

Technical and Economical Comparison of Propulsion Alternatives for Modern

LNG Carriers

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Abstract

In this paper, three LNG carrier alternatives will be compared in terms of technical and economical segments. The three alternatives are dual fuel diesel mechanical propulsion system with 4 stroke medium engines, dual fuel diesel mechanical propulsion system with 2 stroke slow speed engines and combined gas turbine electric propulsion system. Basic technical comparison will be done and the LCC calculation model is the economical comparison model.

Key words: alternatives, comparison, technical, economical, LCC.

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Background

The natural gas and boil off gas

LNG carrier is designed for transporting the liquid natural gas. The first LNG carrier was built in 1960s with the capacity of 5,550 cubic meters. Until 2014, the maximum cargo capacity of LNG carrier has increased to about 250,000 cubic meters.

Compared to other fossil fuel, the natural gas is a relative clean energy. It doesn't contain Sulphur or toxic elements. Thus the global natural gas demands keep increasing during the last decades. The major components of natural gas is methane. When the natural gas is cooled down below its liquefaction point which is minus 163 degrees, the natural gas will convert into liquid state. The liquid natural gas only takes up 1/600th volume of natural gas in gas state. LNG tank must maintain at atmospheric pressure and minus 163 degrees to keep the liquid state of the natural gas. When the carrier is under its laden voyage, it produces 0.10%~ 0.15% (Peter G Noble, 2009) volumes of boil off gas (BOG) per day, and when the carrier is at ballast voyage, the BOG rate is approximate 0.06% (Chang KwangPil, 2008) per day

The LNG containment systems

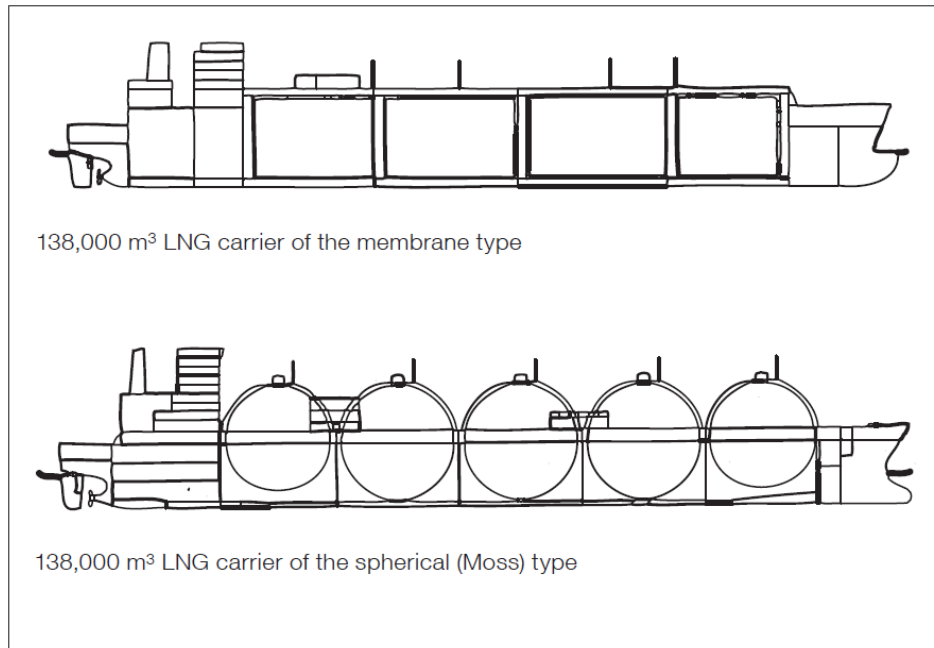


Figure 1. The membrane type and the Moss type LNG carrier

The LNG carrier technology had a significant improvement since the first LNG carrier began its voyage. In 2014, the global LNG carrier fleet contains nearly 400 vessels (LNG Tanker Shipping, 2014). Mainly two types of containment systems of LNG carriers dominate the current LNG fleet: membrane type and spherical type. Most of the current LNG carriers use the spherical (Moss) tank which was introduced in 1971. And the other carriers adopted the membrane type tank which was introduced in 1969.

The most obvious advantage of membrane type is that its relatively high utilization of cargo capacity. With the similar cargo capacity, the membrane type carrier's dimension is smaller than the Moss type.

The size of LNG carriers

Modern LNG carriers could be split up into different groups based on the ship size or cargo capacity.

<u>LNG carrier classes</u>	<u>Dimensions</u>	<u>Ship size - LNG capacity</u>
Small	B: up to 40 m L _{OA} : up to 250 m	up to 90,000 m ³
Small Conventional	B: 41 - 49 m L _{OA} : 270 - 298 m	120,000 - 149,999 m ³
Large Conventional	T _{des} : up to 12.0 m B: 43 - 46 m L _{OA} : 285 - 295 m	150,000 - 180,000 m ³
Q-flex	T _{des} : up to 12.0 m B: approx. 50 m L _{OA} : approx. 315 m	200,000 - 220,000 m ³
Q-max	T _{des} : up to 12.0 m B: 53 - 55 m L _{OA} : approx. 345 m	more than 260,000 m ³

Figure 2. The size of LNG carriers

The most common size of LNG carrier is around 150,000 m³. The Q-flex and Q-max LNG carriers are operated by Qatar Gas Transport Company. The carriers' cargo capacity is over 200,000 m³ with the maximum speed of 19.5 knots. The Q-series carriers are propelled by two slow speed single fuel diesel engines with re-liquefaction system onboard.

Comparison principles

In this thesis, three alternatives will be compared in technical and economical segments. For a valid comparison, the dual fuel electric propulsion power configuration

would be chosen as the standard power configuration.

Three alternatives are:

- Dual fuel diesel mechanical propulsion with 4 stroke medium speed engines;
- Dual fuel diesel mechanical propulsion with 2 stroke slow speed engines;
- Combined gas turbine electric propulsion.

In technical comparison part, the basic comparison would be done. For instance: the thermal efficiency, the volume and weight of power configuration, fuel consumption, fuel flexibility, and emissions, etc.

In the economical part, the comparison model is the Life Cycle Cost comparison.

Introduction of all alternatives

After the steam turbine dominated the LNG carrier for decades, several different power configurations of LNG carriers were introduced to the commercial area.

We could split up the configurations into different categories.

SFDM+R: Single fuel (slow speed) diesel mechanical propulsion with reliquefaction system.

DFGE: Dual fuel gas turbine electric propulsion system

DFDM: Dual fuel (slow speed or medium speed) diesel mechanical propulsion system

DFSM: Dual fuel steam turbine mechanical propulsion system

DFDE: Dual fuel (medium speed) diesel electric propulsion system

According to the different ways of handling the BOG, the LNG carriers could be categorized into different types. The Single fuel (low speed) diesel mechanical propulsion with reliquefaction system (SFDM+R) doesn't use the BOG as fuel. The Dual fuel gas turbine electric propulsion (DFGE), Dual fuel (low speed or medium speed) diesel mechanical propulsion (DFDM), Dual fuel steam turbine mechanical propulsion (DFSM) and Dual fuel (medium speed) diesel electric propulsion (DFDE) could use the BOG as fuel.

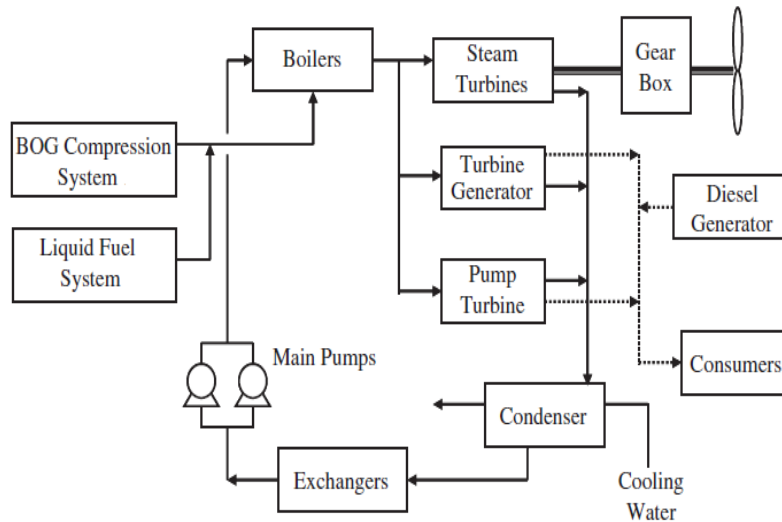


Figure 3. The DFSM power configuration

A). Dual fuel steam turbine mechanical propulsion (DFSMT)

The traditional steam turbine driven propulsion system principle is the BOG would combust in the boiler, and the boiler could produce high-pressure steam to drive the steam turbines which is connected to the propeller via the gear box. The high temperature and pressure steam also drive the turbine generator to produce electricity. And a diesel generator is as an auxiliary generator.

In spite of the thermal efficiency of steam turbine drive system was less than 30%, the traditional propulsion system has advantages. For instance:

- The system was proven to be reliable and simple to operate;
- The system could burn the BOG and the liquid fuel at any ratios simultaneously;
- Compared to other power configurations, the lube oil consumption of steam turbine driven system is relatively low;

- The steam turbine system don't need additional equipment to burn the excessive BOG.

The system either has some evident disadvantages.

- The thermal efficiency of steam turbine propulsion system is less than 30%, but the electric based propulsion system (Dual Fuel Electric propulsion system) is approximately 42.5%. This means compared to Dual Fuel Electric propulsion system, the steam turbine propulsion system has a relatively high fuel consumption rate.
- The operation and maintenance of steam turbine need crew must possess professional knowledge.
- Compared to Dual Fuel Electric propulsion system or Dual Fuel Mechanical propulsion system, the steam turbine system reduced the cargo capacity. The volume of steam turbine power configuration is larger other power configuration. This comparison will be shown in the following content.

