Container feeder

MAN Energy Solutions
Future in the making

Modern two-stroke engine technology
for a modern vessel type

Future in the making

Contents

The current feeder fleet is ageing, and the initialisation of fleet renewal programmes are expected within the near future. 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 and fuel types available for feeder vessels. Technology and engines that will make future feeder vessels both highly competitive and environmentally friendly compared to the current fleet.

The main vessel particulars of container feeder vessels carrying around 2,200-3,000 teu are normally as follows: the overall ship length is 190-210 m, breadth is 30-32.2 m, and scantling draught is 11.0-12.0 m.

Container vessels are measured according to the number of containers they can carry, also known as teu (twenty-foot equivalent unit). Sometimes, this number is also defined in feu (forty-foot equivalent units), but teu is by far the most common size definition, and it is the notation used in this paper.

Moreover, as containers rarely have the same weight, the deadweight (dwt) range for these vessels is based on an approximation. For vessels carrying 2,200-3,000 teu, the approximate dwt would be in the range of 28,000-40,000 dwt. The allowed deadweight will not exceed 40,000 as the ships would then enter energy efficiency design index (EEDI) restrictions of 35% reduction of CO_2 emissions instead of only 30% from April 2022.

In recent years, the goal for the shipping business has been to lower emissions while maintaining or lowering transportation costs. New engine technology has made it possible to cope with the supply demand and environmental restrictions for both feeder vessels and large container vessels.

With the increased focus on reducing CO_2 emissions from ships, as governed by the International Maritime Organization’s (IMO) EEDI and upcoming carbon intensity indicator (CII), further cuts in fuel consumption are needed to decrease carbon emissions. Lately, the EEDI for container vessels has gained increased interest from IMO. On 1 April 2022, the EEDI phase 3 for container vessels introduced a reduction level that depends on the deadweight carried by the ship. New additional phases have not yet been announced by IMO.

Compliance with the emission restrictions can be achieved with the modern super-long-stroke S-type engines and the ultra-long-stroke G-type engines, which offer the possibility of operating at low shaft speeds. The reduced optimum propeller speed of the larger and direct-coupled propellers fits the layout diagrams of these engines.

In addition to the installation of a modern fuel efficient engine, the aftbody and hull lines of the ship can be optimised to enable installation of a propeller with a larger than usual diameter. This increases the propeller efficiency and lowers the optimum propeller speed. Additionally, the combination of high-efficiency propellers, for example of the Kappel design, and other energy saving devices provides a substantial emission reduction potential.

As an alternative to, or in combination with, optimising the hull, operation on alternative fuels such as LNG or methanol also leads to a significantly lower EEDI. Currently, some engines are still on request for methanol, and these will be available in the future. For low-sulphur fuels, EcoEGR can be a solution to both reduce the EEDI and also bring savings to the shipowner. The power take-off (PTO) system offers a technology advantage that not only reduces EEDI values, but also the number of running hours on the auxiliary engines.

Using two case studies of a 2,500 teu container feeder vessel, this paper outlines the effect of possible initiatives to reduce the environmental impact of such a vessel for different engine configurations.

The first case study considers a traditional service speed of 21 knots still seen on some routes. The second case study considers container feeders with a reduced service speed of 19 knots.

All of these efficiency improving technologies are considered to be equally important and will form a basis for attaining a good CII, as introduced by IMO and implemented from 1 January 2023.

All the comparisons of the most recent engine technology in combination with a different propeller diameter and amount of blades, are performed at the two speeds and for different propeller and engine configurations. The propulsion plants shown in Fig. 1 are currently seen as the most optimal engines for this ship type.

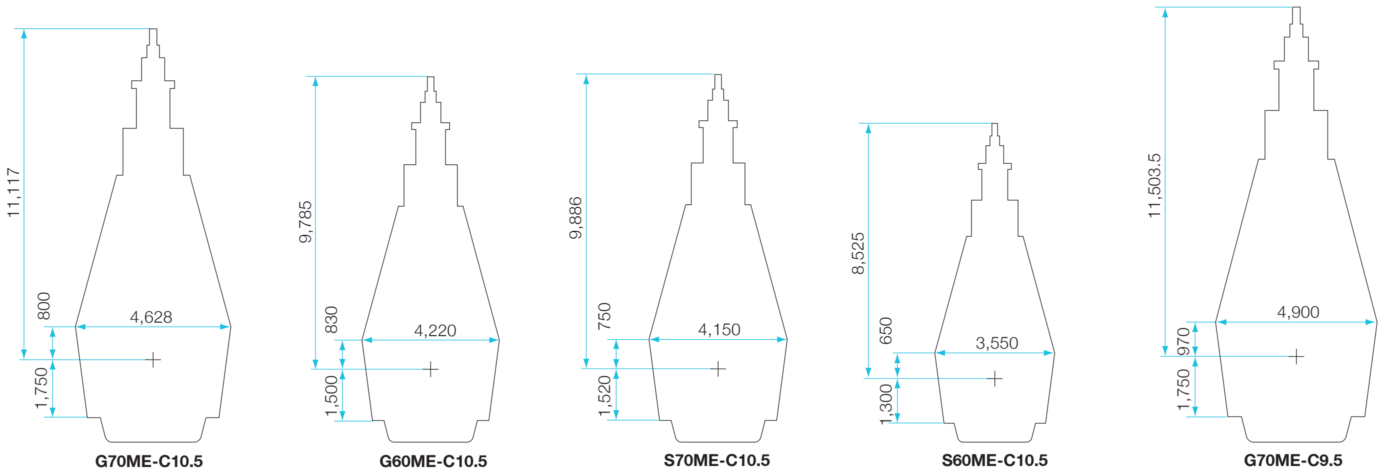

Fig. 1: Main dimensions of potential main engines, all measurements in mm

2,500 teu container feeder example

For a 2,500 teu container feeder, the following case study illustrates the potential for reducing operating costs and complying with regulations by increasing the propeller diameter, adding more blades to the propeller and introducing modern fuel-efficient dual fuel main engines. The vessel particulars assumed are shown in Table 1.

Based on the vessel particulars 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 for propulsion of the container vessel have been found, and the sea, engine, and light running margins are given in the subsequent examples.

For these cases, propeller diameters of 7.3 m, 7.5 m, and 7.7 m have been evaluated, with 5- and 6-bladed designs for the speed of 21 knots, and 4- and 5-bladed designs for 19 knots.

Note that the dimensions in Table 1 are most suitable for 19 knots. The width of a 2,500 teu feeder vessel designed for 21 knots may be reduced by one row of containers and instead the length will be increased.

A lengthening of the vessel will reduce the hull resistance at elevated speeds, as the Froude number is reduced (see chapter 1 in [1]). However, the cost of constructing the vessel will increase due to the increased necessary strength of the hull to prevent sacking and hocking.

The propeller diameter change applied in both case studies corresponds approximately to the constant ship speed factor in equation (1), where P is the propulsion power and n the rotational speed.

Eq.(1)

$\alpha = 0.175$, [ref: $P_{M2} = P_{M1} \times (n_2/n_1)_{\alpha}$]

Table 1: Vessel particulars for evaluation of propulsion configurations, 21-knots and 19-knots

2,500 teu container feeder example

Deadweight, max	dwt	37,200
Deadweight, design	dwt	28,500
Scantling draught	m	11.7
Design draught	m	10
Length overall	m	196
Length between perpendiculars	m	185
Breadth	m	32.2
Sea margin	%	15
Engine margin	%	15
Light running margin	%	5
Design ship speed	kn	19 or 21
Type of propeller		FPP
No. of propeller blades		4, 5 or 6
Propeller diameter	m	7.3, 7.5 and 7.7

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 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) equal to 85% SMCR, including 15% sea margin.

