



Propulsion of 2,200 - 3,000 teu container vessels

MAN Energy Solutions
Future in the making

Container Feeder

Modern two-stroke engine technology
for a modern vessel type

Future in the making

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The current feeder fleet is ageing, and the initialisation of fleet renewal programmes are expected within the near future. The modern feeder vessels will have to compete in a fierce and competitive container market and comply with environmental legislation not present when the current fleet was designed 20 years ago.

This paper will focus on presenting the most modern engine technology available for feeder vessels. Technology that will make new feeder vessels both highly competitive and environmentally friendly compared to the current fleet.

The main ship particulars of 2,200-3,000 teu container vessels are normally approximately as follows: the overall ship length is 190-210 m, breadth 30-32.2 m and scantling draught 11.0-12.0 m, see the front page for an example of a typical vessel.

Development steps within engine technology since the mid-2000s have made it possible to offer solutions, which enable significantly lower transportation costs for and reduced emissions from large feeder container vessels.

With the increased focus on reducing CO₂ emissions from ships, as governed by the International Maritime Organisation's Energy Efficiency Design Index (EEDI), further reductions of the fuel consumption are required. Lately, the EEDI for container vessels has gained increased interest from the IMO: The introduction date of EEDI phase 3 and even a revision of the reduction level of phase 3 will be discussed at IMO's maritime environment protection committee (MEPC) in May 2019.

The modern super-long-stroke S-type engines and ultra-long-stroke G-type engines have a lower than usual shaft speed. The reduced optimum propeller rpm of the larger, direct coupled, propellers can hereby be contained within the layout diagrams of these modern engines.

Some of the measures to reduce fuel consumption extending beyond the installation of a modern fuel efficient engine is the optimisation of the aftbody and hull lines of the ship in order to install a propeller with a larger than usual diameter. Hereby a higher propeller efficiency is obtained, at a reduced optimum propeller rpm. Additionally, high efficiency propellers of e.g. the Kappel design, along with other energy saving devices, provide substantial reduction potential.

As an alternative to or in combination with an optimisation of the hull, alternative fuels such as LNG, LPG, methanol or ethane, offered for a wide palette of engine types, will also result in a significant reduction of the EEDI attained. For traditional fuels, and

especially low-sulphur fuels, EcoEGR can be an attractive solution to both reduce the EEDI and also bring savings to the shipowner.

Through two case studies of a 2,500 teu container feeder vessel, this paper will outline the effect of possible initiatives to reduce the environmental impact of such a vessel. The first case study will consider a traditional service speed of 21 knots still seen on some routes, whereas the second case study will consider a reduced service speed of 19 knots.

All the comparisons of the most recent engine technology in combinations with a larger propeller diameter, are performed with reference to a L70ME-C8.5 in the 21 knots case and a S60ME-C8.5 engine in the 19 knots case, both with a 6.8 m diameter propeller. These propulsion plants are included in many designs delivered in the mid 2010s, and as such, the savings presented in this paper are relative to recent designs.

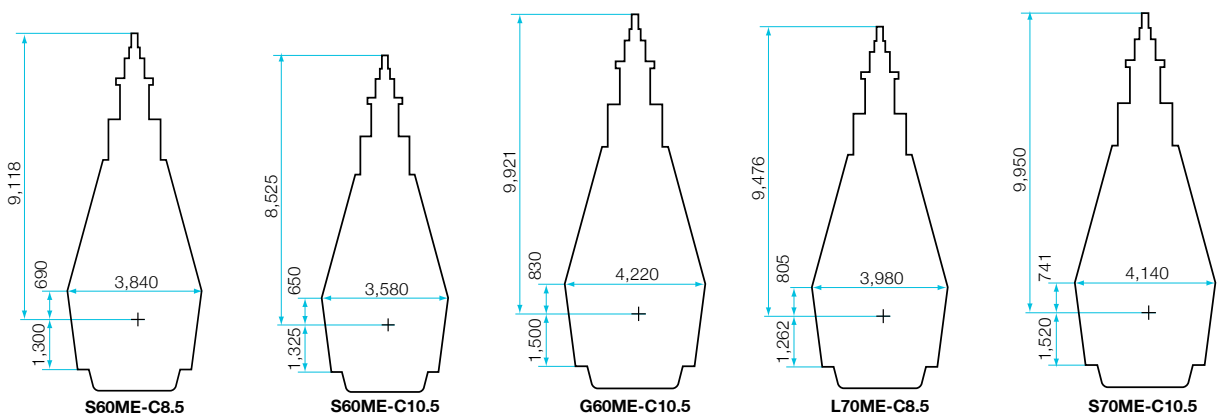


Fig. 1: Main dimensions of possible main engines, all measurements in mm

Energy efficiency design index

The EEDI guidelines are a mandatory instrument adopted by the International Maritime Organization (IMO) that ensures compliance with international requirements on CO₂ emissions of new ships. The EEDI represents the amount of CO₂ in gram emitted when transporting one deadweight tonnage of cargo for one nautical mile:

$$\text{EEDI} \approx \frac{\text{CO}_2}{\text{Transport work}}$$

The EEDI is calculated on the basis of cargo capacity, propulsion power, ship speed, specific fuel consumption and fuel type. However, certain correction factors are applicable, as well as reductions can be obtained by e.g. installing waste heat recovery systems (WHRS). See Chapter 4 of the separate paper “Basic principles of ship propulsion” for further explanations.

A reference index for a specific ship type is calculated based on data from ships built in the period from 2000 to 2010. According to the EEDI guidelines implemented on 1 January 2013, the required EEDI value for new ships is reduced in three steps. This leads to a final EEDI reduction of 30% compared to the reference value for a vessel built after 2025, a date that will possibly be moved forward, depending on the outcome of the ongoing discussions at the MEPC.

For a container vessel, the reference index is calculated based on 100% utilisation of capacity (in dwt) as for all other vessel types. The attained EEDI on the other hand, is calculated based on 70% capacity utilisation, with a reference speed in consistency with

this loading of the vessel, at 75% SMCR with the hull in sea trial condition. The attained EEDI must not exceed the required EEDI.

There are a number of methods that can be applied to lower the EEDI value. By derating the engine, the specific fuel oil consumption (SFOC) is lowered. For a mep derated engine, the mean effective pressure (mep) is reduced relative to the maximum (firing) pressure, which remains constant.

Engine tuning methods such as exhaust gas bypass (EGB) and high-pressure tuning (HPT) can optimise the fuel curve at part- and low-load operation, thus reducing SFOC at 75% load, and thereby the attained EEDI value. Part-load tuning will typically provide the lowest SFOC at the EEDI reference value, whereas low-load tuning also will result in a reduction at this point compared to high-load tuning. In the case studies in this paper, low-load optimisation of the main engine is applied to reflect the slow steaming of modern container vessels, except for the cases where EcoEGR is applied.

