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A Comparative Life cycle Cost Approach

Author
Daejun Chang, Principal Researcher

Co-authors
Taejin Rhee, Chief Researcher
Kiil Nam, Senior Researcher
Sejoong Lee, Senior Researcher

Hyundai Industrial Research Institute

Byungjin Kwak, General Manager
Jongpiil Ha, General Manager

Project Planning Department II

Hyundai Heavy Industries, Co., Ltd.
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Daejun Chang*, Taejin Rhee, Kiil Nam, Sejoong Lee
Hyundai Industrial Research Institute, Hyundai Heavy Industries,

Byungjin Kwak, Jongpil Ha
Project Planning Department II, Hyundai Heavy Industries,
1, Jeonha-dong, Dong-gu, Ulsan 682-792, Korea

ABSTRACT
This study presented the methodology of a comparative life cycle cost to provide impartial assessment of propulsion options for LNG carriers. The comparison set included the commercial available propulsion solutions based on reheating steam turbines, dual-fuel diesel generators, diesel engines with reliquefaction and dual-fuel diesel engines.

In order to achieve unbiased comparison, the scope of the system included not only the main engines for propulsion function but also the systems for BOG handling and electricity generation. One voyage was divided into laden, ballast, port maneuvering, loading, unloading, waiting, and canal transit segment, for each of which the propulsion demand, electrical load and BOG generation were estimated. Operational availability of each subsystem was measured on the basis of its failure rate and repair time.

The comparative life cycle cost analysis for a transport case indicated that the operating expenditure was much larger than the capital expenditure, implying that the optimization efforts should be paid to minimizing the operating expenditure. Of the operating expenditure, the fuel cost component including the natural boil-off gas took the major share while portions of the delivery loss cost affected by the propulsion availability and the maintenance costs showed a significant variation with propulsion options. When the fuel cost was changed, the diesel mechanical propulsion with reliquefaction remained relatively invariant in comparison with the other options. This observation was attributed to the segregation of the propulsion and BOG treatment functions. Improvement in availability of the propulsion availability had larger impact than that of the BOG treatment function for all the propulsion options except for the reliquefaction-equipped propulsion. This was because the failure of propulsion function resulted in the delivery delay as well as the BOG loss. To the contrary, the failure of the BOG treatment function did not do harm the propulsion function.

*All correspondence should be addressed (e-mail: sos21@hhi.co.kr).
1. INTRODUCTION

Recently, the LNG shipping industry has observed a dramatic change in propulsion system. Beyond the old dominator, the steam turbine system, the strong competitors of the dual fuel diesel electric propulsion and the diesel engine propulsion with BOG reliquefaction have entered the territory. Though the traditional steam turbine still takes an overall majority share of the carriers in service, the two followers take a half the carriers in order books.

The competition does not seem to cease here. Other propulsion options are waiting their commercialization. The slow-speed dual-fuel diesel engine, usually called ME-GI, is on the verge of commercial application. A new generation of the steam turbine has reinforced its competence by reheating the intermediate steam to improve its efficiency. The gas turbine electric propulsion is encouraged by the success of the diesel electric propulsion.

Abundance in propulsion options does not guarantee reasonable decision on which one should be taken for a certain voyage. There are several reasons why the decision-making is not as easy as it looks. The first reason is the boundary of the propulsion system. The propulsion system is closely related with BOG handling and electric power generation. The optimal choice should imply the global optimum of the three systems combined. The second is the life-long aspect. For example, some options require high capital investment and low operating cost while others demand moderate capital investment and operating cost. Another reason is a variety of operating conditions. Usually, each carrier has its own path to sail. The cargo capacity, the voyage duration, the main engine idling time, sea water temperature, atmospheric temperature, etc are different from ship to ship. The last is the system availability, which depends on the system configuration (especially the existence of redundant back-up systems), the failure rate, and the repair time. The situation is more entangled by option-specific advocators, especially the manufacturers of the system, who magnify the benefits and shrink the shortcomings of their product.

There are some academic efforts to compare the propulsion options, mainly in terms of capital expenditure, qualitative comparison, safety and reliability [1-3]. These studies initiated comparative investigations into the propulsion options.

One of impartial evaluation methods is assessment of life cycle cost. It evaluates all the costs over the whole life of the propulsion system. The optimal solution is supposed to bear the minimum life cycle cost. The rigorous method requires tremendous efforts from counting the cost of every item to anticipating the life-long operating costs.

This study employs a comparative life cycle cost assessment, a simple but effective version of a complete life cycle cost analysis. The method excludes the cost for common parts, which may be
equipment items, man-hour expenditure or administrative burden. Instead, it concentrates on the cost discrepancy due to difference in the system configuration, reliability, energy efficiency and performance. Section 2 defines the boundary of the propulsion system and describes the propulsion options. The methodology is introduced in Section 3, followed by a case study in Section 4. Further analysis is presented in Section 5 to provide delicate points worth careful consideration in applying the methodology.

2. DESCRIPTION OF PROPULSION OPTIONS

2.1 Boundary of System
The propulsion function of LNG carriers is closely related with the BOG utilization and electric power generation. Most propulsion options use the BOG for fuel as well as the liquid oils. To the contrary, the diesel electric propulsion generates electric power to drive the electric motor connected to propeller shaft. The option with the BOG reliquefaction unit recovers the BOG consuming a huge amount of power. Consequently, it is reasonable to consider that the propulsion system should include the basic propulsion engines themselves, the main power generation, and the BOG utilization. In summary, unbiased comparison should take into account the three parts:

- Main engines
- Electric generators
- BOG treatment system

Throughout this study, the ‘propulsion system’ will denote the system inclusive of the three subsystems.