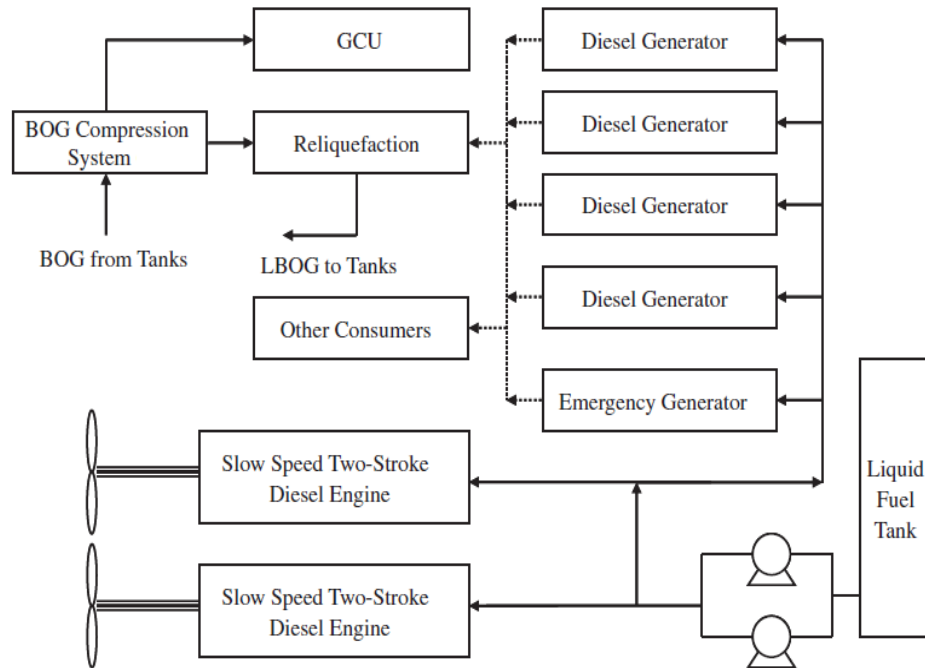


Figure 4. The SFDM+R power configuration

B). Single fuel (low speed) diesel mechanical propulsion with reliquefaction system (SFDM+R)

The carrier with SFDM+R system has 4 diesel generators to produce the electricity for all consumers onboard, include in the reliquefaction system. The BOG from the tank will be reliquefied through the system and return to the tank. If there is more BOG, the extra BOG would combust at the gas combustion unit (GCU). This system uses two twin two stroke slow speed diesel engines which are directly connected to the propeller.

The most obvious advantage of this propulsion configuration is the highest delivery value of the cargo. Since this power configuration doesn't use BOG as fuel. It remains the most volume of the liquid natural gas. And another advantage of SFDM+R is high efficiency and reliability of the engine.

But the engine is the single fuel engine. It uses HFO or MDO as fuel. Since the emission contains relative high proportion SO_x and NO_x .

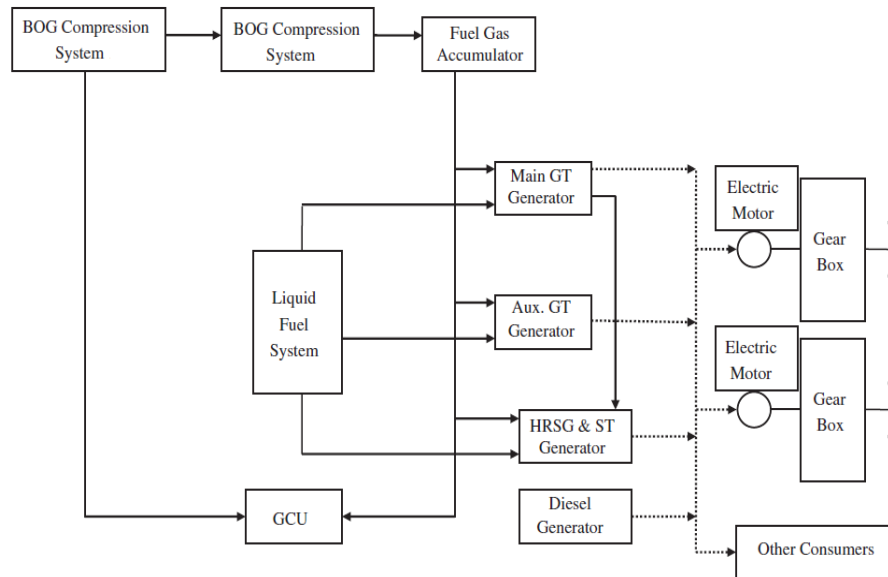


Figure 5. The DFGE power configuration

C) Dual fuel gas turbine propulsion (DFGE)

Compared to the conventional steam turbine, the aero-derivative gas turbine has many advantages. The combined gas turbine electric propulsion configuration could increase about 10% of thermal efficiency. This power configuration consists:

- 1 main gas turbine generator set,
- 1 auxiliary gas turbine generator,
- 1 heat recovery steam generator (HRSG),
- 1 auxiliary diesel generator,
- 1 or 2 electric motors for driving the propeller
- 1 or 2 FPPs (fix pitch propeller)

The heat recovery steam generator (HRSG) could utilize the hot exhaust gas

from the gas turbine to produce high pressure and high temperature steam which could drive the steam generator. The auxiliary gas turbine generator could use as the redundancy. However when the carrier is under the low load demands situation, the auxiliary could provide the electric power. This arrangement increases the operation flexibility. And a GCU is installed for the disposal of extra BOG.

The prime advantages of combined gas turbine electric propulsion:

- Compared to the conventional steam turbine propulsion, the combined gas turbine propulsion could increase the thermal efficiency about 10%.
- Increased the LNG loading capacity. The weight and volume of aero-derivative gas turbine is lower than the steam turbine or dual fuel engine. Since it could reduce the size of engine room and increase the cargo tank capacity.
- This power system could use both BOG and liquid fuel simultaneously.
- The gas turbine is assembled and tested at the factory, hence it could save time at shipyard.
- High reliability of gas turbine.
- Reduced in emission. The gas turbine use BOG as main fuel, and the natural gas is clean energy. Another reason is gas turbine has a little strict requirement about the fuel. High quality fuel could reduce the emissions.
- Compared to the dual fuel engines or single fuel diesel engines, the gas turbine has low noise and vibration.

Drawbacks of combine gas turbine electric propulsion:

- Higher capital cost of propulsion system.
- The gas turbine is a relatively complex technology.
- The crew must have specialized skill and professional knowledge.

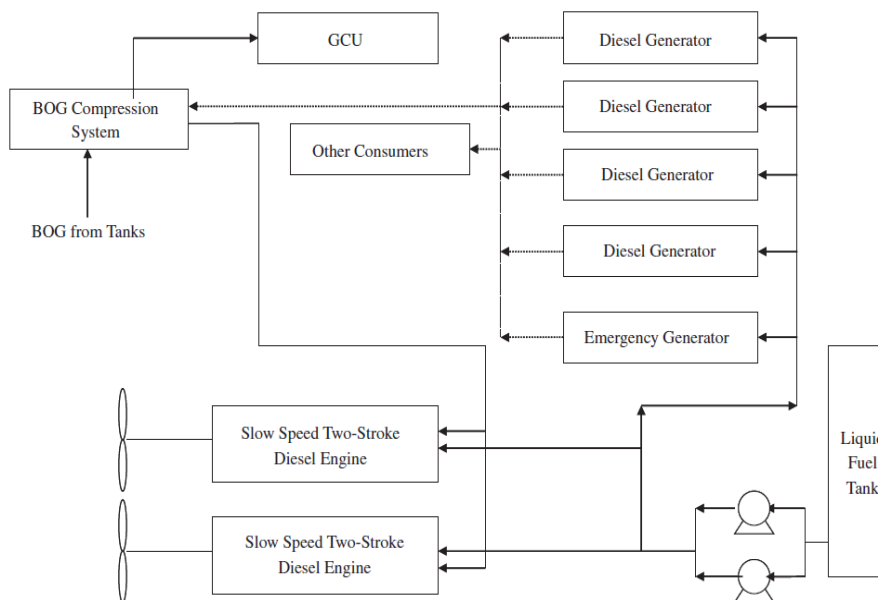


Figure 6. The DFDM power configuration

D) Dual fuel (slow speed) diesel mechanical propulsion (DFDM)

The DFDM has 4 diesel generators and 1 emergency generators in case of main generators shut down because of mechanical failure. The carrier installed 2 slow speed two stroke diesel engines which could burn BOG and liquid fuel simultaneously. The propeller was directly connected to the engines. But one problem of this system is that the fuel gas in the combustion chamber must be compressed to 250 bars (Daejun, 2008). The high pressure fuel gas could bring some serious safety problems.

Advantages of DFDM system:

- High overall thermal efficiency of slow speed engines.
- Higher thermal efficiency indicates lower fuel consumption. When the

BOG could provide the enough energy, the supplementary oil could be reduced or even eliminated.

- High fuel flexibility of dual fuel engine.
- It is much easier to find the crew who qualifies with diesel engines knowledge.

Disadvantages of DFDM system:

- High gas fuel injection pressure. (250 bar for 2 stroke engine)
- More complex control system.
- The maintenance of compressor is expensive.
- Higher emission when engine burn HFO.
- High lube oil consumption rate.

New solutions:

Now Wärtsilä provide the low pressure dual fuel 2 stroke engines and dual fuel 4 stroke engines which are safer to operate.

The engine accord with several principles: engine operating accordingly to Otto process; injection of gas at mid-stroke. Low pressure gas injection (lower than 10 bar) sufficient; high impact on NO_x reduction; meets IMO Tier III without after treatment. (Rudolf. 2013)

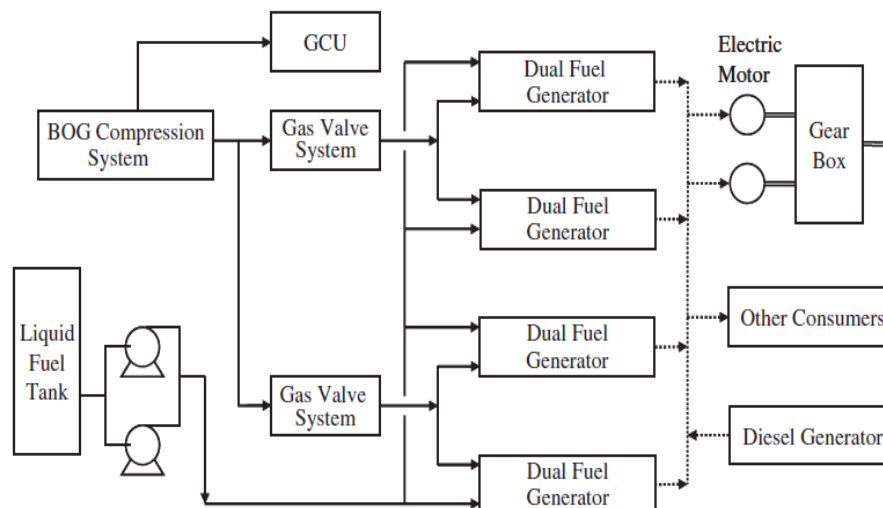


Figure 9. The DFDE configuration

E) Dual fuel (medium speed) diesel electric propulsion (DFDE)

The system contains 4 identical dual fuel engines. The propeller is driven by electric motors. But the dual fuel engines of DFDE systems couldn't burn the BOG and liquid fuel at the same time, it must shift one fuel mode to another mode. Hence it didn't require high gas pressure, only 6 bar is enough for the BOG fuel mode. The GCU is installed for handle the rest BOG.

Technical comparison of alternatives

Comparison principles

For comparison, the LNG carriers are similar, including the containment system and the cargo capacity.