Engines with EcoEGR utilise the EGR system (for Tier III compliance) also in Tier II. Hereby, the combustion parameters can be optimised for maximum efficiency while the EGR plant ensures compliance with the NO_x emission limits. This ensures significant fuel savings, approx. 2-3%, depending on the specific application.

The power installed is also a parameter that can be reduced to achieve a lower EEDI value. This can be achieved by

either lowering the vessel speed, by improving the hull design to minimise resistance, or by optimising the propeller design, e.g. through the application of a Kappel propeller. Additionally, various energy saving devices, typically altering the flow fore or aft of the propeller, can be applied.

Installation of green technologies, like WHRS or changing fuel to e.g. liquid natural gas (LNG) or liquefied petroleum gas (LPG), methanol, etc. will also lower the EEDI value. For further information on the calculation of EEDI, and further details on the reduction hereof, as well as other environmental regulations, see Chapter 4 of the separate paper “Basic principles of ship propulsion”.

The IMO has introduced regulations on minimum propulsion power along with the implementation of EEDI. This is by 2019 only applicable to tankers and bulk carriers and not container vessels, as container vessels have significantly higher design speeds and therefore more power installed.

Major propeller and engine parameters

In general, the larger the propeller diameter, the higher the propeller efficiency, and the lower the optimum propeller speed – here referring to an optimum ratio of the propeller pitch and propeller diameter.

A lower number of propeller blades, for example going from 5 to 4 blades if possible, would mean an approximately 10% higher optimum propeller speed.

When increasing the propeller pitch for a given propeller diameter (initially with optimum pitch/diameter ratio), the corresponding propeller speed may be reduced. The efficiency will also be slightly reduced, of course depending on the extent to which the pitch is changed. The same is valid for a reduced pitch, but here the propeller speed may increase.

The efficiency of a two-stroke main engine depends particularly on the ratio of the maximum (firing) pressure and the mean effective pressure (mep). The higher the ratio, the higher the engine efficiency, and the lower the SFOC. As

previously explained this is exploited in a derated engine.

Furthermore, the higher the stroke/bore ratio of a uniflow scavenging two-stroke engine, the higher the engine efficiency, as the scavenging process improves with a higher stroke/bore ratio. This means that the ultra-long-stroke G-type engines by design have a higher efficiency than the previous K- and L-type engines applied on container vessels.

Through the two case studies of a feeder vessel, the influence on fuel consumption of applying a G-type

engine instead of the traditional L70ME-C8.5 for a speed of 21 knots and a S60ME-C8.5 for 19 knots is illustrated, along with the effect of the increased propeller diameter.

The layout diagrams of the L70ME-C8.5 and S60ME-C8.5 are plotted in Fig. 2 for the two cases of 21 and 19 knots, respectively, along with the modern alternatives, the S60ME-C10.5, G60ME-C10.5 and S70ME-C10.5 designs. In the case studies in this paper, low-load optimisation of the main engine is applied to reflect the slow steaming of modern container vessels.

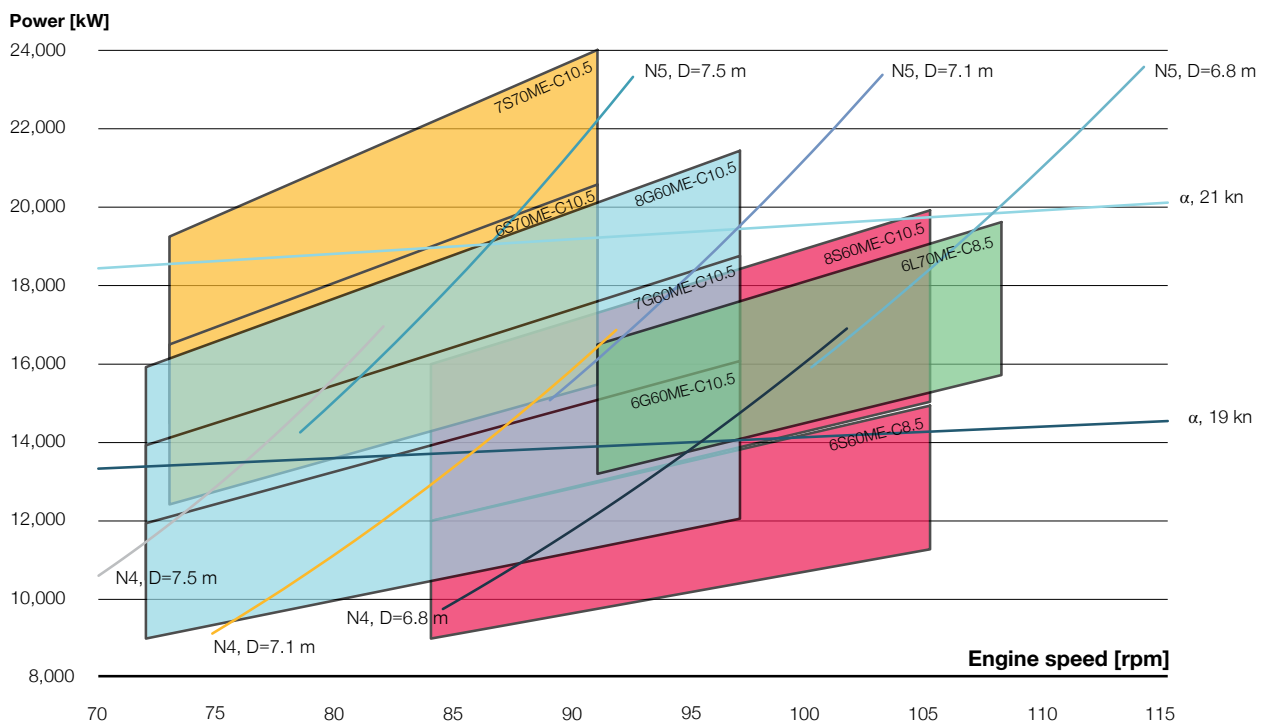


Fig. 2: Engine layout diagrams and propeller curves for a 4/5-bladed propeller with 5% light running margin

2,500 teu container vessel

| | | |
|-------------------------------|----|----------------|
| Deadweight, max | m | 39,100 |
| Deadweight design | m | 27,400 |
| Scantling draught | m | 11.5 |
| Design draught | m | 10.0 |
| Length overall | m | 195.0 |
| Length between perpendiculars | m | 185.0 |
| Breadth | m | 32.0 |
| Sea margin | % | 15 |
| Engine margin | % | 15 |
| Light running margin | % | 5 |
| Design ship speed | kn | 21 / 19 |
| Type of propeller | | FPP |
| No. of propeller blades | | 5/4 |
| Propeller diameter | m | 6.7, 7.1 & 7.5 |

Table 1: Vessel particulars for a typical 2,500 teu container feeder

2,500 teu container feeder example

For a 2,500 teu container feeder, the following case study illustrates the potential for reducing fuel consumption by increasing the propeller diameter and introducing modern fuel-efficient main engines. The ship particulars assumed are as follows:

Based on the vessel particulars assumed in Table 1, power prediction calculations (Holtrop & Mennen's Method) have been performed for different design speeds and propeller diameters. The corresponding SMCR power and speed, point M, for propulsion of the container vessel has been found, including the sea, engine, and light running margin, see Fig. 2. For both cases, propeller diameters of 6.7, 7.2 and 7.6 m have been investigated, with a 5-bladed design for the speed of 21 knots and a 4-bladed design for 19 knots.

