Considerations on economic and ecological analysis of naval propulsion systems

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Abstract. Shipowners have begun to invest in "dual-fuel" propulsion because of the price of fuel and pollution standards that are becoming more and more stringent every day. In order to meet the needs of shipowners, MAN B&W is one of the brains that have invested heavily in research and developed dual-fuel not only economical but also safe, reliable, environmentally friendly. The new Wartsila series engines have been designed to deliver newer and more modern engines with the latest developments in functional, production, common-rail electronic systems, and more, as well as units that develop much higher powers. In these applications, the key needs are economic operations, low oil and fuel consumption, stable operating speeds, high reliability, long service maintenance, compactness and optimized industrialization. The EEDI index implies a minimum acceptable level in terms of ship energy efficiency, quantified by CO₂ emissions and relative to freight and transport distance. Supported values will be reduced depending on the implementation phases; it expects the implementation of this index to drive the deployment of innovative shipboard technologies to influence their energy efficiency. The measures to reduce the EEDI value are foreseen in SEEMP existing on board ships. These include both approaches to the implementation of new technologies and operational ones.

1. Introduction
Gas injection engines (GI) have developed in parallel and have been tested since the early 1990s. In 1994, the first GI engine, a 12K80MC-GI-S engine, was put into operation at an electric power plant in Chiba / Japan. At the same time, all major classification societies have agreed and approved the GI concept for stationary and naval engines. From a technical point of view, there is a small difference between the liquid fuel and the gas injection engine, but the GI engine proves to be more flexible in terms of the fuel used. As we have shown above, the gas supply system is based on the principle of electronic motors, like common rail. In this case, the gas injectors are controlled by an auxiliary oil system. In principle, this system consists of a high-pressure oil system and is controlled by the GI electronic unit. So this system will supply gas oil injectors by commanding the gas injectors to be opened at the right time.
2. Dual fuel injection system
Supply of natural gas into the cylinder has been chosen as the high-pressure gas injection and is made when the piston is near the upper dead point. Initial supply diesel and natural gas are injected into the cylinder using the injection valves. Two diesel fuel injectors and two natural gas injectors are mounted. Thus, in order to ensure the injection of gas and diesel fuel, the following systems are required:
- the common rail system;
- the common rail gas supply system;
- the oil seal system;
- the high-pressure oil system for controlling gas injector.

The gas injector complies in principle with the compact design of the classic injector. The gas is admitted through the holes in the cylinder head to the injector. To prevent any gas leakage between the cylinder head and the injector, sealing rings are made of materials resistant to temperature and natural gas. Any gas escape is collected and led to the space between the two shells of the gas supply pipe. These escapes will be detected by the hydrocarbon detectors.

![Injection system diagram](image1)

**Figure 1.** MAN B&W dual fuel system.

![Injection system diagram](image2)

**Figure 2.** Injection system.
3. Dual fuel engine operation

For engine gas operation, the minimum fuel mode has been designated. In this way diesel is used at a preset minimum level to initiate burning in the cylinder and the rest of the engine power is provided by the gas consumption. The minimum level of pilot oil is between 5-8 %, and depends on the fuel quality. In order to initiate the burning, it is possible to use diesel or heavy oil. Diesel fuel consumption for this mode is calculated as a percentage of the maximum engine load and is maintained at this value at a variation in engine load between 30 and 100 %. Under 30 % of the load, the engine may become unstable, so it has been preset in the engine control that under this load value, fuel consumption only passes through diesel oil.

