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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Besides my supervisor, I would like to thank all the teachers during these 2 years of master study. Without your help I couldn’t finish this master project.

At last I want to thank my parents, without their selfless supporting and understanding I couldn’t stay here and finish my study.
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Emission

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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 1/600\textsuperscript{th} 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.

![Table showing the size of LNG carriers](image)

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 (DFSM)

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 a relatively high proportion of SO\textsubscript{X} and NO\textsubscript{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 (fixed 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 NOx reduction; meets IMO Tier III without after treatment. (Rudolf. 2013)
Figure 7. Dual fuel 2 stroke slow speed engine mechanical propulsion power plant from Wärtsilä

Figure 8. Dual fuel 4 stroke medium speed engine mechanical propulsion power plant from Wärtsilä
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 m$^3$, 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/m$^3$). 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 m$^3$. 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 m$^3$

For the combined gas turbine electric propulsion: the cargo capacity is 165,000 m$^3$
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

<table>
<thead>
<tr>
<th>The specific efficiency of DFDE system</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFDE with single screw propulsion</td>
</tr>
<tr>
<td>system</td>
</tr>
<tr>
<td>Fuel/BOG</td>
</tr>
<tr>
<td>DF engines</td>
</tr>
<tr>
<td>Alternators</td>
</tr>
<tr>
<td>Transformers and conversion</td>
</tr>
<tr>
<td>Electric motors</td>
</tr>
<tr>
<td>Gearbox</td>
</tr>
<tr>
<td>Shafting</td>
</tr>
<tr>
<td><strong>Total efficiency</strong></td>
</tr>
</tbody>
</table>

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*

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length over all:</td>
<td>280 m</td>
</tr>
<tr>
<td>Length between perpendiculars:</td>
<td>268 m</td>
</tr>
<tr>
<td>Breath moulded</td>
<td>43.20 m</td>
</tr>
<tr>
<td>Draught (diesel electric)</td>
<td>11.95 m</td>
</tr>
<tr>
<td>Gross tonnage:</td>
<td>95,500 tons</td>
</tr>
<tr>
<td><strong>Cargo capacity</strong></td>
<td><strong>150.500 m³</strong></td>
</tr>
</tbody>
</table>

*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*

<table>
<thead>
<tr>
<th>Power Distribution</th>
<th>kW</th>
<th>39,900</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total available power</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Propulsion power without sea margin</td>
<td>kW</td>
<td>21,600</td>
</tr>
<tr>
<td>Ship service power</td>
<td>kW</td>
<td>1,500</td>
</tr>
<tr>
<td>Propulsion &amp; Aux. gen. losses</td>
<td>kW</td>
<td>2446</td>
</tr>
<tr>
<td>Extra available power</td>
<td>kW</td>
<td>14354</td>
</tr>
<tr>
<td>Sea margin</td>
<td>kW</td>
<td>4536</td>
</tr>
<tr>
<td>Sea margin %</td>
<td>%</td>
<td>21</td>
</tr>
<tr>
<td>Power reserve</td>
<td>kW</td>
<td>9818</td>
</tr>
<tr>
<td>Missing power for contractual speed</td>
<td>kW</td>
<td>0</td>
</tr>
<tr>
<td>Power utilized for propulsion</td>
<td>kW</td>
<td>21600</td>
</tr>
<tr>
<td>Corresponding ship speed</td>
<td>Kn</td>
<td>19.5</td>
</tr>
</tbody>
</table>

