given within the MARPOL Annex VI will apply to diesel engines (boilers and gas turbines are not covered) over 130 kW which are not used solely for emergency purposes and which are installed on ships built (ie, keel laid) on or after January 1, 2000, or subject to 'major conversions', as defined, on or after January 1, 2000.

The NOx emission limits are related to engine rated crankshaft speed as shown in Table 3.7 and in Figures 3.14 and 3.15:

Table 3.7 NOx emission limit.

Engine speed (n) rev/min	NOx emission Limit g/kWh
Less than 130	17.0
130 - 1999	$45 \times n^{-0.2}$
2000 and above	9.8 x n

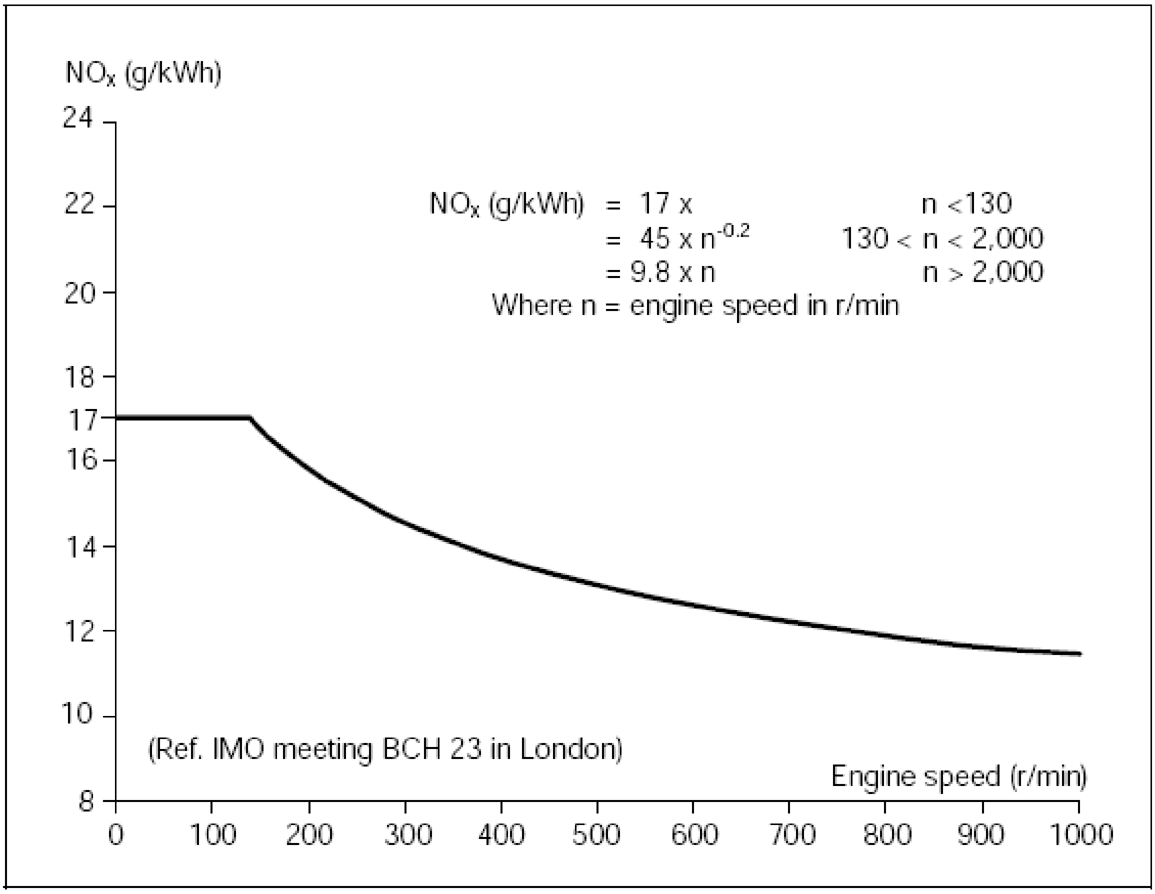
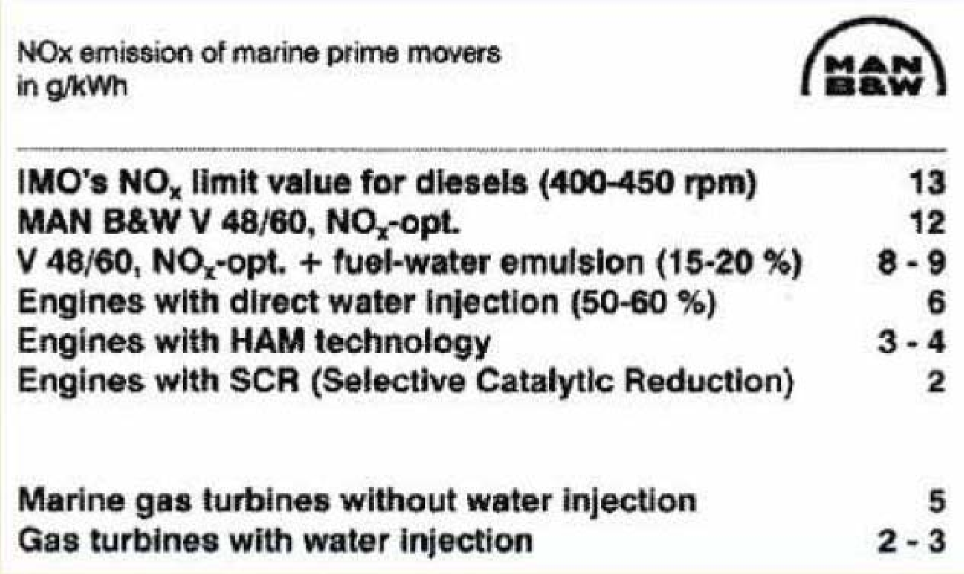


Fig. 3.14 Target emission levels of IMO [18].



NOx emission of marine prime movers
in g/kWh

IMO's NO_x limit value for diesels (400-450 rpm)	13
MAN B&W V 48/60, NO_x-opt.	12
V 48/60, NO_x-opt. + fuel-water emulsion (15-20 %)	8 - 9
Engines with direct water injection (50-60 %)	6
Engines with HAM technology	3 - 4
Engines with SCR (Selective Catalytic Reduction)	2
Marine gas turbines without water injection	5
Gas turbines with water injection	2 - 3

Fig. 3.15 NOx emission of marine prime movers [45].

The SOx limit applies to all vessels in the category of ships with an engine power output of more than 130 kW.

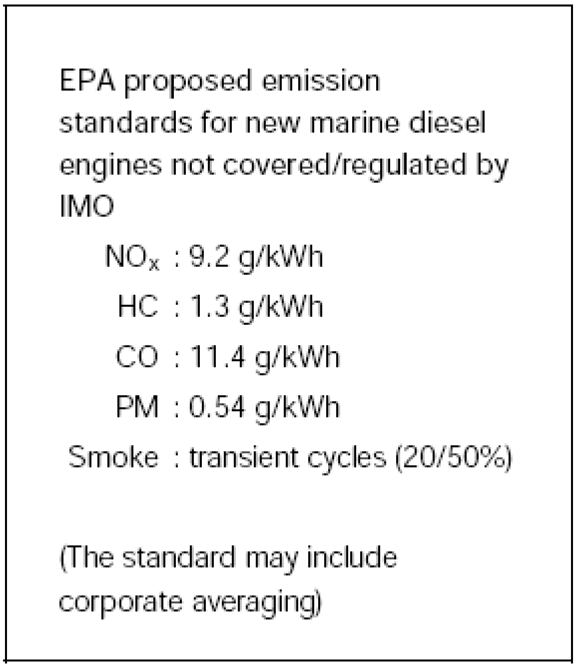
The general international limit on sulphur will be reduced from 5% to 4.5% through ISO 8217 fuel standard.

However, in restricted areas like the Baltic Sea, the English Channel and the North Sea, the limit is 1.5% sulphur, which has been enforced since 19 May 2006.

IMO has indicated that, in future, further limitations will be imposed on SOx as well as on other components in the exhaust gas (NOx, particulate, HC and CO).

The EU has introduced separate regulations to cut sulphur dioxide emissions from ships. The Environment Council has agreed to reduce ships' yearly SO_2 emmisions in the EU by over 500,000 tonnes from 2007, to the benefit of human health and the environment. As part of its 2002 ship emissions strategy, the Comisssion presented a proposal for a directive to reduce the sulphur content in marine fuels used in the EU. The main provisions were:

- A 1.5% sulphur limit on fuels used by all ships in Baltic Sea, the North Sea and the Channel. Implementation date: 19 May 2006.
- A 0.2% sulphur limit on fuels used by inland vessels and seagoing ships at berth in EU ports. The Council has agreed to delay a tighter 0.1% limit until 1 January 2010, to allow single-fuel ships time to adapt their fuel tanks [44].



EPA proposed emission standards for new marine diesel engines not covered/regulated by IMO

NO_x : 9.2 g/kWh
HC : 1.3 g/kWh
CO : 11.4 g/kWh
PM : 0.54 g/kWh
Smoke : transient cycles (20/50%)

(The standard may include corporate averaging)

Fig. 3.16 New emission-limit proposal by EPA [18].

Summary of pollutants and their control[2]

- NOx (Nitrogen Oxides): Function of peak combustion temperatures and oxygen concentration
  Reduction: Primary or secondary methods (see emission reduction methods at Appendix C)
- SOx (Sulphur Oxides): Function of fuel oil sulphur content
  Reduction: The most effective means is to lower the sulphur content in the fuel
- CO (Carbon monoxide): Function of the air excess ratio and combustion temperature and air/fuel mixture.
  Basically very low for two-stroke engines
- HC (Hydrocarbons): During the combustion process a very small part of fuel and lube oil is left unburned.
  Depends on fuel and lube oil types
- Particulate emissions: Originate from:
  · partly burned fuel
  · ash content in fuel/cylinder lube oil
  · partly burned lube oil/dosage
  · deposits peeling off in the combustion chamber/exhaust gas system [18].

3.3.3 Comments

The price of fuel oil depends on the sulphur content, and this fact should be considered when evaluating the use of low-sulphur fuel versus high-sulphur fuel and clean-up systems.

Besides it is not known if it is feasible for the refineries to lower the sulphur level at a reasonable cost and effort or if marine diesel and gas oils will be used, instead of low-

---

[2] see also emission reduction methods at Appendix C.

sulphur HFO, to a wider extent. But it is certain that the low-sulphur HFO will have a higher price than the HFO on the market today, due to increasing demand and the cost of desulphurisation process.

The alternative to reducing the amount of SOx in the exhaust gas is to clean the exhaust gas. So far, only a few plants are operating with such a solution, and it is still considered primarily a test for larger engines. On the other hand the technique for removing SOx from engine exhaust gas on ships requires a large investment.

The most relevant proven methods for NOx reduction are: fuel valve and nozzle optimisation, timing tuning (primary methods) and fuel water emulsification, Exhaust Gas Recirculation (EGR), and Selective Catalytic Reduction (SCR) (secondary methods) but in any case an additional investment is required.

At the same time, some companies are talking about emission trading which, in principle, means that the possibility of polluting more than the specified limits can be bought from ships that are polluting less than they are allowed to.

Whether or not emission trading can be applied in marine sector, in the near future ocean-going ships entering coastal waters will have to switch from a heavy fuel oil (HFO) to a lower viscosity distillate fuel, in order to comply with the low-sulphur requirement if a low-sulphur HFO is not available.

Steam turbine systems will have to switch from HFO to a fuel with low sulphur content (low sulphur HFO or MDO) for the SOx reduction when the vessel approaches coastal areas.

The emissions from the 2-stroke diesel engines when the ship enters coastal waters can be reduced by using fuel with low sulphur content (low sulphur HFO or MDO or by blending HFO (3-4.5% sulphur) with MGO (0.2% sulphur)) for the SOx reduction and by Selective Catalytic Reduction (SCR) in the case of NOx.

However when switching from HFO to a distillate fuel, operators have to take the necessary precautions to avoid incompatibility between the two products and between the fuel and the cylinder lube oil and feed rate. The change-over must be carried out according to a specific procedure and also a low-BN cylinder oil must be used.

Dual-fuel medium speed Diesel engines will not have a problem in complying with the IMO limits for NOx emissions (without the need of SCR) and SOx emissions as well, as long as MDO is used as add-on fuel when BOG is not available.

On the other hand the fuel presently used in gas turbines would more easily meet both the general and SOx Emission Control Areas guidelines set forth in MARPOL Annex VI.

Considering the above gas turbine units could be more beneficial to ship owners due to the recent strides toward limitation of emissions.

We also must mention the environmental and social advantage that an environmentally-friendly propulsion system offers to the company’s social image. The whole LNG industry is based on the transportation of gas for the purpose of a cleaner electric power generation process. That is the more advertised selling point often used from the gas companies for the phase out of more polluting fuels such as oil and coal, in land-based power stations, industries, vehicles and homes. So it would be peculiar if this clean fuel was transported in vessels which burnt heavy fuel oil. After all, any future introduction of carbon taxes would add to the economic advantage of these environmentally-friendly vessels.

4.

CONCLUSIONS

The steam turbine plant is the most reliable and tested solution for the propulsion of liquefied natural gas carries, in spite of its inefficiency, and hence high fuel consumption. Offers a very easy method to utilize the BOG and has the ability to burn low-grade fuel as well as cargo boil-off.

Diesel egines both medium speed dual-fuel and two-stroke with reliquefaction have broken the steam turbine domination in the LNG carrier sector and are also likely candidates for future LNG carrier orders.

In the case of 2-stroke Diesel engine the advantages are the high efficiency and the lower operating cost. The medium speed dual-fuel engine provides fuel flexibility and more flexible machinery arrangement which enables the vessel to carry more cargo compared to the steam and 2-stroke Diesel alternatives. Furthermore for the Diesel propulsion systems there is higher availability of experienced crew comparing to steam turbine propulsion systems.

On the other hand gas turbine propulsion systems for LNG carriers have an advantage over steam turbine and Diesel based systems in terms of increased cargo volume because of their lightweight and flexible machinery arrangement, which leads to increased revenues as shown in the economic evaluation.

Also their low emissions comply with the IMO's MARPOL Annex VI and EU's regulations for emission control in coastal areas without further modifications and additional equipment for emission reduction.

The gas turbine combined cycle plant offers a substancial increase in profits, if the added complication in the machinery arrangement is acceptable.

The results of the techno-economic study for the specific ship size and the selected operating profile, show that considerable economic advantages could be offered if the traditional steam plant will be replaced by Diesel or gas turbine power plants.

The increased cargo carrying capacity in conjunction with the better thermal efficiency compared to the steam turbine, compensates the higher investment cost required for these alternative installations.

Regarding the operating cost, all the alternatives, except the gas turbine, offer significant improvenments in terms of fuel economy although the maintenance cost is higher than the steam turbine plant. The two-stroke Diesel has the lowest operating cost and the gas turbine combined cycle plant follows with a small difference. The medium speed dual fuel Diesel has also lower operating cost than the steam turbine. The gas turbine has the highest operating cost mainly because it requires a high quality petroleum fuel (in the present study MGO was used as back up fuel for gas turbines) with a relative high price.

The economic evaluation results, based on the Net Present Value of each investment, show that in the most of the examined cases all the alternative propulsion systems are more profitable than the steam turbine vessel. The years of operation (the study prformed for 10, 20 and 30 years) and the different interest rates (6%, 8%, 10%) did not change the actual result concerning which alternative is more profitable, but only the NPV result.

With the examined scenarios (owner, charterer, natural gas company and additional income) in paragraph 3.2.3 and the different cases based on the two sensitivity analyses (for the fuel cost and the initial cost) performed in subsection 3.2.4, is possible to see which alternative is more profitable for each case and from different points of view.

The two sensitivity analyses performed for 20 years of operation and for the case of the natural gas company[1], showed that the most beneficial vessel (namely the one with the higher NPV) is the one equipped with the combined gas and steam turbine. Then follows the slow speed Diesel installation. There is a difference between the first and the second analyses concerning the gas turbine installation. In the first analysis (different fuel cost input) the gas turbine is the less beneficial because of its higher operating cost. In the second (different initial cost input) is, with a very small difference, the third more beneficial alternative solution, after the combined gas turbine and the slow speed Diesel installations. In each case the medium speed dual fuel Diesel is more profitable than the steam turbine.

It must be repeated that the economic results are based on the assumptions that were made in this study about the charter rate, the relation between the oil prices and the LNG prices (for the purposes of the sensitivity analysis) and also for the initial cost. In addition in this study was included only a part of the ship's cost and only those concerning the main components of the machinery (the initial cost of some machinery items for which there were no available data, the hull construction cost, port fees, insurance cost, managerial cost, etc., were not included as mentioned analytically in the paragraph 3.2.2.1 and 3.2.2.5).

Meanwhile, the total fuel cost of each alternative depends on the relative unit costs of LNG and fuel oil. Since the unit price ratio may fluctuate due to the mode of LNG transaction (CIF, FOB, etc.) and wider fuel oil market conditions, it is possible to have differences in the results.

In conclusion, it is obvious that there is not an optimum solution for the propulsion of liquefied natural gas carries. Each alternative has its advantages and disadvantages that must be evaluated before the selection of the propulsion plant for a specific project.

So, the decision for the propulsion plant to be installed, must be examined separately for each case, based on the specific size of the vessel, the operating profile (speed, trade distance, use of boil off gas and forced boil off gas or boil off gas and fuel oil as add-on, or fuel oil only and boil off gas reliquifaction, etc.), the fuel oil and LNG prices, the initial cost for each propulsion system, the maintenance cost, the spare parts availability and the crew availability and so on.

The most of these technical and economic parameters that affect the selection of a propulsion plant different to the traditional steam turbine, were included in the present study.

---

[1] This case is the more representative of the examined cases in the paragraph 3.2.2.6 because all costs were calculated together (in other words all the costs are covered from the owner/operator, who is at the same time the charterer) and thereby a complete comparison of the propulsion alternatives can be performed.

FURTHER WORK

If there are enough available data it would be interesting to perform a more detailed study on the propulsion systems mentioned in this diploma thesis, considering the following:

- The exact extra cargo capacity that a ship with a propulsion system different from the basis steam turbine could carry. The study must be based on the cargo tank number, the containment system, the engine room length, the hull shape, and the principal dimensions. Analytical calculations must be performed for the free surface effect and resulting sloshing loads in partially filled cargo tanks in the case of very large LNGC (above 250,000 m^3). A study on the structural strength and vibration of the selected design must be performed also.
- The hydrodynamic characteristics and hull form design (especially by optimising the aftbody-twin/single skeg) for each of the propulsion alternatives and how that improves the manoeuvring characteristics of the vessel compared to the basis steam vessel. Podded propulsors must also be included in this study. Furthermore, the time and cost savings for each alternative must be also concerned.
- A comparative study with different voyage profile scenarios (different trade distances, service speeds, times for loading, unloading and reserve) for each alternative, can lead to interesting conclusions for the more profitable concept.
- In addition, a similar study must be done with different ship sizes (and for larger vessels 200-270k class LNGCs). The impact to the ship's economy for each propulsion alternative concept should be evaluated and the case of not fully loaded voyages (for larger vessels in the spot maket) should be considered.
- The impact, of the new MARPOL Annex VI regulations on the operation on low sulphur fuels and the operational cost of the different alternatives.
- The efficiency of each propulsion alternative at part load must be examined, because the future operating modes will require flexibility and efficient propulsion plants able to accommodate different ship speeds at different market requirements.
- A study on several propulsion scenarios, not so developed until today, such as fuel cells systems, LH_2 gas turbine,etc., as possible candidates for the hotel load coverage or for future electric propulsion purposes.

APPENDIX A

Table A.1

Prime Mover	Configuration	Fuel used for Prime Mover	Fuel treatment before use	BOG Handling Back up BOG Handling	Transmission	Electric Power	Emergency Power	Additional equipment	Propulsion unit
STEAM TURBINE	-TWO BOILERS (OR 1 MAIN +1 SMALLER AUXILIARY) -HP & LP STEAM TURBINE (KAWASAKI UA type - non-reheat two-cylinder cross-compound impulse/reaction-UA440 and UA500 / MITSUBISHI MS-2 non-reheat and MR-2 reheat, series two-cylinder cross-compound impulse-reaction / OTHER)	HFO AND/OR GAS almost in any combination	HFO PREHEATING BOG COMPRESSING (2 bar approximately)	-BURNING ON BOILERS -STEAM DUMPING OR ALTERNATIVELY 1 RELIQUEFACTION PLANT	MECHANICAL DRIVE THROUGH REDUCTION GEAR	2 STEAM TURBINE-GENERATORS +1 OR 2 4-x DIESEL HFO or MDO GEN (STAND BY)	1 (at least) EMERGENCY 4-x DIESEL MDO or MGO GENERATOR	-EXHAUST GAS ECONOMIZER	1 FPP 1 or 2 bow thrusters maybe installed
GAS TURBINE	**SIMPLE CYCLE (with or without POWER TURBINE)**: • 1 OR 2 MAIN GAS TURBINES (Rolls Royce MT30/ GE LM2500 OR LM 2500+) + 1 AUXILIARY (Rolls Royce 501) • 1 GAS TURBINE + 1 ELECTRIC MOTOR FITTED TO THE GEARBOX	GAS OR MGO (pilot fuel maybe needed in gas mode)	BOG COMPRESSING (20-25 bar approximately)	-BURNING ON THE PROPULSION & AUXILIARY TURBINE -1 GAS OXIDIZER	• ELECTRIC DRIVE THROUGH SLOW SPEED PROPULSION MOTORS OR MEDIUM SPEED PROPULSION MOTORS (USUALLY 2) AND REDUCTION GEAR OR ELECTRIC WITH AZIPOD • DIRECT MECHANICAL DRIVE THROUGH REDUCTION GEAR OR ELECTRIC DRIVE THROUGH SLOW SPEED PROPULSION MOTORS OR MEDIUM SPEED PR. MOTORS (USUALLY 2) AND REDUCTION GEAR OR ELECTRIC WITH AZIPODUSUALLY 2) AND REDUCTION GEAR	-ELECTRIC POWER AVAILABLE FROM MAIN OR AUXILIARY GAS TURBINE GEN SETS +1 OR 2 4-x DIESEL MDO GEN (STAND BY) for the case of electric propulsion -3 or 4 4-x DIESEL MDO GEN for the case of a mechanical drive	1 (at least) EMERGENCY 4-x DIESEL MDO or MGO GENERATOR	Maybe there is: EXHAUST GAS BOILER for heat & other purposes (not usually)	1 FPP OR 1 CPP (if there is not reversing mechanism in the reduction gear) OR 1 AZIPOD OR CRP AZIPOD 1 or 2 bow thrusters maybe installed

Continuation of Table A.1

Prime Mover	Configuration	Fuel used for Prime Mover	Fuel treatment before use	BOG Handling Back up BOG Handling	Transmission	Electric Power	Emergency Power	Additional equipment	Propulsion unit
GAS TURBINE	GAS TURBINE COMBINED CYCLES (with or without POWER TURBINE): - 1 GAS TURBINE, **INTER-COOLED CYCLE** +1 ELECTRIC MOTOR FITTED TO THE GEARBOX - 1 GAS TURBINE, **REHEAT CYCLE**+1 ELECTRIC MOTOR FITTED TO THE GEARBOX - 1 GAS TURBINE, **INTER-COOLED REHEAT CYCLE**+1 ELECTRIC MOTOR FITTED TO THE GEARBOX Regenerative cycles: - 1 GAS TURBINE, **RECUPERATED CYCLE**+1 ELECTRIC MOTOR TO THE GEARBOX - 1 GAS TURBINE, **INTER-COOLED RECUPERATED CYCLE**+1 ELECTRIC MOTOR FITTED TO THE GEARBOX - 1 GAS TURBINE, **REHEAT RECUPERATED CYCLE**+1 ELECTRIC MOTOR FITTED TO THE GEARBOX regenerative cycle) - 1 GAS TURBINE, , **INTER-COOLED REHEAT RECUPERATED CYCLE**+1 ELECTRIC MOTOR FITTED TO THE GEARBOX	GAS OR MGO (pilot fuel maybe needed in gas mode)	BOG COMPRESSING (20-25 bar approximately)	-BURNING ON THE PROPULSION & AUXILIARY TURBINE -1 GAS OXIDIZER	DIRECT MECHANICAL DRIVE THROUGH REDUCTION GEAR OR ELECTRIC DRIVE THROUGH SLOW SPEED PROPULSION MOTORS OR MEDIUM SPEED PR. MOTORS (USUALLY 2) AND REDUCTION GEAR OR ELECTRIC WITH AZIPOD	-ELECTRIC POWER AVAILABLE FROM main GAS TURBINE GEN SET + 1 or 2 4-x DIESEL MDO GEN(STAND BY) OR +1 GAS TURBINE-GENERATOR and 1 4-x DIESEL MDO GEN(STAND BY) for the case of electric propulsion system -3 or 4 4-x DIESEL MDO GEN OR 1 GAS TURBINE-GENERATOR and 2 or 3 4-x DIESEL MDO GEN(1 of them STAND BY) for the case of a mechanical drive	1 (at least) EMERGENCY 4-x DIESEL MDO or MGO GENERATOR	INTER-COOLER AND/OR RECUPERATOR (HEAT EXCHANGER) AND/OR REHEATER Maybe there is: EXHAUST GAS BOILER for heat &other purposes (not usually)	1 FPP OR 1 CPP (if there is not reversing mechanism in the reduction gear) OR 1 AZIPOD OR CRP AZIPOD 1 or 2 bow thrusters maybe installed