One way to categorize the propulsion systems for LNG carriers is to follow their nature to handle the BOG, as shown in Figure 1. The acronym in the figure will be used extensively throughout this paper. There are two divisions depending on whether the BOG is recovered or consumed as fuel. The diesel mechanical propulsion with reliquefaction (SFDM+R) is a unique solution for the BOG recovery branch. The other branch bifurcates depending on the completeness of the dual-fuel utilization; whether the engine can burn the BOG with the liquid fuel (HFO or MDO) simultaneously or separately. The dual-fuel medium-speed diesel electric propulsion (DFDE) corresponds to the latter. There are three propulsion systems that can use the BOG and the liquid fuel at once: the dual-fuel steam turbine mechanical propulsion (DFSM), the dual-fuel (low-speed) diesel mechanical propulsion (DFDM), and the dual-fuel gas turbine electric propulsion (DFGE).

For the past several decades, the DFSM has dominated the market of the propulsion system in the
field of the LNG shipping industry [5]. Recently, two new alternatives, SFDM+R and DFDE, have entered into the commercial arena. Roughly speaking, each of these new types accounts for a quarter of the LNG carriers on the order books. Still, half of the LNG carriers will be equipped with steam turbines. Most of the LNG carriers with the SFDM+R type have the cargo capacity greater than 200,000 m³ while the carriers with the DFDE are comparable to the DFSM in the cargo capacity.

![Diagram of propulsion systems for LNG carriers in terms of BOG utilization](image)

**Figure 1** Categorization of propulsion systems for LNG carriers in terms of BOG utilization

### 2.2 Principal Features

**Dual-fuel steam turbine mechanical propulsion (DFSM)**

The dual-fuel steam turbine mechanical propulsion (DFSM) burns the BOG in boilers to produce high pressure steam, which drives the steam turbines connected to the propeller. Its soft spot of low fuel efficiency is reinforced by the reheating the exhaust steam from the high pressure turbine and returning it to the medium-pressure turbine, as shown in Figure 2. The conventional version (DFSMC) had dominated for the past several decades because of its simple operability and intrinsic safety. One of advantages of this type is ease of handling the BOG, capable of burning the BOG with the liquid fuel simultaneously. When the cargo tank pressure is elevated, the boilers burn the excessive BOG and the generated steam is dumped into the main condenser. The simple philosophy for the BOG treatment eliminates the need of the gas combustion unit, which is a requirement for its followers.
Dual-fuel (medium-speed) diesel electric propulsion (DFDE)

The dual-fuel (medium-speed) diesel electric propulsion (DFDE) in Figure 3 is a modified version of the diesel engine in order to burn the BOG as well as diesel oil [4]. The dual-fuel engine generates electric power and propels the ship with electric motors. The engine, however, can not burn the two fuels at once and should shift the fuel mode for different fuels. Additionally, it requires relatively low pressure (about 6 bara) for the BOG to be used as fuel. Note that this propulsion system contains a GCU as a back-up BOG disposal unit for the case where the BOG is greater than the fuel gas demand of the engines.
Single-fuel diesel mechanical propulsion with reliquefaction (SFDM+R)

Figure 4 illustrates the single-fuel (low-speed) diesel mechanical propulsion with BOG reliquefaction (SFDM+R), where the BOG is liquefied in a separate system called the reliquefaction plant, instead of being used as fuel. The low-speed diesel engine is connected directly to a propeller shaft. Conceptually, the propulsion is separated from the BOG treatment. The reliquefaction unit contains several machineries and cryogenic exchanger. Note that this propulsion system is also equipped with a GCU to dispose of the BOG for the case where the BOG is greater than the capacity of the reliquefaction plant.

Dual-fuel gas turbine electric propulsion (DFGE)

This propulsion system combines a gas turbine with a heat recovery steam generator (HRSG), using the hot exhaust gas from the gas turbine to drive a steam turbine to generate electrical power. The HRSG is also fitted with burners for auxiliary firing with the liquid fuel or BOG. The fuel gas supply system equipped with screw compressors boosts the BOG pressure and feeds it into the main gas turbine. The liquid fuel enters the main gas turbine or the HRSG burners for combustion. An auxiliary gas turbine is optionally installed to adapt to low load demands during various operations as well as to perform the propulsion redundancy when required. A GCU is installed for the disposal of BOG as a necessary back-up method of providing cargo tank pressure control when all of the BOG can not be consumed in the main gas turbine or the HRSG. The HRSG generates superheated steam to drive a steam turbine with the hot exhaust gas from the gas turbine. As the gas turbine load reduces to match low load demands, the HRSG steam production decreases correspondingly.
Dual-fuel (low-speed) diesel mechanical propulsion (DFDM)

The dual-fuel (low-speed) diesel mechanical propulsion (DFDM) in Figure 6 combines the advantages of the DFDE and SFDM+R options. It is of dual-fuel type like the DFDE. Moreover, it is capable of burning both the BOG and liquid oil simultaneously. It is equipped with the low-speed diesel engine. This system, however, has a new problem that the fuel gas should be compressed up to around 250 bara, which has been never faced in the LNG shipping industry. Some engineers wonder that this high pressure gas may cause serious trouble in the actual operation. The risk due to high pressure gas was proved to be negligible by a set of safety layers such as double-wall pipes and gas detection systems [4, 6].