*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.
Table 4

Detailed efficiency of three alternatives

<table>
<thead>
<tr>
<th></th>
<th>COGES efficiency</th>
<th>DFDM with 4 stroke engines</th>
<th>DFDM with 2 stroke engines</th>
<th>Total efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel/BOG</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>39.8%</td>
</tr>
<tr>
<td>Gas turbine and</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>steam turbine</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>combined cycle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alternators</td>
<td>97%</td>
<td>99%</td>
<td>99%</td>
<td></td>
</tr>
<tr>
<td>Transformer and</td>
<td>98%</td>
<td>98%</td>
<td>98%</td>
<td></td>
</tr>
<tr>
<td>conversion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric motors</td>
<td>98%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gear box</td>
<td>98%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric motors</td>
<td>99%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>shafting</td>
<td>98%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>DFDE</th>
<th>COGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length overall</td>
<td>291.50 m</td>
<td></td>
</tr>
<tr>
<td>Length between perpendiculars</td>
<td>280.00 m</td>
<td></td>
</tr>
<tr>
<td>Breath moulded</td>
<td>43.00 m</td>
<td></td>
</tr>
<tr>
<td>Draught</td>
<td>12.00 m</td>
<td></td>
</tr>
<tr>
<td>Depth to maindeck</td>
<td>27.00 m</td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td>20 kn</td>
<td></td>
</tr>
<tr>
<td>Cargo capacity (DFDE)</td>
<td><strong>156,700 m³</strong></td>
<td></td>
</tr>
<tr>
<td>Cargo capacity (COGES)</td>
<td><strong>165,000 m³</strong></td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>DFDE</th>
<th>DFDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length overall</td>
<td>280.00 m</td>
<td></td>
</tr>
<tr>
<td>Length between perpendiculars</td>
<td>268.00 m</td>
<td></td>
</tr>
<tr>
<td>Breath moulded</td>
<td>43.20 m</td>
<td></td>
</tr>
<tr>
<td>Draught (DFDE)</td>
<td>11.95 m</td>
<td></td>
</tr>
<tr>
<td>Draught (DFDM)</td>
<td>12.10 m</td>
<td></td>
</tr>
<tr>
<td>Depth to maindeck</td>
<td>26.10 m</td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td>19.5 kn</td>
<td></td>
</tr>
<tr>
<td>Cargo capacity (DFDE)</td>
<td><strong>150,500 m³</strong></td>
<td><strong>149,000 m³</strong></td>
</tr>
</tbody>
</table>

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*

<table>
<thead>
<tr>
<th>LNG capacity (100%)</th>
<th>155,000 m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main engine sets</td>
<td>WÄRTSILÄ 3×12v50DF+1×6L50DF</td>
</tr>
<tr>
<td>Electric propulsion system</td>
<td>21,600 kW</td>
</tr>
</tbody>
</table>

*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*

<table>
<thead>
<tr>
<th>Engine type</th>
<th>Generator Output/kW</th>
<th>Weight /tonnage</th>
<th>Dimensions/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>6L50DF</td>
<td>5,700</td>
<td>96</td>
<td>8115</td>
</tr>
<tr>
<td>12V50DF</td>
<td>11,400</td>
<td>175</td>
<td>10465</td>
</tr>
</tbody>
</table>

*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*

<table>
<thead>
<tr>
<th>Engine type</th>
<th>Engine output/kW</th>
<th>Weight /tonnage</th>
<th>Dimensions/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>8L50DF</td>
<td>7,600</td>
<td>128</td>
<td>9950</td>
</tr>
</tbody>
</table>

*Notes: Data is from WÄRTSILÄ 50DF ENGINE TECHNOLOGY.*

This table is auxiliary generators’ output and dimensions.

Table 10

*Auxiliary generator sets*

<table>
<thead>
<tr>
<th>Engine type</th>
<th>Auxiliary Output/kW</th>
<th>Weight /tonnage</th>
<th>Dimensions/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>9L32</td>
<td>4320</td>
<td>49.2</td>
<td>6869</td>
</tr>
</tbody>
</table>

*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**

<table>
<thead>
<tr>
<th>Cylinder number</th>
<th>Output in kW at 124 rpm</th>
<th>Output in kW at 99 rpm</th>
<th>Length A (mm)</th>
<th>Length A’ (mm)</th>
<th>Weight (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R1</td>
<td>R2</td>
<td>R3</td>
<td>R4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>7,200</td>
<td>6,000</td>
<td>5,750</td>
<td>4,775</td>
<td>200</td>
</tr>
<tr>
<td>6</td>
<td>8,640</td>
<td>7,200</td>
<td>6,900</td>
<td>5,730</td>
<td>225</td>
</tr>
<tr>
<td>7</td>
<td>10,080</td>
<td>8,400</td>
<td>8,050</td>
<td>6,685</td>
<td>255</td>
</tr>
<tr>
<td>8</td>
<td>11,520</td>
<td>9,600</td>
<td>9,200</td>
<td>7,640</td>
<td>280</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dimensions (mm)</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F’</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3,150</td>
<td>1,088</td>
<td>7,646</td>
<td>3,570</td>
<td>1900</td>
</tr>
<tr>
<td>F1</td>
<td>9,270</td>
<td>9,250</td>
<td>8,700</td>
<td>1,636</td>
<td>-</td>
</tr>
<tr>
<td>F2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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 approximately 30,000 kW. The total weight of engines is approximately 875 tons.