Continuation of Table A.1

Prime Mover	Configuration	Fuel used for Prime Mover	Fuel treatment before use	BOG Handling Back up BOG Handling	Transmission	Electric Power	Emergency Power	Additional equipment	Propulsion unit
COMBINED GAS AND STEAM TURBINE	☐ 1 MAIN TURBINE(Rolls Royce MT30) + 1 AUXILIARY (Rolls Royce 501) + STEAM TURBINE (Exhaust gas boiler or auxiliary boiler) ☐ 1 OR 2 GAS TURBINES (Rolls Royce MT30/GE LM2500 OR LM 2500+) +1 ELECTRIC MOTOR FITTED TO THE GEARBOX + STEAM TURBINE (Exhaust gas boiler or aux.boiler)	GAS OR MGO(pilot fuel maybe needed in gas mode) If there is auxiliary boiler HFO AND/OR GAS	BOG COMPRESSING (20-25 bar approximately)	-BURNING ON THE PROPULSION & AUXILIARY TURBINE -1 GAS OXIDIZER	☐ **COGES** ELECTRIC DRIVE THROUGH SLOW SPEED PROPULSION MOTORS OR MEDIUM SPEED PR. MOTORS (USUALLY 2) AND REDUCTION OR ELECTRIC WITH AZIPOD ☐ DIRECT MECHANICAL DRIVE THROUGH REDUCTION GEAR OR **COGES** ELECTRIC DRIVE THROUGH SLOW SPEED PROPULSION MOTORS OR MEDIUM SPEED PR. MOTORS (USUALLY 2) AND REDUCTION GEAR Or ELECTRIC WITH AZIPOD	-ELECTRIC POWER AVAILABLE FROM GAS & STEAM TURBINE'S GEN SETS + 1 OR 2 4-x DIESEL MDO GEN(STAND BY) for the case of an electric propulsion system - ELECTRIC POWER AVAILABLE FROM STEAM TURBINE GEN SET+3 or 4 4-x DIESEL MDO GEN for the case of a mechanical drive	1 (at least) EMERGENCY 4-x DIESEL MDO or MGO GENERATOR	HEAT RECOVERY STEAM GEN (EXHAUST/WASTE HEAT BOILER) If an Auxilliary dual fired boiler, is installed then offers more redundancy for port and take-you home(sail) operation	1 or 2 FPP OR 1 or 2 CPP (if there is not reversing mechanism in the reduction gear) OR 1 or 2 AZIPOD OR CRP AZIPOD 1 or 2 bow thrusters maybe installed
SLOW SPEED DIESEL	1 SLOW SPEED ENGINE (MAN B&W MC OR ME-series/ SULZER RT-series) a combined power take off, power take in (PTO / PTI) installation with e-motor ,powered by the gensets,on the shaft line offers more redudancy	HFO	HFO centrifugal separation (purification-clarification), possible blending, homogenization ,PREHEATING	2 100% RELIQUEFACTION PLANTS(Hamworthy KSE-Moss RS) or 1 RELIQUEFACTION PLANT+ 1 Thermal oxidizer or 1 flare system capable of burning the maximum boil-off rate	-DIRECT DRIVE -A combined power take off, power take in (PTO / PTI) installation with e-motor, powered by the gensets,on the shaft line offers more redudancy especially **for the 1 engine** configuration and is an available option.	USUALLY 4 4-x DIESEL HFO or MDO GENSETS OR 3 4-x DIESEL HFO or MDO GENSETS + 1 shaft generator OR/AND If there is Exhaust gas boiler 1 or 2 STEAM TURBINE-GEN +/-1 or 2 4-x DIESEL HFO or MDO GENSETS(STAND BY)Or/And 1 /2 POWER recovery Gas TURBINE GEN SET(if there is) +/- 3 4-x DIESEL HFO or MDO GENSETS DEPENDING ON THE CHOSEN CONFIGURATION	1 (at least) EMERGENCY 4-x DIESEL MDO or MGO GENERATOR	If needed NOx emissions can be reduced by Selective Catalytic Reduction(SCR units)or direct water Injection(water emulsion) or by EGR & HAM systems Maybe there is: -EXHAUST GAS BOILER for heat &other purposes or driving ST-Gen/s -POWER recovery Gas TURBINE driving 1 or 2 turbogenerator	1 FPP (usually) or 1 CPP 1 or 2 bow thrusters maybe installed

Continuation of Table A.1

Prime Mover	Configuration	Fuel used for Prime Mover	Fuel treatment before use	BOG Handling Back up BOG Handling	Transmission	Electric Power	Emergency Power	Additional equipment	Propulsion unit
SLOW SPEED DIESEL	2 SLOW SPEED ENGINES (MAN B&W MC OR ME-series/ SULZER RT-series)	HFO	HFO centrifugal separation (purification-clarification), possible blending, homogenization ,PREHEATING	2 100% RELIQUEFACTION PLANTS(Hamworthy KSE-Moss RS) or 1 RELIQUEFACTION PLANT+ 1 Thermal oxidizer or 1 flare system capable of burning the maximum boil-off rate	-DIRECT DRIVE -A combined power take off, power take in (PTO / PTI) installation with e-motor, powered by the gensets,on the shaft line offers more redudancy especially **for the 1 engine** configuration and is an available option.	USUALLY 4 4-x DIESEL HFO or MDO GENSETS OR 3 4-x DIESEL HFO or MDO GENSETS + 1 shaft generator OR/AND If there is Exhaust gas boiler 1 or 2 STEAM TURBINE- GEN +/-1 or 2 4-x DIESEL HFO or MDO GENSETS(STAND BY) Or/And 1 /2 POWER recovery Gas TURBINE GEN SET(if there is) +/- 3 4-x DIESEL HFO or MDO GENSETS DEPENDING ON THE CHOSEN CONFIGURATION	1 (at least) EMERGENCY 4-x DIESEL MDO or MGO GENERATOR	If needed NOx emissions can be reduced by Selective Catalytic Reduction(SCR units)or direct water Injection(water emulsion) or by EGR & HAM systems Maybe there is: -EXHAUST GAS BOILER for heat &other purposes or driving ST-Gen/s -POWER recovery Gas TURBINE driving 1 or 2 turbogenerator	2 FPP(usually) or 2 CPP 1 or 2 bow thrusters maybe installed
MEDIUM SPEED DIESEL	2 ENGINES(Wärtsilä/ MAN B&W/Caterpillar/other ordinary models)	MDO OR HFO	HFO centrifugal separation (purification-clarification), possible blending ,homogenization ,PREHEATING	1 Thermal oxidizer or 1 100% RELIQUEFACTION PLANTS(Hamworthy KSE-Moss RS) +1 Thermal oxidizer or 1 flare system capable of burning the maximum boil-off rate	• MECHANICAL DRIVE THROUGH twin-in/single-out GEARBOX • MECHANICAL DRIVE THROUGH single-in/single-out GEARBOXES	USUALLY 4 4-x DIESEL MDO or HFO GENSETS OR 2 or 3 4-x DIESEL HFO or MDO GENSETS + 2 shaft generators	1 (at least) EMERGENCY 4-x DIESEL MDO or MGO GENERATOR	If needed at HFO mode, NOx emissions can be reduced by Selective Catalytic Reduction(SCR units)or direct water injection (water emulsion) or by EGR and (HAM) systems Maybe there is: -EXHAUST GAS BOILER for heat &other purposes or driving ST-Gen/s -POWER recovery Gas TURBINE driving 1 or 2 turbogenerator	• 1 FPP • 1 CPP • 2 CPP 1 or 2 bow thrusters maybe installed

Continuation of Table A.1

Prime Mover	Configuration	Fuel used for Prime Mover	Fuel treatment before use	BOG Handling Back up BOG Handling	Transmission	Electric Power	Emergency Power	Additional equipment	Propulsion unit
MEDIUM SPEED DIESEL	4 ENGINES(Wärtsilä/ MAN B&W/Caterpillar/other ordinary models) probably not all with the same rating	MDO OR HFO	HFO centrifugal separation (purification-clarification), possible blending ,homogenization ,PREHEATING	2 100% RELIQUEFACTION PLANTS(Hamworthy KSE-Moss RS) or 1 RELIQUEFACTION PLANT+1 Thermal oxidizer or 1 flare system capable of burning the maximum boil-off rate	- MECHANICAL DRIVE THROUGH twin-in/single-out GEARBOXES - ELECTRIC DRIVE WITH 2 MOTORS THROUGH REDUCTION GEAR OR ELECTRIC WITH AZIPOD	- 2 or 3 4-x DIESEL MDO or HFO GENSETS + 2 shaft gen sets ELECTRIC POWER AVAILABLE FROM MAIN GENERATOR ENGINES in an electric propulsion system	1 (at least) EMERGENCY 4-x DIESEL MDO or MGO GENERATOR	If needed at HFO mode, NOx emissions can be reduced by Selective Catalytic Reduction(SCR units)or direct water injection (water emulsion) or by EGR and (HAM) systems Maybe there is: -EXHAUST GAS BOILER for heat &other purposes or driving ST-Gen/s -POWER recovery Gas TURBINE driving 1 or 2 turbogenerator	- 2 CPP - 1 or 2 FPP OR 1 or 2 AZIPOD OR CRP AZIPOD 1 or 2 bow thrusters maybe installed
SLOW SPEED GAS-DIESEL ENGINE	• 1 SLOW SPEED GAS-DIESEL(GAS/HFO) ENGINE (MAN B&W MC OR ME-GIseries/MITSUBISHI(licensee of MAN B&W and SULZER models + its own UEC designs)	GAS OR HFO(pilot fuel is needed in gas mode)	BOG COMPRESSING (250-300 bar approximately) HFO centrifugal separation (purification-clarification), possible blending homogenization ,PREHEATING	- BURNING ON DF ENGINES - 1 GAS OXIDIZER (PREFERRED OPTION) OR ALTERNATIVELY 1 RELIQUEFACTION PLANT(Hamworthy KSE-Moss RS)	DIRECT DRIVE	USUALLY 4 4-x DIESEL HFO GENSETS OR 3 4-x DIESEL HFO or MDO GENSETS + 2 shaft generators OR/AND If there is Exhaust gas boiler: 1 or 2 STEAM TURBINE- GEN +/- 1 or 2 4-x DIESEL HFO or MDO GENSETS(STAND BY) Or/And 1 or 2 POWE recovery Gas TURBINE GEN SET(if there is) +/- 3 4-x DIESEL HFO or MDO GENSETS DEPENDING ON THE CHOSEN CONFIGURATION	1 (at least) EMERGENCY 4-x DIESEL MDO or MGO GENERATOR	If needed at HFO mode, NOx emissions can be reduced by Selective Catalytic Reduction(SCR units)or direct water injection(water emulsion) or by Exhaust Gas Recirculation (EGR) and Humid Air Motor (HAM) systems Maybe there is: -EXHAUST GAS BOILER for heat &other purposes or driving ST-Gen/s POWER recovery Gas TURBINE driving 1 or 2 turbogenerator	1 FPP or 1 CPP 1 or 2 bow thrusters maybe installed
	• 2 SLOW SPEED GAS-DIESEL (GAS/HFO) ENGINES (MANB&W MC OR ME GI series / MITSUBISHI(licensee of MAN B&W and SULZER models + its own UEC designs)								2 FPP or 2 CPP 1 or 2 bow thrusters maybe installed

Continuation of Table A.1

Prime Mover	Configuration	Fuel used for Prime Mover	Fuel treatment before use	BOG Handling Back up BOG Handling	Transmission	Electric Power	Emergency Power	Additional equipment	Propulsion unit
MEDIUM SPEED DUAL FUEL DIESEL	• 4 GAS- HFO DIESEL ENGINES (Wärtsilä (SULZER) GD –series) • 4 DUALFUEL(GAS/MDO) ENGINES (Wärtsilä 50 DF series) UPGRADED TO BURN HFO (available on 50DF engines that will enter production after 1/08/05)	GAS OR HFO (pilot fuel is needed in gas mode) OR MDO	BOG COMPRESSING(300-350 bar approximately) BOG COMPRESSING (5 bar approximately)	- BURNING ON DF ENGINES - 1 GAS OXIDIZER (PREFERRED OPTION) OR ALTERNATIVELY 1 RELIQUEFACTION PLANT(Hamworthy KSE-Moss RS	- MECHANICAL DRIVE THROUGH twin-in/single-out GEARBOXES - ELECTRIC DRIVE WITH 2 SLOW SPEED PROPULSION MOTORS OR WITH 2 MEDIUM OR HIGH SPEED PR. MOTORS THROUGH REDUCTION GEAR OR ELECTRIC WITH AZIPOD	ELECTRIC POWER AVAILABLE FROM MAIN GENERATOR ENGINES OR/AND If there is Exhaust gas boiler: 1 or 2 STEAM TURBINE- GEN +/- 1 or 2 4-x DIESEL HFO or MDO GENSETS(STAND BY)	1 (at least) EMERGENCY 4-x DIESEL MDO or MGO GENERATOR	If needed at HFO mode, NOx emissions can be reduced by Selective Catalytic Reduction(SCR units)or direct water injection(water emulsion) or by EGR & HAM systems Maybe there is: EXHAUST GAS BOILER for heat &other purposes or driving ST-Gen/s	1 or 2 FPP OR 1 or 2 CPP(if there is not reversing mechanism in the reduction gear) OR 1 or 2 AZIPOD OR CRP AZIPOD 1 or 2 bow thrusters maybe installed
	- 4 DUAL FUEL(GAS/MDO) ENGINES (Wärtsilä 50DF series)	GAS OR MDO (pilot fuel is needed in gas mode)	BOG COMPRESSING (5 bar approximately)		- ELECTRIC DRIVE WITH 2 SLOW SPEED PROPULSION MOTORS OR WITH 2 MEDIUM OR HIGH SPEED PR. MOTORS THROUGH REDUCTION GEAR OR ELECTRIC WITH AZIPOD	ELECTRIC POWER AVAILABLE FROM MAIN GENERATOR ENGINES			1 or 2 FPP OR 1 or 2 CPP (if there is not reversing mechanism in the reduction gear) OR 1 or 2 AZIPOD OR CRP AZIPOD 1 or 2 bow thrusters maybe installed

Continuation of Table A.1

Prime Mover	Configuration	Fuel used for Prime Mover	Fuel treatment before use	BOG Handling Back up BOG Handling	Transmission	Electric Power	Emergency Power	Additional equipment	Propulsion unit
COMBINE DHFO MEDIUM SPEED DIESEL AND MEDIUM SPEED DUAL FUEL(GAS /MDO) DIESEL	COMBINATION OF HFO MEDIUM SPEED DIESEL AND DUAL FUEL(GAS/MDO) ENGINE: 1 OR 2 HFO MEDIUM SPEED ENGINES (Wärtsilä/ MAN B&W ordinary models) + 1 OR 2 MEDIUM SPEED DUAL –FUEL(GAS/MDO) DIESEL ENGINES (Wärtsilä 50DF series)	HFO GAS OR MDO (pilot fuel is needed in gas mode)	HFO centrifugal separation (purification-clarification),possible blending, homogenization ,PREHEATING BOG COMPRESSING (5 bar approximately)	- BURNING ON DF ENGINES - 1 GAS OXIDIZER (PREFERRED OPTION) OR ALTERNATIVELY 1 RELIQUEFACTION PLANT(Hamworthy KSE-Moss RS	- MECHANICAL DRIVE THROUGH single or twin-in/single-out GEARBOXES - ELECTRIC DRIVE WITH 2 SLOW SPEED PROPULSION MOTORS OR WITH 2 MEDIUM OR HIGH SPEED PR. MOTORS THROUGH REDUCTION GEAR OR ELECTRIC WITH AZIPOD	- 2 to 4 4-x DIESEL MDO or HFO GENSETS + 1 or 2 shaft gen sets DEPENDING ON THE CHOSEN CONFIGURATION - ELECTRIC POWER AVAILABLE FROM MAIN GENERATOR ENGINES+1 4-x DIESEL HFO OR MDO GEN(STAND BY) OR/AND If there is Exhaust gas boiler: 1 or 2 STEAM TURBINE- GEN +/- 1 or 2 4-x DIESEL HFO or MDO GENSETS(STAND BY)	1 (at least) EMERGENCY 4-x DIESEL MDO or MGO GENERATOR	If needed at HFO mode, NOx emissions can be reduced by Selective Catalytic Reduction(SCR units)or direct water injection(water emulsion) or by Exhaust Gas Recirculation (EGR) and Humid Air Motor (HAM) systems Maybe there is: -EXHAUST GAS BOILER for heat &other purposes or driving ST-Gen/s	1 or 2 FPP OR 1 or 2 CPP (if there is not reversing mechanism in the reduction gear) OR 1 or 2 AZIPOD OR CRP AZIPOD 1 or 2 bow thrusters maybe installed
MEDIUM SPEED GAS-ONLY ENGINE	2 to 4 MEDIUM SPEED SPARK IGNITED GAS –ONLY ENGINES (Rolls-Royce Bergen B-series gas engine/Mitsubishi GS-series gas engine) + SUFFICIENT NUMBER OF MDO OR HFO MEDIUM SPEED DIESEL ENGINES ONLY AS A BACK UP (IN THE CASE THAT RR DECIDES NOT TO CONVERT GAS ENGINES TO BURN DIESEL FUEL)	BOG & forced BOG MDO OR HFO	NO BOG COMPRESSING NEEDED	- BURNING ON THE GAS ENGINES - 1 GAS OXIDIZER (PREFERRED OPTION) OR ALTERNATIVELY 1 RELIQUEFACTION PLANT(Hamworthy KSE-Moss RS	- DIRECT MECHANICAL DRIVE THROUGH twin-in/single-out GEARBOXES - DIESEL-ELECTRIC ELECTRIC DRIVE WITH 2 SLOW SPEED PROPULSION MOTORS OR WITH 2 MEDIUM OR HIGH SPEED PR. MOTORS THROUGH REDUCTION GEAR OR ELECTRIC WITH AZIPOD	ELECTRIC POWER AVAILABLE FROM MAIN GENERATOR ENGINES OR/AND1 or 2 4-x DIESEL HFO or MDO GENSETS(STAND BY)	1 (at least) EMERGENCY 4-x DIESEL MDO or MGO GENERATOR	If needed at HFO mode, NOx emissions can be reduced by Selective Catalytic Reduction(SCR units)or direct water injection(water emulsion) or by EGR & HAM systems	1 or 2 FPP OR 1 or 2 CPP(if there is not reversing mechanism in the reduction gear) OR 1 or 2 AZIPOD OR CRP AZIPOD 1 or 2 bow thrusters maybe installed

Continuation of Table A.1

Prime Mover	Configuration	Fuel used for Prime Mover	Fuel treatment before use	BOG Handling Back up BOG Handling	Transmission	Electric Power	Emergency Power	Additional equipment	Propulsion unit
COMBINED SLOW SPEED DIESEL AND MEDIUM SPEED DUAL FUEL DIESEL	COMBINATION OF SLOW SPEED DIESEL AND MEDIUM SPEED DUAL FUEL ENGINE: 1 SLOW SPEED ENGINE (MAN B&W MC OR ME-series /SULZER RT-series) + 1 OR 2 MEDIUM SPEED DUAL – FUEL (GAS/MDO) DIESEL ENGINES (Wärtsilä 50DF series)	HFO GAS OR MDO(pilot fuel is needed in gas mode)	HFO centrifugal separation(purification-clarification), possible blending homogenization ,PREHEATING BOG COMPRESSING (5 bar approximately)	- BURNING ON DF ENGINES - 1 GAS OXIDIZER (PREFERRED OPTION) OR ALTERNATIVELY 1 RELIQUEFACTION PLANT (Hamworthy KSE-Moss RS	DIRECT DRIVE for the propeller driven by the slow speed Diesel -MECHANICAL DRIVE THROUGH single or twin-in/single-out GEARBOXES for the propeller driven by the medium speed engines - ELECTRIC DRIVE WITH 1 or 2 SLOW SPEED PROPULSION MOTORS OR WITH 1 or 2 MEDIUM SPEED PR. MOTORS THROUGH REDUCTION GEAR OR ELECTRIC WITH AZIPOD for the propeller driven by the medium speed engines	- 2 to 3 4-x DIESEL MDO or HFO GENSETS + 1 shaft gen sets DEPENDING ON THE CHOSEN CONFIGURATION - ELECTRIC POWER AVAILABLE FROM MAIN GENERATOR ENGINES + 1 OR 2 4-x DIESEL HFO OR MDO GEN(STAND BY) OR/AND If there is Exhaust gas boiler 1 or 2 STEAM TURBINE-GEN +/-1 or 2 4-x DIESEL HFO or MDO GENSETS(STAND BY) Or/And 1 /2 POWER recovery Gas TURBINE GEN SET(if there is) +/- 3 4-x DIESEL HFO or MDO GENSETS DEPENDING ON THE CHOSEN CONFIGURATION	1 (at least) EMERGENCY 4-x DIESEL MDO or MGO GENERATOR	If needed at HFO mode, NOx emissions can be reduced by Selective Catalytic Reduction(SCR units)or direct water injection(water emulsion) or by Exhaust Gas Recirculation (EGR) and Humid Air Motor (HAM) systems Maybe there is: -EXHAUST GAS BOILER for heat &other purposes or driving ST-Gen/s -POWER recovery Gas TURBINE driving 1 or 2 turbogenerators	1 FPP(usually proposed) OR 1 CPP driven by the slow speed Diesel 1 FPP OR 1 CPP (if there is not reversing mechanism in the reduction gear) for the propeller driven by the medium speed engines OR CRP AZIPOD (CRP(FPP by the slow speed Diesel) AZIPOD (POD THRUSTER driven by the medium speed engines) 1 or 2 bow thrusters maybe installed
COMBINED MEDIUM SPEED DIESEL AND GAS TURBINE (CODAG OR CODLAG)	COMBINATION OF 1 GAS TURBINE GENERATOR (Rolls Royce suitable models/ GE suitable models / MAN B&W THM /other) AND 3 OR 4 MEDIUM SPEED DIESEL GEN SETS	GAS OR MGO(pilot fuel maybe needed in gas mode) MDO OR HFO	HFO centrifugal separation(purification-clarification),possible blending, homogenization ,PREHEATING BOG COMPRESSING (20-25 bar approximately)	-BURNING ON THE TURBINE -1 GAS OXIDIZER OR ALTERNATIVELY 1 RELIQUEFACTION PLANT	- MECHANICAL DRIVE THROUGH REDUCTION GEAR - DIESEL-ELECTRIC ELECTRIC DRIVE WITH 2 SLOW SPEED PROPULSION MOTORS OR WITH 2 MEDIUM OR HIGH SPEED PR. MOTORS THROUGH REDUCTION GEAR OR ELECTRIC WITH AZIPOD	ELECTRIC POWER AVAILABLE FROM MAIN GENERATOR ENGINES OR 2 or 3 4-x DIESEL HFO or MDO GENSETS	1 (at least) EMERGENCY 4-x DIESEL MDO or MGO GENERATOR	Maybe there is: -POWER recovery Gas TURBINE driving 1 turbogenerator	1 OR 2 FPP OR CRP AZIPOD OR 1 OR 2 POD PROPELLERS 1 or 2 bow thrusters maybe installed