The standard cargo capacity is assumed to be approximate 150,000 m³, and the containment system is Membrane system.

The Boil off rate is approximate 0.15% per day for the laden voyage, and for the ballast voyage the BOG rate is 0.06% per day (the LNG density is 450kg/m³). For the laden voyage, the BOG generation rate is approximate 4.22 ton/hr, for ballast voyage this rate is 1.69 ton/hr.

The comparison LNG carriers dimensions

All the carriers used for comparison have similar size. The standard capacity of the steam turbine carrier is assumed to be 150,000 m³. But different power plant configurations have different weight and need different engine space. When the dimensions of the carriers are similar, the tank capacity of the carriers could be distinct.

For the DFDM with 4 stroke engines and DFDM with 2 stroke engines: the capacity is 149,000 m³

For the combined gas turbine electric propulsion: the cargo capacity is 165,000 m³

Basic comparisons

Now the traditional steam turbine carrier doesn't dominate the market. The Dual fuel diesel electric propulsion (DFDE) LNG carrier which is more efficient dominates the market. In this section the DFDE LNG carrier would be chosen as a standard carrier.

System components specific efficiency

Compared to the original steam turbine propulsion system. The DFDE propulsion system has a relative high thermal efficiency.

Table 1

The specific efficiency of DFDE system

DFDE with single screw propulsion system	Efficiency
Fuel/BOG	100%
DF engines	48%
Alternators	97%
Transformers and conversion	98%
Electric motors	98%
Gearbox	98%
Shafting	99%
Total efficiency	43.4%

Notes: Efficiency data from Wärtsilä Dual-Fuel LNGC, 2008.

Volume and weight of three alternatives

In order to comparison, the carrier dimensions are similar. For the standard carrier with DFDE propulsion system, the particulars are:

Table 2

Main dimensions of carriers with DFDE propulsion system

Length over all:	280 m
Length between perpendiculars:	268m
Breadth moulded	43.20m
Draught (diesel electric)	11.95m
Gross tonnage:	95,500 tons
Cargo capacity	150.500 m³

Notes: Data is from EVALUATION OF PROPULSION OPTION FOR LNG

CARRIERS, 2002.

Fuel consumption

This table is power distribution when all engines are in operation.

Table 3

Power distribution

Total available power	kW	39,900
Propulsion power without sea margin	kW	21,600
Ship service power	kW	1,500
Propulsion & Aux. gen. losses	kW	2446
Extra available power	kW	14354
Sea margin	kW	4536
Sea margin	%	21
Power reserve	kW	9818
Missing power for contractual speed	kW	0
Power utilized for propulsion	kW	21600
Corresponding ship speed	Kn	19.5

Notes: Data is from Wärtsilä Dual-Fuel LNGC, 2008.

The standard DFDE LNG carrier installed 3 Wärtsilä 12V50DF engines (maximum output 11,400 kW) and 1 6L50DF engine (maximum output 5,700 kW)

onboard. The total maximum output of these 4 engines is 39,900 kW. All the engines in operation, the power output is 25,546 kW. The 25,546 kW indicate the total required power onboard without power reserve or sea margin. It is the sum of propulsion power without sea margin (21,600 kW), ship service power (1,500 kW) and propulsion & aux.gen. loss (2446 kW).

The gas consumption is 7562 KJ/kWh. The LHV of natural gas is 49.7 KJ/g

The fuel consumption:

$$7562 \div 49.7 = 152.15 \text{ g/kWh}$$

$$160.41 \times 25546 \times 24 \div 10^6 = 93.29 \text{ tonnages}$$

Fuel flexibility

The dual fuel 4 stroke medium engine is flexible on fuel type. It could use Natural BOG, Forced BOG, MDO.HFO and MGO.

Comparison of three alternatives

In this section, basic technical comparison will be done for 3 alternatives:

Thermal efficiency

The next figure shows the different LNG carrier propulsion system efficiencies. The low speed engine has the highest thermal efficiency. The steam turbine propulsion system has the lowest efficiency.

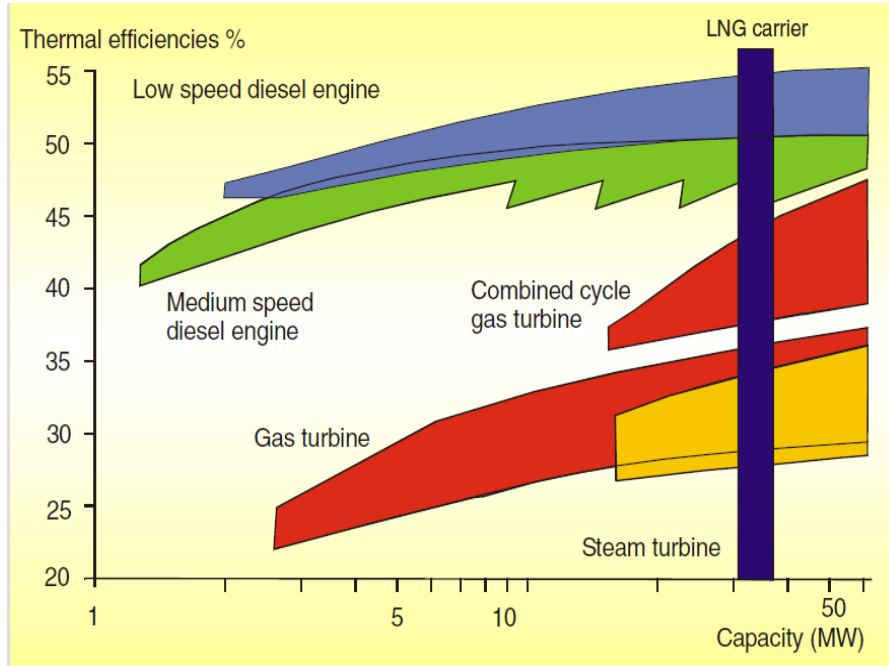


Figure 10. Typical thermal efficiencies of prime movers

Table 4

Detailed efficiency of three alternatives

COGES	efficiency	DFDM with 4 stroke engines	efficiency	DFDM with 2 stroke engines	efficiency
Fuel/BOG	100%	Fuel/BOG	100%	Fuel/BOG	100%
Gas turbine and steam turbine combined cycle	44%	DF 4 stroke engines	46%	DF 2 stroke engine	49%
Alternators	97%	shafting	99%	shafting	99%
Transformer and conversion	98%	Gear box	98%		
Electric motors	98%				
Gear box	98%				
shafting	99%				
Total efficiency	39.8%	Total efficiency	44.6%	Total efficiency	48.5%

Notes: data is from Wärtsilä Dual-Fuel LNGC, 2008.

Compared with the DFDE system, the efficiency of combined gas turbine electric propulsion system is little lower than the DFDE system and the reason is that

the dual fuel engine has a higher efficiency than the combined gas turbine & steam turbine.

For the DFDM with 4 stroke medium speed engines and DFDM with 2 slow speed engines, the efficiencies are higher than the DFDE system. For the mechanical propulsion system, the propellers are directly connected with the engines. The power loss only occurs at shafting and gear box. For the electric propulsion system, the power loss would happen at generators, transformers, motors, gear box and shafting. Even the power loss at each component is only 1 or 2 percent, the total power loss is obvious.

Compared with the 4 stroke and 2 stroke engines, the 2 stroke slow speed engine is more efficient. The medium speed engines need gear box to connect to the propeller. There is 1 to 2 percent power loss at gear box.

In this section, the Dual fuel with 2 stroke slow speed engine mechanical propulsion system has the highest efficiency.

Volume and weight of alternatives

For comparison the DFDE propulsion system and combined gas turbine electric propulsion system, the dimensions of carriers are:

Table 5

Cargo capacity comparison between DFDE and COGES propulsion system

Length overall	291.50 m
Length between perpendiculars	280.00 m
Breath moulded	43.00 m
Draught	12.00m
Depth to maindeck	27.00 m
Speed	20 kn
Cargo capacity (DFDE)	156,700 m³
Cargo capacity (COGES)	165,000 m³

Notes: Data is from Techno-economic Evaluation of Various Energy systems for LNG carriers, 2006.

Table 6

Cargo capacity comparison between DFDE and DFDM propulsion system

Length overall	280.00 m
Length between perpendiculars	268.00 m
Breath moulded	43.20 m
Draught (DFDE)	11.95 m
Draught (DFDM)	12.10 m
Depth to maindeck	26.10 m
Speed	19.5 kn
Cargo capacity (DFDE)	150,500 m³
Cargo capacity (DFDM)	149,000 m³

Notes: For the DFDM power plant configuration, the engine room is similar size. Data is from EVALUATION OF PROPULSION OPTION FOR LNG CARRIERS, 2002.

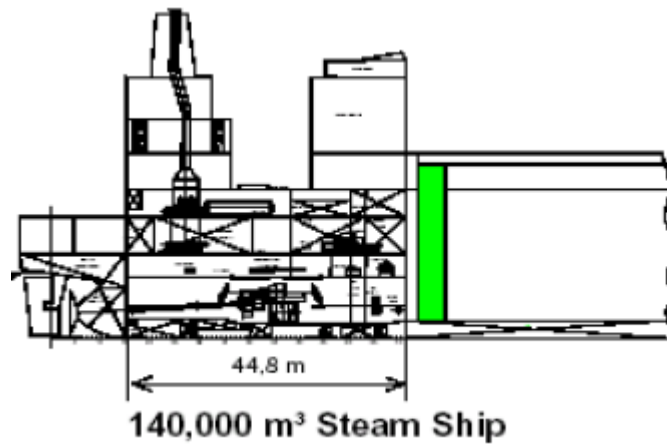


Figure 11. The steam turbine LNG carrier

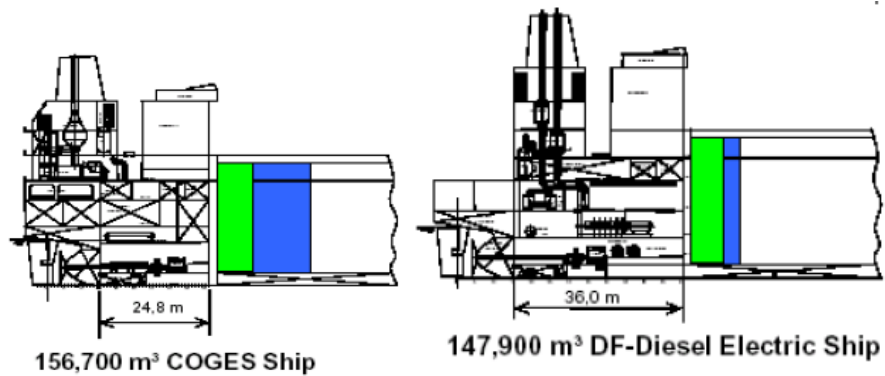


Figure 12. Comparisons of engine room and additional cargo delivery

In this figure, the blue square means the additional LNG delivery, and the green square natural BOG and force BOG for a 6,500 nm voyage. And all these two configurations are compared with a similar size steam turbine LNG carrier.