It must be noted that the dimensions given in Table 1 are most suitable for 19 knots. Possibly, a 2500 teu feeder vessel designed for 21 knots will have its width reduced by one row of containers and instead be elongated. A lengthening of the vessel will reduce the hull resistance at elevated speeds, as the Froude number is reduced (see Chapter 1 of "Basic principles of ship propulsion") but will make the vessel more expensive to construct.

The propeller diameter change applied in both case studies corresponds approximately to the constant ship speed factor:

$$\alpha = 0.17, \text{ [ref: } P_{M2} = P_{M1} \times (n_2/n_1)^\alpha \text{]}$$

where P = propulsion power and n = rotational speed.

The α -coefficient for container vessels is typically low compared to tankers and bulk carriers. Container vessels have a sleeker hull, and typically the "shadow" of the hull seen in the flow to the propeller will be smaller on container vessels compared to fuller vessels. This implies that the effect of increasing the propeller diameter to reduce the power required on container vessels is relatively smaller than on tankers and bulk carriers.

Referring to the two design speeds of 21 knots and 19 knots, potential main engine types and pertaining layout diagrams and SMCR points have been plotted in Fig. 2. The main engine operating costs have been calculated and will be described in detail for both cases in the following sections.

It should be noted that the design speed stated refers to the design draught, and to a normal continuous rating (NCR) = 85% SMCR including 15% sea margin. If based on calm weather, i.e. without a sea margin, the

obtainable vessel speed at NCR = 85% SMCR will be about 0.6 to 0.7 knots higher.

If based on 75% SMCR, 70% of maximum dwt, calm water, and the hull in sea trial condition, as applied for calculation of the EEDI for container vessels, the vessel speed will be about 0.1 knots higher than the design speed.

Main engine operating costs **21 knots**

| Engine | SMCR point | NCR | D _{prop} |
|--------------|--------------------------|---------------|-------------------|
| 7L70ME-C8.5 | M1: 20,050 kW, 108.0 rpm | N1: 17,040 kW | 6.8 m |
| 8G60ME-C10.5 | M2: 19,525 kW, 108.0 rpm | N2: 16,595 kW | 7.1 m |
| 8G60ME-C10.5 | M3: 19,075 kW, 84.5 rpm | N3: 16,215 kW | 7.5 m |
| 6S70ME-C10.5 | M4: 19,075 kW, 84.5 rpm | N4: 16,215 kW | 7.5 m |
| 6S70ME-C10.5 | M5: 19,075 kW, 84.5 rpm | N5: 16,215 kW | 7.5 m |

Table 2: Main engines considered for 21 knots, with 15% sea and engine margin and 5% light running margin - 5 bladed propeller

The main engine fuel consumption and operating costs at N = NCR = 85% SMCR have been calculated for the above five propulsion plants operating at the relatively high speed of 21 knots. The effect of the increased propeller diameter to the power required to propel the ship at the service speed including the sea margin is seen on Fig. 3.

All comparisons related to the 21 knots case are made to a 7L70ME-C8.5 engine, a typical engine for vessels delivered in the mid-2010s. As depicted in Fig. 2, the SMCR point of this engine is found relatively low in the engine layout diagram, and is hereby derated to some extent.

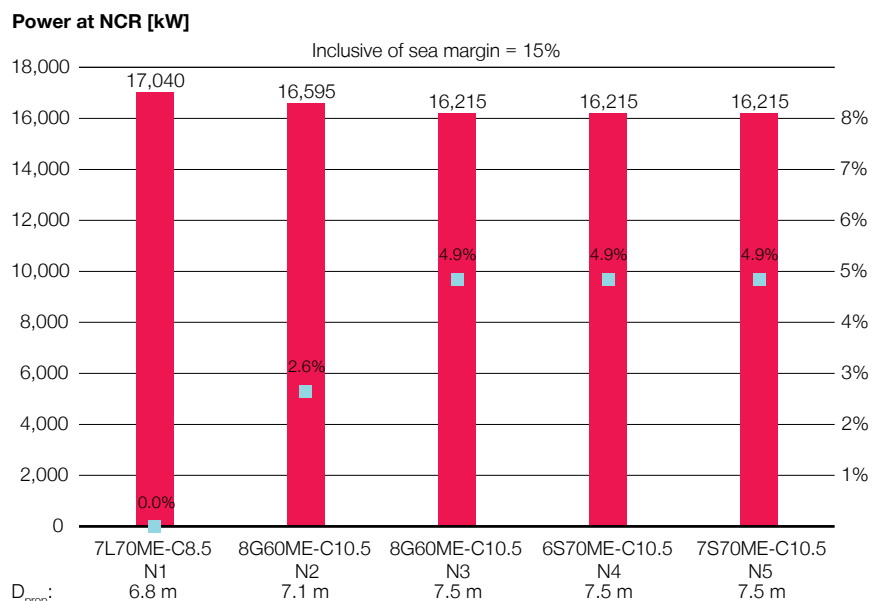


Fig. 3: Expected propulsion power demand at NCR = 85% SMCR for 21 knots

Fig. 4 shows the influence on the main engine efficiency, indicated by the specific fuel oil consumption (SFOC) of marine diesel oil (MDO) for the five cases. Several interesting results can be highlighted:

First of all, a significant reduction can be seen from the L70ME-C8.5 compared to the more modern engine designs. The effect of derating by adding an additional cylinder can be clearly identified: The 6S70ME-C10.5 has an SFOC of 163.0 g/kWh at NCR whereas the heavily derated 7S70ME-C10.5 with the same power output and an added cylinder shows an SFOC of 158.8 g/kWh. If EcoEGR is applied as exemplified through the 7S70ME-C10.5-EcoEGR, it is possible to attain a SFOC as low as 156.1 g/kWh at NCR.

The daily fuel consumption shown in Fig. 5 is found when multiplying the propulsion power demand at NCR = 85% (Fig. 3) with the SFOC (Fig. 4).

The effect of the increased propeller diameter is clearly seen, all designs that employ a propeller of a diameter of 7.5 m, show a significant reduction compared to the original design. Again, the effect of derating can be seen when the 6S70ME-C10.5 engine is compared to the 7S70ME-C10.5. The inclusion of EcoEGR will reduce the daily fuel costs further - compared to the 7L70ME-C8.5 (without EcoEGR) savings of more than 10% can be attained. These savings are especially relevant if more expensive low-sulphur fuels are applied.

Despite the fact that the SFOC of N2 and N5 is equal, N5 will have a lower daily fuel consumption, because the larger propeller reduces the power required to propel the vessel.