Figure 5  System schematic for dual-fuel gas turbine electric propulsion (DFGE)

Figure 6  System schematic for dual-fuel (low-speed) diesel mechanical propulsion (DFDM)
3. METHODOLOGY

3.1 Comparative LCC
The benefit of a carrier over its life cycle is expressed by the equation with the salvation cost or benefit neglected.

\[ C_{P,\text{Net}} = C_{P,\text{Cargo}} - \text{CAPEX} - \text{OPEX} \] (1)

With emphasis on the propulsion system, the CAPEX and OPEX are divided into the CAPEX and OPEX components, as follows.

\[ C_{P,\text{Net}} = C_{P,\text{Cargo}} - \text{CAPEX} - \text{OPEX} = \text{CAPEX}^p - \text{OPEX}^p \] (2)

Conceptually, CAPEX^p is fixed and paid only once over the life time. To the contrary, the OPEX^p is affected by various factors, paid nearly continuously over the life time, and uncertain due to its stochastic feature. In consequence, the OPEX^p is more likely to be subject to an estimation uncertainty.

3.2 Procedure of Analysis
The comparative LCC consists of four steps. Here are the tasks of each step. The overall procedure is generally applicable to any comparative study, and the sub-tasks under the main steps correspond to the works specific to the comparative LCC analysis for the study.

Step 1: Definition of the system configurations 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
   - LCC^p
3.3 Components of Annual Operating Expenditure, OPEX<sup>P</sup>

Note that the comparative LCC assessment deals with only the cost, not the benefit. For impartial comparison, however, the assessment should include not only the cost for operation and maintenance, but also the financial damage due to the imperfect fulfillment of the cargo delivery duty incurred by the propulsion system. For example, the loss of propulsion power results in delayed delivery of the cargo and requires some repair time during which the carrier is out of service. The failure of the BOG treatment system forces the valuable BOG to be burned in the GCU, and an alternative liquid oil should be consumed.

The operating expenditure OPEX<sup>P</sup> is represented by the sum of the annual expenditure, C<sub>N</sub>, which is in turn segmented into ten components as defined below.

\[ C_1 : \text{Delivery loss cost due to propulsion failure} \]
\[ C_2 : \text{BOG loss cost due to BOG evaporation caused by heat ingress} \]
\[ C_3 : \text{BOG loss cost due to BOG treatment failure} \]
\[ C_4 : \text{Penalty cost due to delayed delivery} \]
\[ C_5 : \text{Fuel consumption cost for propulsion} \]
\[ C_6 : \text{Fuel consumption cost for BOG treatment} \]
\[ C_7 : \text{Fuel consumption cost for GCU operation} \]
\[ C_8 : \text{Lubricant consumption cost} \]
\[ C_9 : \text{Preventive maintenance cost for propulsion system} \]
\[ C_{10} : \text{Corrective maintenance cost for propulsion system} \]
\[ C_N : \text{Total sum of the annual cost, } C_N = \sum_{i=1}^{10} C_i \]

Most of the component costs are affected by one of the two availabilities or both.

\[ A_P : \text{Availability of propulsion function} \]
\[ A_{BOG} : \text{Availability of BOG treatment function} \]

Note that the availability is not defined for any subsystem, but for a specific function. For example, the availability of propulsion function A<sub>P</sub> concerns whether the propulsion function is available or not, but whether the main engines are operating or not. Since the propulsion function includes even the BOG treatment system, which supplies gas fuel to the main engines, the BOG treatment system positively contributes to A<sub>P</sub>, as well as to that of BOG treatment function, A<sub>BOG</sub>.

The reason why the availabilities should be considered arises from the relative magnitude of their contribution to the operating cost. Availability is the portion of the operating time to the total conceivable time. The complement of availability (A) is unavailability (UA), which is a collective
representation of functional time loss for any reasons including failure, repair, functional test etc, leading to the following relation.

\[ UA + A = 1 \]  \hspace{1cm} ............................................ (3)

Roughly speaking, the propulsion unavailability around 5 % is interpreted in the long-term average sense as 5 % more time required to deliver a fixed amount of the cargo or 5 % less cargo expected to be delivered within a fixed interval. Assuming the boil-off rate of 0.14 %/day and the voyage of 20 day, the BOG generation accounts for about 3 % of the total cargo loaded. In the same context, the unavailability of 5 % has tremendous impact on the propulsion system economics.

The delivery loss cost due to propulsion failure, \( C_1 \), is affected by the propulsion availability, \( A_p \). The profit from the cargo delivery per voyage is given by \( M_{\text{Offload}} \cdot C_{\text{CIF}} - M_{\text{Load}} \cdot C_{\text{FOR}} \) since the mass as well as the LNG price is different between the two points of loading and offlooding. The annual delivery loss is obtained by multiplying this profit by the number of annual voyages and the unavailability.

\[ C_1 = N_{\text{Voyage}} \cdot (M_{\text{Offload}} \cdot C_{\text{CIF}} - M_{\text{Load}} \cdot C_{\text{FOR}}) \cdot UA_p \]  \hspace{1cm} ............................................ (4)

When the BOG reliquefaction system fully recovers the BOG, as in SFDM+R, the offloaded amount equals the loaded one, \( M_{\text{Offload}} = M_{\text{Load}} \). For the other options, the BOG vaporizes to be used for fuel gas, and the offloaded mass is less than the loaded mass by the amount of BOG over the voyage, \( M_{\text{Offload}} = M_{\text{Load}} - M_{\text{BOG}} \).

\[ M_{\text{Offload}} = \begin{cases} M_{\text{Load}} & \text{for SFDM + R} \\ M_{\text{Load}} - M_{\text{BOG}} & \text{for the others} \end{cases} \]  \hspace{1cm} ............................................ (5)

The mass of BOG evaporated on a round trip is given by the equation.

\[ M_{\text{BOG}} = M_{\text{Load}} \cdot BOR_m \cdot T_{\text{BOG}} \]  \hspace{1cm} ............................................ (6)