Elaborate comparison of volume and weight 3 alternative propulsion system:

The standard LNG carrier used for comparison installed the DFDE propulsion system with single screw. The next table shows the cargo capacity and propulsion configuration of the carrier.

Table 7

Engine configuration and propulsion requirement

LNG capacity (100%)	155,000 m ³
Main engine sets	WÄRTSILÄ 3×12v50DF+1×6L50DF
Electric propulsion system	21,600 kW

Notes: Data is from Wärtsilä Dual-Fuel LNGC, 2008.

According to the WARTSILTA dual fuel engine data, the next table shows the total power output and weight of the engines.

Table 8

Specific data of WÄRTSILÄ dual fuel engines

Engine type	Generator Output/kW	Weight /tonnage	Dimensions/mm				
			A	B	C	D	F
6L50DF	5,700	96	8115	3580	2850	3820	1455
12V50DF	11,400	175	10465	4055	3810	3600	1500

Notes: Data is from WÄRTSILÄ 50DF ENGINE TECHNOLOGY.

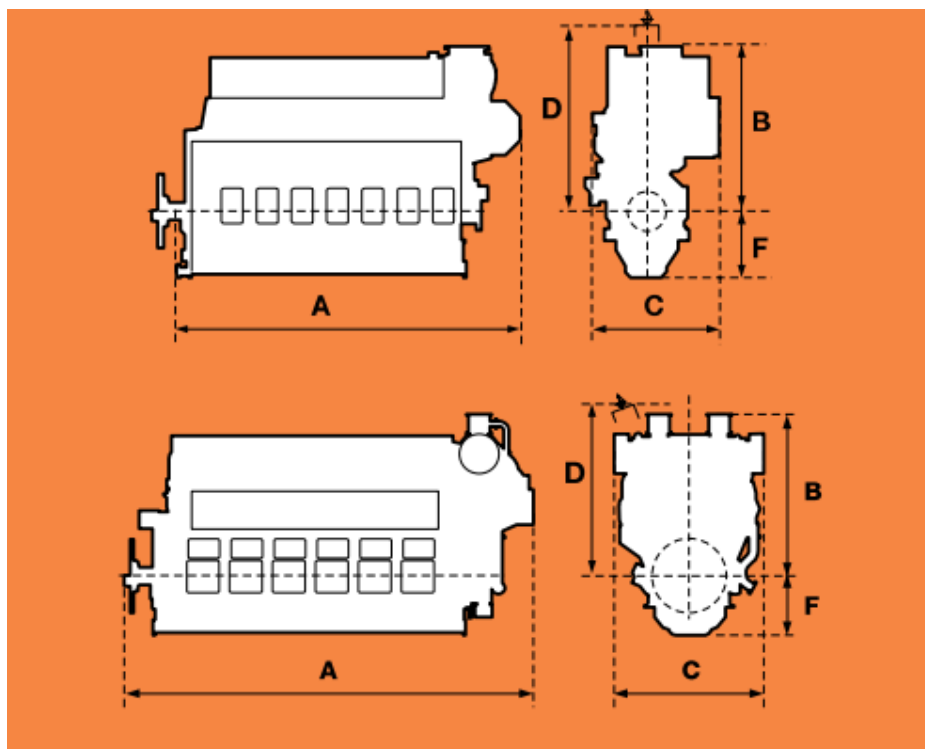


Figure 13. The dimensions of dual fuel engine.

This DFDE LNG carrier total installed power onboard is 39,900 kW and the electric propulsion power is 21,600 kW. The total weight of engines is 621 tons.

DFDM with 4 stroke medium speed engines power configuration:

The next figure shows the overall dual fuel 4 stroke medium speed engines available on the market, and the power output range is from approximate 1,000 kW to 18,000 kW.

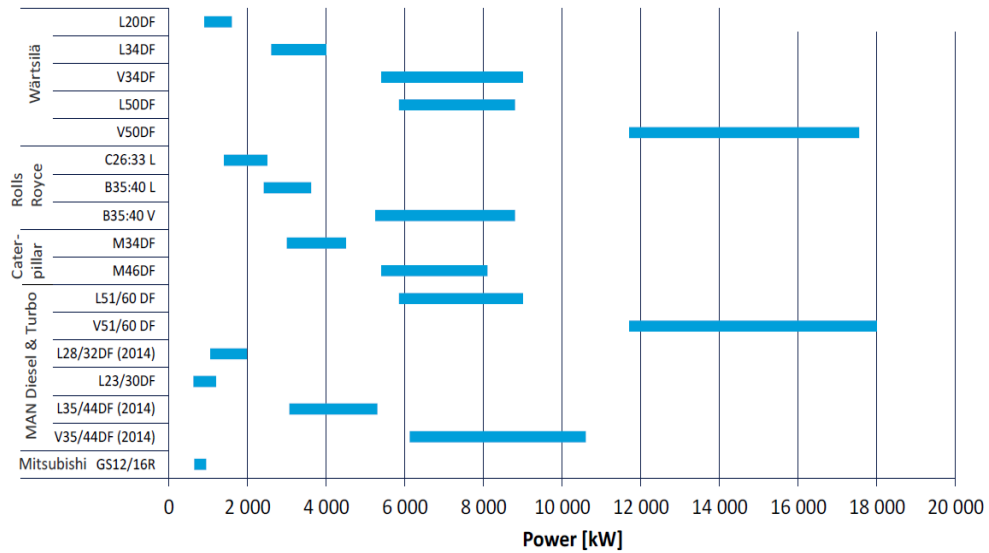


Figure 14. Dual fuel 4 stroke medium speed engines and power output

If the Dual fuel mechanical propulsion LNG carrier has the similar dimensions and propulsion requirements with the Dual fuel electric propulsion LNG carrier.

Considering the sea margin and power reserve the engine configurations could be four 8L50DF engines (4 stroke) and two 9L32 auxiliary generators.

This table is main engines' output and dimensions.

Table 9

Engines sets

Engine type	Engine output/kw	Weight /tonnage	Dimensions/mm				
			A	B	C	D	F
8L50DF	7,600	128	9950	3600	3100	3820	1455

Notes: Data is from WÄRTSILÄ 50DF ENGINE TECHNOLOGY.

This table is auxiliary generators' output and dimensions.

Table 10

Auxiliary generator sets

Engine type	Auxiliary Output/kw	Weight /tonnage	Dimensions/mm				
			A	B	C	D	F
9L32	4320	49.2	6869	2325	2610	2345	1155

Notes: Data is from WÄRTSILÄ 32 PRODUCT ENGINE.

For the DFDM power plant configuration with 4 stroke medium speed engine, the total weight of engines are approximate 610.4 tons.

DFDM with 2 stroke slow speed engines power configuration:

Since the dual fuel 2 stroke slow speed engines are new on the market. The solutions are calculated based on the dual fuel 4 stroke engines configuration. Two solutions are provided in this sub-section.

For the DFDM power plant configuration with 2 stroke slow speed engine. There are over 10 types of dual fuel 2 stroke slow speed engines on the market. The engines output range is from 4,500 kW to 36,000 kW.

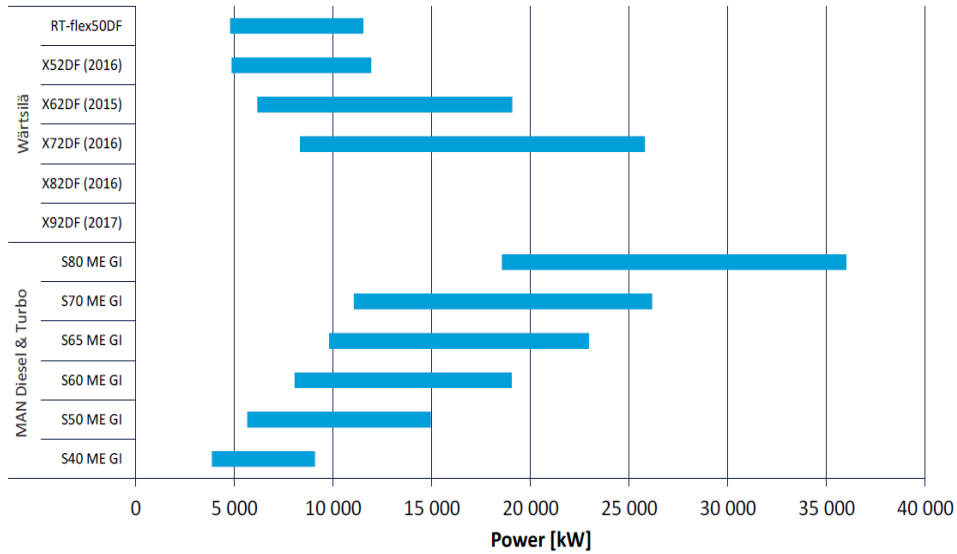


Figure 15. 2 stroke dual fuel engines and power output range

a) Wärtsilä RT-flex50DF

In this section the Wärtsilä RT-flex50DF was taken as the example.

Table 11

RT-flex50DF dual fuel engine output and dimensions

Rated power, principal dimensions and weights							
Cylinder number	Output in KW at				Length A (mm)	Length A* (mm)	Weight (tons)
	124 rpm		99 rpm				
	R1	R2	R3	R4			
5	7,200	6,000	5,750	4,775	5,576	6,793	200
6	8,640	7,200	6,900	5,730	6,456	7,670	225
7	10,080	8,400	8,050	6,685	7,336	-	255
8	11,520	9,600	9,200	7,640	8,216	-	280

Dimensions (mm)	B	C	D	E	F*
	3,150	1,088	7,646	3,570	1900
	F1	F2	F3	G	-
	9,270	9,250	8,700	1,636	-

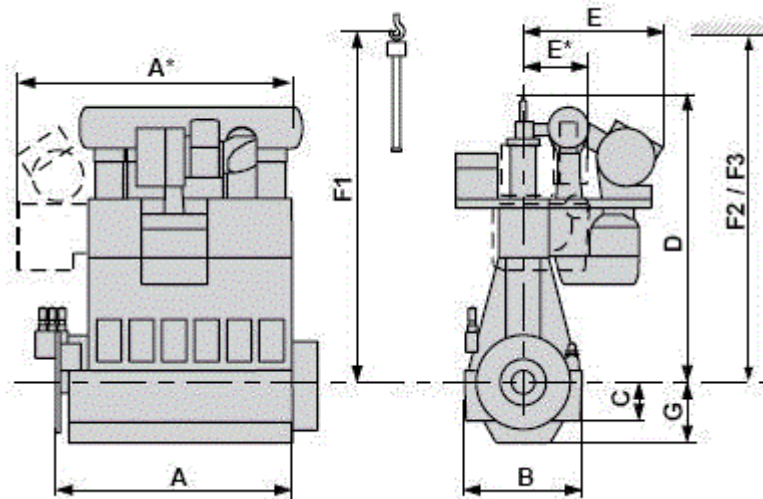


Figure 16. Cross-section of engine.