Continuation of Table A.1

Prime Mover	**Configuration**	**Fuel used for Prime Mover**	**Fuel treatment before use**	**BOG Handling Back up BOG Handling**	**Transmission**	**Electric Power**	**Emergency Power**	**Additional equipment**	**Propulsion unit**
COMBINED SLOW SPEED DIESEL AND STEAM TURBINE	• 1 BOILER(common proposal) • 1 BOILER (+1 AUXILIARY is an alternative option) 1 SLOW SPEED ENGINE(MAN B&W MC OR ME-series/SULZER RT-series) STEAM TURBINE GEN sets	HFO AND/OR GAS almost in any combination HFO	HFO PREHEATING BOG COMPRESSING (2 bar approximately HFO centrifugal separation(purification-clarification),possible blending , homogenization, PREHEATING	-BURNING ON BOILER -STEAM DUMPING via MAIN BOILER and auxiliary boiler (if there is) OR 1 GAS OXIDIZER (if there is not auxiliary boiler) OR ALTERNATIVELY 1 RELIQUEFACTION PLANT	-MECHANICAL DRIVE THROUGH REDUCTION GEAR for the propeller driven by the steam turbine DIRECT DRIVE for the propeller driven by the slow speed Diesel -HYBRID propulsion plant consisting of directly driven FPP and electric driven AZIPOD in a CRP AZIPOD configuration	2 STEAM TURBINE GENERATORS+1 or 2 4-x DIESEL HFO or MDO GEN(STAND BY) OR 2 STEAM TURBINE GENERATORS +1 4-x DIESEL HFO or MDO GENSETS + 1 shaft generator Or/And 1 POWER recovery Gas TURBINE GEN SET(if there is) +/- 1 4-x DIESEL HFO or MDO GENSETS DEPENDING ON THE CHOSEN CONFIGURATION	1 (at least) EMERGENCY 4-x DIESEL MDO or MGO GENERATOR	If needed at HFO mode, NOx emissions can be reduced by Selective Catalytic Reduction(SCR units)or direct water injection(water emulsion)or by Exhaust Gas Recirculation (EGR) and Humid Air Motor (HAM) systems An additional EXHAUST GAS auxiliary BOILER maybe installed in the case of an 1 main boiler Maybe there is: -POWER recovery Gas TURBINE driving 1 turbogenerator	2 FPP OR CRP AZIPOD for the case of a HYBRID propulsion plant (CRP(FPP by the slow speed Diesel) AZIPOD (POD THRUSTER driven by the STEAM GEN SET)) 1 or 2 bow thrusters maybe installed
COMBINED HFO MEDIUM SPEED DIESEL AND MEDIUM SPEED GAS ENGINE	2 MEDIUM SPEED SPARK IGNITED GAS –ONLY ENGINES (Rolls-Royce Bergen B-series gas engine/Mitsubishi GS-series gas engine) + 2 HFO MEDIUM SPEED DIESEL ENGINES (Wärtsilä/ MAN B&W/Caterpillar/other ordinary models)	BOG & forced BOG HFO	NO BOG COMPRESSING NEEDED	BURNING ON THE GAS ENGINES 1 GAS OXIDIZER (PREFERRED OPTION) OR ALTERNATIVELY 1 RELIQUEFACTION PLANT (Hamworthy KSE-Moss RS	- DIRECT MECHANICAL DRIVE THROUGH twin-in/single-out GEARBOXES - DIESEL-ELECTRIC ELECTRIC DRIVE WITH 2 SLOW SPEED PROPULSION MOTORS OR WITH 2 MEDIUM OR HIGH SPEED PR. MOTORS THROUGH REDUCTION GEAR OR ELECTRIC WITH AZIPOD	ELECTRIC POWER AVAILABLE FROM MAIN GENERATOR ENGINES OR/AND 1 or 2 4-x DIESEL HFO or MDO GENSETS(STAND BY)	1 (at least) EMERGENCY 4-x DIESEL MDO or MGO GENERATOR	If needed at HFO mode, NOx emissions can be reduced by Selective Catalytic Reduction(SCR units)or direct water injection(water emulsion) or by EGR & HAM systems	1 or 2 FPP OR 1 or 2 CPP(if there is not reversing mechanism in the reduction gear) OR 1 or 2 AZIPOD OR CRP AZIPOD 1 or 2 bow thrusters maybe installed

Continuation of Table A.1

Prime Mover	Configuration	Fuel used for Prime Mover	Fuel treatment before use	BOG Handling Back up BOG Handling	Transmission	Electric Power	Emergency Power	Additional equipment	Propulsion unit
COMPRESSED NATURAL GAS (CNG) ENGINE (Hybrid system) (UNDER DEVELOPMENT)	Engine that utilizes reformed fuel from CNG using a Catalytic NG Reformer and a CO2 Separator with an accompanying system of a Gas Turbine in combination with an electric generator and steam turbine	GAS		- BURNING ON BOILERS - BURNING ON THE TURBINE - STEAM DUMPING OR ALTERNATIVELY 1 RELIQUEFACTION PLANT	- MECHANICAL DRIVE THROUGH REDUCTION GEAR - DIESEL-ELECTRIC ELECTRIC DRIVE WITH 2 SLOW SPEED PROPULSION MOTORS OR WITH 2 MEDIUM OR HIGH SPEED PR. MOTORS THROUGH REDUCTION GEAR OR ELECTRIC WITH AZIPOD	1 STEAM TURBINE-GENERATORS +1 OR 2 4-x DIESEL HFO or MDO GEN (STAND BY)	1 (at least) EMERGENCY 4-x DIESEL MDO or MGO GENERATOR	-EXHAUST GAS ECONOMIZER	1 FPP 1 or 2 bow thrusters maybe installed
FUEL CELLS (Hybrid system) (UNDER DEVELOPMENT)	• DIESEL ELECTRIC • GAS TURBINE COMBINED CYCLE	GAS OR MDO GAS OR MGO	BOG COMPRESSING (5 bar approximately) BOG COMPRESSING (20-25 bar approximately)	- BURNING ON DF ENGINES - 1 GAS OXIDIZER OR ALTERNATIVELY 1 RELIQUEFACTION PLANT(Hamworthy KSE-Moss RS - Burning on the turbine	- MECHANICAL DRIVE THROUGH REDUCTION GEAR - DIESEL-ELECTRIC ELECTRIC DRIVE WITH 2 SLOW SPEED PROPULSION MOTORS OR WITH 2 MEDIUM OR HIGH SPEED PR. MOTORS THROUGH REDUCTION GEAR OR ELECTRIC WITH AZIPOD	ELECTRIC POWER AVAILABLE FROM MAIN GENERATOR ENGINES OR/AND 1 or 2 4-x DIESEL HFO or MDO GENSETS(STAND BY)	1 (at least) EMERGENCY 4-x DIESEL MDO or MGO GENERATOR		1 FPP 1 or 2 bow thrusters maybe installed

APPENDIX B

Table B1	**CASE 0**
Basic Assumptions for Economic Comparison	**INPUT DATA with Bold**
Ship particulars	
Cargo capacity for the steam turbine vessel (m³)	**150000**
Maximum loading	**98,50%**
Nominal Service Speed (kn)	**20**
Boil-Off Gas rates	
Boil off rate in loaded conditions (Only Methane is considered) (% per day)	**0,12%**
Boil off rate in ballast conditions (Only Methane is considered) (% per day)	**0,06%**
Boil off rate during Manoeuvring (Only Methane is considered) (% per day)	**0,10%**
Boil off rate during Loading (Only Methane is considered) (% per day)	**0,08%**
Boil off rate during Unloading (Only Methane is considered) (% per day)	**0%**
Boil off rate during other modes (Waiting,Bunkering etc.) (Only Methane is considered) (% per day)	**0,10%**
Average Density of liquid BOG (Methane) (kg/m³)	**465**
LHV of BOG (Methane) (kJ/kg)	**49700**
Voyage profile	
Distance (Pilot-Pilot) (nm)	**6500**
Service speed laden voyage (kn)	**20**
Service speed ballast voyage (kn)	**20**
Loaded voyage (hours)	325
Ballast voyage (hours)	325
Manoeuvring (hours)	**6**
Reserve (waiting, bunkering etc.) (hours)	**24**
Loading time (hours)	**12**
Discharging time (hours)	**12**
Time per round-trip (hours)	704
Round-trips per year for steam vessel	12
Round-trips per year for dual -fuel vessel	12
Round-trips per year for two-stroke vessel	12
Round-trips per year for gas turbine vessel	12
Round-trips per year for coges vessel	12
CASE 0:	13/5/2006
X0 (HFO)=	**331,5**

Continuation of table B.1

Oil prices	
Heavy Fuel Oil (IFO 380 or RMG 35) (3-4.5% Sulphur content) price (US$/ton)	**331,5**
LHV of HFO(IFO 380 or RMG 35) (kJ/kg)	**40400**
Marine Diesel Oil (DMB) (1-2% Sulphur content) price (US$/ton)	596,7
LHV of MDO (DMB) (kJ/kg)	**42700**
Marine Gas Oil (DMA) (0,3-1% Sulphur content)price (US$/ton)	629,85
LHV of MGO (DMA) (kJ/kg)	**42700**
Lubrication oil price for four-stroke engine gen-sets (US$/ton)	1326
Cylinder L.O. price for two-stroke engines (US$/ton)	1756,95
System oil price for two-stroke engines (US$/ton)	1326
LNG prices	
LNG price for Natural Boil off Gas (FOB) (US$/ton)	159,12
LNG sales price (the same for possible Forced Boil off Gas)(sales price=CIF) (US$/ton)	364,65

Sources:
1.MAN B&W Diesel A/S,Copenhagen,Denmark & MAN B&W Diesel AG, Augsburg, Germany [Ref.12, 49]
2.Wärtsilä Finland [Ref.5]
3.Maran Gas Maritime Inc.
4.www.bunkerworld.com
5.www.energyintel.com
6.www.eia.doe.gov
7. Marine Service GmbH, Hamburg [Ref.52]

Continuation of table B.1

Basic Data for BOG rates					
	Steam Turbine (Single Screw)	**Dual-fuel-electric (Single Screw)**	**Two-stroke Diesel + Reliquefaction (Twin Screw)**	**Simple-cycle Gas Turbine-electric (Single Screw)**	**Combined-cycle Gas Turbine-electric (Single Screw)**
Cargo capacity (100%) (m^3)	150000	156700	156300	165000	165000
Cargo capacity at 98,5 % max filling ratio (m^3)	147750	154349,5	153955,5	162525	162525
Volume of BOG (Methane) loaded conditions (m^3/day)	177,3	185,2194	184,7466	195,03	195,03
Mass of BOG (Methane) loaded conditions (kg/h)	3435,1875	3588,62588	3579,465375	3778,70625	3778,70625
Mass of BOG (Methane) loaded conditions (kg/day)	82444,5	86127,021	85907,169	90688,95	90688,95
Energy in BOG (Methane) loaded conditions (GJ/day)	4097,49165	4280,51294	4269,586299	4507,240815	4507,240815
Volume of BOG (Methane) ballast conditions (m^3/day)	88,65	92,6097	92,3733	97,515	97,515
Mass of BOG (Methane) ballast conditions (kg/h)	1717,59375	1794,31294	1789,732688	1889,353125	1889,353125
Mass of BOG (Methane) ballast conditions (kg/day)	41222,25	43063,5105	42953,5845	45344,475	45344,475
Energy in BOG (Methane) ballast conditions (GJ/day)	2048,745825	2140,25647	2134,79315	2253,620408	2253,620408
Lost during loaded voyage (m^3/per trip)	2400,9375	2508,17938	0	2641,03125	2641,03125
Lost during ballast voyage (m^3/per trip)	1200,46875	1254,08969	0	1320,515625	1320,515625
Total Lost LNG (m^3/per trip)	3601,40625	3762,26906	0	3961,546875	3961,546875
Reliquefied LNG loaded voyage (m^3/per trip)	0	0	2501,776875	0	0
Reliquefied LNG ballast voyage (m^3/per trip)	0	0	1250,888438	0	0

Continuation of Table B.1

Basic Data for BOG rates					
	Steam Turbine (Single Screw)	**Dual-fuel-electric (Single Screw)**	**Two-stroke Diesel + Reliquefaction (Twin Screw)**	**Simple-cycle Gas Turbine-electric (Single Screw)**	**Combined-cycle Gas Turbine-electric (Single Screw)**
Cargo capacity (100%) (m^3)	150000	156700	156300	165000	165000
Cargo capacity at 98,5 % max filling ratio (m^3)	147750	154349,5	153955,5	162525	162525
Volume of BOG (Methane) during Manoeuvring (m^3/day)	147,75	154,3495	153,9555	162,525	162,525
Mass of BOG (Methane) during Manoeuvring (kg/h)	2862,656	2990,5216	2982,8878	3148,92188	3148,921875
Mass of BOG (Methane) during Manoeuvring (kg/day)	68703,75	71772,518	71589,308	75574,125	75574,125
Energy in BOG (Methane) during Manoeuvring (GJ/day)	3414,576	3567,0941	3557,9886	3756,03401	3756,034013
Volume of BOG (Methane) during Waiting,Bunkering, etc.(m^3 /day)	147,75	154,3495	153,9555	162,525	162,525
Mass of BOG (Methane) during Waiting, etc. (kg/h)	2862,656	2990,5216	2982,8878	3148,92188	3148,921875
Mass of BOG (Methane) during Waiting, etc. (kg/day)	68703,75	71772,518	71589,308	75574,125	75574,125
Energy in BOG (Methane) during Waiting, etc. (GJ/day)	3414,576	3567,0941	3557,9886	3756,03401	3756,034013
Volume of BOG (Methane) during Loading (m^3 /day)	118,2	123,4796	123,1644	130,02	130,02
Mass of BOG (Methane) during Loading (kg/h)	2290,125	2392,4173	2386,3103	2519,1375	2519,1375
Mass of BOG (Methane) during Loading (kg/day)	54963	57418,014	57271,446	60459,3	60459,3
Energy in BOG (Methane) during Loading (GJ/day)	2731,661	2853,6753	2846,3909	3004,82721	3004,82721
Volume of BOG (Methane) during Unloading (m^3 /day)	0	0	0	0	0

Continuation of Table B.1

	Steam Turbine (Single Screw)	**Dual-fuel-electric (Single Screw)**	**Two-stroke Diesel + Reliquefaction (Twin Screw)**	**Simple-cycle Gas Turbine-electric (Single Screw)**	**Combined-cycle Gas Turbine-electric (Single Screw)**
Mass of BOG (Methane) during Unloading (kg/h)	0	0	0	0	0
Mass of BOG (Methane) during Unloading (kg/day)	0	0	0	0	0
Energy in BOG (Methane) during Unloading (GJ/day)	0	0	0	0	0
Lost during Manoeuvring (m^3/per trip)	36,9375	38,587375	0	40,63125	40,63125
Lost during Waiting,Bunkering, etc. (m^3/per trip)	147,75	154,3495	0	162,525	162,525
Lost during Loading (m^3/per trip)	59,1	61,7398	0	65,01	65,01
Lost during Unloading (m^3/pertrip)	0	0	0	0	0
Total Lost LNG at Port (m^3/per trip)	243,7875	254,67668	0	268,16625	268,16625
Reliquefied LNG during Manoeuvring (m^3/per trip)	0	0	38,488875	0	0
Reliquefied LNG duringWaiting,Bunkering,etc. (m^3/per trip)	0	0	153,9555	0	0
Reliquefied LNG during Loading (m^3/per trip)	0	0	61,5822	0	0
Reliquefied LNG during Unloading (m^3/per trip)	0	0	0	0	0

Continuation of Table B.1

	Steam Turbine (Single Screw)	**Dual-fuel-electric (Single Screw)**	**Two-stroke Diesel + Reliquefaction (Twin Screw)**	**Simple-cycle Gas Turbine-electric (Single Screw)**	**Combined-cycle Gas Turbine-electric (Single Screw)**
Total Reliquefied LNG at Port (m^3/per trip)	0	0	254,02658	0	0
Total Lost (consumed) LNG at all conditions (m^3/per trip)	3786,0938	3955,2059	0	4164,703125	4164,703125
Minimum Level Of LNG (m^3)	**2000**	**2000**	**2000**	**2000**	**2000**
Delivered cargo (m^3/trip)	141963,91	148394,29	151955,5	156360,2969	156360,2969
Delivered cargo (m^3/year)	1703566,9	1780731,5	1823466	1876323,563	1876323,563
Extra Delivered cargo (m^3/year)	0	77164,654	119899,13	172756,6875	172756,6875
Value of lost LNG at Port (US$/per trip)	31316,028	32714,811	0	34447,63085	34447,63085
Value of lost LNG at Port (US$/yr)	375792,34	392577,73	0	413371,5702	413371,5702
Value of total lost LNG (US$/ per trip)	641978,57	670653,62	0	706176,4325	706176,4325
Value of total lost LNG (US$/yr)	7703742,9	8047843,4	0	8474117,189	8474117,189
Savings from the Reliquified cargo at Port (US$/per trip)	0	0	32631,301	0	0
Savings from the Reliquified cargo at Port (US$/yr)	0	0	391575,61	0	0
Savings from the Total Reliquified cargo (US$/trip)	0	0	668941,68	0	0
Savings from the Total Reliquified cargo (US$/yr)	0	0	8027300,1	0	0
REVENUES FROM SELLING THE DELIVERED CARGO CAPACITY (US$/per trip)	24071719	25162070	25765916	26512803,75	26512803,75
REVENUES FROM SELLING THE DELIVERED CARGO CAPACITY (US$/year)	288860632	301944845	309190998	318153645	318153645

Table B2		
Initial Cost for the machinery (excluding installation)	**INPUT DATA WITH BOLD**	
Steam Turbine (Single Screw)	**Number of units**	**Cost (million US$)**
Steam Boiler (Dual fuel) [including main Condeser (single pass cooling type), low pressure gas compressor (2 units one in operation at the time)]	**2**	**9**
Main propulsion Steam turbine	**1**	**3,5**
Gear case	**1**	**3**
Steam Turbine Gensets	**2**	**1,8**
Stand-by Diesel gensets	**1**	**0,9**
Emergency Diesel gensets	**1**	**0,5**
Propeller and Shafting	**1**	**0,65**
Rudder/Steering gear	**1**	**0,25**
Bow thruster	**1**	**0,4**
Total initial cost		20
Dual-fuel-electric (Single Screw)	**Number of units**	**Cost (million US$)**
Dual -fuel engines including alternators (genset),Gas Compressor	**4**	**11,5**
Electric propulsion motors,transformers,converters	**2**	**5,6**
Gear case	**1**	**2,3**
Propeller and Shafting	**1**	**0,6**
Rudder/Steering gear	**1**	**0,25**
Thermal oxidiser	**1**	**0,5**
Emergency Diesel gensets	**1**	**0,5**
Bow thruster	**1**	**0,4**
Total initial cost		21,65
Two-stroke Diesel + Reliquefaction (Twin Screw)	**Number of units**	**Cost (million US$)**
Main Two-stroke diesel engine	**2**	**7,6**
Reliquefaction plant	**2**	**8**
Diesel gensets	**3**	**2,7**
Propeller and Shafting	**2**	**1,2**
Rudder/Steering gear	**2**	**0,4**
Emergency Diesel gensets	**1**	**0,5**
Bow thruster	**1**	**0,4**
Total initial cost		20,8

Continuation of Table B.2

Simple-cycle Gas Turbine-electric (Single Screw)	**Number of units**	**Cost (million US$)**
Main Gas Turbine including alternator, Gas Compressor	**1**	**13**
Auxiliary Gas turbine including alternator	**1**	**1,8**
Electric propulsion motors,transformers,converters	**2**	**5,6**
Gear case	**1**	**2,3**
Propeller and Shafting	**1**	**0,6**
Rudder/Steering gear	**1**	**0,25**
Thermal oxidiser	**1**	**0,5**
Stand-by Diesel gensets	**1**	**0,9**
Emergency Diesel gensets	**1**	**0,5**
Bow thruster	**1**	**0,4**
Total initial cost		25,85
Combined-cycle Gas Turbine-electric (Single Screw)	**Number of units**	**Cost (million US$)**
Main Gas Turbine including alternator, Gas Compressor, Condenser	**1**	**13**
Auxiliary Gas turbine including alternator	**0**	**0**
Steam turbo gen-set including alternator	**1**	**1,2**
Exhaust gas boiler	**1**	**0,3**
Auxiliary boiler	**1**	**1**
Electric propulsion motors,transformers,converters	**2**	**5,6**
Gear case	**1**	**2,3**
Propeller and Shafting	**1**	**0,6**
Rudder/Steering gear	**1**	**0,25**
Thermal oxidiser	**1**	**0,5**
Stand-by Diesel gensets	**1**	**0,9**
Emergency Diesel gensets	**1**	**0,5**
Bow thruster	**1**	**0,4**
Total initial cost		26,55

Continuation of Table B.2

Installation Cost (for main engine and auxiliaries,shaftline,propeller,rudder,etc.)	**Cost (million US$)**
Steam Turbine (Single Screw)	**0,5**
Dual-fuel-electric (Single Screw)	**0,45**
Two-stroke Diesel + Reliquefaction (Twin Screw)	**0,6**
Simple-cycle Gas Turbine-electric (Single Screw)	**0,4**
Combined-cycle Gas Turbine-electric (Single Screw)	**0,43**

Approximate Overall Investment Cost assumption	**Cost (million US$)**
Price of Steam Turbine LNGC	**180**
Price of Dual-fuel-electric LNGC	**182**
Price of Two-stroke Diesel + Reliquefaction LNGC	**184**
Price of Simple-cycle Gas Turbine-electric LNGC	**186**
Price of Combined-cycle Gas Turbine-electric LNGC	**187**

Sources:
1.Tractebel Gas Engineering GmbH & Dorchester Maritime Ltd. [Ref.13]
2.Maran Gas Maritime Inc.
3.MAN B&W Diesel A/S,Copenhagen,Denmark & MAN B&W Diesel AG, Augsburg, Germany [Ref.12, 49]
4.Marine Service GmbH, Hamburg [Ref.52]
5.www.gas-turbines.com/trader/kwprice.htm (for gas turbine prices)
6.Wärtsilä Finland

Table B3

Power Needs	**INPUT DATA WITH BOLD**				
Options	**Steam Turbine (Single Screw)**	**Dual-fuel-electric (Single Screw)**	**Two-stroke Diesel + Reliquefaction (Twin Screw)**	**Simple-cycle Gas Turbine-electric (Single Screw)**	**Combined-cycle Gas Turbine-electric (Single Screw)**
Engine power for propulsion (Propeller shaft power)					
Propulsion power demand at Loaded conditions with a sea margin 20% (kW)	**28920,00**	**28920,00**	**28920,00**	**28920,00**	**28920,00**
Delivered power at the propeller at Loaded conditions (kW)	29808,29	31997,29	29510,20	31997,29	31997,29
Propulsion power demand at Ballast conditions with a sea margin 20% (kW)	27763,20	27763,20	27763,20	27763,20	27763,20
Delivered power at the propeller at Ballast conditions(kW)	28615,96	30717,39	28329,80	30717,39	30717,39
Propulsion power demand at Manoeuvring (kW)	**3500,00**	**3500,00**	**3500,00**	**3500,00**	**3500,00**
Delivered power at the propeller at Manoeuvring(kW)	3607,50	3872,42	3571,43	3872,42	3872,42

Continuation of Table B.3

Options	**Steam Turbine (Single Screw)**	**Dual-fuel-electric (Single Screw)**	**Two-stroke Diesel + Reliquefaction (Twin Screw)**	**Simple-cycle Gas Turbine-electric (Single Screw)**	**Combined-cycle Gas Turbine-electric (Single Screw)**
Electrical power (Overall ship service power)*					
Loaded conditions					
Electrical power consumption (kWe)	1688,94	2038,29	4793,11	2822,55	2822,55
Delivered power for electric generation (kW)	1759,31	2101,33	4992,82	2909,84	2909,84
Ballast conditions					
Electrical power consumption (kWe)	1494,47	1669,15	3046,55	2061,27	2061,27
Delivered power for electric generation (kW)	1556,74	1720,77	3173,49	2125,02	2125,02
Manoeuvring					
Electrical power consumption (kWe)	3157,45	3448,58	5744,26	4102,12	4102,12
Delivered power for electric generation (kW)	3289,01	3555,24	5983,60	4228,99	4228,99
Waiting					
Electrical power consumption (kWe)	1157,45	1448,58	3744,26	2102,12	2102,12
Delivered power for electric generation (kW)	1205,67	1493,38	3900,27	2167,14	2167,14