The BOG loss cost due to BOG evaporation caused by heat ingress, \( C_2 \), reflects the naturally vaporized BOG, which should be vented out of the cargo containment system to prevent its overpressure. Since the BOG is considered a loss, the fuel cost of BOG is assumed to be zero in estimating the fuel consumption cost for propulsion, \( C_5 \).

\[ C_2 = N_{\text{Voyage}} \cdot M_{\text{BOG}} \cdot C_{\text{CIF}} \]  \hspace{1cm} ............................................ (7)

The BOG loss cost, \( C_3 \), arises from the failure of the BOG treatment system, which corresponds to either the fuel gas supply system or the BOG reliquefaction system. When the BOG treatment system fails, the BOG cannot be used as fuel or liquefied into LNG, resulting in being incinerated in the GCU.
The BOG loss cost is given by the equation.

\[ C_3 = M_{BOG} \cdot C_{CIF} \cdot UA_{BOG} \] \hspace{1cm} (8)

The penalty due to delayed delivery, \( C_4 \), is based on the contract and is not as apparent as the other costs. This study assumes that the penalty equals the profit loss of the gas seller.

\[ C_4 = N_{Voyage} \cdot M_{Offload} \cdot C_{CIF} \cdot UA_{BOG} \] \hspace{1cm} (9)

The fuel consumption cost for propulsion, \( C_5 \), increases with the fuel consumption rate and the fuel price.

\[ C_5 = N_{Voyage} \cdot T_p \cdot A_p \cdot (MC_{Fuel,Laden} + MC_{Fuel,Ballast}) / 2 \] \hspace{1cm} (10)

The fuel cost rates, \( MC_{Fuel,Laden} \) and \( MC_{Fuel,Ballast} \), are the product of mass flow rate of the fuel and its price. Since each propulsion option except for the SFDM+R, has two or three distinctive fuel modes, the minimum fuel cost rate should be chosen from the conceivable operations.

\[ MC_{Fuel} = \text{Min}(MC_{Gas}, \ MC_{NBOG+HFO}, \ MC_{NBOG+MDO}) \] \hspace{1cm} (11)

The discharge pressure of the BOG treatment system varies from option to option, meaning that its power consumption deserves attention. The power consumption is taken into account as fuel consumption cost, \( C_6 \).

\[ C_6 = N_{Voyage} \cdot T_{BOG} \cdot A_{BOG} \cdot WM_{BOG,Mean} \cdot C_{MDO} \] \hspace{1cm} (12)

\[ WM_{BOG,Mean} = (W_{BOG,Laden} \cdot M_{MDO,BOG,Laden} + W_{BOG,Ballast} \cdot M_{MDO,BOG,Ballast}) / 2 \] \hspace{1cm} (13)

The GCU also requires power supply. Analogous to \( C_6 \), the fuel consumption cost for GCU operation, \( C_7 \), is estimated by the equation.

\[ C_7 = N_{Voyage} \cdot (T_{GCU} + T_{BOG} \cdot UA_{BOG}) \cdot WM_{GCU,Mean} \cdot C_{MDO} \] \hspace{1cm} (14)

The lubricant consumption cost, \( C_8 \), is given by the equation.

\[ C_8 = N_{Voyage} \cdot T_p \cdot A_p \cdot M_{Lube} \cdot C_{Lube} \] \hspace{1cm} (15)

The preventive maintenance cost, \( C_9 \), consists of two parts, the man hour expense and the material
cost. Both are multiplied by the annual preventive maintenance frequency and the number of engines.

\[ C_9 = N_{PM} \cdot N_{Engine} \cdot (MH_{PM} \cdot C_{MH} + R_{PM} \cdot CAPEX_p) \] .................(16)

The annual preventive maintenance frequency, \( N_{PM} \), is determined by ship owner’s maintenance policy. Typically, the engine manufactures recommend preventive maintenance action every two or three years.

The corrective maintenance cost, \( C_{10} \), takes the form similar to the preventive maintenance cost, \( C_9 \).

\[ C_{10} = N_{CM} \cdot N_{Engine} \cdot (MH_{CM} \cdot C_{MH} + R_{CM} \cdot CAPEX_p) \] .................(17)

The corrective maintenance frequency is governed by the failure rate of the engines.

It is worth noting which cost component is related with which availability. Table 1 reveals the connection between the cost components and availabilities.

<table>
<thead>
<tr>
<th>Cost component</th>
<th>( A_P )</th>
<th>( A_{BOG} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_1 ) (delivery loss cost due to propulsion failure)</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>( C_2 ) (BOG loss cost due to BOG evaporation caused by heat ingress)</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>( C_3 ) (BOG loss cost due to BOG treatment failure)</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>( C_4 ) (penalty cost due to delayed delivery)</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>( C_5 ) (fuel consumption cost for propulsion)</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>( C_6 ) (fuel consumption cost for BOG treatment)</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>( C_7 ) (fuel consumption cost for GCU operation)</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>( C_8 ) (lubricant consumption cost)</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>( C_9 ) (preventive maintenance cost for propulsion system)</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>( C_{10} ) (corrective maintenance cost for propulsion system)</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
</tbody>
</table>

### 3.4 Estimation of Life cycle Cost, LCC\(^p\)

The life cycle cost for propulsion system, LCC\(^p\), is possible to estimate on the basis of the CAPEX\(^p\) and OPEX\(^p\) converted to a present-value cost. The future value of the operating cost depends on the capital expenditure as well as the future prices of fuels, man hour, spare parts, etc. These prices are estimated by combining the present value with the inflation rate. The present values of fuels are accessible in the web sites for fuel price [7-9]. The life-cycle cost is presented in the form of cost per volume transported.
4. CASE STUDY

4.1 Backgrounds of Case Study

This section illustrates the application of the comparative LCC methodology to the various propulsion systems for a fixed route. It should be noted that the results of the analysis are subject to change due to the variation, especially in the following points.