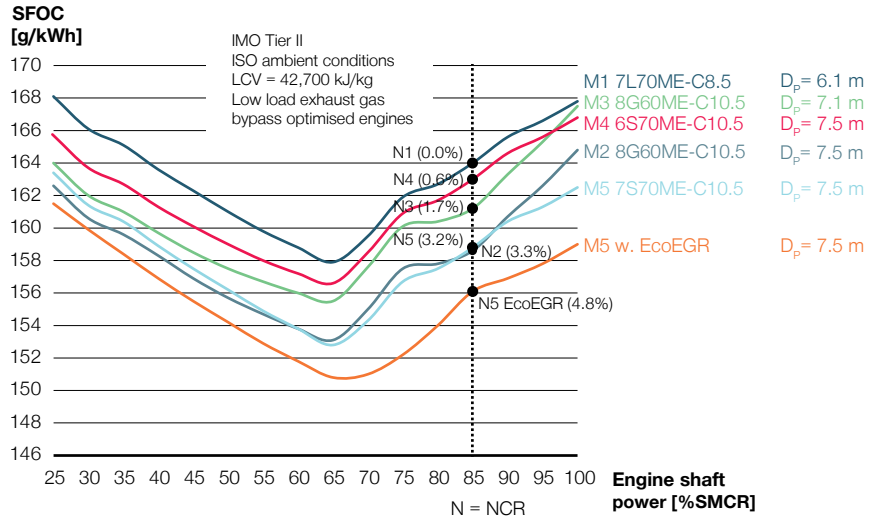


Fig. 4: SFOC for 21 knots as of 2019 with reductions relative to N1 stated in parenthesis. For reference, use the online calculation tool CEAS available on our home page

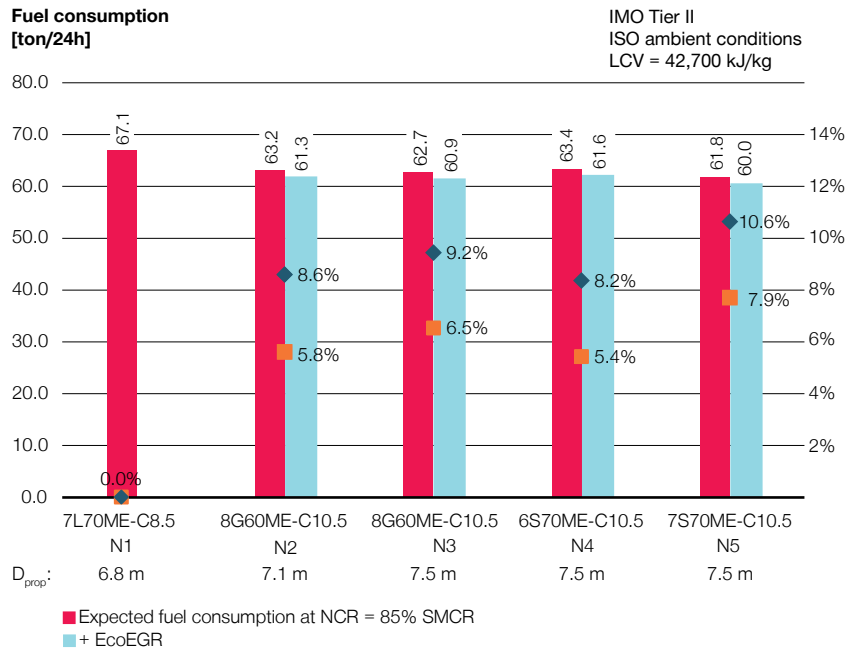


Fig. 5: Expected daily fuel consumption at NCR for 21 knots

EEDI

The reference and the actual EEDI figures have been calculated for a low-load optimised engine including a 6% tolerance on the SFOC, and a SFOC of 200 g/kWh for the auxiliary engines, all operating on MDO. The results are seen in Fig. 6. The reference value is calculated based on the following equation given by the IMO, and reduced according to the EEDI phases (10, 20 and 30%) reduction, as well as a possible 40% reduction requirement is included.

$$EEDI_{ref-container} = 174.22 \times dwt^{-0.201}$$

As mentioned in the section on EEDI, the reference index is calculated based on 100% utilisation of capacity (in dwt). The attained EEDI on the other hand, is calculated based on 70% capacity utilisation, with a reference speed in consistency with this loading of the vessel, at 75% SMCR with the hull in sea trial condition.

All the designs fulfil EEDI phase 3, except the reference design based on the 7L70ME-C8.5. Compliance is attained by the combination of a larger than usual propeller diameter and the significant savings offered by the recent development within propulsion machinery for container vessels.

None of the designs can fulfil a possible 40% reduction, even if a PTO and EcoEGR are included. As previously discussed, the hull considered in this case is most optimal for 19 knots.

A hull optimised for 21 knots will be one container bay longer and a row narrower, in order to decrease the Froude number and hereby the resistance on the hull at elevated speeds, see Chapter 1 of the separate paper "Basic principles of ship propulsion". A 40% reduction is considered within reach for such a speed-optimised hull, especially if the engine margin is reduced to 10%.

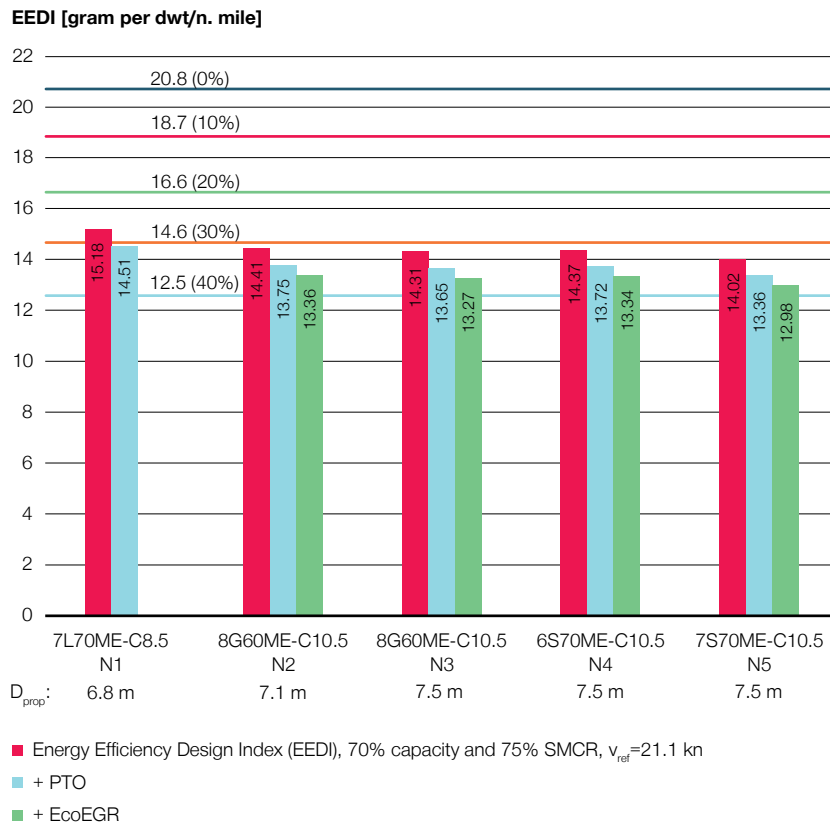


Fig. 6: Required and attained EEDI at 21 knots for MDO

An example of a load profile for the engine of a container feeder, see Fig. 7, is applied to calculate the total main engine operating costs, including lubricating oil per year, assuming an operating profile of 280 days/year at sea (≈25% in port). For this purpose, a fuel price of 600 USD/ton for low-sulphur fuels and a lubricating oil price of 2,000 USD/ton are assumed. The results are shown in Fig. 8.