Continuation of Table B.3

***Electrical power needs in detail**					
Reliquefication plant					
Specific Power Consumption (W/kg/h)	**920,00**				
Power consumption (Loaded voyage) (kWe)	3293,11				
Power consumption (Ballast voyage) (kWe)	1646,55				
Power consumption (Manoeuvring) (kWe)	2744,26				
Power consumption (Waiting) (kWe)	2744,26				
Low and High Pressure Gas Compressors (CH4/N2 = 90/10)					
Specific power consumption for LP Gas compressor for Steam Turbine (W/kg/h)	**55,00**				
Power consumption (Loaded voyage) (kWe)	188,94				
Power consumption (Ballast voyage) (kWe)	94,47				
Power consumption (Manoeuvring) (kWe)	157,45				
Power consumption (Waiting) (kWe)	157,45				
Specific power consumption for LP Gas compressor for DF diesel(W/kg/h)	**150,00**				
Power consumption (Loaded voyage) (kWe)	538,29				
Power consumption (Ballast voyage) (kWe)	269,15				
Power consumption (Manoeuvring) (kWe)	448,58				
Power consumption (Waiting) (kWe)	448,58				
Specific Power Consumption for HP Gas compressor for Gas Turbine (W/kg/h)	**350,00**				
Power consumption (Loaded voyage) (kWe)	1322,55				
Power consumption (Ballast voyage) (kWe)	661,27				
Power consumption (Manoeuvring) (kWe)	1102,12				
Power consumption (Waiting) (kWe)	1102,12				
Cargo pumps (at harbour) (kWe)	**3000,00**				
Bow Thruster (kWe)	**2000,00**				
Other consumers of electrical power (ship service power:heating, cooling (including cargo cooling), lighting, ventilation, kitchen, laundry etc.)	*Sea Load Loaded voyage*	*Sea load Ballast voyage*	*Harbour Load (excluding cargo pumping)*	*Harbour Load (including cargo pumping)*	*Delivered power Harbour load*
For a Steam Turbine LNGC (kWe)	**1500,00**	**1400,00**	**1000,00**	4000,00	4166,67
For a Dual-fuel-electric LNGC (kWe)	**1500,00**	**1400,00**	**1000,00**	4000,00	4123,71
For a Two-stroke Diesel + Reliquefaction LNGC (kWe)	**1500,00**	**1400,00**	**1000,00**	4000,00	4166,67
For a Simple-cycle Gas Turbine-electric LNGC (kWe)	**1500,00**	**1400,00**	**1000,00**	4000,00	4123,71
For a Combined-cycle Gas Turbine-electric LNGC (kWe)	**1500,00**	**1400,00**	**1000,00**	4000,00	4123,71

Sources:
1.MAN B&W Diesel A/S,Copenhagen,Denmark & MAN B&W Diesel AG, Augsburg, Germany [Ref.12, 49]
2.Maran Gas Maritime Inc.[Ref.50]
3.Marine Service GmbH, Hamburg [Ref.52]

Continuation of Table B.3

ENERGY NEEDS LOADED CONDITIONS					
	Steam Turbine (Single Screw)	**Dual-fuel-electric (Single Screw)**	**Two-stroke Diesel + Reliquefaction (Twin Screw)**	**Simple-cycle Gas Turbine-electric (Single Screw)**	**Combined-cycle Gas Turbine-electric (Single Screw)**
Propulsion Power					
ENERGY NEEDED (GJ/h)	369,12	259,59	212,95	282,82	282,82
Available Energy in BOG (GJ/h)	170,73	178,35	0,00	187,80	187,80
Available Energy in Exhaust Gases (GJ/h)	0,00	0,00	0,00	0,00	43,20
Extra Energy Needed (GJ/h)	198,39	81,24	212,95	95,02	51,82
Equivalent HFO Consumption (t/h)	4,91	2,01	5,27	0,00	0,00
Equivalent MDO Consumption (t/h)	0,00	1,90	0,00	0,00	0,00
Equivalent MGO Consumption (t/h)	0,00	0,00	0,00	2,23	1,21
Auxiliary Power					
ENERGY NEEDED (GJ/h)	21,79	17,05	40,51	25,72	25,72
Available Energy in BOG (GJ/h)	0,00	0,00	0,00	0,00	0,00
Available Energy in Exhaust Gases (GJ/h)	0,00	0,00	0,00	0,00	0,00
Extra Energy Needed (GJ/h)	21,79	17,05	40,51	25,72	25,72
Equivalent HFO Consumption (t/h)	0,54	0,42	1,00	0,00	0,00
Equivalent MDO Consumption (t/h)	0,00	0,40	0,00	0,00	0,00
Equivalent MGO Consumption (t/h)	0,00	0,00	0,00	0,60	0,60

Continuation of Table B.3

ENERGY NEEDS BALLAST CONDITIONS					
	Steam Turbine (Single Screw)	**Dual-fuel-electric (Single Screw)**	**Two-stroke Diesel + Reliquefaction (Twin Screw)**	**Simple-cycle Gas Turbine-electric (Single Screw)**	**Combined-cycle Gas Turbine-electric (Single Screw)**
Propulsion Power					
ENERGY NEEDED (GJ/h)	354,35	249,21	204,44	271,51	271,51
Available Energy in BOG(GJ/h)	85,36	89,18	0,00	93,90	93,90
Available Energy in Exhaust Gases (GJ/h)	0,00	0,00	0,00	0,00	42,00
Extra Energy Needed(GJ/h)	268,99	160,03	204,44	177,61	135,61
Equivalent HFO Consumption (t/h)	6,66	3,96	5,06	0,00	0,00
Equivalent MDO Consumption (t/h)	0,00	3,75	0,00	0,00	0,00
Equivalent MGO Consumption (t/h)	0,00	0,00	0,00	4,16	3,18
Auxiliary Power					
ENERGY NEEDED(GJ/h)	19,28	13,96	25,75	18,78	18,78
Available Energy in BOG(GJ/h)	0,00	0,00	0,00	0,00	0,00
Available Energy in Exhaust Gases (GJ/h)	0,00	0,00	0,00	0,00	0,00
Extra Energy Needed (GJ/h)	19,28	13,96	25,75	18,78	18,78
Equivalent HFO Consumption (t/h)	0,48	0,35	0,64	0,00	0,00
Equivalent MDO Consumption (t/h)	0,00	0,33	0,00	0,00	0,00
Equivalent MGO Consumption (t/h)	0,00	0,00	0,00	0,44	0,44

Continuation of Table B.3

ENERGY NEEDS PORT					
	Steam Turbine (Single Screw)	**Dual-fuel-electric (Single Screw)**	**Two-stroke Diesel + Reliquefaction (Twin Screw)**	**Simple-cycle Gas Turbine-electric (Single Screw)**	**Combined-cycle Gas Turbine-electric (Single Screw)**
Propulsion Power for manoeuvring					
ENERGY NEEDED (GJ/h)	44,67	31,42	25,77	34,23	34,23
Available Energy in BOG (GJ/h)	142,27	148,63	0,00	156,50	156,50
Available Energy in Exhaust Gases (GJ/h)	0,00	0,00	0,00	0,00	5,30
Excess Energy available for the auxiliaries(GJ/h)	-97,60	-117,21	25,77	-122,27	-127,57
Equivalent HFO Consumption (t/h)	0,00	0,00	0,64	0,00	0,00
Equivalent MDO Consumption (t/h)	0,00	0,00	0,00	0,00	0,00
Equivalent MGO Consumption (t/h)	0,00	0,00	0,00	0,00	0,00
Auxiliary Power during manoeuvring					
ENERGY NEEDED (GJ/h)	40,73	28,84	48,54	37,38	37,38
Available Energy in BOG (GJ/h)	97,60	117,21	0,00	122,27	127,57
Available Energy in Exhaust Gases (GJ/h)	0,00	0,00	0,00	0,00	0,00
Excess Energy(steam dumping ,incineration)(GJ/h)	-56,87	-88,37	48,54	-84,89	-90,19
Equivalent HFO Consumption (t/h)	0,00	0,00	1,20	0,00	0,00
Equivalent MDO Consumption (t/h)	0,00	0,00	0,00	0,00	0,00
Equivalent MGO Consumption (t/h)	0,00	0,00	0,00	0,00	0,00
Auxiliary Power during Waiting,Bunkering, etc.					
ENERGY NEEDED (GJ/h)	14,93	12,12	31,64	19,16	19,16
Available Energy in BOG (GJ/h)	142,27	148,63	0,00	156,50	156,50
Available Energy in Exhaust Gases (GJ/h)	0,00	0,00	0,00	0,00	0,00
Excess Energy(steam dumping ,incineration)(GJ/h)	-127,34	-136,51	31,64	-137,35	-137,35
Equivalent HFO Consumption (t/h)	0,00	0,00	0,78	0,00	0,00
Equivalent MDO Consumption (t/h)	0,00	0,00	0,00	0,00	0,00
Equivalent MGO Consumption (t/h)	0,00	0,00	0,00	0,00	0,00

Continuation of Table B.3

	Steam Turbine (Single Screw)	**Dual-fuel-electric (Single Screw)**	**Two-stroke Diesel + Reliquefaction (Twin Screw)**	**Simple-cycle Gas Turbine-electric (Single Screw)**	**Combined-cycle Gas Turbine-electric (Single Screw)**
Auxiliary Power for cargo pumping loading					
ENERGY NEEDED (GJ/h)	51,60	33,46	33,80	36,45	51,06
Available Energy in BOG (GJ/h)	0,00	0,00	0,00	0,00	0,00
Available Energy in Exhaust Gases (GJ/h)	0,00	0,00	0,00	0,00	0,00
Extra Energy Needed (GJ/h)	51,60	33,46	33,80	36,45	51,06
Equivalent HFO Consumption (t/h)	1,28	0,83	0,84	0,00	1,26
Equivalent MDO Consumption (t/h)	0,00	0,78	0,00	0,00	0,00
Equivalent MGO Consumption (t/h)	0,00	0,00	0,00	0,85	1,20
Auxiliary Power for cargo pumping unloading					
ENERGY NEEDED (GJ/h)	51,60	33,46	33,80	36,45	51,06
Available Energy in BOG (GJ/h)	0,00	0,00	0,00	0,00	0,00
Available Energy in Exhaust Gases (GJ/h)	0,00	0,00	0,00	0,00	0,00
Extra Energy Needed (GJ/h)	51,60	33,46	33,80	36,45	51,06
Equivalent HFO Consumption (t/h)	1,28	0,83	0,84	0,00	1,26
Equivalent MDO Consumption (t/h)	0,00	0,78	0,00	0,00	0,00
Equivalent MGO Consumption (t/h)	0,00	0,00	0,00	0,85	1,20

Table B4

Plant efficiencies		**INPUT DATA WITH BOLD**

Steam Turbine (Single Screw)	**Efficiency (%)**	**Dual-fuel-electric (Single Screw)**	**Efficiency (%)**	**Two-stroke Diesel + Reliquefaction (Twin Screw)**	**Efficiency (%)**	**Simple-cycle Gas Turbine-electric (Single Screw)**	**Efficiency (%)**	**Combined-cycle Gas Turbine-electric (Single Screw)**	**Efficiency (%)**
Fuel / BOG	**100%**	Fuel / BOG	**100%**	Fuel	**100%**	Fuel / BOG	**100%**	Fuel / BOG	**100%**
Boilers	**89%**	DF engines	**48%**	Two-str. engines	**49%**	Gas turbine cycle	**37%**	Gas turbine & steam turbine combined cycle	**44%**
Steam cycle	**35%**	Alternators	**97%**	Shafting	**98%**	Alternators	**97%**	Alternators	**97%**
Gearbox	**98%**	Transfere & Conversion	**98%**			Transf. & Conversion	**98%**	Transf. & Conversion	**98%**
Shafting	**99%**	Electric motors	**98%**			Electric motors	**98%**	Electric motors	**98%**
		Gearbox	**98%**			Gearbox	**98%**	Gearbox	**98%**
		Shafting	**99%**			Shafting	**99%**	Shafting	**99%**
Propulsion Efficiency	30%	**Propulsion Efficiency (in gas mode)**	43%	**Propulsion Efficiency**	48%	**Propulsion Efficiency**	33%	**Propulsion Efficiency**	40%
Fuel / BOG	**100%**	Fuel / BOG	**100%**	Fuel	**100%**	Fuel / BOG	**100%**	Fuel / BOG	**100%**
Boilers	**89%**	DF engines	**48%**	Aux. engines	**45%**	Gas turbine	**37%**	Gas turbine& steam turbine combined cycle	**44%**
Steam turbogen cycle	**30%**	Alternators	**97%**	Alternators(Generator efficiency for gensets)	**96%**	Alternators	**97%**	Alternators	**97%**
Alternators(Generator efficiency for turbogens)	**96%**								
Electric Power Efficiency	26%	**Electric Power Efficiency**	47%	**Electric Power Efficiency**	43%	**Electric Power Efficiency**	36%	**Electric Power Efficiency**	43%

Sources:
1. Wärtsilä Finland [Ref.5]
2.Tractebel Gas Engineering GmbH & Dorchester Maritime Ltd. [Ref.13]

TABLE B5

Basic Data for the Machinery	**INPUT DATA WITH BOLD**
The specific energy consumption is calculated based on DMX Marine Diesel (MDO) with LCV:42,700 kJ/kg	
Steam Turbine (Single Screw)	
Boiler and Steam turbine	
Specific fuel oil (HFO) consumption (g/kWh)	**290**
Specific energy consumption (kJ/kWh)	12383
Specific L.O. Consumption (g/kWh)	**0**
Boiler and Turbo Generators	
Specific fuel oil (HFO) consumption for steam turbo-gensets (g/kWh)	290

Dual-fuel-electric (Single Screw)	
Specific fuel oil (MDO) consumption (g/kWh)	**190**
Specific energy consumption (kJ/kWh)	8113
Specific L.O. Consumption (g/kWh)	**0,8**
Pilot oil (kg/h)	**54**

Two-stroke Diesel + Reliquefaction (Twin Screw)	
Typically data for MAN B&W Two-Stroke MC engine	
Specific fuel oil (HFO) consumption (g/kWh)	**169**
Specific energy consumption (kJ/kWh)	7216,3
Specific Cylinder L.O. Consumption (g/kWh)	**1,5**
System Oil Consumption (kg/24h)	**75**
Typically data for small MAN B&W Four-Stroke HFO Gensets	
Specific fuel oil (HFO) consumption (g/kWh)	**190**
Specific L.O. Consumption (g/kWh)	**1**

Continuation of Table B.5

Simple-cycle Gas Turbine-electric (Single Screw)	
Gas Turbine	
Specific BOG (Methane) consumption (g/kWh)	**201**
Specific fuel oil (MGO) consumption (g/kWh)	**207**
Specific energy consumption (kJ/kWh)	8838,9
Specific L.O. Consumption (g/kWh)	**0**
Auxiliary gas turbine-genset	
Specific fuel oil (MGO) consumption for auxiliary gas turbine -genset (g/kWh)	**207**

Combined-cycle Gas Turbine-electric (Single Screw)	
Gas Turbine	
Specific BOG (Methane) consumption (g/kWh)	**201**
Specific fuel oil (MGO) consumption (g/kWh)	**207**
Specific energy consumption (kJ/kWh)	**8838,9**
Specific L.O. Consumption (g/kWh)	**0**
Turbo gensets	
Specific fuel oil (HFO) consumption for steam turbo-genset (g/kWh)	**290**
Specific fuel oil (MGO) consumption for auxiliary gas turbine -genset (g/kWh)	**207**

Sources:
1.MAN B&W Diesel A/S,Copenhagen,Denmark & MAN B&W Diesel AG, Augsburg, Germany [Ref.12, 49]
2.Maran Gas Maritime Inc. [Ref.50]
3.Wärtsilä Finland [Ref.5]
4.Marine Service GmbH, Hamburg [Ref.52]

Continuation of Table B.5

Specific Maintenance Cost (US$/MWh)		**Maintenance Cost at loaded conditions (US$/h)**		**Maintenance Cost at ballast conditions (US$/h)**		**Maintenance Cost at Port (US$/h)**	
Steam turbine installation	**0,4**	Steam turbine installation	11,92331478	Steam turbine installation	11,44638219	Steam turbine installation	1,443001443
Dual fuel installation	**3**	Dual fuel installation	102,2958574	Dual fuel installation	97,31449158	Dual fuel installation	39,13425038
Two-stroke Diesel + Reliquefaction	**1,3**	Two-stroke Diesel + Reliquefaction	38,36326531	Two-stroke Diesel + Reliquefaction	36,82873469	Two-stroke Diesel + Reliquefaction	4,642857143
Gas turbine installation	**2,5**	Gas turbine installation	87,26781922	Gas turbine installation	82,10604536	Gas turbine installation	35,98066099
Steam generator installation	**0,5**	Steam generator installation	0,879653809	Steam generator installation	0,778368571	Steam generator installation	4,330673014
Four-stroke auxiliary engines	**3,5**	Four-stroke auxiliary engines	17,47487345	Four-stroke auxiliary engines	11,10722839	Four-stroke auxiliary engines	49,17687241
Auxiliary gas turbine-genset	**2,5**	Auxiliary gas turbine-genset for Simple cycle Gas turbine	0	Auxiliary gas turbine-genset for Simple cycle Gas turbine	0	Auxiliary gas turbine-genset for Simple cycle Gas turbine	15,72712025

TABLE B6

Crew salaries		**INPUT DATA WITH BOLD**						
Crew ranks	**No**	**Payments Atomos 2002 (Euro/month/ person)**	**Payments Atomos 2002 (US$/month/person) 1Euro=1,2 US$**	**Payments for East European crew (M.G. crew department) (US$/month/person)**	**Difference (US$/month)**	**Difference %**	**Salaries (US$/month)**	**Salaries (US$/year) for 12 months**
Bridge and Deck personell							1,2	
Master	**1**	**5041**	6049,2	**11021**	4971,8	82,2	11010	132114,5
Chief officer	**1**	**4200**	5040	**8525**	3485	69,1	8517,6	102211,2
2nd officer	**2**	**3706**	4447,2	**3673**	-774,2	-17,4	7602,1	91224,62
Apprentice Deck	**1**	**1029**	1234,8				1234,8	14817,6
Bosun	**1**	**2426,5**	2911,8	**3040**	128,2	4,4	3028,3	36339,26
Able Body	**6**	**1982,5**	2379	**1074**	-1305	-54,9	9516	114192
Total	12						40908	490899,2
Engine room personell for steam vessels								
Chief Engineer	**1**	**4647**	5576,4	**10484**	4907,6	88	10484	125803,6
2nd Engineer	**1**	**3856**	4627,2	**8525**	3897,8	84,2	8514	102168,6
3rd Engineer	**3**	**2970,5**	3564,6	**3673**	108,4	3,04	11015	132175,4
Engine officer	**1**	**1029**	1234,8				1234,8	14817,6
Gas Engineer	**1**	**3200**	3840	**5705**	1865	48,6	5683,2	68198,4
Electrical technical Officer	**1**	**3014,5**	3617,4	**3914**	296,6	8,2	3906,8	46881,5
Stoker	**3**	**2970,5**	3564,6				10694	128325,6
Wiper	**1**	**2056**	2467,2	**3040**	572,8	23,2	3034,7	36415,87
Total	12						54566	654786,5
Engine room personell for vessels with internal combustion engines(Diesel and gas turbine)							1,2	
Chief Engineer	**1**	**4647**	5576,4	**10484**	4907,6	88	10484	125803,6
2nd Engineer	**1**	**3856**	4627,2	**8525**	3897,8	84,2	8514	102168,6
3rd Engineer	**2**	**2970,5**	3564,6	**3673**	108,4	3,04	7343,1	88116,91
Engine officer	**1**	**1029**	1234,8				1234,8	14817,6
Motorman A	**1**	**2867,5**	3441				3441	41292
Motorman B	**1**	**2059**	2470,8				2470,8	29649,6
Electrical technical Officer	**1**	**3014,5**	3617,4	**3914**	296,6	8,2	3906,8	46881,5
Wiper	**1**	**2056**	2467,2	**3040**	572,8	23,2	3034,7	36415,87
Gas engineer	**1**	**3200**	3840	**5705**	1865	48,6	5683,2	68198,4
Total	10						46112	553344

Continuation of Table B.6

Crew ranks	No	Payments Atomos 2002 (Euro/month/ person)	Payments Atomos 2002 (US$/month/person)	Payments for East European crew (M.G. crew department) (US$/month/person)	Difference (US$/month)	Difference %	Salaries (US$/month) 1Euro=1,2 US$	Salaries (US$/year) for 12 months
Catering personell								
Cook	**1**	**2426,5**	2911,8				2911,8	34941,6
Assist cook	**1**	**1588**	1905,6				1905,6	22867,2
Stewart	**1**	**1882,5**	2259				2259	27108
Assist Stewart	**1**	**1464,5**	1757,4				1757,4	21088,8
Total	4						8833,8	106005,6
Total crew number for steam vessels	28							
Total crew number for vessels with internal combustion engines	26							
Engine room personell for combined gas and steam turbine vessels								
Chief Engineer	**1**	**4647**	5576,4	**10484**	4907,6	88	10484	125803,6
2nd Engineer	**1**	**3856**	4627,2	**8525**	3897,8	84,2	8514	102168,6
3rd Engineer	**2**	**2970,5**	3564,6	**3673**	108,4	3,04	7343,1	88116,91
Engine officer	**1**	**1029**	1234,8				1234,8	14817,6
Motorman A	**1**	**2867,5**	3441				3441	41292
Motorman B	**1**	**2059**	2470,8				2470,8	29649,6
Electrical technical Officer	**1**	**3014,5**	3617,4	**3914**	296,6	8,2	3906,8	46881,5
Stoker	**1**	**2970,5**	3564,6				3564,6	42775,2
Wiper	**1**	**2056**	2467,2	**3040**	572,8	23,2	3034,7	36415,87
Gas Engineer	**1**	**3200**	3840	**5705**	1865	48,6	5683,2	68198,4
Total	11						49677	596119,2

Continuation of Table B.6

Crew	**Steam Turbine (Single Screw)**	**Dual-fuel-electric (Single Screw)**	**Two-stroke Diesel + Reliquefaction (Twin Screw)**	**Simple-cycle Gas Turbine-electric (Single Screw)**	**Combined-cycle Gas Turbine-electric (Single Screw)**
Number of engine room and auxiliary engine room personell	12	10	10	10	11
Salaries for the engine room and auxiliary engine room personell (US$/yr)	654786,5	553344,048	553344,048	553344,048	596119,248
Salaries for all personell (US$/yr)	1251691,3	1150248,855	1150248,855	1150248,855	1193024,06

Sources:
1.ΜΕΛΕΤΗ ΙΙ ΠΑΝΕΠΙΣΤΗΜΙΑΚΕΣ ΣΗΜΕΙΩΣΕΙΣ 2002 ΠΔ 238/1987 ΦΕΚ ΤΕΥΧΟΣ Α, ΦΥΛΛΟ 102,1987 (SAFETY MANNING) [Ref.48]
2.Atomos IV,2002 [Ref.46]
3.Maran Gas Maritime Inc. [Ref.51]

Table B7

LNG account	**INPUT DATA WITH BOLD**				
	Steam Turbine (Single Screw)	**Dual-fuel-electric (Single Screw)**	**Two-stroke Diesel + Reliquefaction (Twin Screw)**	**Simple-cycle Gas Turbine-electric (Single Screw)**	**Combined-cycle Gas Turbine-electric (Single Screw)**
Lost during loaded voyage (m³/per trip)	2400,94	2508,18	0,00	2641,03	2641,03
Lost during ballast voyage (m³/per trip)	1200,47	1254,09	0,00	1320,52	1320,52
Lost at Port (m³/per trip)	243,79	254,68	0,00	268,17	268,17
Total Lost LNG (m³/per trip)	3845,19	4016,95	0,00	4229,71	4229,71
Reliquefied LNG loaded voyage (m³/per trip)	0,00	0,00	2501,78	0,00	0,00
Reliquefied LNG ballast voyage (m³/per trip)	0,00	0,00	1250,89	0,00	0,00
Reliquefied LNG at Port (m³/per trip)	0,00	0,00	254,03	0,00	0,00
Total Reliquefied LNG (m³/per trip)	0,00	0,00	4006,69	0,00	0,00
Cargo capacity for the steam turbine vessel (m³)	**150000,00**	**150000,00**	**150000,00**	**150000,00**	**150000,00**
Extra delivered cargo compared to the 150,000 m³ steam turbine vessel (m³)	**0,00**	**6700,00**	**6300,00**	**15000,00**	**15000,00**
Total cargo capacity (100% full) (m³)	150000,00	156700,00	156300,00	165000,00	165000,00
Minimum Level of LNG (m³)	**2000,00**	**2000,00**	**2000,00**	**2000,00**	**2000,00**
Delivered cargo at terminal port (without the lost LNG at port) (m³)	144398,59	150937,73	154300,00	159038,45	159038,45
Delivered cargo (m³)	141963,91	148394,29	151955,50	156360,30	156360,30

Sources:
1.Tractebel Gas Engineering GmbH & Dorchester Maritime Ltd. [Ref.13]
2.Maran Gas Maritime Inc.
3.MAN B&W Diesel A/S,Copenhagen,Denmark & MAN B&W Diesel AG, Augsburg, Germany [Ref.12, 49]
4.Marine Service GmbH, Hamburg [Ref.52] , 5.MTP Consultancy [Ref.4]

Continuation of Table B.7

	Steam Turbine (Single Screw)	**Dual-fuel-electric (Single Screw)**	**Two-stroke Diesel + Reliquefaction (Twin Screw)**	**Simple-cycle Gas Turbine-electric (Single Screw)**	**Combined-cycle Gas Turbine-electric (Single Screw)**
Value of lost LNG (US$/per trip) (Fuel oil is used only as add-up energy)	641978,57	670653,62	0,00	706176,43	706176,43
Value of lost LNG (US$/yr)	7703742,90	8047843,42	0,00	8474117,19	8474117,19
Savings from the Reliquified cargo (US$/per trip)	0,00	0,00	668941,68	0,00	0,00
Savings from the Reliquified cargo (US$/yr)	0,00	0,00	8027300,10	0,00	0,00
Revenues from selling the delivered cargo capacity (US$/per trip)	24071719,36	25162070,39	25765916,48	26512803,75	26512803,75
Revenues from selling the delivered cargo capacity (US$/year)	288860632,35	301944844,66	309190997,76	318153644,99	318153644,99
Savings from the extra cargo delivered compared to steam vessel (US$/year)	0,00	13084212,31	20330365,41	29293012,64	29293012,64
Delivered annual quantity (t/y)	792158,60	828040,16	847911,69	872490,46	872490,46
Cost for LNG (FOB price) (million US$/year)	126,05	131,76	134,92	138,83	138,83
Income from sale (CIF price) (million US$/year)	288,86	301,94	309,19	318,15	318,15
Income-Cost for LNG (million US$/year)	162,81	170,19	174,27	179,32	179,32

TABLE B8

Gas emissions from LNG carriers *

INPUT DATA WITH BOLD

* Note that the emission level always depends on the load (100%,85%,75% MCR or lower).These figures are typical emission levels for 85% load. Also the emission level depends on the gas composition, in gas operating mode. So these figures should be seen as indicative only.