The total output for the LNG carrier is about 30,000 kW. We can choose three engines with 6 cylinders and one engine with 5 cylinders. The total input is approximate 30,000 kW. The total weight of engines is approximate 875 tons.

b) Wärtsilä X62DF or X72DF

Here is another example from Wärtsilä. This power configuration is designed for 175,000 m³ LNG carrier. The power system has two dual fuel 2 stroke slow speed engines which are directly connected to the propellers, and the maximum output of each engine is 12500 kW. The engine could adopt 72DF engines with 5 cylinders or 62DF engines with 6 or 7 cylinders. The generator sets used 2 types of different dual fuel engines; two 9L34DF engines and one 6L34DF engine. The total electricity output is 10440 kW.

Combined gas turbine electric propulsion configuration:

For the combined gas turbine electric propulsion system: if the combined gas

turbine electric propulsion system has the similar total output range, the output of gas turbine should be around 30,000 kW. The LM2500+ marine gas turbine from GE accords with requirement.

Table 12

Specific data of LM2500+ marine gas turbine

Gas turbine	Output /kw	SFC/ g/kW-hr	Width /m	Length /m	Height /m	Weight /tonnage
LM2500+	29,000	215	3.12	14.38	3.98	94.545

Notes: The weight of gas turbine doesn't include the generator sets. The total propulsion system weight should include the generator weight. Data is from LM2500+ Marine Gas Turbine.

Table 13

Comparison of total weight of alternatives

Configuration	Weight /tons
COGES	94.545
DFDM with 4 stroke engine	610.4
DFDM with 2 stroke engine	973.4

Notes: The COGES propulsion system weight doesn't contain the generator weight.

In this section, the performance of combined gas turbine electric propulsion is the best. One of the most obvious advantages of COGES power plant configuration is the reduction of engine room space and increase the cargo tank capacity.

Limitation: The COGES propulsion system should include the generator weight. Since the generator information is not provided. For COGES propulsion system the generator set is not an ignorable segment. If further information or data about the generator could be provided, more accurate comparison could be carried out.

Fuel consumption

For the DFDM with 4 stroke engine power plant, the engine set adopts 8L50DF type dual fuel engine. The next table shows the fuel consumption under the different situation.

Table 14

Fuel consumption for 8L50DF

		Gas mode	Diesel mode
Total energy consumption at 100% load	kJ/kWh	7300	-
Total energy consumption at 75% load	kJ/kWh	7620	-
Total energy consumption at 50% load	kJ/kWh	8260	-
fuel gas consumption at 100% load	kJ/kWh	7258	-
fuel gas consumption at 75% load	kJ/kWh	7562	-
fuel gas consumption at 50% load	kJ/kWh	8153	-
Fuel oil consumption at 100% load	g/kWh	1.0	189
Fuel oil consumption at 75% load	g/kWh	1.5	192
Fuel oil consumption at 50% load	g/kWh	2.4	204

Notes: Data is from WAWRTSILA 50DF PRODCUT GUIDE.

The DFDM with 4 stroke medium speed engine power plant, we can do a calculation.

For instance we choose the gas mode at 75%. The engine output is 7600 kW and the carrier has four engines. So the total output is

$$P_{\text{total}} = 7600 \times 4 \times 75\% = 22800 \text{ kW}$$

And the gas consumption is 7562 kJ/kWh and the Lower Heating Value (LHV) of natural gas is 49.7kJ/g, so the gas consumption is

$$7562 \div 49.7 = 152.15 \text{ g/kWh}$$

So the gas consumptions per day is

$$22800 \times 24 \times 152.15 \div 10^6 = 83.26 \text{ tonnages}$$

The capacity of LNG carrier is assumed to be 150,000 m³ and the BOG rate is 4.22 ton/hr.

The total mass of natural gas per day is

$$4.22 \times 24 = 101.2 \text{ tonnages}$$

So the NBOG could satisfy the fuel demands when the engines are at 75% load, the most economical fuel is to use the NBOG.

DFDM with 2 stroke engine power plant engine

The fuel consumption of this power configuration is 81 tonnages gas per day.

- The main engines consume 2×37.5 tonnages per day.
- And auxiliary engine's gas consumption is 6 tonnages per day.
- The SFC of 2 stroke engine is approximate 125 g/kWh.

Combined gas turbine electric propulsion power plant

The gas turbine SFC is 215 g/kWh.

The gas turbine maximum output is 29,000 kW. When the engine output is 22,800 kW, the fuel consumption per day is

$$22,800 \times 24 \times 215 \div 10^6 = 117.65 \text{ tonnages.}$$

So when the gas turbine is on 22,800 kW output, the NBOG is not enough, need FBOG or MDO as fuel.

Limitation: when the gas turbine is at the maximum output, the SFC is 215g/kWh. We assumed the SFC here is constant.

Table 15

Comparison of SFC (gas mode)

Power plant	DFDM with 4 stroke engine	DFDM with 2 stroke engine	Combined gas turbine
SFC [g/kWh]	152.15	125	215

Fuel flexibility

Here is the comparison of flexibility of different alternatives.

Table 16

Comparison of fuel flexibility

	NBOG	FBOG	MDO	HFO	MGO
DFDE	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable
4 stroke	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable
2 stroke	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable
COGES	Acceptable	Acceptable	Unacceptable	Unacceptable	Acceptable

Notes: Data is from WÄRTSILÄ Dual-Fuel LNGC, 2008.

In this section, the gas turbine has some restricts on the fuel consumption. It could only accept the boil off gas and marine gas oil. Other alternatives could adopt all 5 types of fuel. All three alternatives could operate in high efficiency when they are in gas mode.

Emission

Emissions of different alternatives are compared in different components, for instance: NO_x, SO_x, CO₂ and particulates.

Emissions of dual fuel 2 stroke slow speed engines compared with diesel engine.

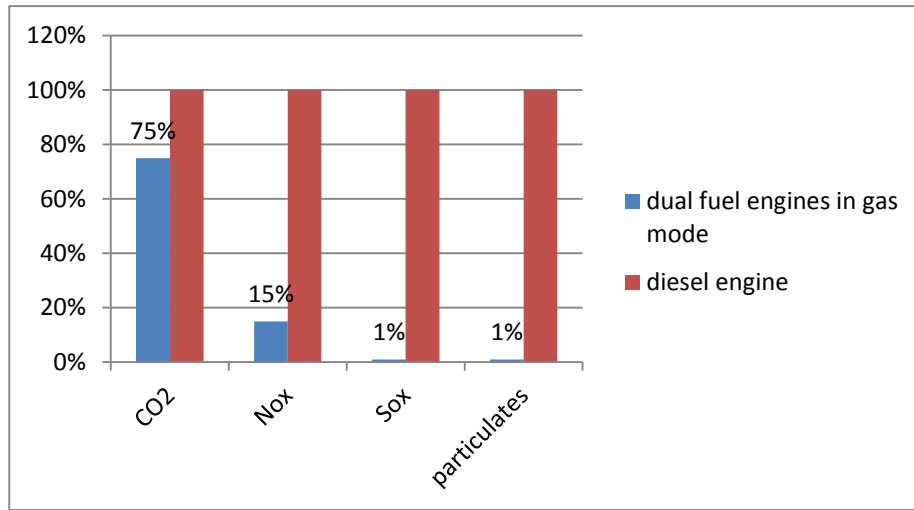


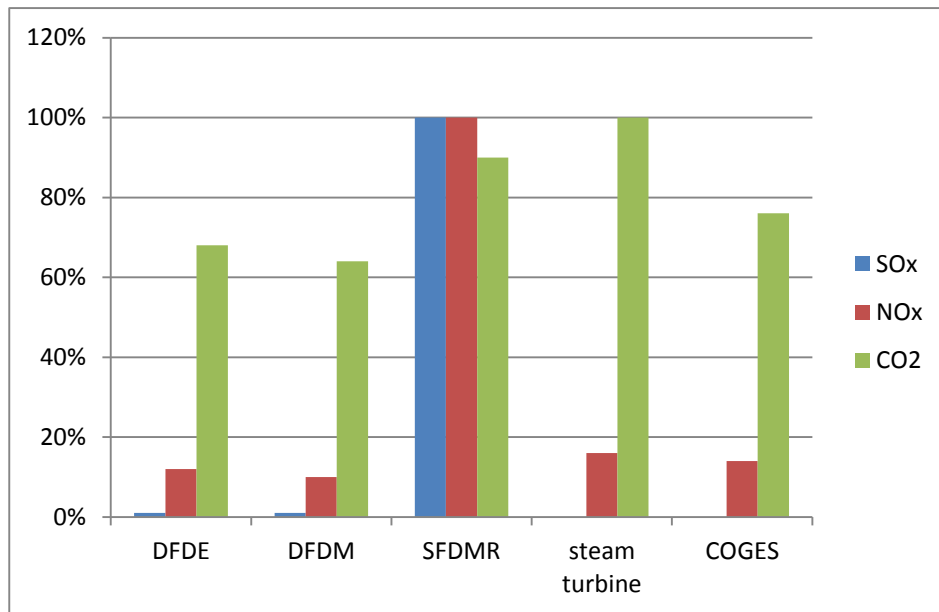
Figure 17. Dual fuel slow speed engine emission comparison

Table 17

Emission comparisons of three alternatives

	NO _x [g/kWh]	SO _x [g/kwh]	CO ₂ [g/kWh]	Particulates [g/kWh]
DFDE	1.3	0.05	5.0	0.05
Gas turbine	2.5	0	5.9	0.01
DFDM	1.2	0.05	1.7	0.05

Notes: The emissions of DFDE propulsion system is used as reference, the DFDM means DFDM with 4 stroke engines. Data is from propulsion alternatives for modern LNG carriers (Dongil Yeo, 2006.)



*Figure 18.*Emissions of three alternatives

In this figure, Single fuel diesel mechanical propulsion with reliquefaction and steam turbine power plant are taken as reference. The SO_x and NO_x from SFDMR are seen as 100% and CO₂ from steam turbine are 100%. Also this comparison is under the maximum gas mode. It means the power plant use the maximum BOG as fuel, including the force BOG.

Compared with the traditional steam turbine and two stroke single fuel with reliquefaction power plant, the DFDE, DFDM and COGES power plant reduced the SO_x and NO_x emission significantly. The DFDE and DFDM power plant have negligible SO_x emission (less than 1%) and the COGES has zero SO_x emission. All three alternatives NO_x emission is approximate 10% and it's acceptable. Compared with the steam turbine power plant, the CO₂ emission is reduced 20 to 30 percent.