b) Wärtsilä X62DF or X72DF

Here is another example from Wärtsilä. This power configuration is designed for 175,000 m$^3$ 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 use 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

<table>
<thead>
<tr>
<th>Gas turbine</th>
<th>Output /kw</th>
<th>SFC/ g/kW-hr</th>
<th>Width /m</th>
<th>Length /m</th>
<th>Height /m</th>
<th>Weight /tonnage</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM2500+</td>
<td>29,000</td>
<td>215</td>
<td>3.12</td>
<td>14.38</td>
<td>3.98</td>
<td>94.545</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Weight /tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>COGES</td>
<td>94.545</td>
</tr>
<tr>
<td>DFDM with 4 stroke engine</td>
<td>610.4</td>
</tr>
<tr>
<td>DFDM with 2 stroke engine</td>
<td>973.4</td>
</tr>
</tbody>
</table>

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 in 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*

<table>
<thead>
<tr>
<th></th>
<th>Gas mode</th>
<th>Diesel mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total energy consumption at 100% load</td>
<td>kJ/kWh</td>
<td>7300</td>
</tr>
<tr>
<td>Total energy consumption at 75% load</td>
<td>kJ/kWh</td>
<td>7620</td>
</tr>
<tr>
<td>Total energy consumption at 50% load</td>
<td>kJ/kWh</td>
<td>8260</td>
</tr>
<tr>
<td>Fuel gas consumption at 100% load</td>
<td>kJ/kWh</td>
<td>7258</td>
</tr>
<tr>
<td>Fuel gas consumption at 75% load</td>
<td>kJ/kWh</td>
<td>7562</td>
</tr>
<tr>
<td>Fuel gas consumption at 50% load</td>
<td>kJ/kWh</td>
<td>8153</td>
</tr>
<tr>
<td>Fuel oil consumption at 100% load</td>
<td>g/kWh</td>
<td>1.0</td>
</tr>
<tr>
<td>Fuel oil consumption at 75% load</td>
<td>g/kWh</td>
<td>1.5</td>
</tr>
<tr>
<td>Fuel oil consumption at 50% load</td>
<td>g/kWh</td>
<td>2.4</td>
</tr>
</tbody>
</table>

*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 m$^3$ 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 $2 \times 37.5$ 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 215 g/kWh. We assumed the SFC here is constant.

Table 15

*Comparison of SFC (gas mode)*

<table>
<thead>
<tr>
<th>Power plant</th>
<th>DFDM with 4 stroke engine</th>
<th>DFDM with 2 stroke engine</th>
<th>Combined gas turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFC [g/kWh]</td>
<td>152.15</td>
<td>125</td>
<td>215</td>
</tr>
</tbody>
</table>

Fuel flexibility

Here is the comparison of flexibility of different alternatives.

Table 16

*Comparison of fuel flexibility*

<table>
<thead>
<tr>
<th></th>
<th>NBOG</th>
<th>FBOG</th>
<th>MDO</th>
<th>HFO</th>
<th>MGO</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFDE 4 stroke</td>
<td>Acceptable</td>
<td>Acceptable</td>
<td>Acceptable</td>
<td>Acceptable</td>
<td>Acceptable</td>
</tr>
<tr>
<td>COGES 2 stroke</td>
<td>Acceptable</td>
<td>Acceptable</td>
<td>Acceptable</td>
<td>Acceptable</td>
<td>Acceptable</td>
</tr>
</tbody>
</table>

*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: NOX, SOX, CO2 and particulates.
Emissions of dual fuel 2 stroke slow speed engines compared with diesel engine.