![Figure 3. Dual fuel operation mode.](image)

4. Gas engine emissions for ME-G1

Compared to heavy oil, gas engine emissions are much cleaner. With very low or no sulfur concentration in the fuel, sulfur oxides (SOx) are negligible in the exhaust gases. Particle, NOX and CO2 emissions are also considerably reduced. In the table below, the differences in emissions between oil consumption and methane gas are compared to the same engine type.

|                | 6S50ME-C on HFO | 6S50ME-G1 minimum fuel |
|----------------|-----------------|------------------------|
| Load 100 %     | g/kWh           | g/kWh                  |
| CO2            | 556             | 469                    |
| O2 %           | 1223            | 1255                   |
| CO             | 0.71            | 0.89                   |
| NOx            | 11.97           | 10.51                  |
| HC             | 0.28            | 0.57                   |
| SOx            | 10.57           | 0.85                   |
| PM(mg/m³)      | 0.49            | 0.31                   |

5. Use of gas turbines

Modern ship gas turbines are compact, efficient, powerful and well-functioning propulsion engines that work well in the marine environment as long as they are powered by good fuel. The element, which is usually contained in inferior quality fuel and which is a particular concern for builders, designers and turbine users, is vanadium metal because at high temperatures there may be a risk of corrosion. Vaporized LNG contains no vanadium at all, so it is a very good quality fuel for gas turbines. When used in a turbine-electric configuration, a particular advantage with regard to the use of gas turbines as the main propulsion system of commercial ships is, in particular, that the power plant can be configured in such a way so that it can allow the creation of an additional space dedicated.
For some vessels and for certain types of commerce, the additional cargo space attenuates the low efficiency of gas turbines compared to the efficiency of diesel engines.

5.1. Simple cycle gas turbine propulsion system
Although it has been thought that gas turbines (GT) mounted on a propulsion system have several advantages in terms of power / weight ratio, flexible arrangement of the installation, emission level, efficiency and consistent volume increase for the cargo, it was not used as a new propulsion system on board ships carrying LNG. While a GT propulsion system has features and limitations compared to conventional propulsion systems, the detailed technical and economic characteristics need to be resolved to be able to deploy this power facility onboard an LNG carrier.

5.2. Combined cycle gas turbine propulsion system
Typically has the same configuration as the one with a simple cycle, with respect to the number of power turbines. It is also equipped with a heat recovery system that uses the exhaust gas energy from the gas turbine to add extra power generation from the propulsion system / auxiliary system. This configuration can provide an efficiency gain of 10% compared to simple cycles, but it increases the plant's capital cost of a total of 25% and adds a considerable degree of complexity to this installation. The figures below show typical disposition of three types of propulsion configurations associated with the gas turbine which is used as the main propeller engine.
6. Calculation of engine emission

6.1. EEOI calculation for diesel engine

The LNG vessel is equipped with the engine mentioned in the previous chapter which has an actual specific consumption of $SFC = 171 \text{ g/kWh}$, and the conversion factor for main engine power and auxiliary engines is $C_f = 3,1144$. We have the formula:

$$EEOI = \frac{(P_{ME} \cdot C_f \cdot SFC) + (P_{AE} \cdot C_f \cdot SFC)}{V_{ref} \cdot \Delta}$$

where:

- $P_{ME} = 40282,91 \text{ kW}$ - effective power for speed of 17 Knots;
- $P_{AE} = 1500 \text{ kW}$ - auxiliary engines power;
- $SFC = 171 \text{ g/kWh}$ - effective fuel specific consumption;
- $V_{ref} = 17 \text{ Knots}$ – has value between 0-20 Knots and is ship speed;
- $\Delta=105700 \text{ dwt}$ – ship capacity in tons;
- $C_f = 3,1144$ - conversion factor.

In the same way, the index for the 0-17 Knots speed range will be calculated and the values in table 2.
Table 2. EEOI calculation for diesel engine.