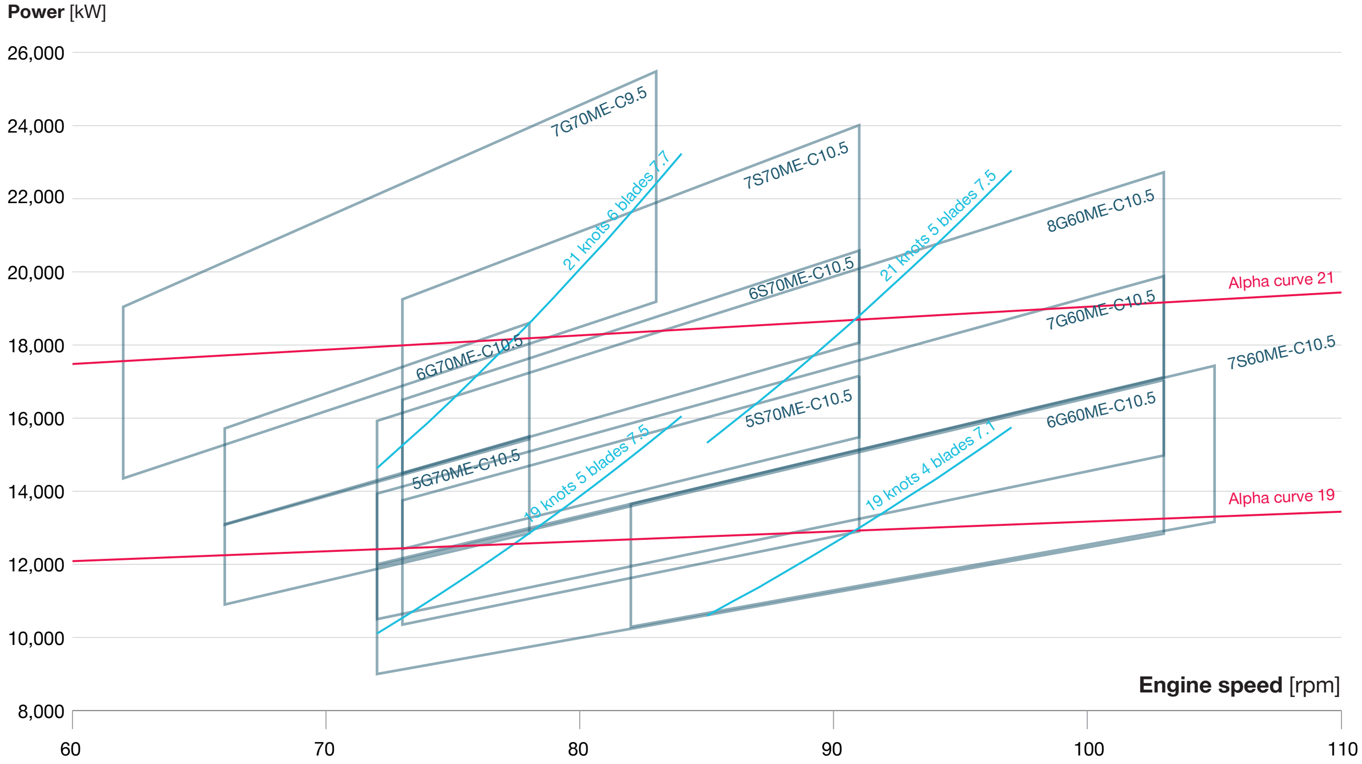

Fig. 2: Propeller and alpha factor curves in relation to engine layout diagrams for propulsion systems for container feeder vessels

Energy efficiency design index

The EEDI guidelines are a mandatory instrument adopted by IMO that ensures compliance with international requirements on CO_2 emissions of new ships. The EEDI represents the amount of CO_2 in gram emitted when transporting one deadweight tonnage of cargo for one nautical mile:

$$EEDI \approx \frac{CO_2}{Transport\ work} \quad \text{Eq.(2)}$$

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 for certain ship types, and reductions can be obtained by installing, for example, waste heat recovery systems (WHRS). This is explained further in chapter 4 in [1].

A reference index for a specific ship type is calculated on the basis of 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 will be reduced in three phases. Phase 3 was later revised for container vessels due to the significant increase in engine power for larger container ships in that period. This results in a final EEDI reduction of 15-50% compared to a reference value depending on dwt, and which came into force on 1 April 2022.

Table 2 shows how the reduction levels are distributed for container vessels in phase 3 for different dwt values, and their approximated teu size.

Fig. 3 illustrates how the EEDI reductions have developed through the three defined phases.

For container vessels, the reference index calculation is based on 100% utilisation of capacity (in dwt), as is the case for all other vessel types. However, the attained EEDI calculation is based on a 70% capacity utilisation, and a reference speed at 75% SMCR with the hull in sea trial condition. The calculated EEDI must meet the required EEDI.

A number of methods can be applied to lower the EEDI value. One is to derate the engine, and thereby lower the specific fuel oil consumption (SFOC). For a mep (the mean effective pressure) derated engine, mep is reduced relative to the maximum (firing) pressure, which remains constant.

Another method could be to add an EcoEGR system. 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.

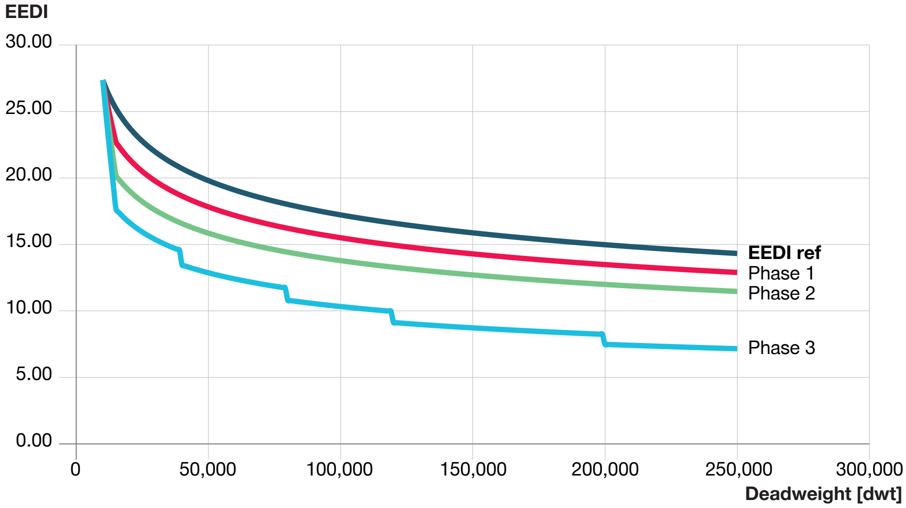

Fig. 3: The EEDI reduction compared to deadweight for all three phases

Table 2: Approximated teu relative to deadweight and the applied reduction to ensure EEDI compliance

dwt	Approximated teu	Reduction of EEDI phase 3, 1 April 2022
200,000 and above	**21,000 and more**	50%
120,000 – 200,000	**10,500 – 21,000**	45%
80,000 – 120,000	**6,500 – 10,500**	40%
40,000 – 80,000	**3,000 – 6,500**	35%
15,000 – 40,000	**1,150 – 3,000**	30%
10,000 – 15,000	**750 – 1,150**	15-30%*

* Reduction factor to be linearly interpolated between the two values depending on ship size. The lower value of the reduction factor is to be applied to the smaller ship size

The power installed is also a parameter that can be reduced to achieve a lower EEDI value. This is achieved by either lowering the vessel speed, 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 can be applied, typically altering the flow fore or aft of the propeller.