![Graph showing emissions comparison]  
*Figure 17. Dual fuel slow speed engine emission comparison*

<table>
<thead>
<tr>
<th>Emission comparisons of three alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>DFDE</td>
</tr>
<tr>
<td>Gas turbine</td>
</tr>
<tr>
<td>DFDM</td>
</tr>
</tbody>
</table>

*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\textsubscript{X} and NO\textsubscript{X} from SFDMR are seen as 100% and CO\textsubscript{2} 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\textsubscript{X} and NO\textsubscript{X} emission significantly. The DFDE and DFDM power plant have negligible SO\textsubscript{X} emission (less than 1%) and the COGES has zero SO\textsubscript{X} emission. All three alternatives NO\textsubscript{X} emission is approximate 10% and it’s acceptable. Compared with the steam turbine power plant, the CO\textsubscript{2} 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\textsubscript{X} and CO\textsubscript{2} emission, but still it has few SO\textsubscript{X} emissions. And the COGES has zero
SO_{\text{x}} emission but higher NO_{\text{x}} and CO_{2} emission. Especially in CO_{2} 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 m$^3$, 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 Inchon is 6,233 nm and average voyage time is 13.3 days.
Table 18

Voyage information

<table>
<thead>
<tr>
<th>voyage</th>
<th>condition</th>
<th>Voyage time hr</th>
<th>Main engine Operation time, hr</th>
<th>BOG generation time, hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laden</td>
<td>Port-loading</td>
<td>25</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>sea voyage</td>
<td>320</td>
<td>319.2</td>
<td>319.2</td>
</tr>
<tr>
<td>Ballast</td>
<td>Port-unloading</td>
<td>20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>sea voyage</td>
<td>320</td>
<td>319.2</td>
<td>319.2</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>685</td>
<td>638.4</td>
<td>638.4</td>
</tr>
</tbody>
</table>

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\textsuperscript{P} and OPEX\textsuperscript{P} calculation
• LCC\textsuperscript{P} calculation

The Operating Expenditure, OPEX\textsuperscript{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;

C₆₉: Total sum of the annual cost.

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

Aₚ: availability of propulsion system.

A₉BOG: 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.

\[ C₁ = N_{voyage} \cdot (M_{Offload} \cdot C_{CIF} - M_{load} \cdot C_{FOB}) \cdot UAₚ \]

In this equation \( M_{Offload} \cdot C_{CIF} - M_{load} \cdot C_{FOB} \) 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

\[ M_{\text{BOG}} = M_{\text{load}} \cdot BOR_m \cdot T_{\text{BOG}} \]

\( N_{\text{voyage}} \) Number of voyage per year

\( M_{\text{offload}} \) The offloading LNG mass

\( M_{\text{load}} \) The loading LNG mass

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

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

\( BOR_m \) Average BOG rate for laden and ballast voyage

\( T_{\text{BOG}} \) 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.

\[ C_2 = N_{\text{voyage}} \cdot M_{\text{BOG}} \cdot C_{\text{CIF}} \]
The mass of BOG is denoted by $M_{BOG}$. 

$C_3$ is the BOG loss due to the failure of BOG treatment system. When the BOG treatment system fails, 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. 

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

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. 

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

$$WM_{BOG,mean} = (W_{BOG,laden} \cdot M_{MDO,BOG,laden} + W_{BOG,ballast} \cdot M_{MDO,BOG,ballast})/2$$

$T_{BOG}$ 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
The GCU requires power supply. $C_7$ is calculated by the equation:

$$C_7 = N_{voyage} \cdot (T_{GCU} + T_{BOG} \cdot U_{ABOG}) \cdot W_{MGCU, mean} \cdot C_{MDO}$$

- $T_{GCU}$: Time over which GCU should be operated. hr
- $T_{BOG}$: Time over which BOG is generated. hr
- $W_{MGCU, mean}$: Mean fuel consumption for GCU
- $C_{MDO}$: Price of MDO. $\$/ton

The lube oil cost is expressed in the equation:

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

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.

$$C_9 = N_{PM} \cdot N_{engine} \cdot (M_{HPM} \cdot C_{MH} + R_{PM} \cdot CAPEX_P)$$

- $N_{PM}$: The number of PM action
- $N_{engine}$: Number of engine
- $M_{HPM}$: 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

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

Table 19

### Connection between cost components and availabilities

<table>
<thead>
<tr>
<th>components</th>
<th>$A_P$</th>
<th>$A_{BOG}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$: Delivery loss cost due to the propulsion failure</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>$C_2$: BOG loss cost due to BOG evaporation caused by heat ingress;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_3$: BOG loss due to BOG treatment failure</td>
<td></td>
<td>Y</td>
</tr>
<tr>
<td>$C_4$: Penalty cost due to delayed delivery</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>$C_5$: Fuel consumption cost for operation</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>$C_6$: fuel consumption cost for BOG treatment</td>
<td></td>
<td>Y</td>
</tr>
<tr>
<td>$C_7$: fuel consumption for GCU operation</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>$C_8$: lubricant consumption cost</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>$C_9$: preventive maintenance cost for propulsion system</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>$C_{10}$: corrective maintenance cost for propulsion system</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