The savings in annual main engine costs by applying EcoEGR is relatively smaller than the resulting fuel saving of applying EcoEGR (see Figs. 4 & 5), as the cost of operating the EcoEGR has been included. A price of 200 USD/ton is assumed for the NaOH (in a 50% solution) required to operate the EGR, as well as a price for handling the discharged sludge of 100 USD/ton is assumed.

Load profile [%running hours]

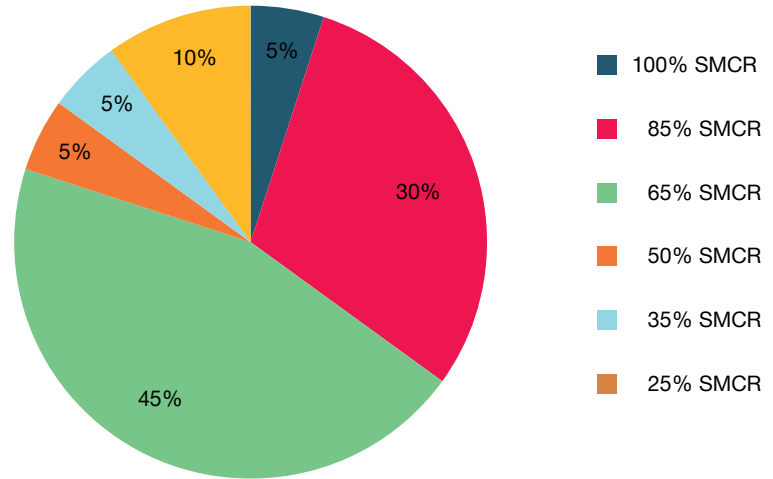


Fig. 7: Load profile for the time at sea

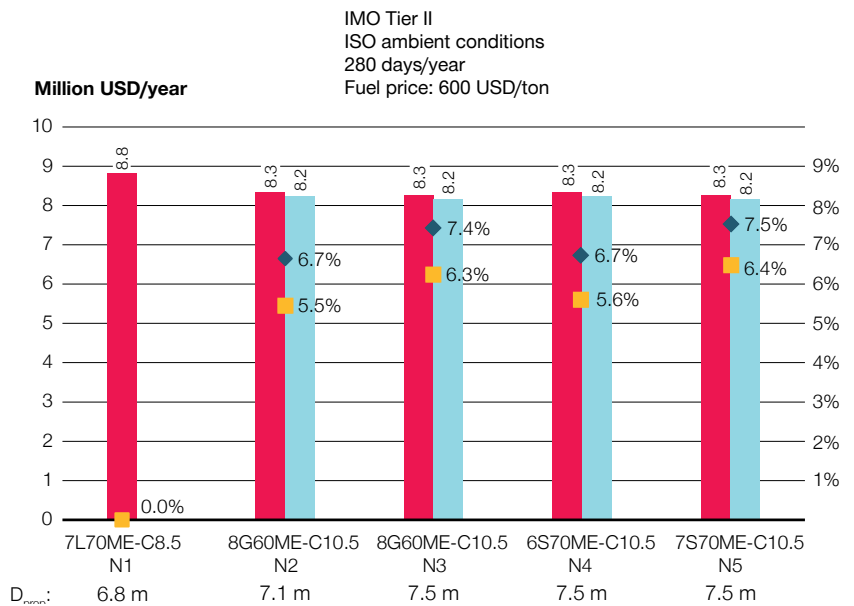


Fig. 8: Total annual main engine operations costs including fuel, cylinder, and system lubricating oil for 21 knots

The relative savings in operating costs in net present value (NPV) are calculated with the 6S50ME-C8.5 with a propeller diameter of 6.8 m as a reference. Significant NPV savings can be attained for designs with a propeller diameter of 7.5 m, as illustrated in Fig. 9.

For M2, with a propeller of 7.1 m, a saving of 4.2 million USD is attained over 10 years, the same value attained for M4, the non-derated 6S70ME-C10.5 with a propeller diameter of 7.5 m. M3, a derated 8G60ME-C10.5 with a propeller diameter of 7.5 m, attains a saving of 4.8 million USD over 10 years, which can be compared to the heavily derated M5, a 7S70ME-C10.5 that attains a saving of 5.9 million USD.

If EcoEGR is included the magnitude of the savings are increased by approx. 0.8 million USD over 10 years.