Installation of green technologies, like WHRS or changing fuel to liquid natural gas (LNG), 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 in [1]. The calculation is outlined in equation (3).

Eq.(3)

$$EEDI = \frac{P_{ME}\times C_{F,ME}\times SFC_{ME}+P_{AE}\times SFC_{AE}\times C_{F,AE}}{Capcity\times V_{ref}}$$

$\mathbf{P_{Me}}$ – power of the main engine
$\mathbf{P_{AE}}$ – power of the auxiliary system
$\mathbf{C_{F}}$ – carbon factor for the fuel used
SFC – specific fuel consumption
$\mathbf{V_{ref}}$ – reference speed of the vessel
Capacity – 70% deadweight capacity that the ship can carry.

Using alternative fuels is one way to cope with the EEDI restrictions. Alternative fuels are not exactly new fuel types for combustion, but because of emission restrictions, these fuels might end up shaping the future of the industry.

Methanol and LNG are suitable options, but they require dual fuel engines such as the GI (gas injection) for LNG and the LGIM (liquid gas injection methanol) for methanol. Both engine designs would be able to run on MDO or VLSFO if necessary.

Both fuel types are relevant thanks to their lower carbon content, see Table 3. However, methanol offers the easiest transition, as it can be stored at ambient temperature conditions in coated tanks, whereas LNG needs to be stored at very low temperatures. This sets requirements to the storage tanks, but allows for a higher power under the EEDI and thereby increased speed. For feeder vessels, type C tanks are most commonly applied when storing LNG.

Fuel types

When looking to reduce the emissions of greenhouse gases, the obvious choice is to focus on the direct emissions from the combustion.

When calculating CO_2 emissions, MDO is typically used as reference, but the ship will most likely operate on VLSFO because of its lower sulphur content. The properties of MDO and VLSFO are approximately similar.

The combustion engine can also run on other fuels such as liquid natural gas (LNG), methanol, ethanol and liquid petroleum gas (LPG). In the near future, ammonia will also be an option for an MAN B&W engine. This paper compares MDO, LNG, methanol and VLSFO. The properties of the four fuels are given in Table 3.

MDO demonstrates the highest energy density on a volume basis, but as most ships are burning VLSFO, this would be the highest energy density on volume basis in operation. This implies that if a ship is to operate on methanol or LNG, the fuel storage space will need to be increased. LNG and methanol have a lower carbon content than VLSFO, and they are therefore interesting from a perspective of EEDI reduction.

As is the case with MDO, methanol can be stored at room temperature if the tanks are coated. LNG, on the other hand, requires special tanks to pressurise and cool the fuel to keep it in a liquid state. This means that the storage of LNG often requires special considerations for the accommodation of the fuel tanks on board the vessel.

Smaller vessels such as container feeders normally store the LNG in type C tanks. Type C tanks can pressurise the LNG in the tanks, but have a size limit and a cylindrical shape. However, this is not a big issue on container feeders. On larger vessels, type B and type A tanks are more common as they are more space-efficient, but they have the disadvantage that the LNG cannot be pressurised.

A comparison of the carbon content per GJ for the fuels in Table 3 shows how much the EEDI can be lowered simply by changing fuel type. However, this does not take the extra challenges

Table 3: Approximate values for carbon content, carbon factor, density, lower calorific value (LCV), density, energy density and carbon content per GJ for MDO, VLSFO, LNG and methanol [2], [10]

Fuel	Carbon content	Carbon factor, Cf	Density [kg/m³]	LCV [kJ/kg]	Density [MJ/m³]	Carbon content per GJ
MDO	0.8744	3.206	~900	42,700	38,430	75.1
VLSFO	0.8493	3.114	~940	40,200	37,788	78.38
LNG	0.7500	2.750	~450	48,000	21,600	57.3
Methanol	0.3750	1.375	~792	19,900	15,760	69.1

into account, such as the larger storage space needed for both LNG and methanol, which means less storage space for goods. Also, it does not include the added power consumption needed to cool the LNG either.

Equation (4) can be used for calculating the potential EEDI reduction by switching fuel. The example shows the calculation for MDO compared to LNG.

Table 4 shows the relative EEDI figure when switching fuel.

Table 4: Relative EEDI when switching from MDO to LNG or methanol

Relative EEDI	MDO
MDO	100%
LNG	76%
Methanol	92%

Changing from MDO to LNG lowers the EEDI by 24%, whereas a decrease of 8% can be achieved by changing from MDO to methanol. Note that MDO is used for calculation of EEDI, even though VLSFO is mostly used due to its low sulphur level.

Shaft generator/power take-off systems (PTO)

Another solution that can be implemented is a power take-off (PTO) system with a shaft generator. A PTO is an addition to the main engine shaft that enables electricity production from the power of the main engine.

With a shaft generator, the specific fuel consumption from the auxiliary engine (SFC_{AE}) can be substituted by the specific fuel consumption for the main engine (SFC_{ME}).

The SFC_{ME} is significantly lower than the SFC_{AE} and the EEDI index can therefore be reduced. In addition, the power for the main engine (P_{ME}) can be reduced by the nameplate power of the PTO ($P_{(PTO)}$), but only if $P_{PTO}/0.75$ is sufficient to cover the power of the auxiliary system (P_{AE}). Nothing more than P_{AE} may be subtracted from P_{ME} because of the P_{PTO}.

In this calculation, MCR is the power of all main engines. The EEDI can be calculated by using equation (5) when adding the PTO.

The P_{PTO} could be larger than the P_{AE}, but in the calculation it cannot be taken larger than P_{AE}. The effect of the PTO can be estimated along with the auxiliary engine system. All of these estimates and implementations are described further in [2].

The installation of a PTO will lower the EEDI, as the auxiliary engines (gensets) do not need to be running, because the main engine will produce the necessary power through the PTO at a higher efficiency. However, auxiliary engines are still necessary while the vessel is in port or anchored.

A PTO system is relevant for all vessels, but especially for vessels operated on alternative fuels. PTO is beneficial for smaller vessels because not all the auxiliary engines will need to run on the alternative fuels.

Taking LNG as an example, it would be possible to have one genset burning the boil-off gas from the fuel tanks, and two running on VLSFO or similar and, thereby, saving the costs of expensive pumps. For more information on PTO, see [6].

Eq.(4)

$$Relation\,of\;saving\;for\,EEDI = \frac{CF_{LNG}}{CF_{MDO}} \times \frac{LCV_{MDO}}{LCV_{LNG}} = 0.76$$

Eq.(5)

$$EEDI = \frac{\left(\left(\sum MCR_{ME} - \sum P_{PTO}\right)0.75 + P_{PTO}\right) \times C_{F,ME} \times SFOC_{ME} + \left(P_{AE} - P_{PTO}\right) \times SFOC_{AE} \times C_{F,AE}}{Capcity \times V_{ref}}$$

Fuel prices

The prices of alternative fuels must be evaluated as well. The prices in Table 5 represent an estimate as of mid-2022.