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 CAPEXP$^p$ and OPEXP$^p$, 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 m$^3$ 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.

\[
\text{Figure 20. The electric load of alternatives}
\]

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:

\[
\frac{7562}{49.7} = 152.15 \text{ g/kWh}
\]

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

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:

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

![fuel consumption rate tonns/hr](image)

*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*

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

*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*

<table>
<thead>
<tr>
<th>System</th>
<th>DFDE</th>
<th>4 stroke</th>
<th>2 stroke</th>
<th>COGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPEX /M $</td>
<td>27.89</td>
<td>21.76</td>
<td>24.28</td>
<td>21.84</td>
</tr>
</tbody>
</table>

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

Table 22

*Fuel price*

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>LHV (KJ/KG)</th>
<th>Price ( $ /ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNG</td>
<td>49,700</td>
<td>119.06</td>
</tr>
<tr>
<td>MDO</td>
<td>42,667</td>
<td>564</td>
</tr>
<tr>
<td>HFO</td>
<td>40,639</td>
<td>313</td>
</tr>
</tbody>
</table>


Calculation of LCC\(^p\)

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

\[
M_{BOG} = M_{load} \cdot BOR_m \cdot T_{BOG}
\]

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

The LNG density is 450 kg/m\(^3\);

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*

<table>
<thead>
<tr>
<th>variables</th>
<th>DFDM with 4 stroke engine</th>
<th>DFDM with 2 stroke engine</th>
<th>Combined gas turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td>N_voyage</td>
<td>12.2</td>
<td>12.2</td>
<td>12.2</td>
</tr>
<tr>
<td>M_offload, tonnages</td>
<td>65480.63</td>
<td>65480.63</td>
<td>65480.83</td>
</tr>
<tr>
<td>C_CIF, us dollars/ tonnages</td>
<td>386.70</td>
<td>386.70</td>
<td>386.70</td>
</tr>
<tr>
<td>M_load, tonnages</td>
<td>67500</td>
<td>67500</td>
<td>67500</td>
</tr>
<tr>
<td>C_FOB, us dollars/ tonnage</td>
<td>119.06</td>
<td>119.06</td>
<td>119.06</td>
</tr>
<tr>
<td>U_A</td>
<td>0.06</td>
<td>0.06</td>
<td>0.03</td>
</tr>
<tr>
<td>C₁ us dollars</td>
<td>12652097</td>
<td>12652097</td>
<td>6366048.4</td>
</tr>
<tr>
<td>C₁ us dollars per transporting unit</td>
<td>6.91</td>
<td>6.91</td>
<td>3.46</td>
</tr>
</tbody>
</table>

After the calculation *C₁* for DFDM is 6.91 us dollars per transporting unit. And *C₁* for COGES is 3.46 us dollars per transporting unit.

*C₂ is the cost due to BOG evaporation.

\[ C₂ = N_voyage \cdot M_{BOG} \cdot C_{CIF} \]

Table 24

*C₂ calculation table*

<table>
<thead>
<tr>
<th>Variables</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of voyage</td>
<td>12.2</td>
</tr>
<tr>
<td>M_{BOG} tonnages</td>
<td>2019.9375</td>
</tr>
<tr>
<td>C_{CIF}</td>
<td>386.70</td>
</tr>
<tr>
<td>C₂ us dollars</td>
<td>9529527.8</td>
</tr>
<tr>
<td>C₂ us dollars per transporting unit</td>
<td>5.20</td>
</tr>
</tbody>
</table>

For all 3 alternatives, *C₂* is identical.
$C_3$ is the BOG lost due to the BOG treatment system failure.

\[ C_3 = M_{BOG} \cdot C_{CIF} \cdot U_{A_{BOG}} \]