Compared with the dual fuel mechanical propulsion power plant (DFDM) and combined gas turbine electric propulsion power plant (COGES), the DFDM has lower NO_x and CO₂ emission, but still it has few SO_x emissions. And the COGES has zero

SO_x emission but higher NO_x and CO₂ emission. Especially in CO₂ emission, it's nearly 10% higher than the DFDM power plant.

The conclusion is that if the dual fuel engine and gas turbine could use the maximum BOG, including the NBOG and FBOG, it could reduce the emission significantly.

Economical comparison of alternatives

Comparison principle

The comparison principle is same with the technical comparison part. For a valid comparison:

The capacity of LNG carrier is 150,000 m³, and all alternatives are same.

The laden voyage BOG rate is 0.15% per volume per day, and the ballast voyage BOG rate is 0.06% per volume per day.

The carrier speed is 19.5 knots.

Choosing a voyage route:

The voyage route is from RasLaffen, Qatar to Inchenon, South Korea.



Figure 19. The LNG shipping route from Qatar to South Korea

The voyage days is calculated based on the maximum carrier speed 19.5 knots, the distance between Ras Laffan and Incheon is 6,233 nm and average voyage time is 13.3 days.

Table 18

Voyage information

voyage	condition	Voyage time hr	Main engine Operation time, hr	BOG generation time, hr
Laden	Port-loading	25	-	-
	sea voyage	320	319.2	319.2
Ballast	Port-unloading	20	-	-
	sea voyage	320	319.2	319.2
total		685	638.4	638.4
Number of voyage/year			12.2	

Notes: Data is from economic evaluation of propulsion systems for LNG carriers: a comparative life cycle cost approach. (Daejun Chang, 2008)

Life cycle cost comparison

Life cycle cost (LCC) means the cost of a carrier life cycle.

$$LCC^P = CAPEX^P + OPEX^P$$

The CAPEX usually contains the equipment cost, building cost. It is fixed and only need to be paid once over the life cycle. Compared with the CAPEX, the OPEX is paid continuously over the life cycle. It is affected by many factors. Like oil price, the crew cost and maintenance cost etc.

The Life cost analysis procedure.

The main procedure includes four steps. Depend on different cases, the sub-tasks under the total general four steps could do some adjustments. The overall four steps is applicable to many comparative case studies.

Step 1. Definition of the system configuration and functions

- Definition of scope of analysis
- System configuration
- Design specification

Step 2. Assessment of the system performance

- Electric load analysis
- Fuel (BOG and liquid oil) consumptions

Step 3. Estimation of the reliability of the system

- Functional block diagram
- Availability for propulsion and BOG treatment functions

Step 4. Assessment of the comparative life cycle cost

- CAPEX^P and OPEX^P calculation
- LCC^P calculation

The Operating Expenditure, OPEX^P

The operating cost deals with the expenditure, not the benefit. The expenditure includes not only the operation and maintenance cost, but also the financial damage due to the imperfect fulfillment of the cargo delivery duty incurred by the propulsion system.

The operating expenditure is the sum of various variables, C_N , N is from 1 to 10:

C_1 : Delivery loss cost due to the propulsion failure;

C_2 : BOG loss cost due to BOG evaporation caused by heat ingress;

C_3 : BOG loss due to BOG treatment failure;

C₄: Penalty cost due to delayed delivery;

C₅: Fuel consumption cost for operation;

C₆: fuel consumption cost for BOG treatment;

C₇: fuel consumption for GCU operation;

C₈: lubricant consumption cost;

C₉: preventive maintenance cost for propulsion system;

C₁₀: corrective maintenance cost for propulsion system;

C_N: Total sum of the annual cost.

And most of the components cost are affected by the two availabilities or both

A_P: availability of propulsion system.

A_{BOG}: availability of BOG treatment system.

Availability is the asymptotic ratio of operating time to total time including the maintenance time. The availability (A) and unavailability (UA)

$$UA+A=1$$

The availability should be considered is because it has tremendous impact on the propulsion system economics.

C₁ is the delivery loss cost due to propulsion failure and is affected by the propulsion availability.

$$C_1 = N_{\text{voyage}} \cdot (M_{\text{Offload}} \cdot C_{\text{CIF}} - M_{\text{load}} \cdot C_{\text{FOB}}) \cdot UA_P$$

In this equation $M_{\text{Offload}} \cdot C_{\text{CIF}} - M_{\text{load}} \cdot C_{\text{FOB}}$ means the profit of one voyage. After it times the number of voyage per year and unavailability of propulsion, it means the delivery loss.

For the SFDM+R power plant, there is the reliquefaction system onboard. The offloading LNG mass and loading mass is identical. For other power plant configuration, the LNG mass of offloading equals the mass of loading minus the mass of BOG

$$M_{\text{offload}} = \begin{cases} M_{\text{load}} & \text{for SFDM + R} \\ M_{\text{load}} - M_{\text{BOG}} & \text{for the others} \end{cases}$$

The mass of BOG on a round trip

$$M_{\text{BOG}} = M_{\text{load}} \cdot \text{BOR}_m \cdot T_{\text{BOG}}$$

N_{voyage} Number of voyage per year

M_{offload} The offloading LNG mass

M_{load} The loading LNG mass

C_{CIF} Cost, insurance and freight price of LNG, \$/ton

C_{FOB} Free-on-board price of LNG, \$/ton

BOR_m Average BOG rate for laden and ballast voyage

T_{BOG} Time of BOG evaporation, hour

In a CIF, a seller is responsible for paying for shipping and providing a minimum amount of insurance coverage up to the named port of destination, while the buyer is responsible for the transportation risk beyond the minimum coverage as soon as the good or product is loaded onto the ship.

C_2 is BOG loss due to BOG evaporation, it reflects the natural BOG evaporation rate. Since the BOG is considered as loss, the BOG fuel consumption in C_5 should be zero.

$$C_2 = N_{\text{voyage}} \cdot M_{\text{BOG}} \cdot C_{\text{CIF}}$$

M_{BOG} Mass of BOG

C_3 is the BOG loss due to the failure of BOG treatment system. When the BOG treatment system fail, the BOG couldn't be supplied to the engine as fuel or to the reliquefaction system. Eventually it must be supplied to the Gas Combustion Unit.

$$C_3 = M_{BOG} \cdot C_{CIF} \cdot UA_{BOG}$$

In this thesis the penalty was assumed to equal the profit loss of the gas seller

$$C_4 = N_{voyage} \cdot M_{offload} \cdot C_{CIF} \cdot UA_{BOG}$$

C_5 is the fuel consumption cost.

$$C_5 = N_{voyage} \cdot T_P \cdot A_P \cdot (MC_{fuel,laden} + MC_{fuel,ballst})/2$$

Except for the SFDM+R power plant system, all the other power plants could use two or three fuel modes, hence the minimum fuel cost should be chosen for the operations.

T_P Propulsion overall operation system, hr

A_P Availability of propulsion system

C_6 is the fuel consumption cost for the BOG treatment system. The fuel cost varies between the laden voyage and ballast voyage.

$$C_6 = N_{voyage} \cdot T_{BOG} \cdot A_{BOG} \cdot WM_{BOG,MEAN} \cdot C_{MDO}$$

$$WM_{BOG,MEAN} = (W_{BOG,LADEN} \cdot M_{MDO,BOG,LANDEN} + W_{BOG,BALLAST} \cdot M_{MOD,BOG,BALLAST})/2$$

T_{BOG} Time over which BOG is generated, hr

A_{BOG} Availability of BOG treatment system

$WM_{BOG, Mean}$ Mean fuel consumption for BOG treatment system kg/hr

$W_{\text{BOG,Laden}}$ Power consumption of BOG treatment system, W/hr

The GCU requires power supply. C_7 is calculated by the equation:

$$C_7 = N_{\text{voyage}} \cdot (T_{\text{GCU}} + T_{\text{BOG}} \cdot UA_{\text{BOG}}) \cdot WM_{\text{GCU,mean}} \cdot C_{\text{MDO}}$$

T_{GCU} Time over which GCU should be operated. hr

T_{BOG} Time over which BOG is generated. hr

$WM_{\text{GCU,Mean}}$ Mean fuel consumption for GCU

C_{MDO} Price of MDO. \$/ton

The lube oil cost is expressed in the equation:

$$C_8 = N_{\text{voyage}} \cdot T_p \cdot A_p \cdot M_{\text{lube}} \cdot C_{\text{lube}}$$

The preventive maintenance cost C_9 contains two parts, man hour expense and material cost. Both these two parts are multiplied by the preventive frequency and number of engines. Typically every two or three years, the engine manufactures suggest the carrier should do a preventive maintenance.

NOTE: the preventive maintenance here is the major maintenance which is done by the engine producer. And the frequent preventive maintenance is carried out by the crew onboard. This part maintenance job has insignificant influence on the total LCC. Hence only major maintenance job is considered.

$$C_9 = N_{\text{PM}} \cdot N_{\text{engine}} \cdot (MH_{\text{PM}} \cdot C_{\text{MH}} + R_{\text{PM}} \cdot \text{CAPEX}_p)$$

N_{PM} The number of PM action

N_{engine} Number of engine

NH_{PM} Man hours per PM action, hr

R_{PM} Ratio of PM material cost to CAPEX_p

The corrective maintenance cost C_{10} is similar with the preventive cost

$$C_{10} = N_{CM} \cdot N_{engine} \cdot (MH_{CM} \cdot C_{MH} + R_{CM} \cdot CAPEX_P)$$

Table 19

Connection between cost components and availabilities

components	A _P	A _{BOG}
C ₁ : Delivery loss cost due to the propulsion failure	Y	
C ₂ : BOG loss cost due to BOG evaporation caused by heat ingress;		
C ₃ : BOG loss due to BOG treatment failure		Y
C ₄ : Penalty cost due to delayed delivery	Y	
C ₅ : Fuel consumption cost for operation	Y	
C ₆ : fuel consumption cost for BOG treatment		Y
C ₇ : fuel consumption for GCU operation	Y	Y
C ₈ : lubricant consumption cost	Y	
C ₉ : preventive maintenance cost for propulsion system	Y	Y
C ₁₀ : corrective maintenance cost for propulsion system	Y	Y

Notes: The table illustrates which components are connected with either propulsion availability or BOG treatment availability, or both. Data is from Economic Evaluation of Propulsion Systems for LNG carriers: A Comparative Life Cycle Cost Approach. (Daejun Chang, 2008)

Estimation of Life Cycle Cost, LCC^P

After combined the CAPEX^P and OPEX^P, the Life Cycle Cost is possible to evaluate the present-value cost. The future-value cost depend on the future price of fuels, man hours, etc. these price are estimated by combining the present-value with the inflation rate. The present oil and gas price are available online. And the LCC^P is presented in the form of cost per volume transported.