MAN B&W dual fuel engines provide fuel flexibility. This means that the engine can use both LNG and VLSFO as the main fuel. Not at the same time, but it is possible to switch between the fuels and operate part time on LNG and part time on VLSFO if desired. The engine can run on the preferred fuel in the current market depending on fuel prices and regulations. As an example, the carbon intensity factor (CII) will be explained later. Methanol engines for the feeder vessels will be on the market in the future when the demand arises. The calculations in this paper are made from estimations of how the engine will cope with methanol as a fuel if the engine has the same efficiency as the current engines from MAN B&W.

Table 5: Fuel prices per GJ, tonne, and the HFO equivalent price for VLSFO, LNG and methanol

	$ per GJ	$ per tonne	$ per tonne HFO equivalent
VLSFO [3]	20.14	860	860
LNG [4]	31.29	1,500	1,256
Methanol [5]	33.17	660	1,333

Carbon intensity indicator (CII)

The carbon intensity factor was implemented by IMO on 1 January 2023 as an operational measure to assess the ship's efficiency in transporting passengers or goods. It is implemented for all vessels larger than 5,000 GT to reduce the annual carbon emission of the operation of the vessel. The CII calculation is approximately as stated in equation (6).

For the carbon intensity indicator there will be a grading system consisting of ratings A, B, C, D and E. A is best and E is worst. Following three consecutive years of grade D, as shown in Fig. 4 by the "Attained annual operational CII", or one year of E, the owner must submit a corrective action plan to reduce carbon emissions.

If, for example, a container feeder complies with the reference value for 2023 requirements, which is a 5% CII reduction compared to the reference line, it will be graded C. In 2026, the ship would be graded D if no corrective CII measures are taken. It means that within three years a corrective reduction plan has to be submitted. This is illustrated in Fig. 4 by the attained annual operational CII.

Each year, the required emission reduction must be lowered compared to the reference line. At the time of writing, the extent of the annual reduction is only given until 2026 (see Table 6). As of now, it seems that factors for the years 2027 to 2030 are to be further strengthened and developed, taking into account the review of the short-term measure. However, it has not yet been determined.

Dual fuel engines will have an advantage, as the CO_2 emission can be regulated by changing the fuel. And the share of alternative fuel used during operation can be increased over time as reduction requirements are tightened.

$$CII = \frac{Annual\ fuel\ consumption \cdot CO_2\ factor}{Annual\ distance\ travedlled \cdot Capacity} \cdot Correction\ factors \qquad \text{Eq.(6)}$$

Table 6: Carbon intensity reductions for the coming years [7]

Year	Reduction compared to 2019 [%]
2023	5
2024	7
2025	9
2026	11
2027	-

This means that the regulatory requirements must be updated and filled in every year as is shown in Fig. 4.

The percentages shown in Fig. 4 are determined from the emission statistics of ships from 2019. The data showed that 15% would be rated E, 20% would be rated D, and so on, from the current CII definition.

Fig. 4 also shows that the CII will be reviewed in 2025 to assess how the future restrictions should be. The faded area shows the period where the CII reduction has not yet been defined.

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, 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 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 SFC. As previously explained this is exploited in a derated engine.

Furthermore, the higher the stroke/bore ratio of an 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 engine design in itself has a very high efficiency.

Two case studies of a feeder vessel implement the influence on fuel consumption of applying engines running on alternative fuels. Engines for speeds of 21 knots and 19 knots, respectively, are used as examples along with the effect of the increased propeller diameter and the influence of the number of blades.

Fig. 2 shows the layout diagrams of the different engines that will be able to comply with different propeller configurations and ship speeds, including G70ME-C10.5, G60ME-C10.5, S70ME-C10.5, S60ME-C10.5, and G70ME-C9.5.

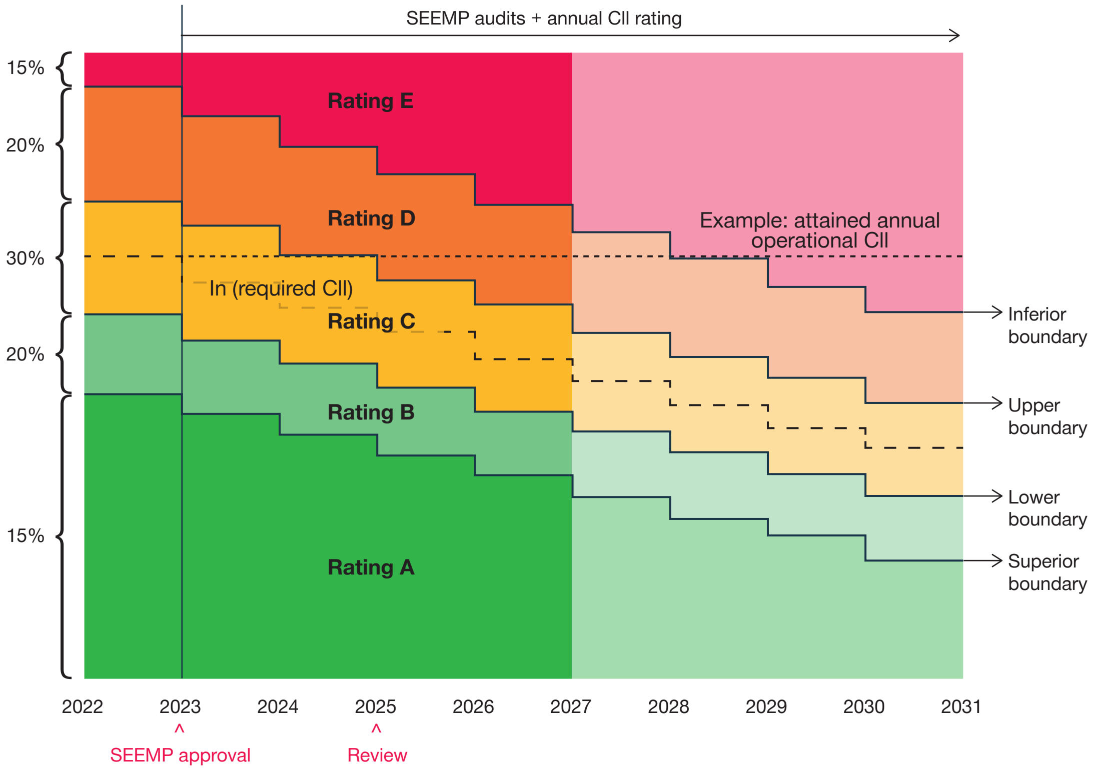

Fig. 4: Reduction of CII will proceed in the future – more information about CII can be found in [7] and [8]