Table 25

$C_3$ calculation table

<table>
<thead>
<tr>
<th>variables</th>
<th>DFDM with 4 stroke engine</th>
<th>DFDM with 2 stroke engine</th>
<th>Combined gas turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{BOG}$, tonnages</td>
<td>2019.9375</td>
<td>2019.9375</td>
<td>2019.9375</td>
</tr>
<tr>
<td>$C_{CIF}$</td>
<td>386.70</td>
<td>386.70</td>
<td>386.70</td>
</tr>
<tr>
<td>$U_{A_{BOG}}$</td>
<td>0.07</td>
<td>0.07</td>
<td>0.06</td>
</tr>
<tr>
<td>$C_3$, us dollars</td>
<td>54677.619</td>
<td>54677.619</td>
<td>46866.53</td>
</tr>
<tr>
<td>$C_3$, us dollars per transporting unit</td>
<td>0.36</td>
<td>0.36</td>
<td>0.31</td>
</tr>
</tbody>
</table>

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

\[ C_4 = N_{voyage} \cdot M_{offload} \cdot C_{CIF} \cdot U_{A_{BOG}} \]

Table 26

$C_4$ calculation table

<table>
<thead>
<tr>
<th>variables</th>
<th>DFDM with 4 stroke engine</th>
<th>DFDM with 2 stroke engine</th>
<th>Combined gas turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of voyage</td>
<td>12.2</td>
<td>12.2</td>
<td>12.2</td>
</tr>
<tr>
<td>$M_{offload}$, tons</td>
<td>65480.063</td>
<td>65480.063</td>
<td>65480.063</td>
</tr>
<tr>
<td>$C_{CIF}$</td>
<td>386.70</td>
<td>386.70</td>
<td>386.70</td>
</tr>
<tr>
<td>$U_{A_{BOG}}$</td>
<td>0.07</td>
<td>0.07</td>
<td>0.06</td>
</tr>
<tr>
<td>$C_3$, us dollars</td>
<td>21624226.16</td>
<td>21624226.16</td>
<td>18535050.99</td>
</tr>
<tr>
<td>$C_3$, us dollars per transporting unit</td>
<td>11.82</td>
<td>11.82</td>
<td>10.13</td>
</tr>
</tbody>
</table>

$C_5$ 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.

\[
\text{Mean fuel cost} = \frac{\text{MC}_{\text{fuel,laden}} + \text{MC}_{\text{fuel,ballast}}}{2}
\]

Table 27

<table>
<thead>
<tr>
<th>Propulsion type</th>
<th>SFC (g/kWh)</th>
<th>Fuel consumption rate (t/hr)</th>
<th>Mean fuel cost ($/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFDM with 4 stroke</td>
<td>152.15</td>
<td>3.469</td>
<td>808.793</td>
</tr>
<tr>
<td>DFDM with 2 stroke</td>
<td>125</td>
<td>3.375</td>
<td>766.689</td>
</tr>
<tr>
<td>COGES</td>
<td>215</td>
<td>4.902</td>
<td>1449.930</td>
</tr>
</tbody>
</table>

*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.

\[ C_5 = N_{\text{voyage}} \cdot T_P \cdot A_P \cdot \left( M_{\text{fuel,laden}} + M_{\text{fuel,ballast}} \right) / 2 \]

Table 28

c_{5c} calculations table 2

<table>
<thead>
<tr>
<th>Propulsion type</th>
<th>( N_{\text{voyage}} )</th>
<th>( T_P ) /hr</th>
<th>( A_P )</th>
<th>Mean fuel cost $/hr</th>
<th>Total fuel cost $/hr</th>
<th>Cost per transporting unit $/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFDM with 4 stroke</td>
<td>12.2</td>
<td>638.4</td>
<td>0.94</td>
<td>808.793</td>
<td>5921314.0</td>
<td>3.236</td>
</tr>
<tr>
<td>DFDM with 2 stroke</td>
<td>12.2</td>
<td>638.4</td>
<td>0.94</td>
<td>577.847</td>
<td>5686276.4</td>
<td>3.107</td>
</tr>
<tr>
<td>COGES</td>
<td>12.2</td>
<td>638.4</td>
<td>0.97</td>
<td>1449.930</td>
<td>10953971.0</td>
<td>5.986</td>
</tr>
</tbody>
</table>