- System configuration
- CAPEX, especially the equipment purchase cost
- OPEX, especially the fuel costs including LNG, MDO, and HFO as well as the maintenance cost

The ensuing case study is just an example. That is, a set of inputs different from those of the study would lead to different conclusions. It is emphasized again that the objective of this study is to propose the methodology for comparative LCC, not to put the propulsion options in order of life cycle cost.

4.2 Step 1: Definition of the system configurations and functions

All the four new propulsion options are considered. For the DFDE, there are two options, one with redundant main engines and the other without it. The DFGE and DFSMC are excluded from consideration.

- DFDE I with four diesel engines without any redundant engine (4 x 25 %)
- DFDE II with four diesel engines with one redundant engine (4 x 33 %)
- DFDM with two diesel engines without any redundant engine (2 x 50 %)
- SFDM+R with two diesel engines without any redundant engine (2 x 50 %)
- DFSMR with three steam turbines in series (1 x 100 %)

These systems are assumed to follow the process configuration described in Section 2.2

The cargo and its containment systems are identical for all the propulsion options.

- The cargo capacity of the LNG is assumed to be 210,000 m$^3$.
- The boil-off rate (BOR) of 0.14 %/day gives rise to BOG generation at 5.7 ton/hr on the laden voyage and 2.6 ton/hr on the ballast voyage.
- Information on the voyage route, dubbed Route R-C, is shown in Table 2. Note that the main engine operation time as well as the BOG generation time is a little less than the total voyage duration.
### Table 2  Voyage information for Route R-C (from Ras Laffan, Qatar to Corpus Christi, USA)

<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>30</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1st sea-going</td>
<td>153</td>
<td>153</td>
<td>153</td>
</tr>
<tr>
<td></td>
<td>Waiting Suez Canal</td>
<td>4</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Transit Suez</td>
<td>11</td>
<td>-</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>2nd sea-going</td>
<td>346</td>
<td>346</td>
<td>346</td>
</tr>
<tr>
<td>Ballast</td>
<td>Port - unloading</td>
<td>30</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1st sea-going</td>
<td>346</td>
<td>346</td>
<td>346</td>
</tr>
<tr>
<td></td>
<td>Waiting Suez Canal</td>
<td>4</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Transit Suez</td>
<td>11</td>
<td>-</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>2nd sea-going</td>
<td>153</td>
<td>153</td>
<td>153</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>1088</td>
<td>998</td>
<td>1028</td>
</tr>
<tr>
<td></td>
<td>No. of voyage/year</td>
<td></td>
<td></td>
<td>8.1</td>
</tr>
</tbody>
</table>

### 4.3 Step 2: Assessment of the system performance

An electric load in the LNG carrier falls into one of the following six categories: continuous, intermittent, cargo system, deck machinery, emergency, and propulsion load.

![Electric load with propulsion options](image)

**Figure 7  Electric load with propulsion options**

Note that the loads other than the propulsion load may vary when the propulsion system is changed. This is because the main engines, fuel supply, electric generation and utility supply are highly
integrated. The electric load of DFDE I and II is significantly larger than those of the others due to its nature of electric propulsion. Roughly, 33 MW is required for the propulsion. SFDM+R has the electric load larger than those of the least two since the BOG reliquefaction plants consumes the power 2.8 MW on ballast voyage and 5.7 MW on laden voyage.

Figure 8 shows the fuel consumption rate. All the propulsion options except for DFSM+R should consume the NBOG before the other fuels. Since the NBOG cannot satisfy all the fuel demand, additional fuel supply is required. The relative price of the rest fuels determines which should be the secondary source. Under the fuel price condition assumed in the case study, the LNG is cheaper than the others. Consequently, vaporized LNG, usually called FBOG, is the back-up fuel. Compared with DFDE, DFSMR consumes more FBOG due to its lower efficiency.

Both DFDM and SFDM+R utilize MDO for diesel generators to supply electricity to the machinery parts of the cargo handling system. For SFDM+R, the nitrogen compressors of the BOG reliquefaction plant account for the majority of the electric demand. For DFDM, the high-pressure reciprocating compressors are the main sink of electric power.

4.4 Step 3: Estimation of the reliability of the system.
The main tasks of this step are to construct the functional block diagram and to evaluate the availability of the propulsion and BOG treatment functions. The reliability and maintenance information including the failure rate (equivalently the mean-time-between-failure) and the mean-time-to-repair is essential for these tasks. Since the new propulsion systems do not have long-term operation record,
the information is referred to the ORED A handbook [10]. Data for the key components are listed in Table 3.