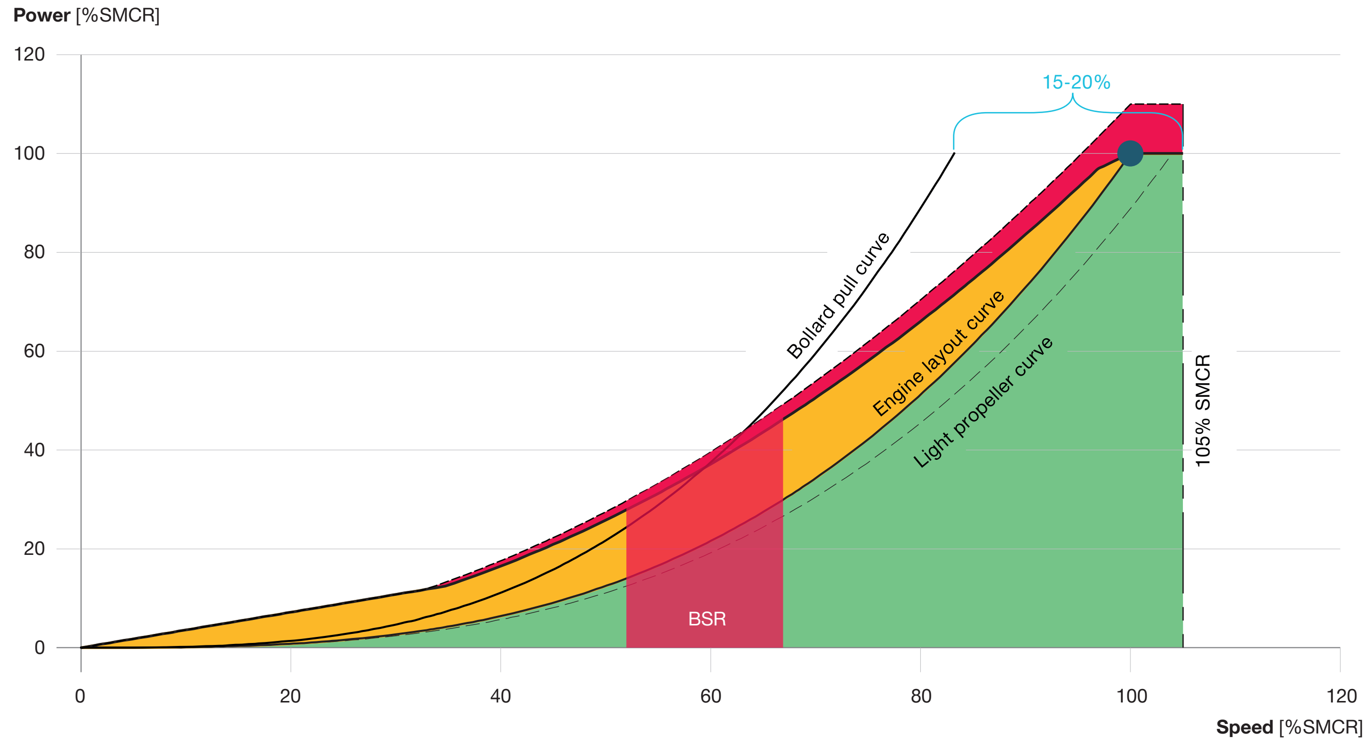

Fig. 5: Bollard pull curve. The two-stroke engine can always accelerate the propeller to about 50% rpm quickly. The BSR in the figure is placed high up in the rpm range, and the BSR passage may not be quick

Barred speed range

A barred speed range (BSR) imposed by vibrations must be passed “sufficiently quick” in order not to damage the shafting due to vibrations resulting in excessive stress levels.

What is meant by “sufficiently quick” depends on the stress level in the shaft compared to the strength of the shaft material. Furthermore, the definition of “sufficiently quick” depends on how often the barred speed range will be passed during the expected lifetime of the ship.

For example, a container feeder vessel with many port calls will pass the barred speed range more frequently than a large crude carrier that mostly performs ocean crossings.

In general, the barred speed range must be passed within seconds, not minutes.

For this reason, it is recommended to lower the barred speed range (BSR) as much as possible to avoid the risk of slow passages. This applies especially to engines with a low number of cylinders. For some engines, a “barring zero” is available. This barring makes it possible to add a heavy tuning wheel, which will help counteract torsional vibrations.

The BSR is illustrated in Fig. 5, which shows an example of the BSR at a relatively high location. Usually, the BSR is in the span between 45-60% rpm.

MAN Energy Solutions has established the barred speed range power margin (BSRpm) for evaluation of the capability for a quick passage, for further information, see chapter 3 in [1]. Some class societies have guidelines of their own.

Main engine operating costs – 21 knots

The running costs of an engine is a very important factor as the engine is expected to be in service for at least 20 years. Accordingly, it is highly important that the engine can cope with existing and future emission regulations. The following sections show examples of selected engines that can maintain a speed of 21 knots while still meeting the emission regulations and being cost-efficient on three different kinds of fuels, including MDO, LNG and methanol.

The main engine fuel consumption and operating costs at N = NCR = 85% SMCR have been calculated for six propulsion plants operating at the relatively high speed of 21 knots. See Fig. 6.

Table 7 shows the effect of the increased propeller diameter on the power required to propel the ship at the service speed, including the sea margin. Fig. 6 shows the influence on main engine efficiency for six different engine types. This is illustrated by the specific fuel oil consumption (SFOC) of marine diesel oil (MDO), or equivalent for alternative fuels, because the engine has the same efficiency no matter which fuel is used. Several interesting results can be highlighted.

Fig. 7 confirms the fact also stated in Table 3, namely that methanol has around half the LCV value of VLSFO and LNG. This means that to get the same amount of power, twice as much fuel must be burned. It can also be seen that both LNG and methanol engines require pilot fuel to ignite the fuels, and combustion of methanol requires significantly more pilot fuel than LNG. The engines presented can run on all three fuel types, except for the 7G70ME-C9.5 engine, which cannot run on methanol. With that in mind, it must be noted that the efficiency of each engine is exactly the same, no matter which fuel is used.

Table 7: SMCR point, engine speed, NCR, propeller diameter, and number of blades for six propulsion plants

Engine	SMCR [kW]	rpm	NCR [kW]	D_{prop}	No. of blades
6G70ME-C10.5	18,600	78	15,810	7.7	6
7S70ME-C10.5	18,600	78	15,810	7.7	6
7G70ME-C9.5	18,600	78	15,810	7.7	6
6S70ME-C10.5	18,800	91	15,980	7.5	5
7S70ME-C10.5	18,800	91	15,980	7.5	5
8G60ME-C10.5	18,800	91	15,980	7.5	5