Option	**Fuel used for the prime mover loaded&ballast**	NOx t/year /ship	SOx t/year /ship	CO2 t/year /ship
Steam Turbine	BOG only	250,64	0	110509,5
	HFO only	314,9223	4060,602	144377
Dual-fuel-electric	BOG only	342,4221	0	105172,5
	MDO only	2812,753	746,0623	154090
Two-stroke Diesel + Reliquefaction	HFO only	3505,463	3626,341	128936,6
Simple-cycle Gas Turbine-electric	BOG only	354,6515	0	110064,3
	MGO only	463,439	579,2987	92687,79
Combined-cycle Gas&Steam Turbine-electric	BOG only	354,6515	0	110064,3
	MGO only	338,9312	423,6641	67786,25

Sourses:
1. Propulsion alternatives, LNG ,DNV
2.‘Pioneering Gas Turbine-Electric System in Cruise Ships:A Performance Update’ [53]
3.Wärtsilä [Ref.5]
4.Table C7 TECHNE's proposed emission factors used for the European Commission's MEET project [Ref.54]

Table B9

Cost-Benefir Analysis :Owner/Operator

Propulsion Plant	INVESTMENT COST (million US $)	INSTALLATION COST (million US $)	TOTAL OPERATING COST (million US $/yr)	PROFIT (FROM TIME CHARTER MINUS THE OPERATING COST) (million US$/year)	SAVINGS COMPARED TO STEAM VESSEL (million US$/year)	REVENUES FROM SCRAP VALUE (million US$)
Steam Turbine Direct Drive (Single Screw)	20,00	0,50	1,35	18,01	0,00	0,60
Medium Speed Dual Fuel Diesel (GAS/MDO) Electric Drive (Single Screw)	21,65	0,45	2,21	20,41	2,40	0,65
Slow Speed Diesel Direct Drive (Twin Screw)	20,80	0,60	2,99	24,00	5,99	0,62
Gas Turbine Electric Drive (Single Screw)	25,85	0,40	1,82	17,50	-0,51	0,78
Combined Gas and Steam Turbine Electric Drive (Single Screw)	26,55	0,43	1,78	23,10	5,09	0,80

Continuation of Table B.9. NPV results

Propulsion Plant	NPV10 (million US$)	NPV20 (million US$)	NPV30 (million US$)
Steam Turbine Direct Drive (Single Screw)	105,63	174,57	212,47
Medium Speed Dual Fuel Diesel (GAS/MDO) Electric Drive (Single Screw)	120,57	198,60	241,55
Slow Speed Diesel Direct Drive (Twin Screw)	145,88	237,28	287,48
Gas Turbine Electric Drive (Single Screw)	96,53	163,41	200,22
Combined Gas and Steam Turbine Electric Drive (Single Screw)	134,65	223,16	272,02

i (MARKET INTEREST RATE) :	0,06

Continuation of Table B.9. NPV results

Propulsion Plant	NPV10 (million US$)	NPV20 (million US$)	NPV30 (million US$)
Steam Turbine Direct Drive (Single Screw)	92,85	144,03	167,36
Medium Speed Dual Fuel Diesel (GAS/MDO) Electric Drive (Single Screw)	106,09	164,02	190,47
Slow Speed Diesel Direct Drive (Twin Screw)	128,80	196,67	227,57
Gas Turbine Electric Drive (Single Screw)	84,24	133,89	156,56
Combined Gas and Steam Turbine Electric Drive (Single Screw)	118,29	184,00	214,08

i (MARKET INTEREST RATE):	0,08

Continuation of Table B.9. NPV results

Propulsion Plant	NPV10 (million US$)	NPV20 (million US$)	NPV30 (million US$)
Steam Turbine Direct Drive (Single Screw)	81,91	120,22	134,76
Medium Speed Dual Fuel Diesel (GAS/MDO) Electric Drive (Single Screw)	93,70	137,06	153,54
Slow Speed Diesel Direct Drive (Twin Screw)	114,18	164,98	184,23
Gas Turbine Electric Drive (Single Screw)	73,74	110,90	125,02
Combined Gas and Steam Turbine Electric Drive (Single Screw)	104,29	153,48	172,21

i (MARKET INTEREST RATE):	0,1

Table B10

Cost-Benefit Analysis:Charterer

Propulsion Plant	TRANSPORTATION COST (million US $/yr)	PROFIT (FROM SELLING THE DELIVERED CARGO CAPACITY MINUS THE EXPENCES) (million US$/year)	SAVINGS COMPARED TO STEAM VESSEL (million US$/year)
Steam Turbine Direct Drive (Single Screw)	38,98	123,83	0,00
Medium Speed Dual Fuel Diesel (GAS/MDO) Electric Drive (Single Screw)	40,96	129,22	5,40
Slow Speed Diesel Direct Drive (Twin Screw)	42,66	131,61	7,78
Gas Turbine Electric Drive (Single Screw)	41,27	138,05	14,22
Combined Gas and Steam Turbine Electric Drive (Single Screw)	41,89	137,43	13,60

Continuation of Table B.10. NPV results

Propulsion Plant	NPV10 (million US$)	NPV20 (million US$)	NPV30 (million US$)
Steam Turbine Direct Drive (Single Screw)	892,45	1438,34	1771,93
Medium Speed Dual Fuel Diesel (GAS/MDO) Electric Drive (Single Screw)	931,88	1502,68	1851,90
Slow Speed Diesel Direct Drive (Twin Screw)	949,98	1533,12	1890,59
Gas Turbine Electric Drive (Single Screw)	994,44	1602,01	1972,87
Combined Gas and Steam Turbine Electric Drive (Single Screw)	991,26	1598,68	1970,46

i (MARKET INTEREST RATE):	0,06

Continuation of Table B.10. NPV results

Propulsion Plant	NPV10 (million US$)	NPV20 (million US$)	NPV30 (million US$)
Steam Turbine Direct Drive (Single Screw)	797,46	1202,09	1407,20
Medium Speed Dual Fuel Diesel (GAS/MDO) Electric Drive (Single Screw)	832,68	1255,76	1470,48
Slow Speed Diesel Direct Drive (Twin Screw)	848,82	1281,04	1500,83
Gas Turbine Electric Drive (Single Screw)	888,61	1338,97	1567,00
Combined Gas and Steam Turbine Electric Drive (Single Screw)	885,72	1335,95	1564,54

i (MARKET INTEREST RATE):	0,08

Continuation of Table B.10. NPV results

Propulsion Plant	NPV10 (million US$)	NPV20 (million US$)	NPV30 (million US$)
Steam Turbine Direct Drive (Single Screw)	716,01	1018,42	1146,01
Medium Speed Dual Fuel Diesel (GAS/MDO) Electric Drive (Single Screw)	747,62	1063,81	1197,38
Slow Speed Diesel Direct Drive (Twin Screw)	762,08	1085,09	1221,81
Gas Turbine Electric Drive (Single Screw)	797,87	1134,45	1276,31
Combined Gas and Steam Turbine Electric Drive (Single Screw)	795,24	1131,71	1273,91

i (MARKET INTEREST RATE):	0,1

Table B11

Cost-Benefit Analysis:LNG producing and trading (NG company)

Propulsion Plant	INVESTMENT COST (million US $)	INSTALLATION COST (million US $)	TOTAL OPERATING COST (million US $/yr)	PROFIT (FROM SELLING THE DELIVERED CARGO CAPACITY MINUS THE EXPENCES) (million US$/year)	SAVINGS COMPARED TO STEAM VESSEL (million US$/year)	REVENUES FROM SCRAP VALUE (million US$)
Steam Turbine Direct Drive (Single Screw)	20,00	0,50	20,97	141,84	0,00	0,60
Medium Speed Dual Fuel Diesel (GAS/MDO) Electric Drive (Single Screw)	21,65	0,45	20,55	149,63	7,80	0,65
Slow Speed Diesel Direct Drive (Twin Screw)	20,80	0,60	18,66	155,61	13,77	0,62
Gas Turbine Electric Drive (Single Screw)	25,85	0,40	23,77	155,56	13,72	0,78
Combined Gas and Steam Turbine Electric Drive (Single Screw)	26,55	0,43	18,80	160,53	18,69	0,80

Continuation of Table B.11. NPV results

Propulsion Plant	NPV10 (million US$)	NPV20 (million US$)	NPV30 (million US$)
Steam Turbine Direct Drive (Single Screw)	998,08	1612,91	1984,39
Medium Speed Dual Fuel Diesel (GAS/MDO) Electric Drive (Single Screw)	1052,45	1701,27	2093,45
Slow Speed Diesel Direct Drive (Twin Screw)	1095,86	1770,40	2178,07
Gas Turbine Electric Drive (Single Screw)	1090,98	1765,42	2173,09
Combined Gas and Steam Turbine Electric Drive (Single Screw)	1125,91	1821,84	2242,48

i (MARKET INTEREST RATE):	0,06

Continuation of Table B.11. NPV results

Propulsion Plant	NPV10 (million US$)	NPV20 (million US$)	NPV30 (million US$)
Steam Turbine Direct Drive (Single Screw)	890,30	1346,12	1574,57
Medium Speed Dual Fuel Diesel (GAS/MDO) Electric Drive (Single Screw)	938,77	1419,78	1660,95
Slow Speed Diesel Direct Drive (Twin Screw)	977,62	1477,70	1728,40
Gas Turbine Electric Drive (Single Screw)	972,86	1472,86	1723,56
Combined Gas and Steam Turbine Electric Drive (Single Screw)	1004,01	1519,95	1778,63

i (MARKET INTEREST RATE):	0,08

Continuation of Table B.11. NPV results

Propulsion Plant	NPV10 (million US$)	NPV20 (million US$)	NPV30 (million US$)
Steam Turbine Direct Drive (Single Screw)	797,92	1138,64	1280,77
Medium Speed Dual Fuel Diesel (GAS/MDO) Electric Drive (Single Screw)	841,32	1200,87	1350,91
Slow Speed Diesel Direct Drive (Twin Screw)	876,26	1250,07	1406,04
Gas Turbine Electric Drive (Single Screw)	871,61	1245,35	1401,33
Combined Gas and Steam Turbine Electric Drive (Single Screw)	899,53	1285,19	1446,13

i (MARKET INTEREST RATE):	0,1

Table B12

Cost-Benefit Analysis:Additional income

Propulsion Plant	INVESTMENT COST (million US $)	INSTALLATION COST (million US $)	TOTAL OPERATING COST (million US $/yr)	SAVINGS FROM THE EXTRA CARGO DELIVERED COMPARED TO STEAM VESSEL (US$/year)	SAVINGS COMPARED TO STEAM VESSEL (Savings from extra cargo delivered minus the extra operating cost) (million US$/year)	REVENUES FROM SCRAP VALUE (million US$)
Steam Turbine Direct Drive (Single Screw)	20,00	0,50	20,97	0,00	0,00	0,60
Medium Speed Dual Fuel Diesel (GAS/MDO) Electric Drive (Single Screw)	21,65	0,45	20,55	13,08	13,51	0,65
Slow Speed Diesel Direct Drive (Twin Screw)	20,80	0,60	18,66	20,33	22,64	0,62
Gas Turbine Electric Drive (Single Screw)	25,85	0,40	23,77	29,29	26,50	0,78
Combined Gas and Steam Turbine Electric Drive (Single Screw)	26,55	0,43	18,80	29,29	31,47	0,80

Continuation of Table B.12. NPV results

Propulsion Plant	ΔNPV10 (million US$)	ΔNPV20 (million US$)	ΔNPV30 (million US$)
ALT1			
ΔNPV ALT2-ALT1	95,32	154,06	189,74
ΔNPV ALT3-ALT1	161,40	259,58	319,03
ΔNPV ALT4-ALT1	184,57	299,60	369,32
ΔNPV ALT5-ALT1	219,50	356,03	438,71

i (MARKET INTEREST RATE):	0,06

ALT 1: Steam Turbine Direct Drive (Single Screw)
ALT 2: Medium Speed Dual Fuel Diesel (GAS/MDO) Electric Drive (Single Screw)
ALT 3: Slow Speed Diesel Direct Drive (Twin Screw)
ALT 4: Gas Turbine Electric Drive (Single Screw)
ALT 5: Combined Gas and Steam Turbine Electric Drive (Single Screw)

Continuation of Table B.12. NPV results

Propulsion Plant	ΔNPV10 (million US$)	ΔNPV20 (million US$)	ΔNPV30 (million US$)
ALT1			
ΔNPV ALT2-ALT1	85,06	128,60	150,54
ΔNPV ALT3-ALT1	144,18	216,96	253,52
ΔNPV ALT4-ALT1	164,48	249,76	292,63
ΔNPV ALT5-ALT1	195,64	296,85	347,70

i (MARKET INTEREST RATE):	0,08

Continuation of Table B.12. NPV results

Propulsion Plant	ΔNPV10 (million US$)	ΔNPV20 (million US$)	ΔNPV30 (million US$)
ALT1			
ΔNPV ALT2-ALT1	76,26	108,81	122,46
ΔNPV ALT3-ALT1	129,41	183,81	206,56
ΔNPV ALT4-ALT1	147,26	211,00	237,67
ΔNPV ALT5-ALT1	175,19	250,84	282,47

i (MARKET INTEREST RATE):	0,1

APPENDIX C

Exhaust gas Emissions from HFO Diesel Engines

When talking about exhaust gas emissions from ships, the relevant components are NOx, SOx, CO, CO2, HC, and particulates, see Fig. C.1.

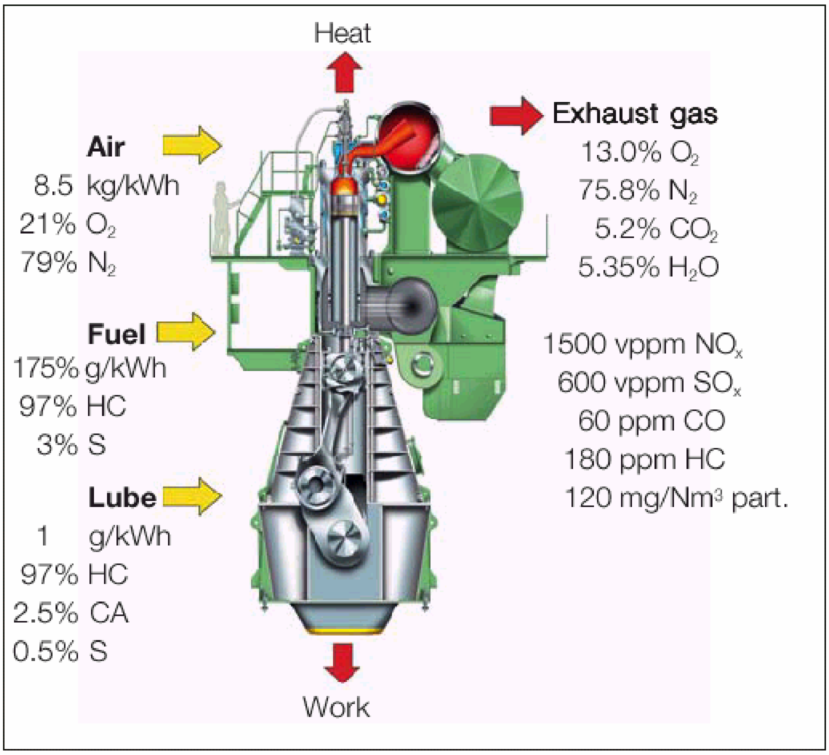


Fig. C.1 Flow process and typical exhaust gas composition [18].

So far, particulates and HC, together with NO_2 and water vapour (constituting visible smoke) are being judged by not so accurate opacity measurements. At this stage, and probably for many years ahead, NOx and SOx will be the only components that will be given international measurable limits in the marine market. It is expected that HC and particulates will follow, but it is uncertain when this will happen.

The industry is still considering the optimum methods of controlling HC and particulates, and the method of measuring also remains to be agreed upon. The situation is different for power plants, for which there are often limits to all polluting components of the Diesel exhaust gas. It should be noted that pollutants are usually measured as concentrations, whereas rules are formulated as absolute emission factors (mass per unit, time or power) arrived at by calculation, based on the concentration measurements [18].

Oxides of Sulphur (SOx)

Because of the organic origin of fuel oils, various amounts of sulphur are present in the oil injected into the combustion chamber. During combustion, the fuel sulphur is oxidised into different oxides of sulphur (SOx), mainly SO_2 and SO_3, typically in a ratio of 15:1. The emission of SOx from the engine is therefore a function of the sulphur content in the fuel oil [18].

Nitrogen Oxides (NOx)

Nitrogen Oxides (NOx) are formed during the combustion process within the burning fuel sprays. NOx is controlled by local conditions in the spray with temperature and oxygen concentration as the dominant parameters. At the temperature in the burning fuel spray, nitrogen is no longer inactive, and oxygen and nitrogen will inevitably react to form oxides of nitrogen. A rule of thumb says that a change of 100^{o}C in combustion temperatures may change the NOx amount by a factor of 3 (in other words high combustion temperature increases the NOx). The immediate reaction is the formation of NO. Later in the process, during expansion and in the exhaust system, part of the NO will convert to form NO_2 and N_2O, typically 5% and 1%, respectively, of the original NO amount [18].

Hydrocarbons (and trace organics)

During the combustion process, a very small part of the hydrocarbons will leave the process unburned, and others will be formed. These are referred to as unburned hydrocarbons, and they are normally stated in terms of equivalent CH_4 content.

The content of hydrocarbons in the exhaust gas from large Diesel engines depends on the type of fuel, and the engine adjustment and design. Reduced sac volume in the fuel valves has greatly reduced HC emissions. The sac volume is the void space in the fuel valve downstream of the closing face, as seen in Fig. C.2.

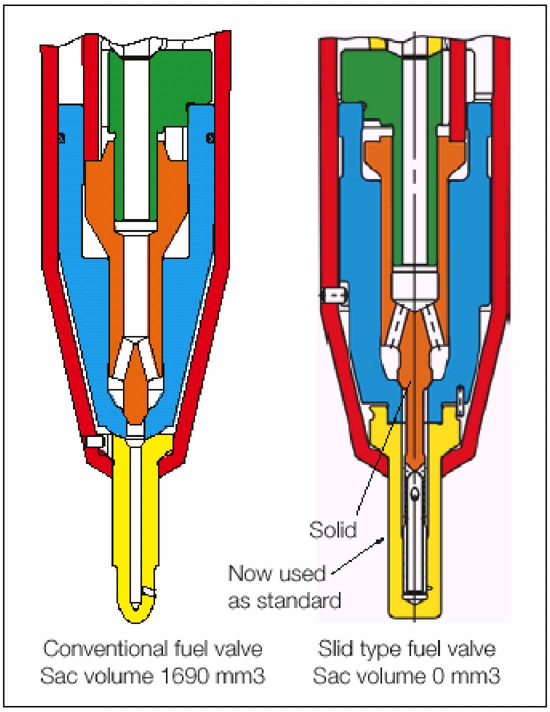


Fig. C.2 Fuel valves for K98MC [18].

The slide-type fuel valve design has quite an impact on HC and particulates. For compliance with the IMO rules, low-NOx nozzles are used. For HC and particulate control in general, slide-type fuel valves are used. The latest valves feature both the zero-sac volume and the low-NOx spray pattern, see Fig.C.3.

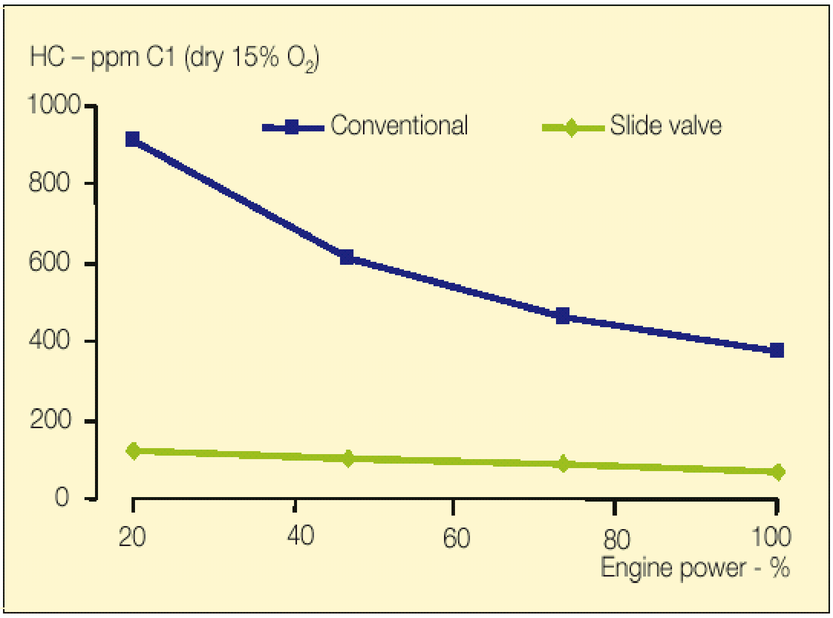


Fig. C.3 Hydrocarbon emission, fuel valve comparison – 7S50MC-C [18].

It should be mentioned that the IMO NOx -regulation, when ratified, does not apply for ships where the keel was laid before January 2000 [18].

Particulate emissions

Particulate emissions in the exhaust gas may originate from a number of sources:

- agglomeration of very small particles of partly burned fuel,
- partly burned lube oil,
- ash content of fuel oil and cylinder lube oil,
- sulphates and water.

The contribution from the lube oil consists mainly of calcium compounds, viz.sulphates and carbonates, as calcium is the main carrier of alkalinity in lube oil to neutralise sulphuric acid. Once fuel is atomised in the combustion chamber, the combustion process in a Diesel engine involves small droplets of fuel which evaporate, ignite, and are subsequently burned. During this process, a minute part of the oil will be left as a “nucleus” comprising mainly carbon. Consequently; particulate emission will vary substantially with fuel oil composition and with lube oil type and dosage. It is therefore difficult to state general emission rates for particulates.

In general, the particles are small, and it can be expected that over 90% will be less than 1 μm when heavy fuel oil is used, excluding flakes of deposits, peeling-off from them combustion chamber or exhaust system walls, which in general are much larger.Apart from the fact that a smoking engine can cause health problems it is also not a very pleasant sight. The soot from an engine can cause difficulties, especially if it is “wet” with oil. In such cases, it may deposit in the exhaust gas boiler, especially on cold surfaces, thus increasing the back pressure and representing a boiler fire hazard. Combustion process control, together with appropriate temperature control in the boiler, and frequent cleaning, are the ways to avoid this problem [18].