Table 3  Failure rate and MTTR for key components

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Failure rate (per 10^6 hr)</th>
<th>MTTR (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LD Compressor</td>
<td>256.4</td>
<td>25.7</td>
</tr>
<tr>
<td>Screw Compressor</td>
<td>47.4</td>
<td>22.8</td>
</tr>
<tr>
<td>BOG Feed Pump</td>
<td>48.0</td>
<td>11.4</td>
</tr>
<tr>
<td>BOG Feed Pump-Motor Drive</td>
<td>22.8</td>
<td>7.8</td>
</tr>
<tr>
<td>Liquid Fuel Feed Pump</td>
<td>98.5</td>
<td>14.6</td>
</tr>
<tr>
<td>Liquid Fuel Feed Pump-Motor Drive</td>
<td>94.5</td>
<td>9.5</td>
</tr>
<tr>
<td>Cryogenic Heat Exchanger</td>
<td>9.7</td>
<td>39.5</td>
</tr>
<tr>
<td>BOG Liquid Separator</td>
<td>28.8</td>
<td>2.1</td>
</tr>
<tr>
<td>BOG Return Pump</td>
<td>43.0</td>
<td>11.4</td>
</tr>
<tr>
<td>BOG Return Pump-Motor Drive</td>
<td>22.8</td>
<td>7.8</td>
</tr>
<tr>
<td>N2 Cooling Compressor</td>
<td>205.6</td>
<td>13.0</td>
</tr>
<tr>
<td>N2 Cooling Expander</td>
<td>101.9</td>
<td>0.0</td>
</tr>
<tr>
<td>Boiler</td>
<td>66.5</td>
<td>23.5</td>
</tr>
<tr>
<td>HP/IP/LP Steam Turbine</td>
<td>40.0</td>
<td>16.0</td>
</tr>
<tr>
<td>S/T Generator</td>
<td>73.7</td>
<td>18.0</td>
</tr>
<tr>
<td>Re-heater</td>
<td>42.5</td>
<td>22.5</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>Electric Motor</td>
<td>58.6</td>
<td>47.5</td>
</tr>
<tr>
<td>GCU</td>
<td>66.5</td>
<td>23.5</td>
</tr>
</tbody>
</table>

Figure 9 shows the availability for propulsion function. DFDE I demonstrates the lowest availability, and DFDE II attains the highest with the others in between. This contrast comes from the dependence of availability on redundancy and the number of main engines. All the option except DFDE II has no redundant engines. If one of the engines fails, the full propulsion function is not available until the maintenance is finished. Provided the failure rate is invariant over the different types of engines, the failure rate of a set of engines is proportional to the number of engines. DFDE II has three engines in operation while the others have two, leading to the observation that it has the least propulsion availability. To the contrary, DFDE II has one redundant engine with the other three operating. This configuration improves the availability, even better than DFSMR.
Figure 9  Availability for propulsion function with propulsion options

Figure 10  Fuel consumption rate with propulsion options

In terms of BOG treatment availability, $A_{\text{BOG}}$, SFDM+R is found to be best with DFDE II being a close second, as shown in Figure 10. It should be noted that $A_{\text{BOG}}$ is dependent on the propulsion function for the options other than SFDM+R since the failure of propulsion function implies no consumption of BOG.

4.5 Step 4: Assessment of the comparative life cycle cost

The assumed CAPEX of the case study is in Table 4. The common units are not included in the CAPEX, such as the liquid fuel supply system. The GCU is considered since DFSMR has no need for it while the others require it. It should be reemphasized again that these values are subject to a significant variation.
Table 4  CAPEX (US$) of propulsion options-assumed value

<table>
<thead>
<tr>
<th>System</th>
<th>DFDE I</th>
<th>DFDE II</th>
<th>MEGI</th>
<th>DE+R</th>
<th>DFSMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum</td>
<td>37,400,000</td>
<td>39,000,000</td>
<td>26,800,000</td>
<td>30,300,000</td>
<td>27,000,000</td>
</tr>
</tbody>
</table>

The price of fuels including LNG is shown in Table 5, based on the current international values [7-9].

Table 5  Price of fuels

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>LHV (kJ/kg)</th>
<th>Price (US$/MMBTU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNG</td>
<td>49,457</td>
<td>6.24</td>
</tr>
<tr>
<td>HFO</td>
<td>40,639</td>
<td>9.21</td>
</tr>
<tr>
<td>MDO</td>
<td>42,677</td>
<td>14.38</td>
</tr>
</tbody>
</table>

Table 6  Parameters for life cycle cost estimation

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life cycle</td>
<td>Year</td>
<td>20</td>
</tr>
<tr>
<td>Man-hour rate for maintenance</td>
<td>US$/hr</td>
<td>50</td>
</tr>
<tr>
<td>CIF/FOB</td>
<td>-</td>
<td>1.4</td>
</tr>
<tr>
<td>Lubricant price</td>
<td>US$/ton</td>
<td>1,250</td>
</tr>
<tr>
<td>Sales profit ratio to CIF</td>
<td>%</td>
<td>15</td>
</tr>
<tr>
<td>Interest rate</td>
<td>%</td>
<td>11.0</td>
</tr>
<tr>
<td>Equipment inflation rate</td>
<td>%</td>
<td>9.0</td>
</tr>
<tr>
<td>Man-hour inflation rate</td>
<td>%</td>
<td>9.0</td>
</tr>
<tr>
<td>LNG FOB inflation rate</td>
<td>%</td>
<td>12.0</td>
</tr>
<tr>
<td>MDO price inflation rate</td>
<td>%</td>
<td>17.0</td>
</tr>
<tr>
<td>HFO price inflation rate</td>
<td>%</td>
<td>17.0</td>
</tr>
<tr>
<td>Lubricant price inflation rate</td>
<td>%</td>
<td>10.0</td>
</tr>
</tbody>
</table>

Figure 11 presents the LCC$^P$ of a unit volume of LNG transported. DFDE I and SFDM+R show a little high LCC$^P$ while DFDE II attains the lowest though it has an idle redundant engine. Note that the results are correct under the conditions assumed previously.
5. FURTHER ANALYSIS

5.1 Acceptance Criteria

The LCC\textsuperscript{P} is not the unique parameter, but just one of the several criteria that determine which propulsion option should be chosen. Probably, the following will be included in the criteria:

- CAPEX
- Life cycle cost
- Technical feasibility
- Safety
- Operational ease

Even in terms of life cycle cost, the lowest LCC does necessarily imply that the option should be taken. In order for an option to be accepted, the following condition should be satisfied.

\[
LCC_A^p + \sigma_A < LCC_i^p - \sigma_i \quad \text{for all } i \neq A \quad \text{..........................}(18)
\]

It states that the LCC of Option A should be less than that of the others even when the uncertainty plays negatively against it. The standard variation of the system is the sum of those of its cost components.

\[
\sigma_A^2 = \sum \sigma_{A,j}^2 \quad \text{for all component } j \quad \text{.................................}(19)
\]

Note that the cost components include not only the equipment components as well as the operating
components such as fuel cost and man-hour rate.