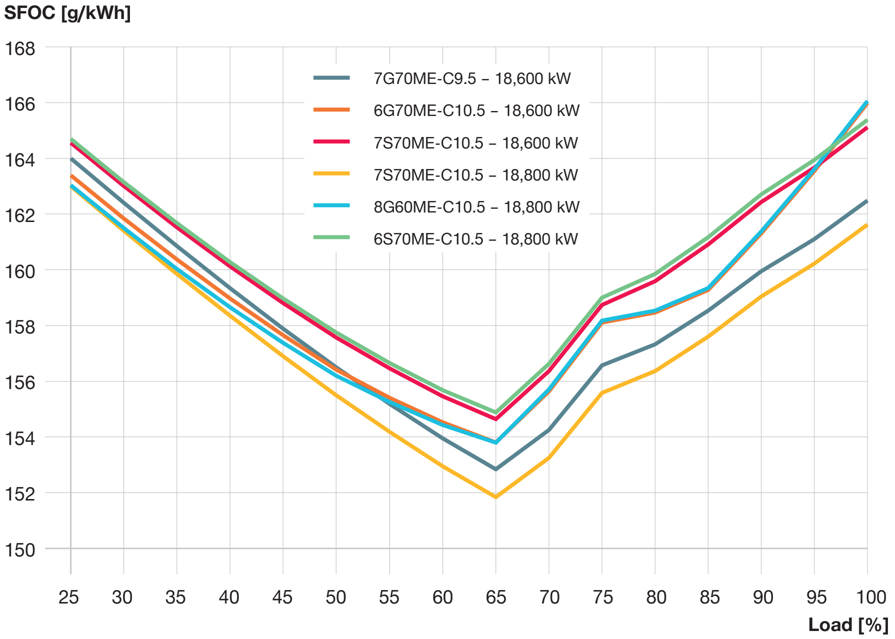

Fig. 6: SFOC for each of the six different engines, depending on the load

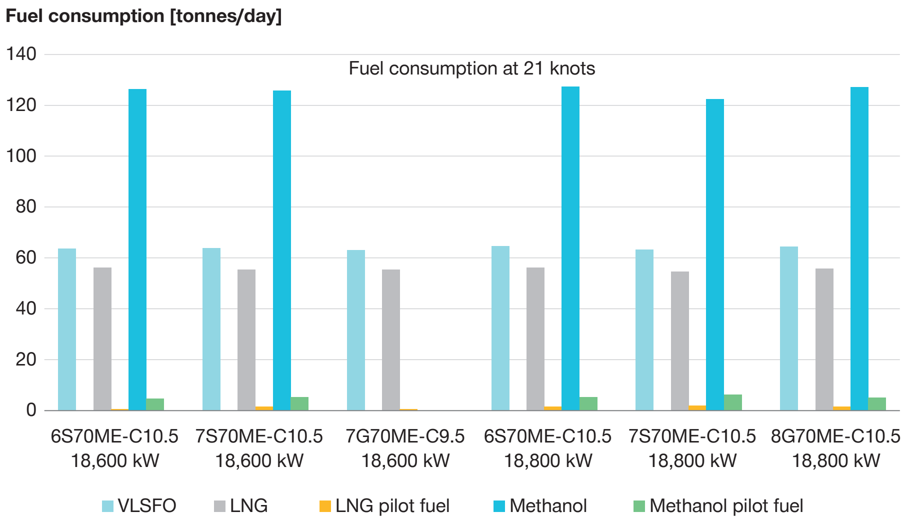

Fig. 7: Daily fuel consumption for the six engines and different fuel types

EEDI

The reference and the actual EEDI figures have been calculated for a Tier III engine. The calculation includes a 6% tolerance on the SFOC, and an SFOC of 200 g/kWh for the auxiliary engines, all operating on MDO. The results are shown in Figs. 8 and 9. The reference value is calculated based on equation (7) in [9].

$$EEDI_{\text{ref-container}} = 174.22 \times dwt^{-0.201} \qquad \text{Eq.(7)}$$

As mentioned in the section on EEDI, the reference index is calculated based on 100% utilisation of capacity (in dwt). On the other hand, the EEDI attained 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.

As seen in Tables 9-12 and Figs. 8-9, all the designs fulfil the EEDI requirements for phase 3. However, it can be seen that the methanol engines and the LNG engines have a lower EEDI than the MDO engines. If a phase 4 of 40% reduction was implemented, only the engines running on LNG would be compliant, even if a PTO is installed. Methanol engines would be very close to compliance with a future phase 4, while MDO can only just fulfil the requirement for phase 3.

An example of a load profile for an engine of a container feeder, see Fig. 10, is applied to calculate the total main engine operating costs, including lubricating oil per year, assuming an operating profile of 250 days/year at sea (≈30% in port). The latter might seem like a high estimate for some container feeders, however, it is used for comparison with the busy container feeders which are in operation 70% of the time. For this purpose, the fuel prices in Table 4 are used, and a lubricating oil price of 1,500 USD/tonne is assumed. The results are shown in Fig. 11. A price of 200 USD/tonne is

Table 8: EEDI for phase 3

EEDI	Percentage
14.70	70%

Table 9: EEDI values without PTO

	MDO		LNG		Methanol	
	EEDI	%	EEDI	%	EEDI	%
6G70ME-C10.5	14.429	68.8	10.991	52.4	13.062	62.3
7G70ME-C9.5	14.299	68.2	10.898	52	-	-
7S70ME-C10.5	14.486	69.1	11.090	52.9	13.122	62.6

EEDI values (MDO, LNG, and methanol) for propulsion systems with a 6-bladed propeller 7.7 m in diameter, 18,600 kW power, and an engine speed of 78 rpm. Vessel speed is 21 knots.

Table 10: EEDI values with PTO

	MDO		LNG		Methanol	
	EEDI	%	EEDI	%	EEDI	%
6G70ME-C10.5	13.773	65.7	10.534	50.2	12.920	61.6
7G70ME-C9.5	13.642	65	10.440	49.8	-	-
7S70ME-C10.5	13.831	65.9	10.634	50.7	12.981	61.9

EEDI values (MDO, LNG, and methanol) for propulsion systems with a 6-bladed propeller 7.7 m in diameter, 18,600 kW power, and an engine speed of 78 rpm, including a PTO. Vessel speed is 21 knots.

Table 11: EEDI values without PTO

	MDO		LNG		Methanol	
	EEDI	%	EEDI	%	EEDI	%
6S70ME-C10.5	14.655	69.9	11.225	53.5	13.281	63.3
7S70ME-C10.5	14.360	68.5	11.007	52.5	13.023	62.1
8G60ME-C10.5	14.590	69.6	11.165	53.2	13.215	63.0

EEDI values (MDO, LNG, and methanol) for propulsion systems with a 5-bladed propeller 7.5 m in diameter, 18,800 kW power, and an engine speed of 91 rpm. Vessel speed is 21 knots.

Table 12: EEDI values with PTO

	MDO		LNG		Methanol	
	EEDI	%	EEDI	%	EEDI	%
6S70ME-C10.5	13.995	66.7	10.766	51.3	13.140	62.6
7S70ME-C10.5	13.696	65.3	10.546	50.3	12.879	61.4
8G60ME-C10.5	13.929	66.4	10.706	51.0	13.073	62.3

EEDI values (MDO, LNG, and methanol) for propulsion systems with a 5-bladed propeller 7.5 m in diameter, 18,800 kW power, and an engine speed of 91 rpm, including a PTO. Vessel speed is 21 knots.

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/tonne. The PTO is not included in the calculation, but this would lower the operating price slightly.

Though it shows that the performances of 7G70ME-C9.5 at 18,600 kW and 7S70ME-C10.5 at 18,800 kW are somewhat the same or better than the 6G70ME-C10.5 at 18,600 kW, it is important to keep in mind that the maintenance of an extra cylinder is an additional operating expense.

These plots again show the importance of considering the engine and propeller in combination when evaluating the overall system efficiency. With the dual fuel engine, it would be possible to make the transition once the market turns or during voyage to fulfil the reduction requirements caused by CII for the annual greenhouse gas emission.