Sulphur content in fuel and particulates in exhaust gas

As mentioned above, the sulphur content in fuel oil has a large impact on the particle level in the exhaust gas. IMO has proposed restrictions of sulphur to 1.5% in special areas like the North Sea and the Baltic Sea in northern Europe, and local marine emission rules, e.g. in Sweden and Norway, are aimed at reducing the particulate emission substantially. Tests and analysis of exhaust gas have shown that a high-sulphur HFO can give several times higher particle levels than if the engine is operated on gas oil. A large part of the difference between HFO and DO is related to the sulphur, which together with water forms particulates. This is seen in Fig.C.4.

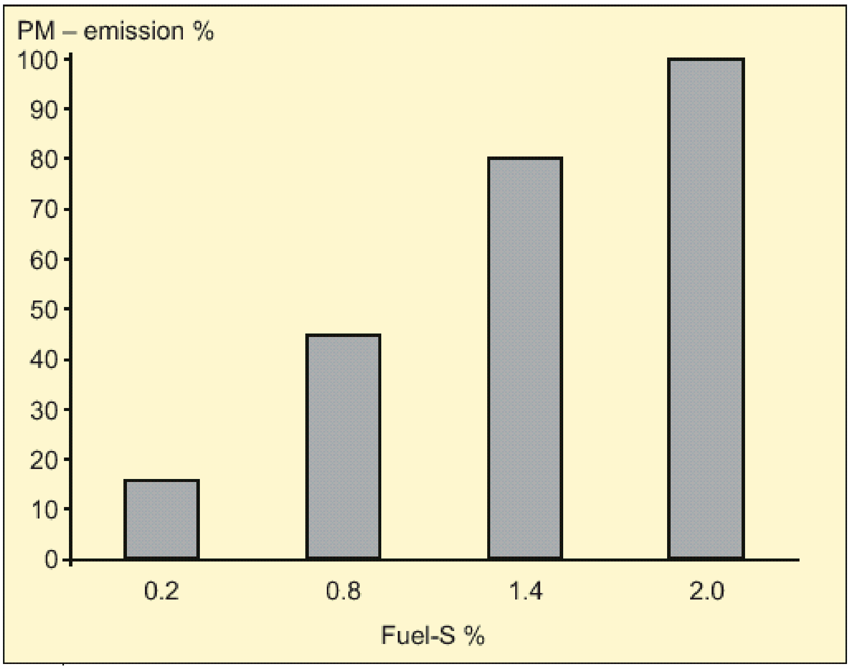


Fig.C.4 Emission of particulates as a function of fuel sulphur content [18].

Correspondingly, long time use of lower-than-average sulphur fuels will, contrary to normal marine applications, call for the use of lower BN lube oils in order not to overdose the combustion chamber with deposit-generating additivated oils. This will be particularly relevant for engines operated continuously at high load having less need for SOx neutralising on the liner surface due to high temperature.

It has been established that a certain level of controlled corrosion enhances lubrication, in that the corrosion generates small "pockets" in the cylinder liner running face from which hydrodynamic lubrication from the oil in the pocket is created. The alternative, no corrosion, could lead to bore-polish and, subsequently, hamper the creation of the necessary oil film on the liner surface, eventually resulting in accelerated wear.

This phenomenon also occurs on trunk piston engines where a bore-polished cylinder liner surface hampers the functioning of oil scraper rings and leads to accelerated lube oil consumption due to the open access to the crankcase oil. **Corrosion control – not avoiding corrosion – is therefore crucial, and adjusting the BN to the fuel oil sulphur content is essential particularly on high-load stationary engines.**

It should be considered that, irrespective of the sulphur content being high or low, the fuels used in low speed engines are usually low quality heavy fuels. Therefore, the cylinder oils must have full capacity in respect of detergency and dispersancy , irrespective of the BN specified. This is a newly developed technology now mastered by the well-reputed lube oil suppliers, who can individually tailor cylinder lube oil to the relevant fuel.

In consequence of the above, the cylinder oil feed rate has an impact on the particulate emission. Tests show that when reducing the cylinder oil feed rate, the particulate emission is also reduced, see Fig.C.5.

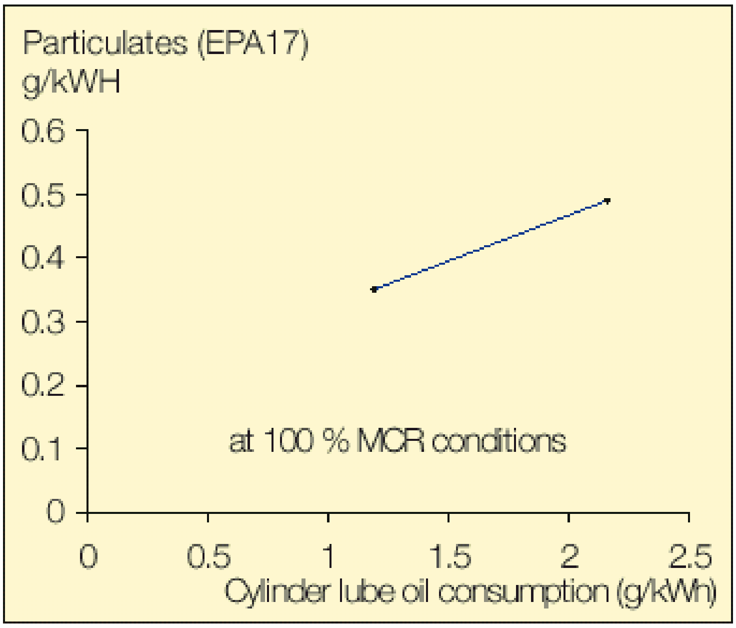


Fig. C.5 Particulate emission as a function of cyl.lube oil consumption [18].

Cylinder lube oil consumption represents a large expenditure for engine operation, and the reduction of cylinder lubrication is an important development theme. The aim is to reduce the cylinder lube oil dosage, while at the same time maintaining a satisfactory piston ring/liner wear rate and maintaining, or improving, the time between overhauls [18].

Smoke

A traditional measure of the combustion quality, and a traditional way of qualifying the ‘emission ’, is to look at, or to measure, the smoke intensity. The exhaust gas plume, when it leaves the top of the stack, may be visible for various reasons, e.g. due to its content of particulate matter and nitrogen dioxide, NO_2 (a yellow/brown gas), or of condensing water vapour. Although it may be argued that these components are either subject to separate legislation (NOx ,particulate matter) or not harmful (water),it is a fact that smoke and/or opacity limits are traditionally applied in certain countries, e.g. in the USA.

Unfortunately, methods of measuring smoke and opacity vary, and the figures resulting from the different methods are not really comparable.

When considering visible emissions, we should bear in mind that the larger the engine, the more likely it is that the exhaust gas plume will be visible. This is because, for a given Bosch Smoke Number (BSN value), **the greater the diameter of the plume, the greater the amount of light it will absorb**. For instance, **a BSN of 1 will mean almost invisible exhaust gas from a truck engine, but visible exhaust gas from a large, low-speed engine**.

At transient load and at low load, smoke is often visible, but typical smoke values for the most recent generation of MAN B&W engines are so low that the exhaust plume will be invisible, unless water vapour condenses in the plume, producing a grey or white colour. However, the NO_2 may give the plume a yellowish appearance. As mentioned, low and transient load smoke will practically disappear on electronically controlled engines [18].

CO_2 emission

Emission control has turned into the most important driving force for development. Hence, this is an area to which extensive development effort is allocated. This emphasises both on NOx control, SOx limitation, and particulate control and, to an increasing extent, on CO_2 emission, the latter reflecting thermal efficiency.

The so-called greenhouse effect is widely discussed, and the CO_2 concentration in the atmosphere is looked at with some anxiety. In any case, the low speed Diesel is the heat engine available for LNG vessels propulsion with lower CO_2 emission than the steam turbine (see Fig. C.6). This is possible simply by virtue of its high thermal efficiency.

The boil-off rate of modern LNG containment systems is so low that this gas, when burned in the boiler only constitutes about 30-50% of the energy consumed to produce the steam for the turbines. The rest is supplied as heavy fuel.

By reliquefying the boil-off gas and returning it to the tanks, and by using regular heavy fuel burning low speed Diesels for LNG carrier propulsion, the CO_2 emission could be reduced by up to 30%, and the returned gas could be sold offering a great economic benefit as well.

The development of new measuring equipment for emission control will continue in the coming years, and especially techniques like EGR will be further developed and tested. The concern of local authorities will change from focussing on NOx and SOx to include also smoke, in particular, and CO_2 [18].

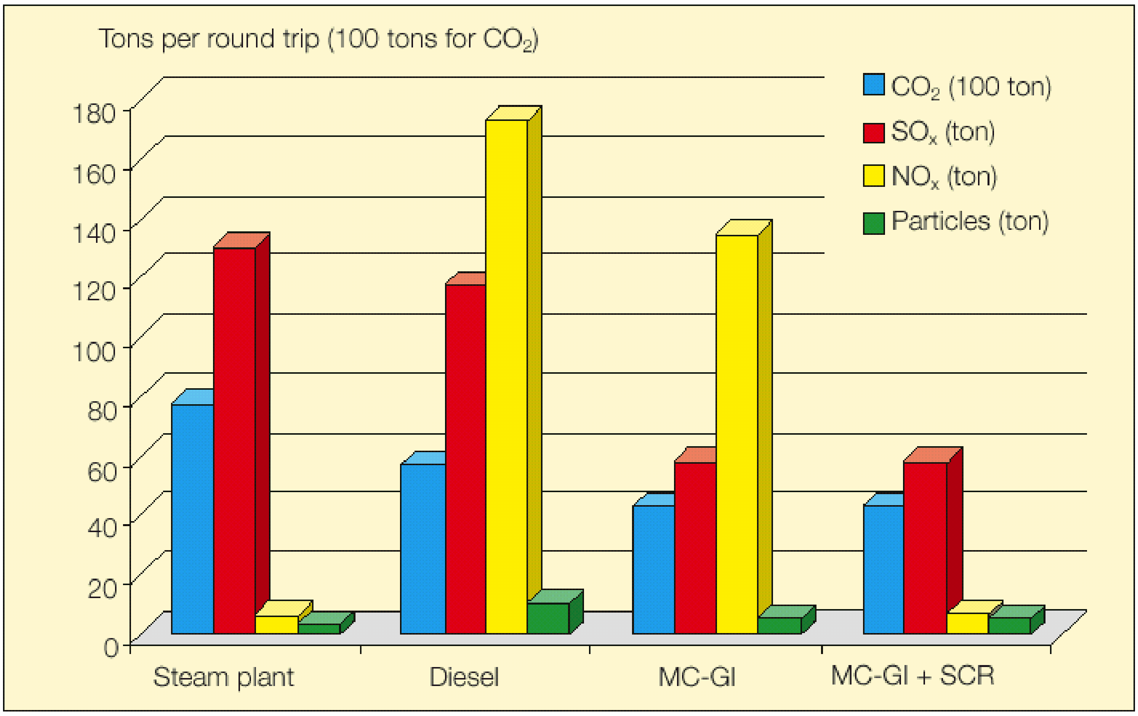


Fig. C.6 Round trip emissions, for a 135,000 m^3 LNG carrier [18].

Emission reduction

The IMO Annex VI was ratified in 2004 and, thereby, an international exhaust gas emission limit for ships will be introduced, but more local rules may also be introduced.

Local rules that encourage the use of emission cutting means, such as SCR reactors, through harbour fee reductions can become more dominant than today, whereas an international rule is preferred by the industry on the ground that the emission cutting means on board are the same wherever a ship is operating and trading. SCR units are preferably installed during the construction of the vessel, however retrofitting is also possible.

The challenge to shipowners will increase as vessels are required to have, or be prepared for, emission control equipment. The sulphur content in fuel will have to be reduced, and vessel tank systems will have to be prepared for dual fuel and dual cylinder lube oil systems. In some areas, the operating profile of the ship will have to be adapted to local rules for reduced smoke emission.

Over the years, engine manufacturers have worked with the exhaust gas emission issue in order to develop means to reduce the levels so as to comply with limitations which can be expected to come.

The next generation of emission control systems, which is on the drawing board and on the test facility, involves systems integrated into the engines.

To lower (NOx) emissions there are in principle two ways to: primary and secondary methods.

While primary methods prevent the NOx and other pollutants from being formed, secondary methods aim at reducing or removing the already formed pollutants.

Primary methods: fuel valve and nozzle optimisation and timing tuning.

Secondary methods (see also Fig.C7):

SCR –Technique

SCR (Selective Catalytic Reduction) reduces NOx –emission up to 80-95% by using urea. This method requires low sulphur bunker oil of good quality and exhaust temperature above 300 ^{o}C. There will be no increased oil consumption. The method requires investment in installations and increased running costs due to the urea consumption [47].

HAM- Technique

HAM-technique (Humid Air Motor) prevents the production of NOx during the combustion through adding water steam to the engine’s combustion air. The method is insensitive to the oil quality and the engine’s work load. Sea water can be used for the process and NOx- reduction will be between 50 and 80%. There will be no increased fuel consumption. The method requires investment in installations, but very limited increased running costs [47].

Water Injection

Water injection in the combustion room prevents and reduces NOx-emission with 20-50%. The method requires rebuilding of the engine and fresh water without salt. Increased fuel consumption occurs in proportion to the NOx- reduction. The system is today technically complicated [47].

Water Emulsion

Water emulsion in the fuel prevents the production of NOx. The method needs simple installation but can cause problems with quick stop and maneuver. Stability problem with water/oil emulsion requires special measures.The method increases fuel consumption at higher NOx reduction levels [47].

These methods, so far, look very promising, and a reduction of NOx of up to 50% and a reduction of particulates and HC seems achievable, even though final tests and production maturing still need to be taken care of.

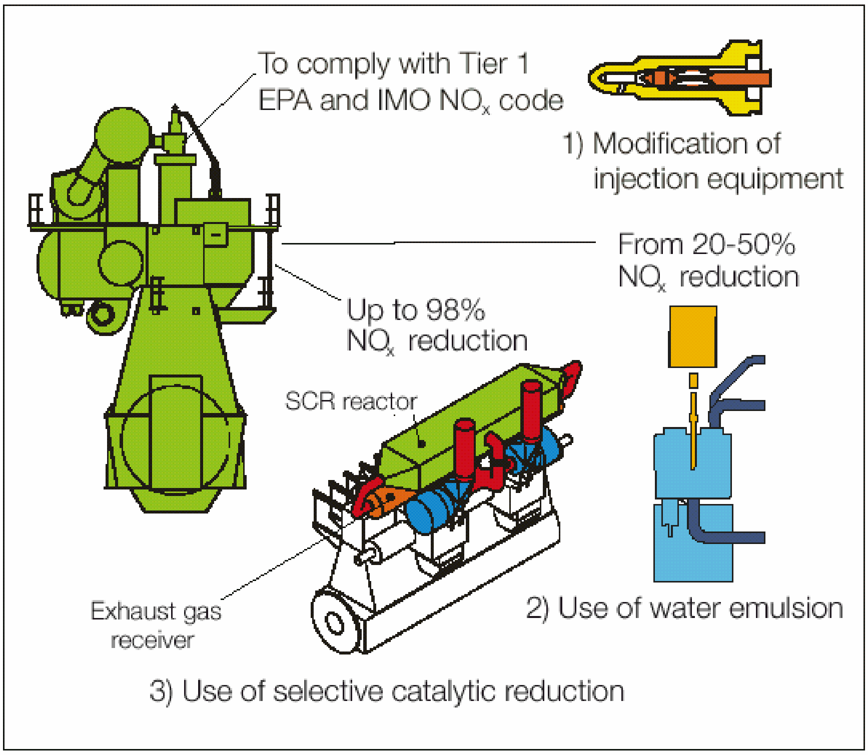


Fig. C.7 NOx reduction methods [18].

The reduction of the sulphur content in HFO is so far the most efficient method to reduce SOx, and this reduction has therefore been the reason for a lot of considerations from the Industry. The oil companies may need to change their equipment to low-sulphur fuel production, and the shipowners could face considerably higher fuel costs.

Alternatively SOx can be removed from the exhaust gas by water washing the gas in a scrubber; but this leaves the problemof sulphuric acid in the water, which must consequently be neutralized chemically, in turn creating a disposal problem. Also, SOx can be used to produce raw sulphur or sulphuricacid, both of which are marketable commodities. In either case, the handling of SOx from engine exhaust gas on ships has proved to be very expensive and complicated and does not seem to be a viable solution with the systems being used today [18].

APPENDIX D

LNG Properties, Potential Hazards and Emissions when used as fuel

LNG properties and potential Hazards

To consider whether LNG is a hazard, we must understand the properties of LNG and the conditions required in order for specific potential hazards to occur.

Natural gas produced from the wellhead consists of methane, ethane, propane and heavier hydrocarbons, plus small quantities of nitrogen, helium, carbon dioxide, sulfur compounds and water. LNG is liquefied natural gas. The liquefaction process first requires pre-treatment of the natural gas stream to remove impurities such as water, nitrogen, carbon dioxide, hydrogen sulphide and other sulfur compounds. By removing these impurities, solids cannot be formed as the gas is refrigerated. The product then also meets the quality specifications of LNG end users. The pre-treated natural gas becomes liquefied at a temperature of approximately -256 ^{o}F (-160 ^{o}C) and is then ready for storage and shipping. LNG takes up only 1/600th of the volume required for a comparable amount of natural gas at room temperature and normal atmospheric pressure. Because the LNG is an extremely cold liquid formed through refrigeration, it is not stored under pressure. The common misperception of LNG as a pressurized substance has perhaps led to an erroneous understanding of its danger.

LNG is a clear, non-corrosive, non-toxic, cryogenic[3] liquid at normal atmospheric pressure. It is odorless; in fact, odorants must be added to methane before it is distributed by local gas utilities for end users to enable detection of natural gas leaks from hot-water heaters and other natural gas appliances. Natural gas (methane) is not toxic. However, as with any gaseous material besides air and oxygen, natural gas that is vaporized from LNG can cause asphyxiation due to lack of oxygen if a concentration of gas develops in an unventilated, confined area.

The density of LNG is about 3.9 pounds per gallon (for comparison, the density of water, is about 8.3 pounds per gallon). Thus, LNG, if spilled on water, floats on top and vaporizes rapidly because it is lighter than water.

Vapours released from LNG as it returns to a gas phase, if not properly and safely managed, can become flammable but explosive only under certain well-known conditions. Yet safety and security measures contained in the engineering design and technologies and in the operating procedures of LNG facilities and ships greatly reduce these potential dangers.

The flammability range is the range between the minimum and maximum concentrations of vapour (percent by volume) in which air and LNG vapours form a flammable mixture that can be ignited and burn.

Figure D.1 below indicates that the *upper flammability limit* and *lower flammability limit* of methane, the dominant component of LNG vapour, are 5 percent and 15 percent by volume, respectively. When fuel concentration exceeds its upper flammability limit, it cannot burn because too little oxygen is present. This situation exists, for example, in a closed, secure storage tank where the vapour concentration is approximately 100 percent

---

[3] Cryogenic means extreme low temperature, generally below -100 ^{o}F (-73 ^{o}C).

methane. When fuel concentration is below the lower flammability limit, it cannot burn because too little methane is present. An example is leakage of small quantities of LNG in a well-ventilated area. In this situation, the LNG vapour will rapidly mix with air and dissipate to less than 5 percent concentration.

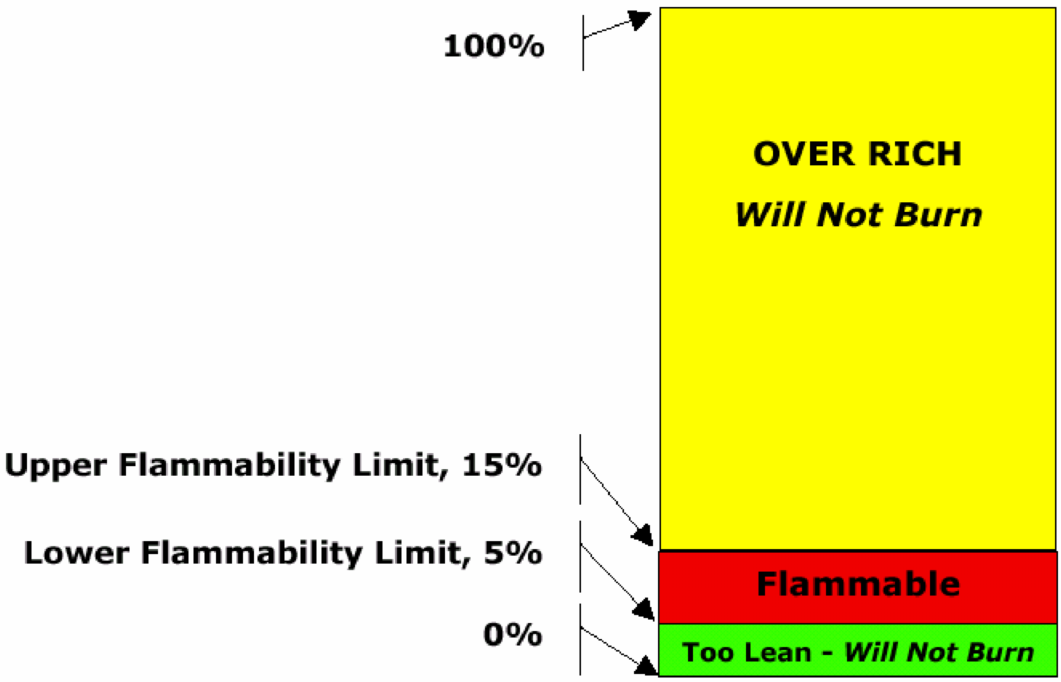


Fig. D.1 Flammable Range for Methane (LNG) [31].

A comparison of the properties of LNG to those of other liquid fuels, as shown in the Table D.1, also indicates that the Lower Flammability Limit of LNG is generally higher than other fuels. That is, more LNG vapours would be needed (in a given area) to ignite as compared to LPG or gasoline.

Methane gas will ignite only if the ratio or mix of gas vapour to air is within the limited flammability range. An often expected hazard is ignition from flames or sparks. Consequently, LNG facilities and LNG ships are designed and operated using standards and procedures to eliminate this hazard and equipped with extensive fire detection and protection systems should flames or sparks occur.

The autoignition temperature is the lowest temperature at which a flammable gas vapour will ignite spontaneously, without a source of ignition, after several minutes of exposure to sources of heat. Temperatures higher than the autoignition temperature will cause ignition after a shorter exposure time. With very high temperatures, and within the flammability range, ignition can be virtually instantaneous. For methane vapours derived from LNG, with a fuel-air mixture of about 10 percent methane in air (about the middle of the 5-15 percent flammability limit) and atmospheric pressure, the autoignition temperature is above 1000°F (540°C). This extremely high temperature requires a strong source of thermal radiation, heat or hot surface. If LNG is spilled on the ground or on water and the resulting flammable gas vapour does not encounter an ignition source (a flame or spark or a source of heat of 1000°F (540°C) or greater), the vapour will generally dissipate into the atmosphere, and no fire will take place.

When compared to other liquid fuels, LNG vapor (methane) requires the highest temperature for autoignition, as shown in the Table D.2.

Table D.1. Comparison of Properties of Liquid Fuels[4] [32].

Properties	**LNG**	**Liquefied Petroleum Gas (LPG)**	**Gasoline**	**Fuel Oil**
Toxic	No	No	Yes	Yes
Carcinogenic	No	No	Yes	Yes
Flammable Vapor	Yes	Yes	Yes	Yes
Forms Vapor Clouds	Yes	Yes	Yes	No
Asphyxiant	Yes, but in a vapor cloud	Same as LNG	Yes	Yes
Extreme Cold Temperature	Yes	Yes, if refrigerated	No	No
Other Health Hazards	None	None	Eye irritant, narcosis, nausea, others	Same as gasoline
Flash point[4] (°F)	-306	-156	-50	140
Boiling point (°F)	-256	-44	90	400
Flammability Range in Air, %	5-15	2.1-9.5	1.3-6	N/A
Stored Pressure	Atmospheric	Pressurized (atmospheric if refrigerated)	Atmospheric	Atmospheric
Behavior if Spilled	Evaporates, forming visible "clouds". Portions of cloud could be flammable or explosive under certain conditions.	Evaporates, forming vapor clouds which could be flammable or explosive under certain conditions.	Evaporates, forms flammable pool; environmental clean up required.	Same as gasoline

---

[4] "Flash point" means the minimum temperature at which a liquid gives off vapour within a test vessel in sufficient concentration to form an ignitable mixture with air near the surface of the liquid.

Table D.2. Autoignition Temperature of Liquid Fuels [31].