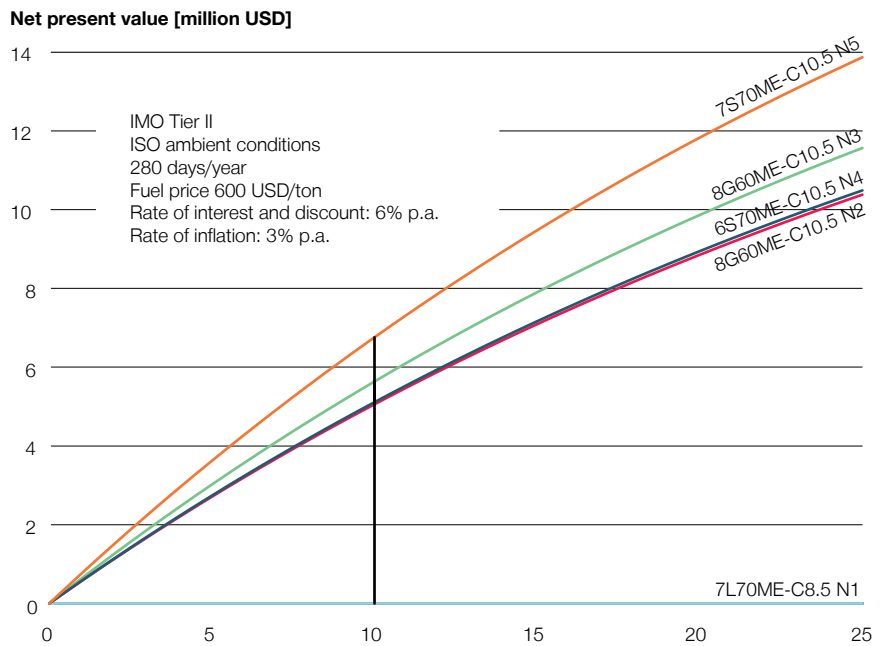
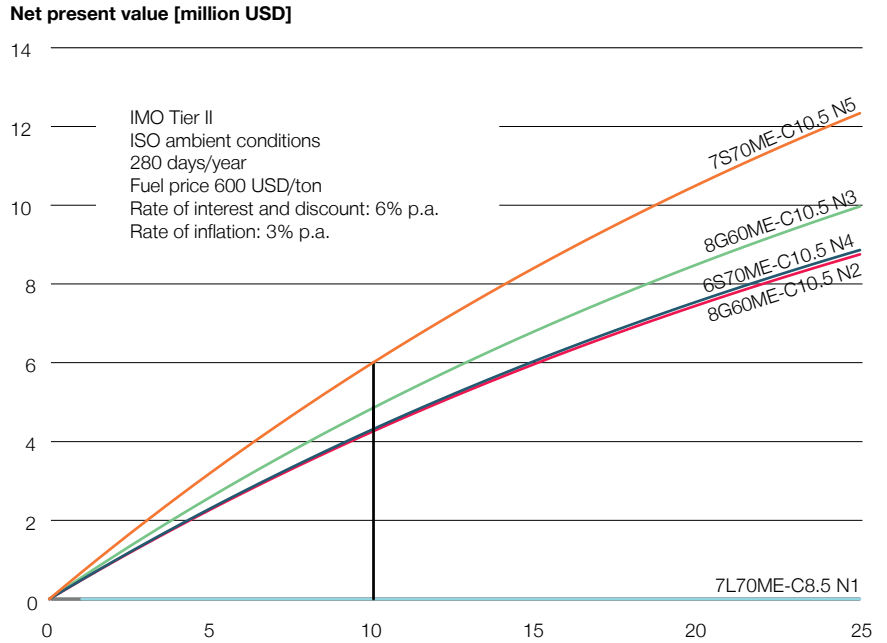


Fig. 9: Saving in main engine operating costs (NPV) for 21 knots without (above) and with EcoEGR (below)

Main engine operating costs 19 knots

| Engine | SMCR point | NCR | D _{prop} |
|--------------|--------------------------|---------------|-------------------|
| 7S60ME-C8.5 | M1': 14,080 kW, 95.5 rpm | N1: 11,970 kW | 6.8 m |
| 7S60ME-C10.5 | M2': 14,080 kW, 95.5 rpm | N2: 11,970 kW | 6.8 m |
| 7S60ME-C10.5 | M3': 13,775 kW, 85.5 rpm | N3: 11,710 kW | 7.1 m |
| 7G60ME-C10.5 | M4': 13,775 kW, 85.5 rpm | N4: 11,710 kW | 7.1 m |
| 7G60ME-C10.5 | M5': 13,500 kW, 74.5 rpm | N5: 11,475 kW | 7.5 m |
| 8G60ME-C10.5 | M6': 13,500 kW, 74.5 rpm | N6: 11,475 kW | 7.5 m |

Table 3: Calculated main engine examples for 19 knots, with 15% sea and engine margin and 5% light running margin - 4 bladed propeller

The main engine fuel consumption and operating costs at N = NCR = 85% SMCR have been calculated for the above six propulsion plants operating at the reduced service speed of 19 knots. The effect of the increased propeller diameter to the NCR power required to propel the ship at the service speed including the sea margin is shown in Fig. 10.

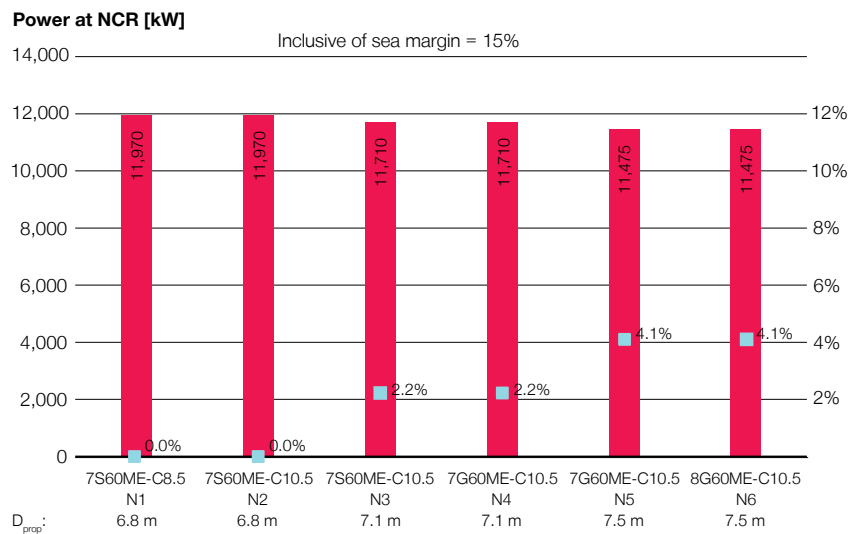


Fig. 10: Expected propulsion power demand at NCR = 85% SMCR for 19 knots

Fig. 11 shows the influence on the main engine efficiency, indicated by the specific fuel oil consumption (SFOC) of marine diesel oil (MDO) for the six cases.

The significantly lower power required to propel the vessel at 19 knots allows for a more derated engine. This is reflected in an approx. 2 g/kWh lower SFOC than for the 21 knots case, where a more derated engine would be of an impractical size. This further contributes to the savings achieved by reducing the service speed. The modern engine designs outperform the traditional S60ME-C8.5 design, with up to 7.0% lower consumption when EcoEGR is included.

The daily fuel consumption shown in Fig. 12 is found when multiplying the propulsion power demand at NCR = 85% (Fig. 10) with the SFOC (Fig. 11). The derated 8G60ME-C10.5 has the lowest SFOC and the largest propeller diameter, resulting in the lowest daily fuel consumption.

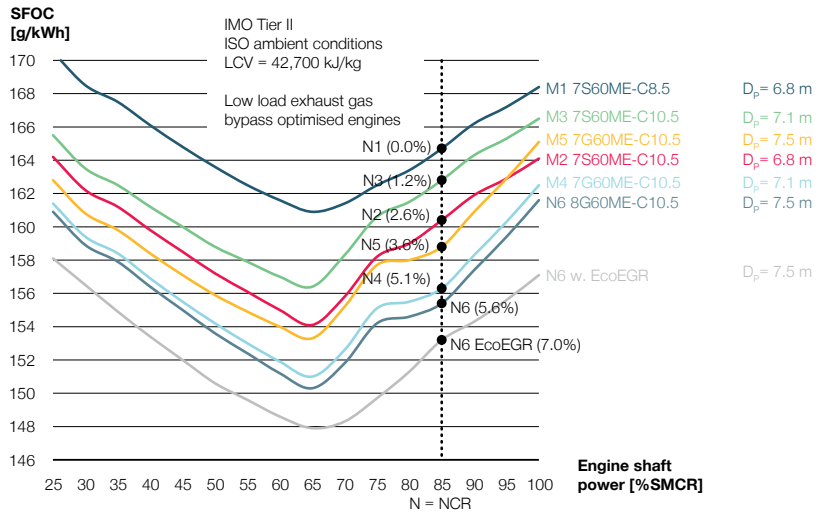


Fig. 11: SFOC for 19 knots as of 2019 with reductions relative to N1 stated in parenthesis. For reference, use the online calculation tool CEAS available on our homepage