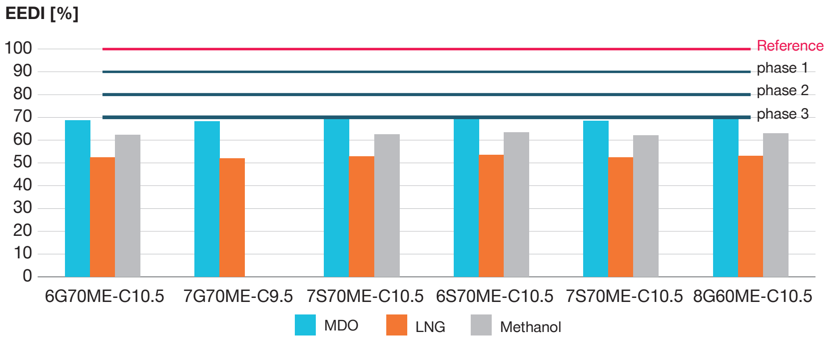

Fig. 8: EEDI values compared to the phase limitations

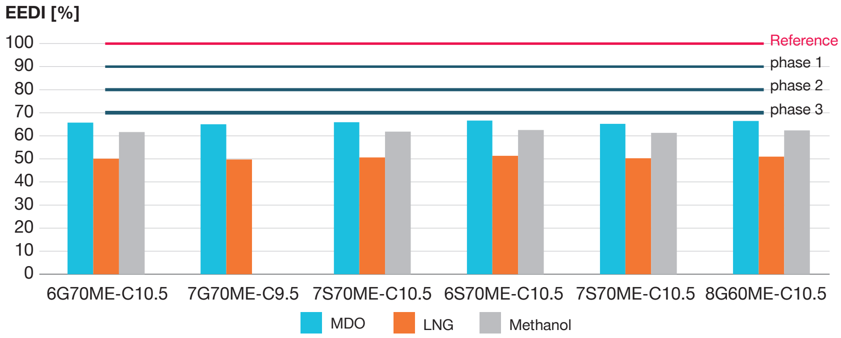

Fig. 9: EEDI values compared to the phase limitations including a PTO

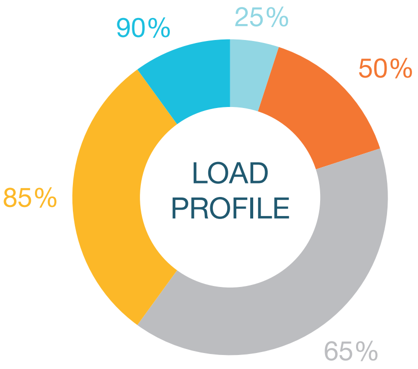

Fig. 10: Load profile for container feeder showing how much of the time the engine is loaded by the described percentage

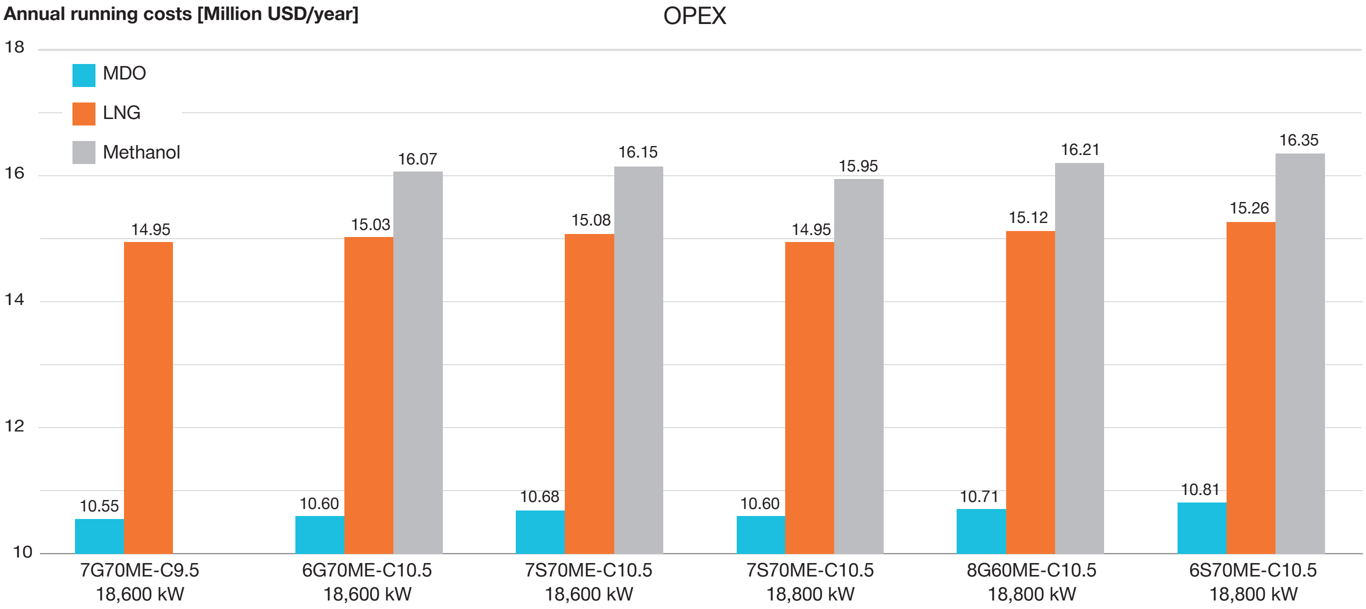

Fig. 11: Comparison of annual running costs for the six engine and all fuels, operating at 21 knots (prices as of april 2022)

Main engine operating costs – 19 knots

As for the 21 knots example, the running costs of an engine are an important factor. The following sections show examples of selected engines that can maintain a speed of 19 knots while still meeting the emission regulations and being cost-efficient on three different kinds of fuels, including MDO, LNG and methanol.

In Table 12, the main engine fuel consumption, EEDI, and operating costs at N = NCR = 85% SMCR have been calculated for six propulsion plants operating at a reduced service speed of 19 knots. The effect of the different fuels on the EEDI at the service speed including the sea margin is estimated as well. Fig. 15 shows the influence on the main engine efficiency, indicated by the specific fuel oil consumption (SFOC) of marine diesel oil (MDO) for the six plants. It is not done for all fuels, as all of the fuels are given as SFOC equivalent, which is equal for all fuels within the same engine as the efficiency is the same.

The significantly lower power required to propel the vessel at 19 knots allows for a more derated engine. This is reflected in the approx. 3 g/kWh lower SFOC compared to the SFOC for the 21 knots example, where a more derated engine would be of an impractical size. The lower SFOC further contributes to the savings achieved by reducing the service speed.

Furthermore, it can be seen that the lowered power also results in lower SFOC for almost all engine configurations with a larger propeller diameter, though the SFOC values for the 7G60ME-C10.5 engine running 12,850 kW at 78 rpm seem comparable to those of the 6G60ME-C10.5 engine running 13,000 kW at 91 rpm.

The daily fuel consumption in Fig. 16 has been calculated by multiplying the propulsion power demand at NCR = 85% with the SFOC (Fig. 15). Just as for the 21 knots example, the consumption

Table 12: SMCR point, engine speed, NCR, propeller diameter, and number of blades for six propulsion plants

Engine	SMCR [kW]	rpm	NCR [kW]	D_{prop}	No. of blades
8G60ME-C10.5	12,850	78	10,925	7.5	5
5G70ME-C10.5	12,850	78	10,925	7.5	5
7G60ME-C10.5	12,850	78	10,925	7.5	5
5S70ME-C10.5	13,000	91	11,050	7.3	4
6G60ME-C10.5	13,000	91	11,050	7.3	4
7S60ME-C10.5	13,000	91	11,050	7.3	4