Fuel	Autoignition Temperature, °F
LNG (primarily methane)	1004
LPG	850-950
Ethanol	793
Methanol	867
Gasoline	495
Diesel Fuel	Approx. 600

Questions about LNG safety often demonstrate how LNG is confused with other fuels and materials. It is important to understand the difference between Liquefied Natural Gas (LNG), Compressed Natural Gas (CNG), Natural Gas Liquids (NGL), Liquefied Petroleum Gas (LPG), and Gas to Liquids (GTL). Figure D.2 shows the difference in typical composition of these products. LNG is also quite different from gasoline, which is refined from crude oil. All of these fuels can be used safely as long as proper safety, security and environmental protections are in place.

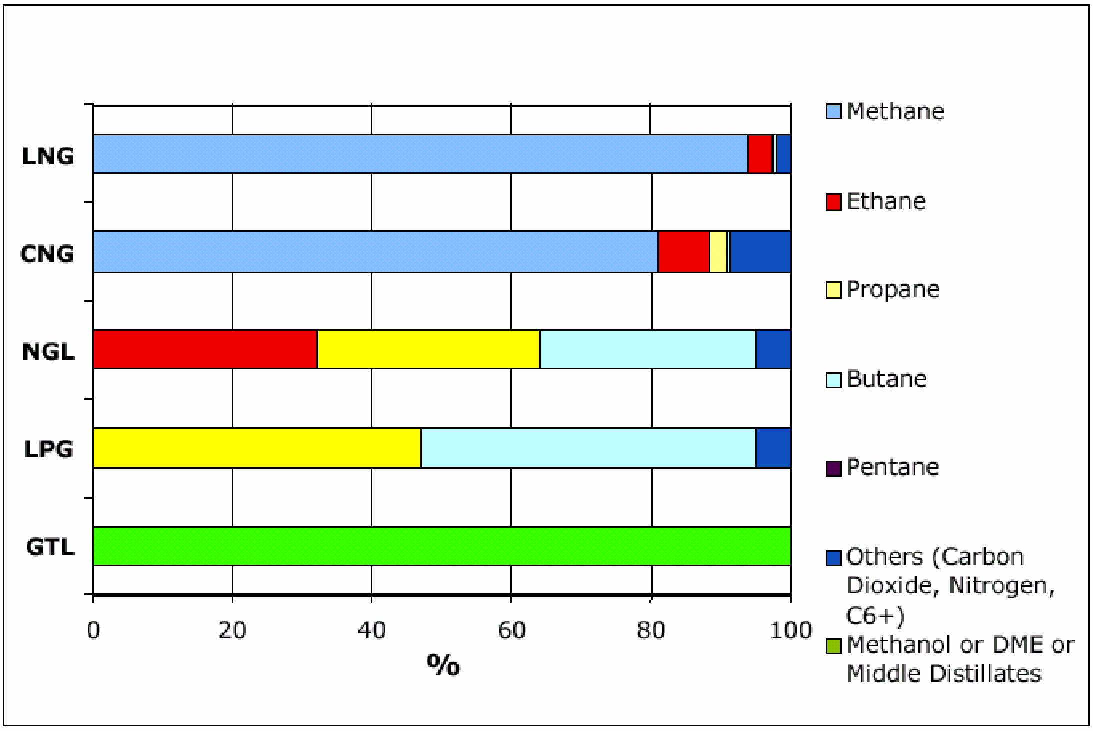


Fig. D.2 Typical Composition of LNG, NGLs, CNG, GTL, and LPG [31].

LNG is made up of mostly methane. The liquefaction process requires the removal of the non-methane components like carbon dioxide, water, butane, pentane and heavier components from the produced natural gas. CNG is natural gas that is pressurized and stored in welding bottle-like tanks at pressures up to 3,600 psig. Typically, CNG is the same composition as pipeline quality natural gas. NGLs are made up mostly of molecules that are heavier than methane like ethane, propane, butane. LPG is a mixture of propane and butane in a liquid state at room temperatures. GTL refers to the conversion of natural gas to products like methanol, dimethyl ether (DME), middle distillates (Diesel and jet fuel), specialty chemicals and waxes.

In summary, LNG is an extremely cold, non-toxic, non-corrosive substance that is transferred and stored at atmospheric pressure. It is refrigerated, rather than pressurized, which enables LNG to be an effective, economical method of transporting large volumes of natural gas over long distances. LNG itself poses little danger as long as it is contained within storage tanks, piping, and equipment designed for use at LNG cryogenic conditions. However, vapours resulting from LNG as a result of an uncontrolled release can be hazardous, within the constraints of the key properties of LNG and LNG vapours – flammability range and in contact with a source of ignition – as described above [31].

LNG Emissions when used as fuel

When LNG is vaporized and used as fuel, it reduces particle emissions to near zero and carbon dioxide (CO_2) emissions by 70 percent in comparison with heavier hydrocarbon fuels. When burned for power generation, the results are even more dramatic. **Sulfur dioxide (SO_2) emissions are virtually eliminated and CO_2 emissions are reduced significantly.** If spilled on water or land, LNG will not mix with the water or soil, but evaporates and dissipates into the air leaving no residue. It does not dissociate or react as does other hydrocarbon gases and is not considered an emission source. Additionally there are significant benefits when natural gas is used as fuel over other fossil fuels. **However, methane, a primary component of LNG, is considered to be a greenhouse gas** (Fig. D3) **and may add to the global climate change problem if released into the atmosphere** [31].

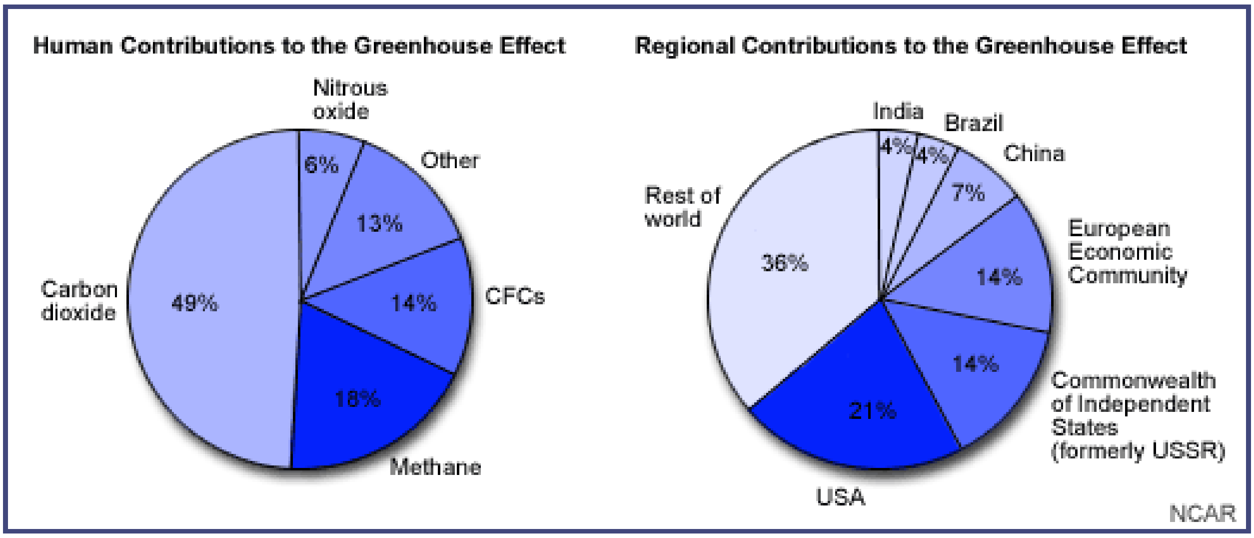
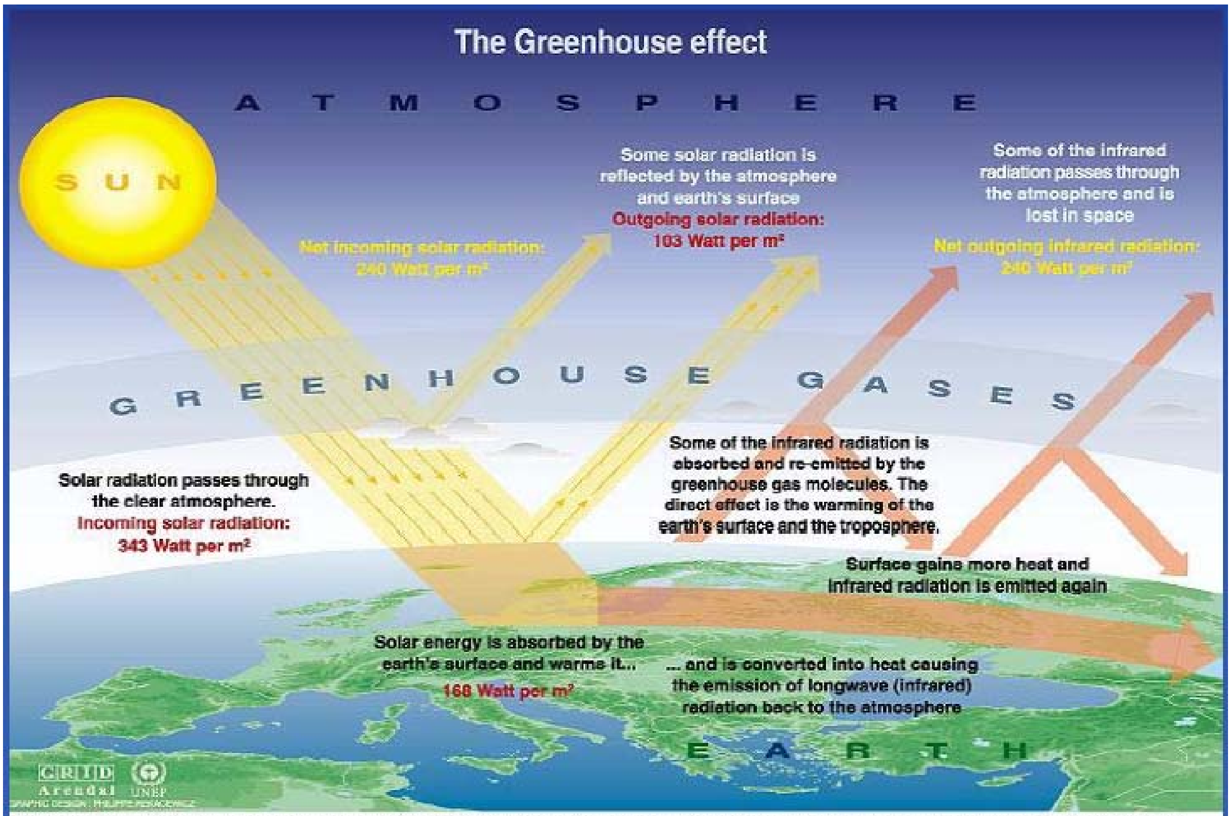


Fig. D.3 Contribution to the Greenhouse effect. [43].



Net incoming solar radiation: 240 Watt per m²

Some solar radiation is reflected by the atmosphere and earth's surface
Outgoing solar radiation: 103 Watt per m²

Some of the infrared radiation passes through the atmosphere and is lost in space
Net outgoing infrared radiation: 240 Watt per m²

Solar radiation passes through the clear atmosphere.
Incoming solar radiation: 343 Watt per m²

Some of the infrared radiation is absorbed and re-emitted by the greenhouse gas molecules. The direct effect is the warming of the earth's surface and the troposphere.

Surface gains more heat and infrared radiation is emitted again

Solar energy is absorbed by the earth's surface and warms it...
168 Watt per m²

... and is converted into heat causing the emission of longwave (infrared) radiation back to the atmosphere

Sources: Okanagan university college in Canada, Department of geography, University of Oxford, school of geography; United States Environmental Protection Agency (EPA), Washington; Climate change 1995, The science of climate change, contribution of working group 1 to the second assessment report of the intergovernmental panel on climate change, UNEP and WMO, Cambridge university press, 1996.

Fig. D.4 The Greenhouse effect. [43].

APPENDIX E

LNG Infrastructure

LNG Value Chain

The major components of the LNG value chain include the following (see Figure E.1):

- Natural gas production, the process of finding and producing natural gas for delivery to a processing facility.
- Liquefaction, the conversion of natural gas into a liquid state so that it can be transported in ships.
- Transportation, the shipment of LNG in special purpose ships for delivery to markets.
- Re-gasification, conversion of the LNG back to the gaseous phase by passing the cryogenic liquid through vaporizers.
- Distribution and delivery of natural gas through the national natural gas pipeline system and distribution to end users.

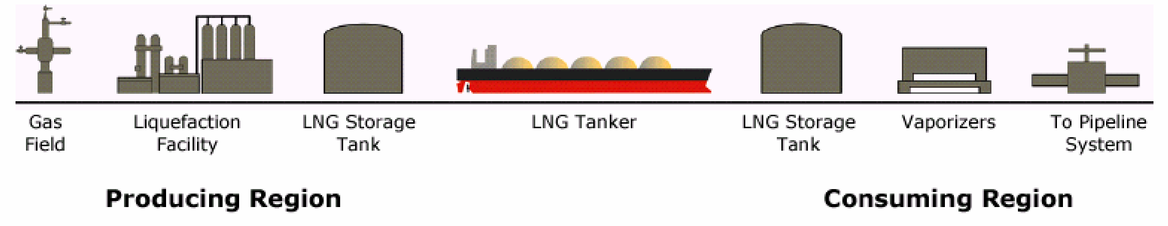


Fig. E.1 LNG Value Chain [31].

Storage is a major focus for safety and security. Once natural gas is liquefied, it is stored before shipment or loaded directly into the ship. LNG ships are required to have double hulls by regulation (International Maritime Organization) to facilitate safe transportation by sea. LNG receiving terminals and re-gasification facilities store LNG before it is re-gasified for pipeline transportation [31].

LNG ships

Containment system

Engineering design for safety applies to all LNG ships. An on board containment system stores the LNG, where it is kept at atmospheric pressure (to keep air from entering the tank) and at -256 ^{o}F (-160 ^{o}C). Existing LNG ship cargo containment systems reflect one of three designs:

- ➢ Spherical (Moss) design account for 52 percent of the existing ships,
- ➢ Membrane design account for about 46 percent and
- ➢ Self-supporting structural prismatic design account for about 2 percent.

Ships with spherical tanks are most readily identifiable as LNG ships because the tank covers are visible above the deck. Many ships currently under construction, however, are membrane type ships. The membrane and prismatic ships look more like oil tankers with a less visible containment tank structure above the main deck [31].

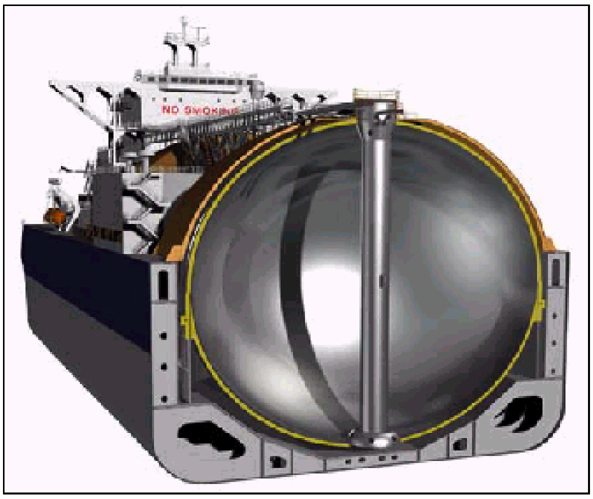


Fig. E.2 Tank Section of a Spherical Moss Design [31].

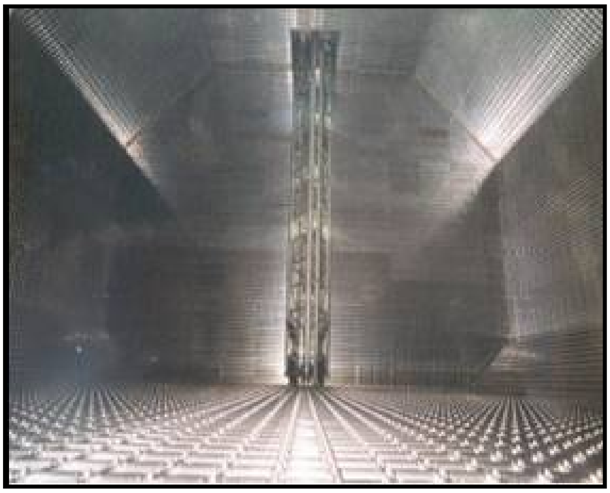


Fig. E.3 Membrane tank Containment system [35].

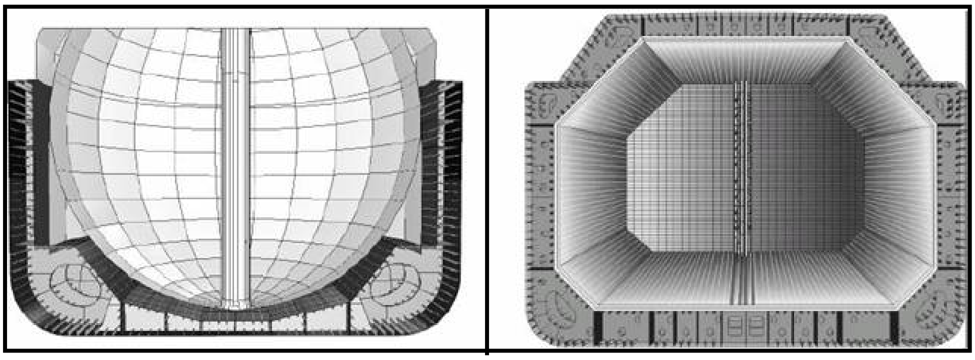
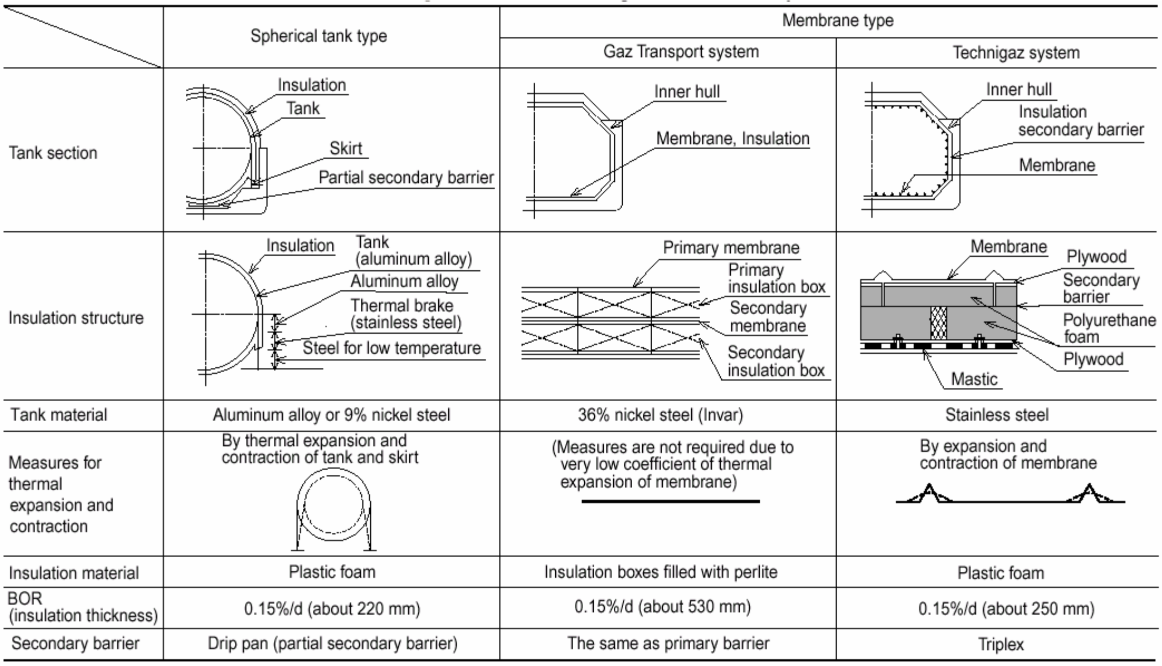


Fig. E.4 Moss Spherical tank containment system and Membrane tank Containment system [35].

Table E.1 Comparison of Kvaerner Moss Spherical Tank Design and No96 (Gas Transport), MARK III (Technigaz) Membrane cargo containment systems [35].



	Spherical tank type	Membrane type	
		Gaz Transport system	Technigaz system
Tank section	Insulation Tank Skirt Partial secondary barrier	Inner hull Membrane, Insulation	Inner hull Insulation secondary barrier Membrane
Insulation structure	Insulation Tank (aluminum alloy) Aluminum alloy Thermal brake (stainless steel) Steel for low temperature	Primary membrane Primary insulation box Secondary membrane Secondary insulation box	Membrane Plywood Secondary barrier Polyurethane foam Plywood Mastic
Tank material	Aluminum alloy or 9% nickel steel	36% nickel steel (Invar)	Stainless steel
Measures for thermal expansion and contraction	By thermal expansion and contraction of tank and skirt	(Measures are not required due to very low coefficient of thermal expansion of membrane)	By expansion and contraction of membrane
Insulation material	Plastic foam	Insulation boxes filled with perlite	Plastic foam
BOR (insulation thickness)	0.15%/d (about 220 mm)	0.15%/d (about 530 mm)	0.15%/d (about 250 mm)
Secondary barrier	Drip pan (partial secondary barrier)	The same as primary barrier	Triplex

A new gas containment system the GTT CS1 (Fig. E.5) developed by Gas Transport & Technigaz (GTT) combines the best of the two previous membrane technologies. About 80% of the LNG vessels ordered in recent years use one of the two membrane cargo containment systems available on the market – either the No96 (Gas Transport) or MARK III (Technigaz). Both of these membrane technologies are composed of gastight barriers and of insulation layers, as shown in the Table E.1. The CS1 technology is the combination of the invar steel plates to form the gastight barriers (No96 technology) and of the reinforced polyurethane foam to form the insulation layers (MARK III technology).CS 1 technology reduces the thickness of the cryogenic by 50%, increases the cargo capacity of the ship by 4000 m^3 and cuts in half the number of components requiring assembly compared with previous solutions.

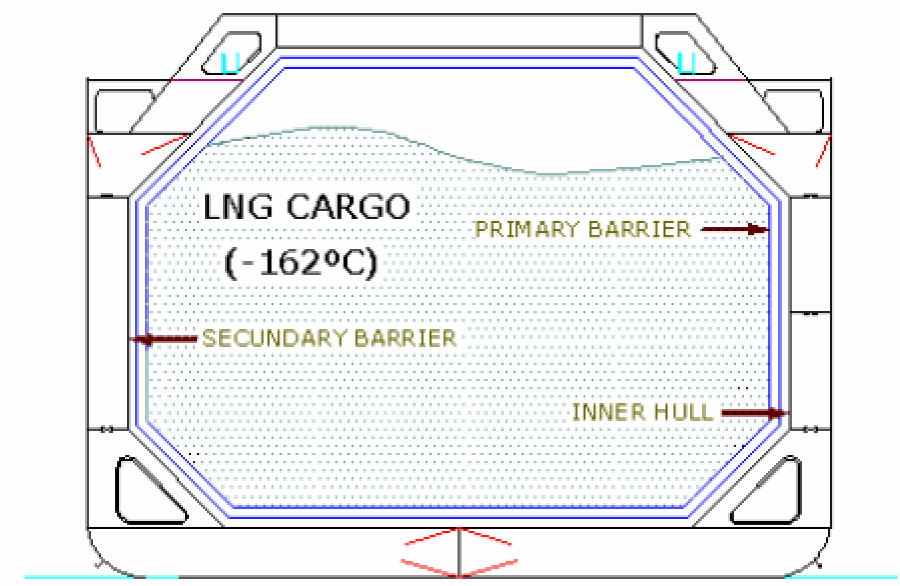


Fig. E.5 GTT CS1 Membrane tank Containment system [35].

Kvaerner Masa Yards (KMY) is also offering a stretched tank concept of its Moss design which it claims will allow it to build large LNG carriers. The 2002 also saw the yard integrate the tank cover structure into the hull longitudinal strength allowing what it claims are remarkable improvements. These include the elimination of the negative consequences that result from a large deck spherical tanks, excellent hull stiffness and an improved hull form. The designers of the concept claim that this will result in 10% lower propulsion power requirements with any type of machinery and significantly reduced construction costs. Maintenance will also be improved resulting in lower operational costs [36].

Relative cargo handling equipment

HD Cargo Compressors

Are used for:

- During cargo tank gas filling: To return inert gas and then LNG vapour to the shore terminal.
- During loading : To return the cargo vapour generated by gas displacement if piping pressure drop does not allowed it to be done directly.
- During warming-up: For gas circulation and heating (HD + gas heaters) (tank warming up)

Main heaters

The heaters are used for the following functions:

- In conjunction with the high duty compressors for warming up the cargo tanks prior to gas freeing operations.This will normally only be done prior to a dry docking or in the event that a one tank warm-up operation has to be carried out for maintenance purposes. The heater gas outlet temperature is to be controlled to 80°C throughout the warm-up operation.
- In conjunction with the low duty compressors for supplying boil-off or forced gas as fuel to the main boilers.