\( C_6 \) and \( C_7 \) 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  

\textit{\textbf{C\textsubscript{6} calculation table}}

<table>
<thead>
<tr>
<th>Type</th>
<th>(N_{\text{voyage}})</th>
<th>TBOG</th>
<th>ABOG</th>
<th>(\text{WM}_{GCU,\text{mean}}) t/hr</th>
<th>CMDO $$/hr</th>
<th>\text{C6 per transporting unit}</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 stroke</td>
<td>12.2</td>
<td>638.4</td>
<td>0.93</td>
<td>0.00096</td>
<td>564</td>
<td>0.261</td>
</tr>
<tr>
<td>2 stroke</td>
<td>12.2</td>
<td>638.4</td>
<td>0.93</td>
<td>0.00096</td>
<td>564</td>
<td>0.261</td>
</tr>
<tr>
<td>COGES</td>
<td>12.2</td>
<td>638.4</td>
<td>0.94</td>
<td>0.001075</td>
<td>564</td>
<td>0.296</td>
</tr>
</tbody>
</table>

Table 30  

\textit{\textbf{C\textsubscript{7} calculation table}}

<table>
<thead>
<tr>
<th>Type</th>
<th>(N_{\text{voyage}})</th>
<th>TBOG</th>
<th>ABOG</th>
<th>(\text{WM}_{GCU,\text{mean}}) t/hr</th>
<th>CMDO $$/hr</th>
<th>\text{C7 per transporting unit}</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 stroke</td>
<td>12.2</td>
<td>638.4</td>
<td>0.93</td>
<td>0.00096</td>
<td>564</td>
<td>0.261</td>
</tr>
<tr>
<td>2 stroke</td>
<td>12.2</td>
<td>638.4</td>
<td>0.93</td>
<td>0.00096</td>
<td>564</td>
<td>0.261</td>
</tr>
<tr>
<td>COGES</td>
<td>12.2</td>
<td>638.4</td>
<td>0.94</td>
<td>0</td>
<td>564</td>
<td>0</td>
</tr>
</tbody>
</table>

\(C\textsubscript{8}\) 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:** \(C\textsubscript{8}\) 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

$C_8$ calculation table

<table>
<thead>
<tr>
<th>Type</th>
<th>$N_{voyage}$</th>
<th>$T_p, \text{ hr}$</th>
<th>$A_P$</th>
<th>$M_{lube}, \text{ ton}$</th>
<th>$C_{lube} $/hr$</th>
<th>$C_8$ per transporting unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 stroke</td>
<td>12.2</td>
<td>638.4</td>
<td>0.94</td>
<td>0.0684</td>
<td>1250</td>
<td>0.342</td>
</tr>
<tr>
<td>2 stroke</td>
<td>12.2</td>
<td>638.4</td>
<td>0.94</td>
<td>0.0684</td>
<td>1757</td>
<td>0.481</td>
</tr>
<tr>
<td>COGES</td>
<td>12.2</td>
<td>638.4</td>
<td>0.97</td>
<td>0.0684</td>
<td>1250</td>
<td>0.353</td>
</tr>
</tbody>
</table>

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.

$C_9$ and $C_{10}$ 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

<table>
<thead>
<tr>
<th></th>
<th>4 stroke</th>
<th>2 stroke</th>
<th>COGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>6.91</td>
<td>6.91</td>
<td>3.46</td>
</tr>
<tr>
<td>$C_2$</td>
<td>5.20</td>
<td>5.20</td>
<td>5.20</td>
</tr>
<tr>
<td>$C_3$</td>
<td>0.36</td>
<td>0.36</td>
<td>0.31</td>
</tr>
<tr>
<td>$C_4$</td>
<td>11.82</td>
<td>11.82</td>
<td>10.13</td>
</tr>
<tr>
<td>$C_5$</td>
<td>3.236</td>
<td>3.107</td>
<td>5.986</td>
</tr>
<tr>
<td>$C_6$</td>
<td>0.261</td>
<td>0.261</td>
<td>0.296</td>
</tr>
<tr>
<td>$C_7$</td>
<td>0.261</td>
<td>0.261</td>
<td>0</td>
</tr>
<tr>
<td>$C_8$</td>
<td>0.342</td>
<td>0.481</td>
<td>0.353</td>
</tr>
<tr>
<td>Sum</td>
<td>28.390</td>
<td>28.261</td>
<td>25.735</td>
</tr>
</tbody>
</table>

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

For DFDM with 4 stroke engine:

$$\text{OPEX} = N_{voyage} \times C_{cargo} \times \text{Sum} \times 10 = 519.537 \text{ M } \$ $$
LCC = 519.537 + 21.76 = 541.297 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 } \$

LCC = 517.176 + 24.28 = 541.456 M $

For COGES:

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

LCC = 470.950 + 21.84 = 492.79 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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