Comparison of three alternatives

In this section the LCC method would be used to compare all three alternatives: dual fuel 4 stroke diesel mechanical propulsion system, dual fuel 2 stroke diesel mechanical propulsion system and combined gas turbine electric propulsion. With different inputs, the comparison study would be different.

Step 1: Definition of the systems configurations and functions

All three alternatives are chosen for the comparison. The difference between DFDM I and DFDM II is the DFDM I has two 4 stroke medium speed engines and DFDM II has two 2 stroke slow speed engines. COGES means the combined gas turbine electric propulsion system.

DFDM I power plant has 4 medium speed diesel engines without any redundancy

DFDM II power plant has 3 slow speed diesel engines without any redundancy

COGES power plant has 1 gas turbine generator and 1 steam turbine generator, and 1 auxiliary generator and 1 diesel generator as redundancies.

The power plant configuration has been illustrated at previous content.

Step 2: Assessment of the system performance

Electric load of alternatives:

Since the combined gas turbine power plant (COGES) is electric propulsion and the other two alternatives are mechanical propulsion. So the electric load different is

distinct.

A 155,000 m³ LNG carrier with DFDE power plant, the total electric output is 38.5 MW. Combined gas turbine electric propulsion (COGES), the gas turbine power output is 29 MW, and combined with a HRSG the total output electric load is over 30 MW. Assumed the total electric load is 35 MW. And the total output for the DFDM power plant is 4 MW

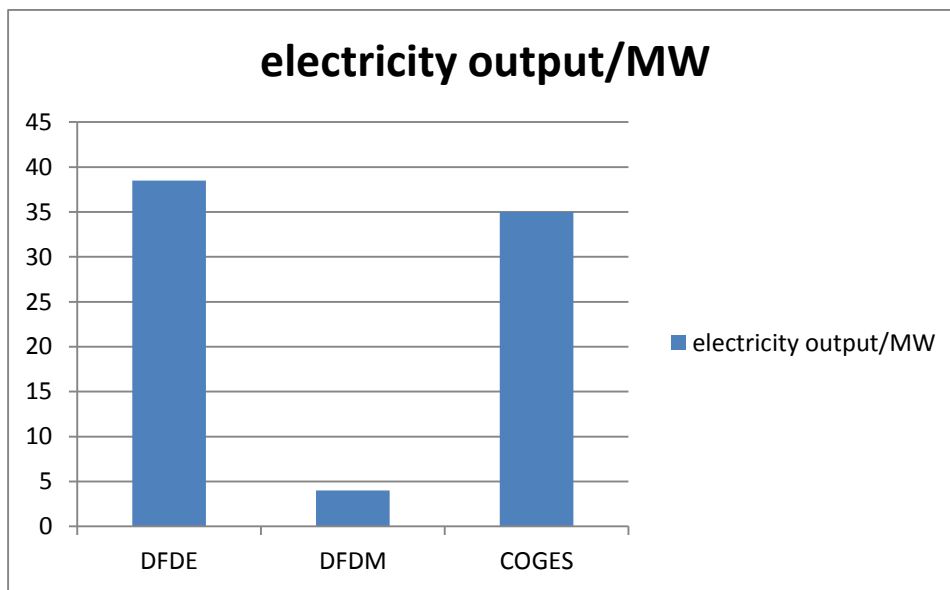


Figure 20. The electric load of alternatives

Fuel consumption rate

DFDM with 4 stroke engine: when the engine is under the gas mode and the engine load is 75%, the fuel gas consumption is 7562 kJ/kWh. And the Lower Heating Value (LHV) of natural gas is 49.7 KJ/g. So the fuel consumption rate is:

$$7562 \div 49.7 = 152.15 \text{ g/kWh}$$

$$152.15 \times 7600 \times 4 \times 75\% \div 10^6 = 3.47 \text{ tons/hr}$$

DFDM with 2 stroke engine: the fuel consumption rate is 81 tonnages per day, **3.375 tons/hr.**

COGES: the fuel consumption for gas turbine is 215 g/kWh. That is only gas turbine fuel consumption rate:

$$215 \times 29,000 \times 100\% \div 10^6 = 6.235 \text{ tons/hr}$$

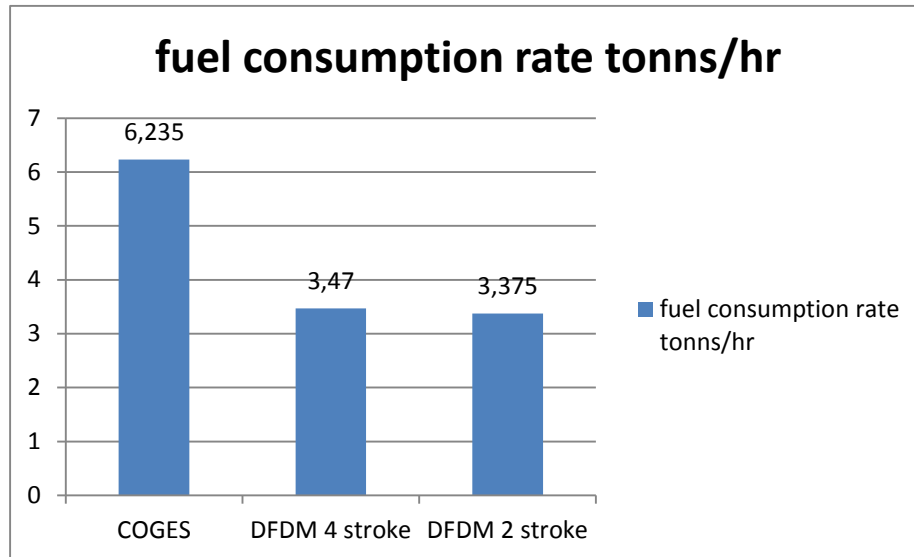


Figure 21. Fuel consumption rate for alternatives

All the alternatives should use the NBOG before using other fuels. Before the calculation, the for a LNG carrier with 150,000 m³ cargo capacity, the NBOG could supply the engines at 75% load. The combined gas turbine electric propulsion system has the highest fuel consumption rate, the NBOG couldn't satisfy the fuel demands. The most economical and environmental solution is using the FBOG as fuel.

Step 3: Estimation of the reliability of the system

In this section, the availability of propulsion system and BOG treatment system need to be evaluated.

The data of comparison of availability quote from the reference article, including the failure rates and MTTR (mean-time-to-repair) of different equipment's,

propulsion availability and BOG treatment system availability.

Table 20

Failure rate and MTTR for key components

Equipment	Failure rate, per 10^6 h	MTTR, h
Gas turbine	756.8	23.7
Diesel engine	324.7	78.8
Electric generator	48.9	18.0
Electric motor	32.8	35.3
Gear box	1.5	0.1
S/T generator	73.7	18
BOF Feed pump	48	11.4
BOG feed pump-Motor Drive	22.8	7.8
Re-heater	42.5	22.5
LD Compressor	256.4	25.7
GCU	66.5	23.5
Screw Compressor	47.4	22.8

Notes: Data is from A Study On Availability and Safety of New Propulsion Systems for LNG Carriers, 2008.

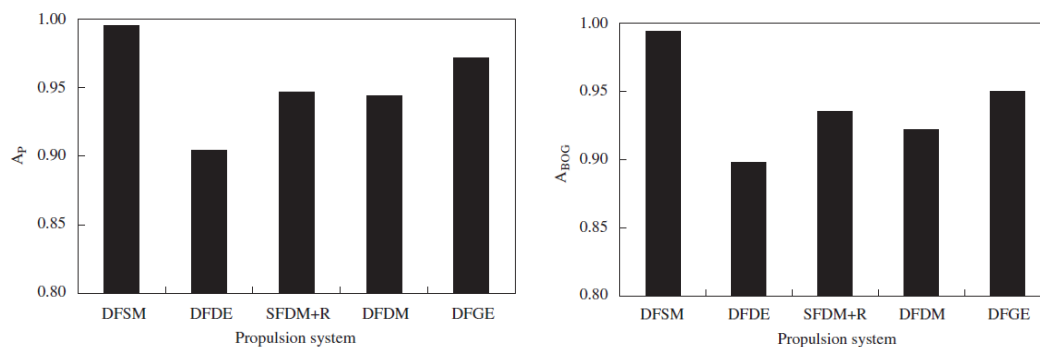


Figure 22. Availability of propulsion system and BOG treatment system

The traditional steam turbine power plant has the highest propulsion availability and BOG treatment system availability. The DFDE power plant system shows the lowest propulsion availability and BOG treatment system availability.

The propulsion system availability and BOG treatment system availability of

dual fuel mechanical propulsion system are 0.94 and 0.93. The A_P and A_{BOG} of combined gas turbine electric system are 0.97 and 0.94.

NOTE: The data for 4 stroke engine and 2 stroke engines are not comprehensive. I assumed that the availability of dual fuel mechanical propulsion system with 4 stroke engines and dual fuel mechanical propulsion system with 2 stroke engines is identical.

Step 4: Assessment of the comparative life cycle cost

In this section, the Life Cycle Cost will be calculated.

NOTE: In this section 4 stroke represent DFDM with 4 stroke medium speed engines; 2 stroke represent DFDM with 2 stroke engines and COGES represent combined gas turbine electric propulsion.

The CAPEX price for DFDM with 4 stroke engine is 21.76 million us dollars and the engine price is 15.15 million us dollars. The total installed power onboard (include the auxiliary engine) is 39040 kW. The cost for each is 387.94 us dollars.

As usual, the 2 stroke slow speed engine cost is higher than 4 stroke engine. Then I assume the 2 stroke engine cost is 450 us dollars per kW (Hans Klein Woud, 2002). The total installed power onboard is 39000 kW (include the auxiliary engine). The CAPEX for dual fuel 2 stroke engine is 15.6 million us dollars. The shaft price and other equipment is the same with dual fuel four stroke engine. The CAPEX is 24.28 million us dollars.

For COGES, the every installed kW cost is from 200-315 us dollars (simple cycle). I assumed the cost is 258 us dollars per kW. The engine price is approximate

10.06 million dollars. The other equipment cost is the same with the DFDE propulsion system. The CAPEX for COGES is 21.84 million us dollars.

Table 21

CAPEX of three alternatives

System	DFDE	4 stroke	2 stroke	COGES
CAPEX /M \$	27.89	21.76	24.28	21.84

Note: this price is propulsion system price not just the engine price. Data is from WÄRTSILÄ dual fuel LNGC, 2008.