LNG Vaporiser

The LNG vaporizer has four functions:

- To supply the gaseous natural gas to the cargo tanks and displace the inert gas before the initial cool down/loading operation. Normally this will only be carried out during the first cargo after a dry docking, or in the event of one of a one tank gas freeing operation.
- To supply vapour to the cargo tanks during discharge operations in the event of the discharge terminal return gas blowers being in-operative.
- To supply the main boilers with forced fuel gas via the LD compressors when the natural boil-off is insufficient. The LNG vaporizer will only be used in this mode in the event of an emergency, such as the failure of the forcing vaporizer. The vaporizer outlet temperature must be controlled at -40°C during the emergency forcing operation.
- To supply the cargo tanks with inert gas, using liquid nitrogen supplied by the terminal,in the event of the vessels' inert gas generator being in-operative. This operation would only be carried out at the initial inerting of cargo tanks or at the first loading terminal after dry dock. The vaporizer outlet temperature must be controlled at 20°C during the inerting operation.

Inert gas system unit

The vessel is equipped with an Inert Gas Generator. The inert gas contains approximately 85% N_2, 15% CO_2 and about 0.5% O_2 and is at a temperature approximately 5ºC above the sea water temperature. After combustion, the inert gas has a level of corrosive sulphur oxides from the combustion process which first have to be removed. Inert gas is produced by the combustion of gas oil supplied by the fuel oil pump with air, provided by the blowers, in the combustion chamber of the inert gas generator. Good combustion is essential for the production of a good quality, soot free, low oxygen inert gas. The products of the combustion are mainly CO_2, water and small quantities of oxygen, carbon monoxide, sulphur oxides and hydrogen. The nitrogen content is generally unchanged during the combustion process and the inert gas produced consists mainly of 85% nitrogen and 15% CO_2.

Nitrogen gas generators

Nitrogen generators produce gaseous nitrogen which is used for the pressurization of the barrier insulation spaces, as shaft seal gas for the HD and LD compressors, fire extinguishing in the vent mast risers and for purging various parts of the cargo piping and BOG system.The two high capacity units, are able to produce almost pure nitrogen, which is mainly required for the topping up of the barrier insulation spaces during loading, cool-down and other services.

Safety equipment

LNG ships are especially designed with a double hull to provide optimum protection for the integrity of the cargo in the even of collision or grounding. The ship has safety equipment to facilitate ship handling and cargo system handling.

The ship-handling safety features include sophisticated radar and positioning systems that enable the crew to monitor the ship's position, traffic and identified hazards around the ship. A global maritime distress system automatically transmits signals if there is an on board emergency requiring external assistance.

The cargo-system safety features include an extensive instrumentation package that safely shuts down the system if it starts to operate outside of predetermined parameters.

Ships also have gas-and fire-detection systems, nitrogen purging, double hulls and double containment tanks or leak pans. Should fire occur on the ship, two 100 % safety relief valves on each tank are designed to release the ensuing boil off to the atmosphere without over pressurizing the tank.

LNG ships use approach velocity meters when berthing to ensure that the prescribed impact velocity for the berth fenders are not exceeded. When moored, automatic mooring line monitoring provides individual line loads to help maintain the security of the mooring arrangement while alongside. When connected to the onshore system, the instrument systems and the shore-ship LNG transfer system acts as one system, allowing emergency shutdowns of the entire system from ship and from shore [31].

Fig. E.6 LNG carrier with Moss Spherical tank containment system and LNG carrier with Membrane tank Containment system [35].

LNG Facilities

A typical, onshore LNG receiving terminal and re-gasification facility consists of marine facilities, LNG receiving and storage facilities, and vaporization facilities.

Marine Facilities

The LNG dock facilities are designed to berth and unload LNG from ships. Tugboats provide assistance when berthing. The dock is designed to accept a specified size range of LNG ships.

LNG Receiving and Storage

Once the LNG ship is moored and the unloading arms on the dock have been connected, the ship's pumps will transfer LNG into the onshore LNG storage tanks. Unloading generally takes about 12 hours depending on cargo size. Figure E.7 illustrates unloading arms at an LNG marine terminal.

Fig.E.7 LNG marine terminal [31].

Double-walled tanks store LNG at atmospheric pressure.LNG is a cryogenic fluid, and it is not stored at high pressures, so an explosion of LNG from overpressure is not a potential hazard. The issues regarding LNG storage tanks apply both to the liquefaction and re-gasification facilities because the storage tanks are of the same design. New technologies could enable offshore LNG storage and re-gasification. **Offshore LNG receiving facilities** have not yet been built, but engineering and economic feasibility is under development in the U.S. and elsewhere.

Research and development is also being conducted on the feasibility of unloading and storing LNG in **salt cavern**s, which would eliminate the need for storage tanks.

The most commonly used types of LNG storage tanks are the following:

- ❑ Above-ground tanks. Above-ground tanks have been the most widely accepted and used method of LNG storage primarily because they are less expensive to build and easier to maintain than in-ground tanks.
- ❑ Below-ground tanks.Below-ground LNG tanks are more expensive than above-ground tanks. They harmonize with the surroundings. There are three different types of below-ground LNG storage tanks currently in use:
  - i) In-ground Storage Tanks. The roof of the tank is above ground.
  - ii) Underground Storage tanks.Underground tanks are buried completely below ground and have concrete caps.
  - iii) Underground in-pit LNG storage tank.The tank has a double metal shell with inner and outer tank.

LNG Vaporization Facilities

Each LNG storage tank has send-out pumps that will transfer the LNG to the vaporizers. Ambient air, seawater at roughly 59°F (15° C), or other media such as heated water, can be used to pass across the cold LNG (through heat exchangers) and vaporize it to a gas. The most commonly used types of vaporizers are the Open Rack (ORV) and the Submerged Combustion (SCV). Other types include Shell & Tube exchanger (STV), Double Tube Vaporizer (DTV), Plate Fin Vaporizer (PFV), and Air Fin Vaporizer (AFV) [31].

At this point recent technology trends must be mentioned, involving **LNG regasification vessels (RV)** as an alternative for on-shore LNG storage and vaporization facilities [33].

All facilities that handle LNG have built-in systems to contain LNG and prevent fires.

This is true whether in the LNG facility, transferring LNG to and from LNG ships, shipping LNG or vaporizing (re-gasifying) LNG. There are differences in design among these types of facilities, but the environmental, health and safety issues are the same [31].

Development of LNG infrastructure

LNG Fleet

The global fleet of LNG tankers needs to expand by 66% by 2010 to meet current and future demand from exporters including Qatar, Australia and Nigeria, according to LNG Shipping Solutions. About 205 carriers need to be ordered, adding to the 182 ships in service and 127 vessels already contracted to be built, to meet demand for existing and future LNG projects.

As many as 105 vessels need to be ordered to meet demand for future projects and 100 vessels for current contracts. Projects including Qatar’s RasGas III, Australia’s Gorgon LNG and Nigeria’s OKLNG I & II are set to start operations in four years. Shipyards in South Korea account for 71% of the vessels on order, followed by Japan with 23% [38].

LIST OF ABBREVIATIONS

AC:	Alternative Current
AFC:	Alkaline Fuel Cell
AFV:	Air Fin Vaporizer
APU:	Auxiliary Power Unit
AZIPOD:	Azimuth Podded Drive
BCM:	Billion Cubic Meters
BN:	Basic Number
BOG:	Boil Off Gas
BP:	British Petroleum
BSN:	Bosch Smoke Number
CH_2:	Compressed Hydrogen
CIF:	Cost, Insurance and Freight
CNG:	Compressed Natural Gas
CO:	Carbon monoxide
CO_2:	Carbon dioxide
CODAG:	Combined Diesel And Gas turbine
CODLAG:	Combined Diesel Electric and Gas turbine
COGES:	Combined cycle Gas turbine Electric and Steam turbine
CGH_2:	Compressed gaseous hydrogen (H_2)
CPP:	Controllable Pitch Propeller
CRP:	Contra Rotating Propeller
DC:	Direct Current
DE:	Diesel Engine
DF:	Dual Fuel
DFE:	Dual Fuel Electric
DFXB:	Dual Fuel Exhaust Boiler
DME:	Dimethyl ether
DNV:	Det Norske Veritas
DSME:	Daewoo Shipbuilding and Marine Engineering
DTV:	Double Tube Vaporizer
EC:	European Commission
E/G:	Electric Generator
EGR:	Exhaust Gas Recirculation
EMS:	Engine Management System
ESD:	Emergency Shut Down
EU:	European Union
FBOG:	Forced Boil Off Gas
FCMA:	Fuel Cell plant for Maritime Applications
FCSHIP:	Fuel Cell Ship
FMEA:	Failure Mode and Effect Analysis
FOB:	Free On Board
FPP:	Fixed Pitch Propeller
FPSO:	Floating Production, Storage and Offloading Unit
GE:	General Electric
GHG:	Greenhouse Gas emissions
GI:	Gas Injection

GL:	Germanischer Lloyd
GT:	Gas Turbine
GTL:	Gas to Liquid
GTT:	Gas Transport & Technigaz
HAM:	Humid Air Motor
HAZID:	Hazard Identification Studies
HAZOP:	Hazard and Operability Studies
HC:	Hydrocarbons
HD:	High Duty
HFCS:	HDW Fuel Cell Systems
HFO:	Heavy Fuel Oil
HHI:	Hyundai Heavy Industries
IACS:	International Association of Classification Societies
ICR:	Intercooling and Recuperation
IGS:	International Gas Code
i.e.:	id est (Latin) (that is)
IMO:	International Maritime Organisation
KMY:	Kvaerner Masa Yards
LD:	Low Duty
LH_2:	Liquid Hydrogen
LNG:	Liquefied Natural Gas
LNGC:	LNG Carrier
LPG:	Liquefied Petroleum Gas
LR:	Lloyds Register
LRS:	Lloyds Register of Shipping
M:	Million
MAN B&W:	Maschinenfabrik Augsburg-Nürnberg Burmeister & Wein Diesel AG
MARAD:	US Marine Administration
MARPOL:	Marine Pollution Prevention Resolution (The International Convention for the Prevention of Marine Pollution from Ships)
MCFC:	Molten Carbonate Fuel Cell
MCR:	Maximum Continuous Rating
MDF:	Marine Diesel Fuel
MDO:	Marine Diesel Oil
MGO:	Marine Gas Oil
MHI:	Mitsubishi Heavy Industries, Ltd.
NBOG:	Natural Boil Off Gas
NG:	Natural Gas
NGL:	Natural Gas Liquids
NMD:	Norwegian Maritime Directorate
NOx:	Nitrogen Oxides
NSA:	Norwegian Ship Owner’s Association
ONR:	US Office of Naval Research
ORV:	Open Rack Vaporizers
PFV:	Plate Fin Vaporizer
PEMFC:	Polymer Exchange Membrane Fuel Cell
PM:	Particulate Matters
PM:	Propulsion Motor

POD:	Podded Drive
PTI:	Power Take In
PTO:	Power Take Off
RINA:	Registro Italiano Navale
R&D:	Research & Development
RL:	Reliquefaction System
RLP:	Reliquefaction Plant
ROV:	Remote Operated Vehicle
RR:	Rolls Royce
RV:	Regasification Vessel
SCV:	Submerged Combustion Vaporizer
SCR:	Selective Catalytic Reduction
SFOC:	Specific Fuel Oil Consumption
SOx:	Sulphur Oxides
SOF:	Ship and Ocean Foundation
SOFC:	Solid Oxide Fuel Cell
ST:	Steam Turbine
ST-BY:	Stand By
STV:	Shell Tube Vaporizer
TBN:	Total Basic Number
TOx:	Thermal Oxidiser
US DoD:	United States Department of Defence

Symbols of the equations

A:	Available energy in BOG	(GJ/h)
AD:	Average LNG density (methane)	(kg/m^3)
AE:	Available Energy in Exhaust Gases	(GJ/h)
AI:	Additional Initial cost	(US$)
BOR:	Boil-off rate	(%/day)
C:	Cargo capacity	(m^3)
CCd:	Crew Cost difference	(US$/trip)
CO:	Cylinder oil price	(US$/ton)
CRD:	Charter rate difference	(US$/trip)
C_t:	Annual Operating Cost	(million US$/year)
D:	Delivered power demand	(kW)
DC:	Delivered cargo	(m^3)
DO:	MDO price	(US$/ton)
E:	Fuel Energy needed for propulsion and electric generation	(GJ/h)
EBOG:	Energy in BOG (methane)	(GJ/day or GJ/kg)
EDC:	Extra Delivered Cargo	($m^{3/}$/trip)
EQ:	Equivalent consumption HFO/MDO/MGO	(t/h)
EX:	Extra energy needed from fuel oil	(GJ/h)
FCd:	Fuel cost difference	(US$/trip)
GO:	MGO price	(US$/ton)
H:	Hours per trip for each condition	(h)
HE:	Minimum level of LNG for cargo tank cooling (heel)	(m^3)

HF:	HFO price	(US$/ton)
η:	Plant's efficiency	(%)
η_i:	Propulsion transmission losses	(%)
η_j:	Electric generation losses	(%)
I:	Initial Cost	(million US$)
i:	Market interest rate	(%)
LHVG:	LHV of BOG (methane)	(kJ/kg)
LHVO:	LHV of liquid fuel oil	(kJ/kg)
LoR:	Used or Reliquefied LNG	(m^3/per trip)
LO:	Lub oil price	(US$/ton)
LCd:	Lub oil cost difference	(US$/trip)
M:	Mass of BOG (methane)	(kg/day)
MCd:	Maintenance cost difference	(US$/trip)
ML:	Maximum loading	(%)
MS:	Mean square	
N:	Cycle life of the investment	(years)
NGC:	LNG CIF price	(US$/ton)
NGF:	LNG FOB price	(US$/ton)
NPV:	Net Present Value	(million US$)
$P_{propeller}$:	Propulsion power demand	(kW)
$P_{electric}$:	Electrical power demand	(kW)
PC:	Power consumption of the Reliquefaction plant and of the gas compressors for the main engines	(kW)
R:	Revenues from selling the delivered cargo capacity	(US$/trip)
R_t:	Annual Revenues	(million US$/year)
RT:	Round trips per year	(the closest integer)

SEC:	Specific energy consumption	(kJ/kWh)
SFC:	Specific fuel oil consumption	(g/kWh)
SO:	System oil price	(US$/ton)
SPC:	Specific power consumption	(W/kg/h)
SV_N:	Salvage value of the investment at the end of N years	(million US$)
s:	Distance	(nm)
T:	Time per round trip	(h)
t:	Time for loaded/ballast voyage	(h)
t_1:	Loaded voyage time	(h)
t_2:	Ballast voyage time	(h)
t_3:	Manoeuvring time	(h)
t_4:	Reserve time	(h)
t_5:	Loading time	(h)
t_6:	Unloading time	(h)
TL:	Total used or lost LNG per trip	(m^3)
u:	Service speed	(kn)
V:	Volume of BOG (methane)	(m^3/day)
VLoR:	Value of used or Reliquefied LNG	(US$/trip)
Vo:	Volume of total used or Reliquefied cargo	(m^3/trip)

REFERENCES

1. ‘Competitive pressure rises on steam propulsion for LNG tankers’, The Naval Architect, March 2004.
2. ‘Steam turbines fight back’, Design and Operation of Gas Carriers, Supplement to The Naval Architect, September 2004.
3. ‘LNG Carrier Alternative Propulsion Systems’, Richard Gilmore, Stavros Hatzigrigoris, Steve Mavrakis, Andreas Spertos, Antonis Vordonis, Maran Gas Maritime Inc., SNAME-Greek Section Technical Seminar, February 17, 2005.
4. ‘Increasing LNG Carrier Cargo Capacity’, MTP Consultancy, Sweden. site: www.mtpconsult.com
5. ‘Dual-Fuel-Electric LNG Carrier Propulsion’, Barend Thijssen, Sales Director, Wärtsilä Ship Power Solutions, Finland.
6. ‘Marine Aero Gas Turbine Applications’, site: www.mtpconsult.com
7. ‘MT 30 Gas Turbine Applications’, Rolls-Royce Marine Systems, UK. site: www.rolls-royce.com
8. ‘Fuel cell technology for ferries’, Bard Meek-Hansen, MARINTEK paper at the IMTA conference Gold Coast, Australia, October 2002.
9. ‘The world-leading features of the Rolls-Royce Solid-Oxide Fuel Cell System’, Rolls-Royce Fuel Cell Systems, UK. site: www.rolls-royce.com
10. ‘Race to develop large fuel cells’, Simon Jones, The Motor Ship, July 2002.
11. ‘LNG carriers: gas turbines poised to strike’, The Naval Architect, January 2005.
12. ‘LNG Carrier Propulsion by ME-GI Engines and/or Reliquefaction’ MAN B&W Diesel A/S, Copenhagen, Denmark, September 2003.
13. ‘Evaluation of Propulsion Options for LNG Carriers’, Gastech 2002, Dr. Manfred Küver (Tractebel Gas Engineering GmbH), Chris Clucas (Dorchester Maritime Ltd.), Nils Fuhrmann (Tractebel Marine Engineering GmbH).
14. ‘Development of Next-Generation LNGC Propulsion Plant and HYBRID System’ ,Masaru Oka, Kazuyoshi Hiraoka, Kenji Tsumura (Nagasaki Shipyard & Machinery Works),Mitsubishi Heavy Industries, Ltd. Technical Review Vol. 41 No. 6 ,Dec. 2004.
15. ‘Dual-fuel scores in LNG propulsion battle’, The Motor Ship, January/February 2005.
16. ‘The DF-electric LNG carrier concept’, Janne Kosomaa, Product and Application Development, Wärtsilä, The Ship Power Supplier, Marine News 2002.
17. ‘CNG engine system - the power plant of the future’, Dr. Hideo Kawamura, Technical Advisor to ‘Ship and Ocean Foundation’ (SOF), The Motor Ship, November 2003.
18. ‘Emission Control MAN B&W Two-stroke Diesel Engines’, MAN B&W Diesel A/S,Copenhagen, Denmark.
19. ‘Field experience with considerably reduced NOx and Smoke Emissions’, Horst W. Koehler, MAN B&W Diesel.
20. ‘More gas for LNG carriers’,Oskar Levander and Susanna Hannula Marine Technology Wärtsilä Corporation, The Ship Power Supplier, Marine News 2004.
21. ‘The Norwegian LNG Ferry’, Per Magne Einang - Norwegian Marine Technology Research Institute (MARINTEK), Konrad Magnus Haavik - Norwegian Maritime Directorate,PAPER A-095 NGV YOKOHAMA,2000.
22. ‘Wärtsilä 50DF Technology review’, Wärtsilä.
23. ‘FCSHIP:Environmental Impacts and Costs of Hydrogen, Natural Gas and Conventional Fuels for Fuel Cell Ships’, Matthias Altmann, Werner Weindorf, Reinhold Wurster (L-B-Systemtechnik GmbH), Dr. Helle Brit Mostad (Norsk Hydro ASA Hydro Energy),

Martin Weinberger, Dr. Gerhard Filip(MTU Friedrichshafen GmbH, Project Center PEM Fuel Cells), 15th World Hydrogen Energy Conference, Yokohama / Japan, June 27 – July 2, 2004.

24. ‘Mini LNG tankers - an optimistic new market’, The Naval Architect, November 2002.

25. ‘The Application and Fuel Economy of Gas Turbine Combined Cycle for LNG carriers’, S.Hieda, T.Kusano, Ishikawajima-Harima Heavy Industries Co. Ltd., April 1986.

26. ‘The Application of Gas Turbines to the Propulsion of Liquefied Natural Gas Tankers’, A.O. White (Manager-systems design unit Gas Turbine department General Electric Co. U.S.A.), 9th International Congress on Combustion engines Stockholm Sweden, 1971.

27. ‘Gas fired low-speed engine alternatives’, The Naval Architect, April 2005.

28. ‘Combined systems strengthen gas turbine competitiveness’, Marine Engineers Review, April 2002.

29. ‘Lean and clean marine gas engines launched, The Motor Ship, June 2004.

30. ‘Gas fuelled engine applications in ships-experience with LNG fuelled ferries, supply vessels and LNG carriers’ Torill Grimstad Osberg**,** Det Norske Veritas AG, MSc, HOVIK, Norway.

31. ‘LNG safety and security’, Institute for Energy, Law and Enterprise, University of Houston Law center, October 2003.

32. ‘LNG Facilities – The Real Risk’, Lewis, William W., James P. Lewis and Patricia Outtrim, PTL, American Institute of Chemical Engineers, New Orleans, April 2003.

33. ‘Recent Evolution of LNG carriers’, Ho-Chung Kim, Executive Vice President, Head of Engineering & Technology Division of Daewoo Shipbuilding & Marine Engineering Co.,Ltd, SNAME-Greek Section Technical Seminar, October 2005.

34. ‘Maritime Fuel Cell Applications’, Kickulies Marc,Krummrich Stefan, Sattler Gunter HDW - Fuel cell systems GMBH , Werftstraße 112-114, D-24143 Kiel.

35. ‘Key Technologies of Mitsubishi LNG Carriers - Present and Future’. Kazuaki Yuasa, Katsuya Uwatoko, Junshiro Ishimaru Mitsubishi Heavy Industries, Ltd. Technical Review Vol.38 No.2 (Jun. 2001).

36. ‘Replacing the ageing LNG fleet’, Mark Langdon, The Motor Ship, January 2004.

37. ‘LNG carrier propulsion options for the future’, Marine Engineers Review, November 1997.

38. ‘LNG tanker fleet needs to expand dramatically’, Motor ship news, October 2005. site: www.motoship.com

39. ‘Wärtsilä DF engines get gas boost’, Motor ship news, April 2005. site: www.motoship.com

40. ‘MAN B&W finalising LNG safety study’, Motor ship news, August 2005. site: www.motoship.com

41. ‘LR approves GE’s turbine propulsion for LNG carriers’, ‘Gas turbine propulsion gets LR approval’, Motor ship news, May 2005, July 2005. site: www.motoship.com

42. ‘World LNG Industry Review’, Project Services Group, 2003. site: www.ergconsultancy.com

43. ‘Παραγωγή ενέργειας από συμβατικά ορυκτά καύσιμα και από εναλλακτικές πηγές ενέργειας’, Κ. Τσακαλάκης , Αναπλ. Καθηγητής Ε.Μ.Π.- Σχολή Μηχ. Μεταλλείων-Μεταλλουργών- Παρουσίαση Διατμηματικού μαθήματος ‘Περιβάλλον και Ανάπτυξη’, Ε.Μ.Π., Αθήνα, Μάιος 2005.

44. ‘Operation on Low-Sulphur Fuels Two-Stroke Engines’, Kjeld Aabo, MAN B&W Diesel A/S, Copenhagen, Denmark ,RINA Technical Seminar, Athens 15 December 2005.

45. ‘Diesel Engines and Gas Turbines in Cruise Vessel Propulsion’, Horst W. Koehler, MAN B&W Diesel A/S, Copenhagen, Denmark.

46. ‘Detailed Cost-Benefit Analysis subtask 7.2.2 technical report ATOMOS IV’, Nikolaos Bentikos, Konstantinos Dilzas, Panagiotis Zaxarioudakis, Dimitrios Lyridis, Pantelis Anajagorou, Athens 2002, Hellas.
47. ‘Environmental differentiated fairway and port dues’, Swedish Maritime Administration.
48. Μελέτη ΙΙ Πανεπιστημιακές σημειώσεις 2002 ΠΔ 238/1987 ΦΕΚ τεύχος Α, φύλλο 102, 1987.
49. ‘Diesel Engines for LNG Carrier Propulsion’ Ole Grøne & Peter Skjoldager MAN B&W Diesel A/S, Copenhagen, Denmark and Werner Oehlers & Dirk Fabry MAN B&W Diesel AG, Augsburg, Germany August 2002.
50. ‘Report of theoretical daily fuel consumption’, Maran Gas Maritime Inc.
51. Crew salaries data for West and East European officers, Maran Gas Maritime Inc.
52. ‘Revenue Maximisation in the transportation of LNG at sea by using alternativeship propulsion systems’, Marine Service GmbH, Hamburg, SIGTTO panel meeting Hamburg, September 2003.
53. ‘Pioneering Gas Turbine-Electric System in Cruise Ships:A Performance Update’, Bruce N. Sanneman, Marine Programs Manager, GE Marine Engines, Cincinnati, Ohio, USA, Marine Technology, October 2004.
54. Table C7 TECHNE's proposed emission factors used for the European Commission's MEET project.