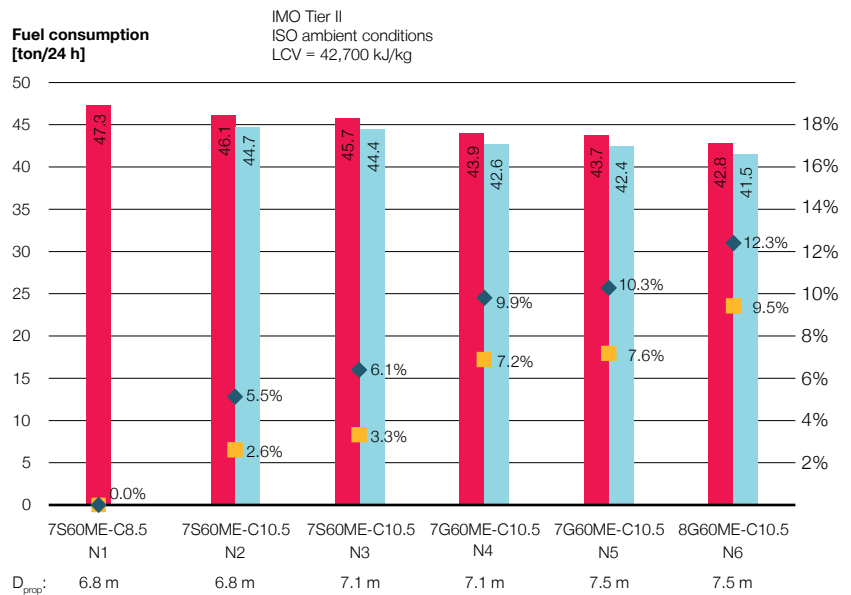


Fig. 12: Expected daily fuel consumption at NCR for 19 knots

EEDI

The reference and the actual EEDI figures have been calculated for a low-load optimised engine including a 6% tolerance on the SFOC, and a SFOC of 200 g/kWh for the auxiliary engines, all operating on MDO. The results are seen in Fig. 6. The reference value is calculated based on the following equation given by the IMO, and reduced according to the EEDI phases (10, 20 and 30%) reduction, as well as a possible 40% reduction requirement is included.

$$EEDI_{ref-containerer} = 174.22 \times dwt^{-0.201}$$

When comparing to the EEDI of the 21 knots case, see Fig. 6, it is clear that a speed reduction greatly influences the EEDI. On average, the attained EEDI is reduced by an index of approx. 3. This massive reduction is attained as the wave making resistance on the relatively short hull is significantly reduced, because the Froude number is lower when the vessel speed is reduced; see Chapter 1 of the separate paper “Basic principles of ship propulsion”. At this speed, all the designs fulfil EEDI phase 3 (30% reduction) and even a possible 40% reduction.

EEDI [gram per dwt/n. mile]

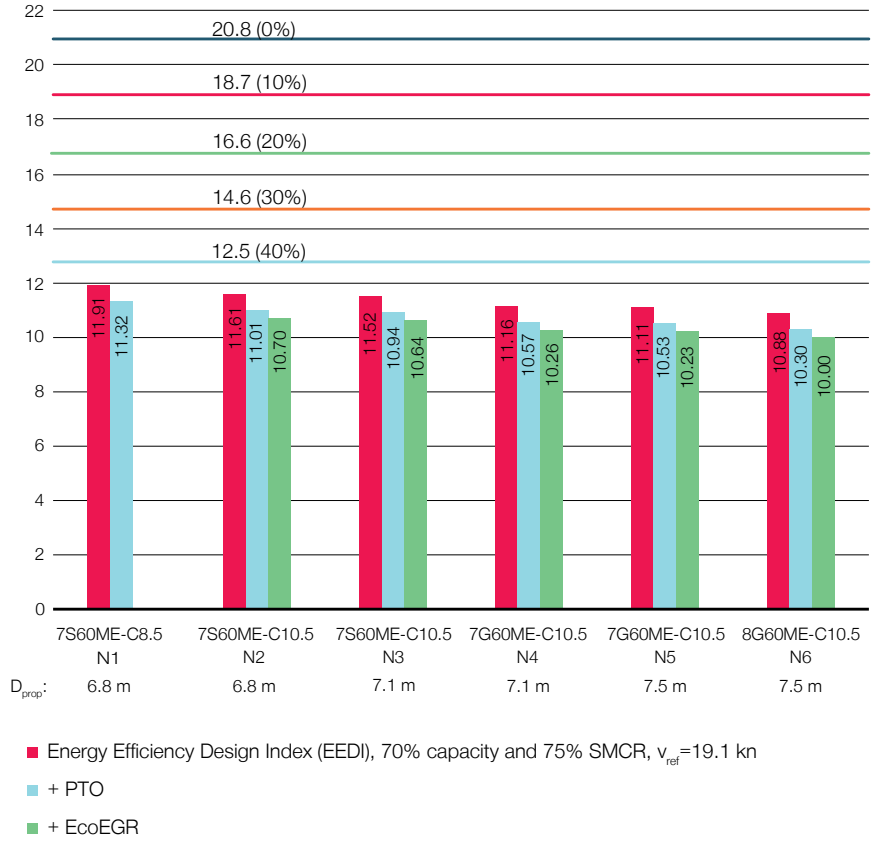


Fig. 13: Required and attained EEDI at 19 knots for MDO

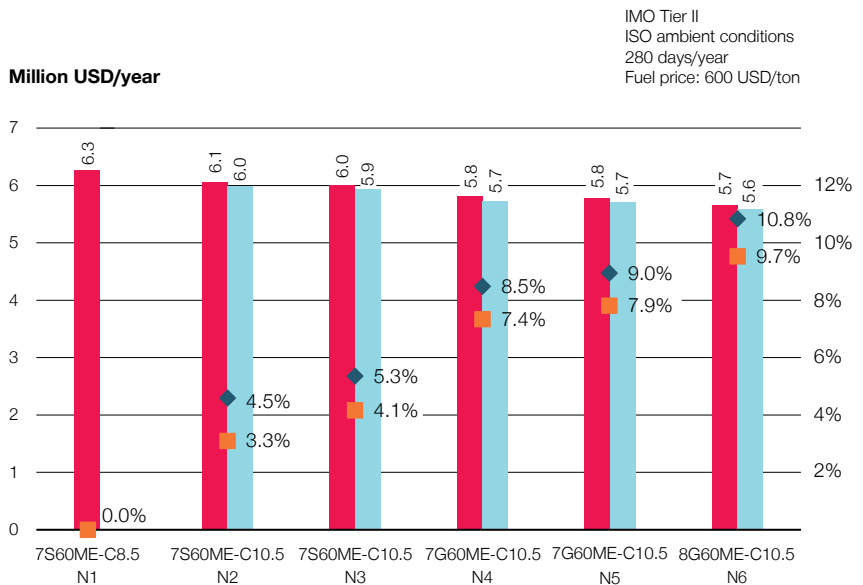


Fig. 14: Total annual main engine operating costs including fuel, cylinder, and system lubricating oil for 19 knots

Operating costs

Whereas the previous comparisons of engine fuel performance are based on a constant engine load of 85% (NCR), the yearly operational costs of the engine greatly depend on the engine’s load profile, as already depicted in Fig. 7. For this calculation, 280 days per year at sea (≈25% in port), along with a fuel price of 600 USD/ton for low-sulphur fuels, and a lubricating oil price of 2,000 USD/ton are assumed. The results are shown in Fig. 14.