| Ship speed [Knots] | Propulsion power [kW] | EEOI – diesel engine |
|--------------------|-----------------------|----------------------|
| 0                  | 0                     | 0                    |
| 1                  | 17.7970313            | 7.647319108          |
| 2                  | 35.5940626            | 3.868494132          |
| 3                  | 150.5321878           | 2.772032114          |
| 4                  | 265.470313            | 2.223801105          |
| 5                  | 541.7549193           | 2.057449196          |
| 6                  | 872.2150176           | 1.992041191          |
| 7                  | 1340.933566           | 2.044836327          |
| 8                  | 2077.838828           | 2.25337787           |
| 9                  | 3021.822733           | 2.53143583           |
| 10                 | 4267.988912           | 2.906162742          |
| 11                 | 6058.656993           | 3.462162646          |
| 12                 | 8455.190772           | 4.179880393          |
| 13                 | 11901.11172           | 5.193892891          |
| 14                 | 16537.14384           | 6.491353301          |
| 15                 | 21905.86156           | 7.861924824          |
| 16                 | 29841.32672           | 9.869449017          |
| 17                 | 40282.91584           | 12.38355498          |

Figure 6. EEOI variation for diesel engine.

6.2. EEOI calculation for dual fuel engine

The LNG vessel is equipped with the gas engine mentioned in the previous chapter which has an actual specific consumption of $SFC = 158\, \text{g/kWh}$, and the conversion factor for main engine power and auxiliary engines is $C_f = 2.3358$. We have the formula:

$$EEOI = \frac{\left(P_{ME} \cdot C_f \cdot SFC\right) + \left(P_{AE} \cdot C_f \cdot SFC\right)}{V_{ref} \cdot \Delta}$$

where:

- $P_{ME}$ - effective power for speed;
- $P_{AE} = 1500 \text{ kW}$ - auxiliary engines power;
- $SFC = 158 \text{ g/kWh}$ - effective fuel specific consumption;
- $V_{ref} = 17 \text{ Knots}$ – has value between 0-17 Knots and is ship speed;
- $\Delta = 105700 \text{ dwt}$ – ship capacity in tons;
- $C_f = 2.3358$ - conversion factor.

In the same way, the index for the 0-17 Knots speed range will be calculated and the values in table 3.

**Table 3.** EEOI calculation for gas engine.

| Ship speed [Knots] | Propulsion power [kW] | EEOI – gas engine |
|-------------------|-----------------------|-------------------|
| 0                 | 0                     | 0                 |
| 1                 | 17.7970313            | 7.647319108       |
| 2                 | 35.5940626            | 3.868494132       |
| 3                 | 150.5321878           | 2.772032114       |
| 4                 | 265.470313            | 2.223801105       |
| 5                 | 541.7549193           | 2.057449196       |
| 6                 | 872.2150176           | 1.992041191       |
| 7                 | 1340.933566           | 2.044836327       |
| 8                 | 2077.838828           | 2.253337787       |
| 9                 | 3021.822733           | 2.531435383       |
| 10                | 4267.988912           | 2.906162742       |
| 11                | 6058.656993           | 3.462162646       |
| 12                | 8455.190772           | 4.179880393       |
| 13                | 11901.11172           | 5.193892891       |
| 14                | 16537.14384           | 6.491353301       |
| 15                | 21905.86156           | 7.861924824       |
| 16                | 29841.32672           | 9.869449017       |
| 17                | 40282.91584           | 12.38355498       |

**Figure 7.** EEOI variation for gas engine.
7. Conclusions
After presenting the way of increasing the energy efficiency index, practically and theoretically, we calculated the efficiency index and the consumption for each system:

- for the diesel engine we will have an efficiency index of 12,383 and an hourly consumption of 6888.378 kg / h at 17 knots speed;
- for the two-stroke dual fuel engine, we obtained 8.581 for the energy efficiency index and the hourly consumption is 6364.70 kg / h;

The EEDI index implies a minimum acceptable level in terms of ship energy efficiency, quantified by CO₂ emissions and relative to freight and transport distance. Supported values will be reduced depending on the implementation phases; it expects the implementation of this index to drive the deployment of innovative shipboard technologies to influence their energy efficiency. The values of the reduction factors have a decreasing trend during the implementation periods, reaching a minimum of 30% reduction of the emissions of emissions in the years 2025 compared to the levels before the implementation of this index. EEDI has been conceived as the largest and most powerful segments of the maritime industry.

8. References
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