5.2 Cost Structure

It is found that the capital expenditure takes just a small portion of the total life cycle cost, as shown in Figure 12. The CAPEX\(^\text{P}\) is in the rage of 4 % to 6 %. It means that the optimization should focus on the minimization of the OPEX\(^\text{P}\).

![Figure 12](image_url)  
**Figure 12** Fraction of CAPEX\(^\text{P}\) of LCC\(^\text{P}\)

![Figure 13](image_url)  
**Figure 13** Fraction of each cost component of OPEX\(^\text{P}\)

Figure 13 shows the fraction of each component of the OPEX\(^\text{P}\). Of the cost components, C\(_7\) (the fuel consumption cost for GCU operation) and C\(_8\) (the lubricant consumption cost) are excluded since they are less than 1 %. The net fuel cost is introduced by combining C\(_2\) (the BOG loss cost due to BOG evaporation caused by heat ingress) and C\(_5\) (the fuel consumption cost for propulsion). For all the
options, the net fuel cost is the governing factor taking more than half the operating cost. The fuel consumption cost for BOG treatment ($C_6$) is significant for DFDM and SFDM+R since the machinery equipment of the options requires high electric demands. The corrective maintenance cost ($C_{10}$) is commonly around 10%.

### 5.3 Sensitivity Analysis

There are many factors that are uncertain and need sensitivity analysis. This section, however, shows results for some selective parameters. The results will be presented in the form of the relative life cycle cost ($LCC^p$) or the ratio of the $LCC^p$ of the base case to that of the target case.

Figure 14 presents the relative $LCC^p$ with the LNG price variation. Naturally, the increase in LNG price leads to the increase in the BOG loss or the increase in the fuel cost. The degree of the impact is different from option to option. The impact is insignificant for SFDM+R since the BOG is recovered and through the BOG reliquefaction plant. The slight increase is ascribed to the BOG loss cost due to BOG treatment failure ($C_3$). For the other options, the LNG and BOG are used as fuel gas, and the fuel cost increases with the LNG CIF price.

The reduced cost of the liquid fuel (HFO) results in a decreased life cycle cost, as presented in Figure 15. Analogous to the previous sensitivity study, the degree of reduction depends on the propulsion option. SFDM+R shows the largest decreases since it uses the liquid fuel for all the fuel demand. For the other options, the trend is not apparent until the liquid fuel price reaches a sufficiently low level. Without choice, they should use NBOG at first and then have opportunity to choose between FBOG (LNG) and HFO.
Figure 15  Effect of decrease in HFO price on relative LCC<sub>P</sub>

Figure 16  Effect of reduction in A<sub>P</sub> on relative LCC<sub>P</sub>

Figure 16 indicates that the decreased availability for propulsion function, A<sub>P</sub>, means a significant increase in the life cycle cost. Roughly speaking, a reduction by 10% leads to an increase of 30 to 40%. The deterioration is mild for SFDM+R since for the option the propulsion and BOG treatment functions are decoupled. For the other options, the implication of the propulsion function failure is twofold: failure of delivery and that of BOG consumption as fuel. It should be noted that the cost for the same degree of improvement in A<sub>P</sub> depends on the option.

The effect of A<sub>BOG</sub> is not as significant as that of A<sub>P</sub>, as shown in Figure 17. For all the options, the failure of the BOG treatment function means more than itself, unlike that of the propulsion function.
The voyage difference has direct impact on the life cycle cost. Table 7 compares three routes. Note that the number of voyages per year changes significantly.

Table 7  Distance and voyage duration of three selected voyage routes

<table>
<thead>
<tr>
<th>Route</th>
<th>Export port - import port</th>
<th>Distance, NM</th>
<th>Voyage duration, hr</th>
<th>No. of voyages /year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route R-C</td>
<td>Las Laffan, Qatar - Corpus Christi, USA</td>
<td>9818</td>
<td>1088</td>
<td>8.1</td>
</tr>
<tr>
<td>Route R-I</td>
<td>Las Laffan, Qatar - Incheon, Korea</td>
<td>6435</td>
<td>720</td>
<td>12.2</td>
</tr>
<tr>
<td>Route K-I</td>
<td>De Kastri, Russia - Incheon, Korea</td>
<td>1463</td>
<td>210</td>
<td>41.7</td>
</tr>
</tbody>
</table>

The more frequent the annual voyage is, the lower the life cycle cost per volume transported. The reduction is nearly proportional to the number of annual voyages.
6. CONCLUSIONS

In order to assess the propulsion options in terms of cost, the methodology of a comparative life cycle cost was suggested to include the availability of propulsion and BOG treatment functions and to exclude the cost for the parts common to all the options. The life cycle cost was divided into two parts of capital and operating expenditure.

Of the life cycle cost for the propulsion system, the operating expenditure was found much larger than the capital expenditure. It means that the difference in the initial capital investment is considered insignificant since it is typically around 5% of the life cycle cost with the rest ascribed to the operating expenditure. For example, DFDE II with one redundant engine has a larger capital expenditure and a lower life cycle cost than DFDE I without any redundant engine.

Of the operating expenditure, the fuel cost including the natural boil-off gas took the major share while both the GCU operation cost and the lubricant cost were negligible. Portions of the delivery loss cost affected by the propulsion availability and the maintenance costs varied with propulsion options.

When the fuel cost was changed, the option SFDM+R remained relatively invariant in comparison with the other options. This observation was attributed to the segregation of the propulsion and BOG treatment functions with the BOG recovered.