The saving in annual main engine costs by applying EcoEGR is relatively smaller than the resulting fuel saving of applying EcoEGR (see Fig. 11 & 12), as the cost of operating the EcoEGR has been included. A price of 200 USD/ton is assumed for the NaOH (in a 50% solution) required to operate the EGR, as well as a price for handling the discharged sludge of 100 USD/ton is assumed.

The saving in net present value will be lower compared to the first case, as the actual fuel oil consumption is approximately 30% lower for the reduced design speed of the second case. Nevertheless, a saving of 5.2 million USD is attained over 10 years for M6’, the heavily derated 8G50ME-C10.5 engine, and a saving of 4.3 million USD for M5’, the 7G50ME-C10.5 engine. The same NPV calculations are carried out for EcoEGR. In general, an additional saving of 0.6 million USD is attained over 10 years.

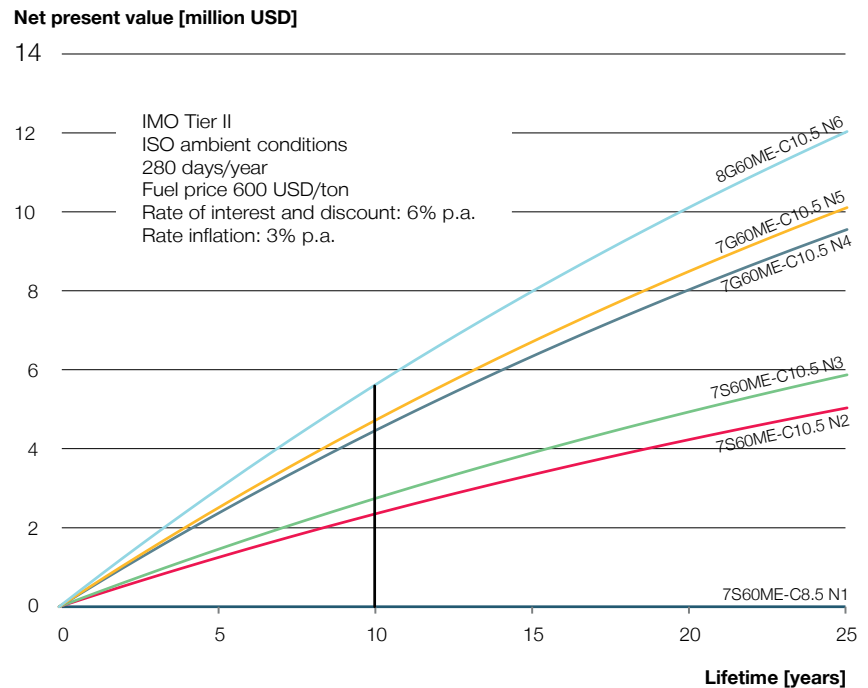
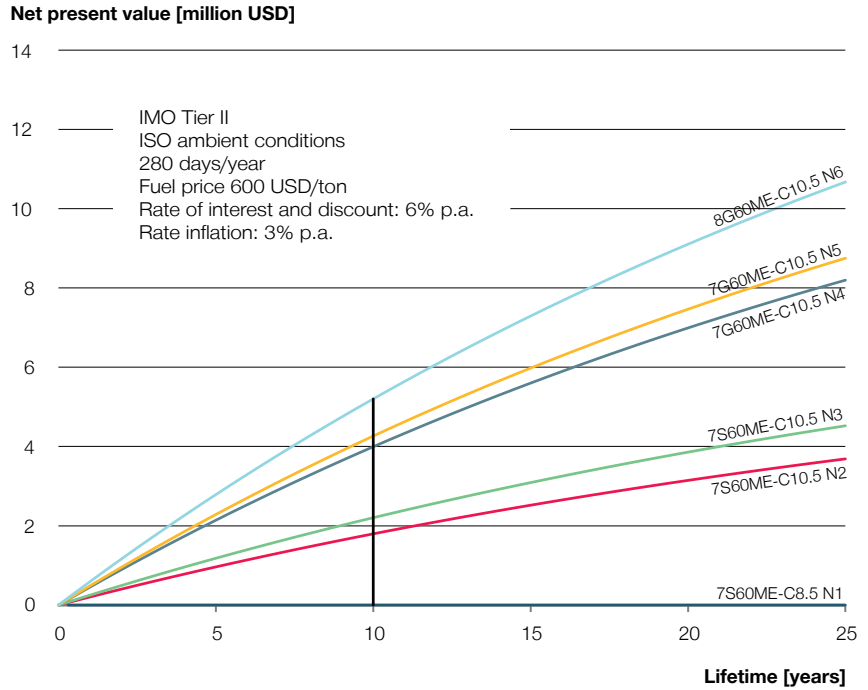


Fig. 15: Saving in main engine operating costs (NPV) for 19 knots without (above) and with EcoEGR (below)

Summary

Modern designs of container vessels in the feeder segment show significant savings compared not only to vessels delivered recently but especially compared to the current fleet with a high average age. New feeder vessels will not only bring savings to the owner but also reduce the environmental impact of the fleet significantly.

Modern container vessels with a larger than usual propeller and a fuel efficient S- or G-type engine fulfil EEDI phase 3 requirements (30% reduction) without further initiatives. If 40% reductions are to be achieved without reducing the speed from 21 knots, a PTO, various energy saving devices, waste heat recovery or EcoEGR must be applied, or alternative fuels must be considered. The installation of such equipment will also ensure significant savings on the running costs.

Modern container vessels carry a large number of reefer containers, and have a large electrical consumption at sea. Therefore, the inclusion of a power take off/shaft generator on the main engine can be sensible, as the main engine can produce electric power at a lower SFOC than the auxiliary engines on board.

Besides offering the capability to use different fuels, the MAN B&W S- and G-type engines also offer a significant variety of possible bores and stroke lengths for the feeder segment. This ensures that an optimum fit can always be achieved for each individual project, and that the optimum rpm of a desired propeller always can be contained within the layout diagram of one of the many possible engine designs.



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