Table 22

Fuel price

Fuel type	LHV (KJ/KG)	Price (\$ /ton)
LNG	49,700	119.06
MDO	42,667	564
HFO	40,639	313

Notes: fuel price is from <http://www.nasdaq.com/markets/natural-gas.aspx> and <http://www.bunkerworld.com/prices>

Calculation of LCC^P

$$C_1 = N_{\text{voyage}} \cdot (M_{\text{Offload}} \cdot C_{\text{CIF}} - M_{\text{load}} \cdot C_{\text{FOB}}) \cdot UA_P$$

$$M_{\text{BOG}} = M_{\text{load}} \cdot BOR_m \cdot T_{\text{BOG}}$$

The BOG rate is 0.15% of carrier volume per day;

The LNG density is 450 kg/m³;

The LNG export price is 2.417 us dollars/mmbtu, and the LNG import price at

South Korea is 7.85 us dollars/mmbtu. 1mmbtu=0.0203 tons

Table 23

C₁ calculation table

variables	Value		
	DFDM with 4 stroke engine	DFDM with 2 stroke engine	Combined gas turbine
N_{voyage}	12.2	12.2	12.2
M_{offload} , tonnages	65480.63	65480.63	65480.83
C_{CIF} , us dollars/ tonnages	386.70	386.70	386.70
M_{load} , tonnages	67500	67500	67500
C_{FOB} us dollars/ tonnage	119.06	119.06	119.06
U_{AP}	0.06	0.06	0.03
C_1 us dollars	12652097	12652097	6366048.4
C_1 us dollars per transporting unit	6.91	6.91	3.46

After the calculation C_1 for DFDM is 6.91 us dollars per transporting unit. And

C_1 for COGES is 3.46 us dollars per transporting unit.

C_2 is the cost due to BOG evaporation.

$$C_2 = N_{\text{voyage}} \cdot M_{\text{BOG}} \cdot C_{\text{CIF}}$$

Table 24

C₂ calculation table

Variables	Value
Number of voyage	12.2
M_{BOG} tonnages	2019.9375
C_{CIF}	386.70
C_2 us dollars	9529527.8
C_2 us dollars per transporting unit	5.20

For all 3 alternatives, C_2 is identical.

C_3 is the BOG lost due to the BOG treatment system failure.

$$C_3 = M_{\text{BOG}} \cdot C_{\text{CIF}} \cdot UA_{\text{BOG}}$$

Table 25

C₃ calculation table

variables	value		
	DFDM with 4 stroke engine	DFDM with 2 stroke engine	Combined gas turbine
M_{BOG} , tonnages	2019.9375	2019.9375	2019.9375
C_{CIF}	386.70	386.70	386.70
UA_{BOG}	0.07	0.07	0.06
C_3 , us dollars	54677.619	54677.619	46866.53
C_3 , us dollars per transporting unit	0.36	0.36	0.31

In this thesis, the penalty equals the profit loss of gas seller

$$C_4 = N_{\text{voyage}} \cdot M_{\text{offload}} \cdot C_{\text{CIF}} \cdot UA_{\text{BOG}}$$

Table 26

C₄ calculation table

variables	value		
	DFDM with 4 stroke engine	DFDM with 2 stroke engine	Combined gas turbine
Number of voyage	12.2	12.2	12.2
M_{offload} , tons	65480.063	65480.063	65480.063
C_{CIF}	386.70	386.70	386.70
UA_{BOG}	0.07	0.07	0.06
C_3 , us dollars	21624226.16	21624226.16	18535050.99
C_3 , us dollars per transporting unit	11.82	11.82	10.13

C_5 is the fuel consumption cost. Fuel assumptions should be made:

All 3 alternatives propulsion output is 22800 kW.

The SFC of DFDM with 4 stroke medium speed engine is 176 g/kWh and efficiency is 44.6%, the efficiency of DFDM with 2 stroke slow speed engine is 48.5%. The thermal efficiency and fuel consumption is inverse proportion. The SFC of DFDM with 2 stroke engine could be assumed 125 g/kWh when engine output is 22800 kW.

The BOG rate is 4.22 t/hr for laden voyage and for ballast voyage the BOG rate is 1.69 t/hr.

The LNG price is 119.06 us dollars per ton and MDO price is 564 us dollars per tonnage.

$$\text{Mean fuel cost} = (\text{MC}_{\text{fuel,laden}} + \text{MC}_{\text{fuel,ballst}}) / 2$$

Table 27

C₅ calculation table 1

Propulsion type	SFC (g/kWh)	Fuel consumption rate (t/hr)	Mean fuel cost \$/hr
DFDM with 4 stroke	152.15	3.469	808.793
DFDM with 2 stroke	125	3.375	766.689
COGES	215	4.902	1449.930

Note: SFC in this section include both the main engine and generator's SFC.

Mean fuel cost procedure: For the DFDM with 4 stroke engine and 2 stroke engine, the BOG rate at laden voyage could satisfy the fuel consumption rate. Since the fuel consumption at laden voyage equals LNG CIF price multiply fuel consumption rate. And for the ballast voyage the BOG couldn't satisfy the fuel consumption, since fuel consumption cost for ballast voyage contains BOG cost and

MDO cost. For the COGES both the laden and ballast voyage, the fuel cost contains BOG cost and MDO cost. Since the BOG rate during the laden voyage and ballast voyage is not enough for fuel consumption.

$$C_5 = N_{\text{voyage}} \cdot T_P \cdot A_P \cdot (MC_{\text{fuel,laden}} + MC_{\text{fuel,ballst}})/2$$

Table 28

C₅ calculations table 2

Propulsion type	N _{voyage}	T _P /hr	A _P	Mean fuel cost \$/hr	Total fuel cost \$/hr	Cost per transporting unit \$/hr
DFDM with 4 stroke	12.2	638.4	0.94	808.793	5921314.0	3.236
DFDM with 2 stroke	12.2	638.4	0.94	577.847	5686276.4	3.107
COGES	12.2	638.4	0.97	1449.930	10953971.0	5.986

C₆ and C₇ are fuel consumption for BOG and GCU system. The power requirements are both 50 kW.

The combined gas turbine electric system doesn't need GCU system on service. Because the natural BOG for combined gas turbine electric propulsion system is not enough.

Table 29

C₆ calculation table

Type	N _{voyage}	TBOG	ABOG	WM _{GCU,mean} t/hr	CMDO \$/hr	C ₆ per transporting unit
4 stroke	12.2	638.4	0.93	0.00096	564	0.261
2 stroke	12.2	638.4	0.93	0.00096	564	0.261
COGES	12.2	638.4	0.94	0.001075	564	0.296

Table 30

C₇ calculation table

Type	N _{voyage}	TBOG	ABOG=	WM _{GCU,mean} t/hr	CMDO \$/hr	C ₇ per transporting unit
4 stroke	12.2	638.4	0.93	0.00096	564	0.261
2 stroke	12.2	638.4	0.93	0.00096	564	0.261
COGES	12.2	638.4	0.94	0	564	0

C₈ is the cost of lube oil.

For the DFDM with 4 stroke medium speed engine, the lube oil consumption rate is 3 g/kWh.

NOTE: C₈ has an insignificant influence on the LCC. And the lube oil consumption for dual fuel 2 stroke slow speed engine and gas turbine are not available, since I assumed that the lube oil consumption rate is identical with dual fuel 4 stroke medium speed engine.

Table 31

C₈ calculation table

Type	N _{voyage}	T _P , hr	A _P	M _{lube} , ton	C _{lube} \$ /hr	C ₈ per transporting unit
4 stroke	12.2	638.4	0.94	0.0684	1250	0.342
2 stroke	12.2	638.4	0.94	0.0684	1757	0.481
COGES	12.2	638.4	0.97	0.0684	1250	0.353

Note: 4 stroke engine data is from Wärtsilä 50DF Product Guide. 2 stroke engine and COGES data assumption is based on the 4 stroke data.

C₉ and C₁₀ calculation depend on the frequency of maintenance. This data is different between different alternatives. And the data is difficult to find. If further data could be provided, these two components could be calculated.

Table 32

Sum of 8 variables and OPEX assessment

	4 stroke	2 stroke	COGES
C ₁	6.91	6.91	3.46
C ₂	5.20	5.20	5.20
C ₃	0.36	0.36	0.31
C ₄	11.82	11.82	10.13
C ₅	3.236	3.107	5.986
C ₆	0.261	0.261	0.296
C ₇	0.261	0.261	0
C ₈	0.342	0.481	0.353
Sum	28.390	28.261	25.735

The OPEX calculation: the life cycle we assume is 10 year (without considering the interesting rate)

For DFDM with 4 stroke engine:

$$\text{OPEX} = N_{\text{voyage}} \times C_{\text{cargo}} \times \text{Sum} \times 10 = 519.537 \text{ M \$}$$

$$\text{LCC}=519.537+21.76=541.297 \text{ M \$}$$

For DFDM with 2 stroke engine:

$$\text{OPEX}= N_{\text{voyage}} \times C_{\text{cargo}} \times \text{Sum} \times 10 = 517.176 \text{ M \$}$$

$$\text{LCC}=517.176+24.28=541.456 \text{ M \$}$$

For COGES:

$$\text{OPEX}= N_{\text{voyage}} \times C_{\text{cargo}} \times \text{Sum} \times 10 = 470.950 \text{ M \$}$$

$$\text{LCC}=470.950+21.84=492.79 \text{ M \$}$$

Conclusion:

After LCC calculation, the result shows that DFDM with 4 stroke medium engines has the highest LCC and the COGES has the lowest LCC. The major reason for COGES system has the lowest LCC is because of its high availability of propulsion system and BOG treatment system. The gas turbine system is widespread in military marine vessel.

Compared with the DFDM with 2 stroke slow speed engine propulsion system and DFDM with 4 stroke medium speed engine propulsion system, the LCC are approximate same and similar technical performance. The choice between 4 stroke engine and 2 stroke engine could depend on specific situation.

Conclusion

Because of the low efficiency and high emission of steam turbine power plant, it is not suitable for LNG carrier market anymore. Compared with steam turbine power plant, the standard DFDE system increases the efficiency and reduces the emission.

From the technical comparison, the dual fuel diesel mechanical propulsion system with 2 stroke slow speed engine has the highest efficiency. At volume and weight segments, the combined gas turbine illustrates the best performance. But the combined gas turbine has some requirements on the fuel type. All three alternatives could reduce the emission significantly.

The economical comparison includes capital cost and LCC cost. The gas turbine has the highest cost and lowest LCC cost. If the maintenance cost could be calculated, the COGES system could have higher cost than other 2 alternatives, since the gas turbine system is more complex than the dual fuel engine.

Overall the dual fuel diesel mechanical propulsion system with 2 stroke slow speed engine is the best alternative.

Limitation:

In this comparison study the data is not very comprehensive, some of calculation can't be done. And all of data in this study is from the reference article and Wärtsilä's website and MAN B&W's website. It is not the newest data, since the calculation is not 100% accurate. If further more data could be provided, the comparison study could be done continuously.

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