Improvement in the propulsion availability had larger impact than that of the BOG treatment function.
for all the propulsion options except for SFDM+R. This was because the failure of propulsion function resulted in the delivery delay as well as the BOG loss. To the contrary, the failure of the BOG treatment function did not do harm the propulsion function.

It is never overemphasized that the comparative life cycle cost is just one of the critical factors, some of which are difficult to express in monetary unit, such as technical feasibility, safety, and operational convenience. The final decision on the propulsion option should be made with these aspects taken into account simultaneously. Further study is recommended to incorporate these into the life cycle cost. For example, the risk of application of an immature new technical solution may be expressed as a risk expenditure.

### Nomenclature

- \( A_{BOG} \) Availability of BOG treatment function
- \( A_P \) Availability of propulsion function
- bara bar absolute
- BOG Boil-off gas
- BOR Boil-off rate, /hr
- \( BOR_m \) Mean boil-off rate averaged over a round trip, /hr
- CAPEX Capital expenditure, $
- CAPEX^C \) CAPEX excluding propulsion system, $
- CAPEX^P \) CAPEX for propulsion system, $
- \( C_{CIF} \) CIF (cost insurance and freight) price of LNG, $/ton
- \( C_{FOB} \) FOB (free-on-board) price of LNG, $/ton
- \( C_{Lube} \) Price of lubricant, $/kg
- \( C_{MDO} \) Price of MDO, $/kg
- \( C_{MH} \) Man hour rate, $/hr
- \( C_{P,Net} \) Net profit of a carrier, $
- \( C_{P,Cargo} \) Profit from cargo delivery, $
- \( C_1 \) Delivery loss cost due to propulsion failure
- \( C_2 \) BOG loss cost due to BOG evaporation caused by heat ingress
- \( C_3 \) BOG loss cost due to BOG treatment failure
- \( C_4 \) Penalty due to delayed delivery
- \( C_5 \) Fuel consumption cost for propulsion
- \( C_6 \) Fuel consumption cost for BOG treatment
- \( C_7 \) Fuel consumption cost for GCU operation
- \( C_8 \) Lubricant consumption cost
- \( C_9 \) Preventive maintenance cost for propulsion system
C\textsubscript{10}  
Corrective maintenance cost for propulsion system  

C\textsubscript{N}  
Total sum of the annual cost  

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

DFDM  
Dual-fuel (low-speed) diesel mechanical propulsion  

DFGE  
Dual-fuel gas turbine electric propulsion  

DFSM  
Dual-fuel steam turbine mechanical propulsion  

FBOG  
Forcing BOG  

GCU  
Gas combustion unit  

HFO  
Heavy fuel oil  

HRSG  
Heat recovery and steam generation  

LCC  
Life cycle cost  

LCC\textsuperscript{P}  
LCC for propulsion system, $  

M\textsubscript{BOG}  
Mass of BOG evaporated over a round trip  

MC\textsubscript{Gas}  
Fuel cost rate for the gas mode, $/hr  

MC\textsubscript{NBOG+HFO}  
Fuel cost rate for the NBOG + HFO mode, $/hr  

MC\textsubscript{NBOG+MDO}  
Fuel cost rate for the NBOG + MDO mode, $/hr  

MDO  
Marine diesel oil  

M\textsubscript{Fuel,Ballast}  
Fuel cost rate for the ballast voyage, $/hr  

M\textsubscript{Fuel,Laden}  
Fuel cost rate for the laden voyage, $/hr  

MH\textsubscript{PM}  
Man hours per PM action, hr  

M\textsubscript{Load}  
Mass of LNG loaded to LNG carrier per voyage, ton/voyage  

M\textsubscript{Lube}  
Consumption rate of lubricant, kg/hr  

M\textsubscript{MDO,BOG}  
MDO flow rate per power generated for BOG treatment system, kg/W  

M\textsubscript{Offload}  
Mass of LNG offloaded from LNG carrier per voyage, ton/voyage  

MTTR  
Mean time to repair  

NBOG  
Natural BOG  

N\textsubscript{CM}  
Number of CM actions per year, /yr  

N\textsubscript{PM}  
Number of PM actions per year, /yr  

N\textsubscript{Engine}  
Number of engines installed  

N\textsubscript{Voyage}  
Number of voyages per year, /yr  

OPEX  
Operating expenditure, $  

OPEX\textsuperscript{C}  
OPEX excluding propulsion system, $  

OPEX\textsuperscript{P}  
OPEX for propulsion system, $  

R\textsubscript{CM}  
Ratio of CM material cost to CAPEX\textsuperscript{P}  

R\textsubscript{PM}  
Ratio of PM material cost to CAPEX\textsuperscript{P}  

SFDM+R  
Single-fuel diesel mechanical propulsion with reliquefaction  

T\textsubscript{BOG}  
Time over which BOG is generated, hr  

T\textsubscript{GCU}  
Time over which GCU should be operated, hr
\( T_P \) \hspace{1cm} \text{Time over which propulsion system should be operating, hr}

\( T_{Round} \) \hspace{1cm} \text{Time required for a round trip, hr}

\( UA_B \) \hspace{1cm} \text{Unavailability of BOG treatment function}

\( UA_P \) \hspace{1cm} \text{Unavailability of propulsion function}

\( W_{BOG} \) \hspace{1cm} \text{Power consumption of BOG treatment system, W/hr}

\( WM_{BOG, Mean} \) \hspace{1cm} \text{Mean fuel consumption for BOG treatment system, kg/hr}

\( WM_{GCU, Mean} \) \hspace{1cm} \text{Mean fuel consumption for GCU, kg/hr}

REFERENCES