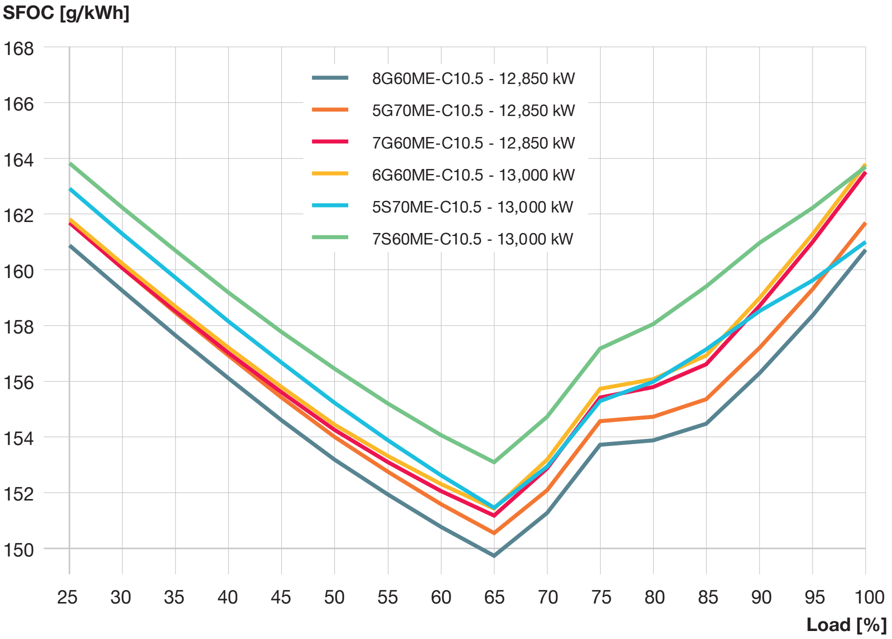

Fig. 15: SFOC for each of the six different engines, depending on the load

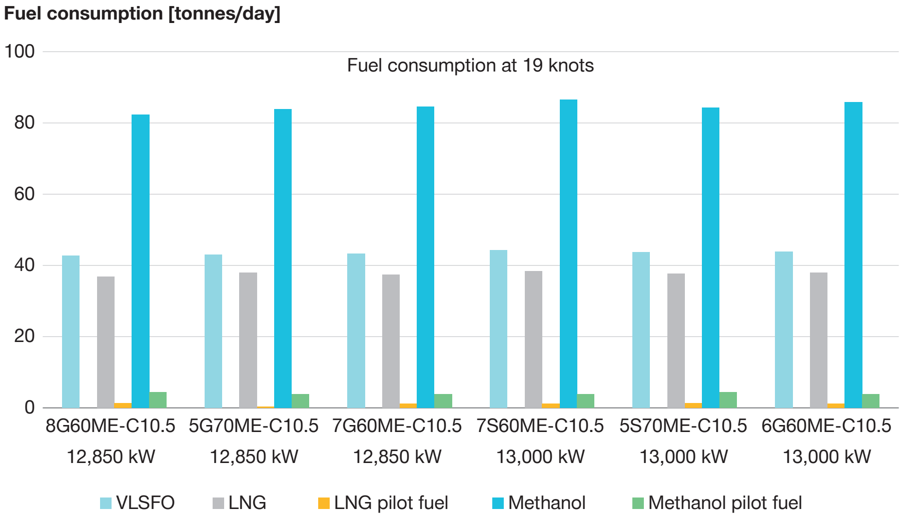

Fig. 16: Daily fuel consumption for the six engines and different fuel types

of methanol is twice the amount of VLSFO and LNG, including the pilot fuels, for all engines. Again, this is due to the fuel properties in Table 3 since the LCV of methanol is half of the LCV of MDO and LNG. As mentioned previously, each engine offers the same efficiency and is therefore not fuel dependent. However, the extra space necessary to store methanol and LNG due to the lower density must also be considered.

Comparing the 19 and 21 knots examples, the approximate power reduction is 30% at 19 knots, which is reflected in a similar reduction of fuel consumption.

Table 13: EEDI values without PTO

	MDO		LNG		Methanol	
	EEDI	%	EEDI	%	EEDI	%
5G70ME-C10.5	10.90	52.0	8.304	39.6	9.825	46.8
7G60ME-C10.5	10.956	52.2	8.388	40.0	9.876	47.1
8G60ME-C10.5	10.851	51.7	8.315	39.6	9.785	46.6

EEDI values (MDO, LNG, and methanol) for propulsion systems with a 5-bladed propeller 7.5 m in diameter, 12,850 kW power, and an engine speed of 78 rpm. Vessel speed is 19 knots.

Table 14: EEDI values with PTO

	MDO		LNG		Methanol	
	EEDI	%	EEDI	%	EEDI	%
5G70ME-C10.5	10.327	49.2	7.904	37.7	9.705	46.3
7G60ME-C10.5	10.383	49.5	7.990	38.1	9.757	46.5
8G60ME-C10.5	10.276	49.0	7.916	37.7	9.665	46.1

EEDI values (MDO, LNG, and methanol) for propulsion systems with a 5-bladed propeller 7.5 m in diameter, 12,850 kW power, and an engine speed of 78 rpm, including a PTO. Vessel speed is 19 knots.

Table 15: EEDI values without PTO

	MDO		LNG		Methanol	
	EEDI	%	EEDI	%	EEDI	%
5S70ME-C10.5	11.074	52.8	8.482	40.4	9.990	47.6
6G60ME-C10.5	11.099	52.9	8.496	40.5	10.006	47.7
7S60ME-C10.5	11.193	53.4	8.568	40.8	10.093	48.1

EEDI values (MDO, LNG, and methanol) for propulsion systems with a 4-bladed propeller 7.3 m in diameter of, 13,000 kW power, and an engine speed of 91 rpm. Vessel speed is 19 knots.

Table 16: EEDI values with PTO

	MDO		LNG		Methanol	
	EEDI	%	EEDI	%	EEDI	%
5S70ME-C10.5	10.497	50.0	8.082	38.5	9.871	47.1
6G60ME-C10.5	10.523	50.2	8.096	38.6	9.887	47.1
7S60ME-C10.5	10.618	50.6	8.169	38.9	9.975	47.6

EEDI values (MDO, LNG, and methanol) for propulsion systems with a 4-bladed propeller 7.3 m in diameter of, 13,000 kW power, and an engine speed of 91 rpm, including a PTO. Vessel speed is 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 shown in Tables 13-16 and Figs. 17-18.

When comparing to the EEDI of the 21 knots example, see Figs. 8 and 9 compared to Figs. 17 and 18, it is clear that a speed reduction greatly influences the EEDI. On average, the attained EEDI is reduced by an index of approx. 15%. 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 in [1]. At 19 knots, all the designs fulfil EEDI phase 3 (30% reduction) and all engine configurations would even fulfil a 40% reduction with and without PTO, respectively.

The load profile is estimated as being the same as for 21 knots, see Fig. 10. This is used for estimating the operational costs.

Operating costs

Whereas the previous comparisons of engine fuel performance are based on a constant engine load of 85% (NCR), the annual operating costs of the engine largely depend on the engine's load profile, as illustrated in Fig. 10. This calculation assumes 250 days per year at sea (≈30% in port), along with the fuel prices in Table 5 and a lubricating oil price of 1,500 USD/tonne. A price of 200 USD/tonne 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/tonne. The results are shown in Fig. 19.

The saving in annual main engine operating costs mainly depends on the market. In the current market, VLSFO is cheaper than LNG and methanol, if comparing the prices per GJ in Table 5.

This makes VLSFO the most cost-effective fuel currently. But as the CII must be taken into account from 1 January 2023, this could pave the way for an advantageous transition to alternative fuels in the near future.
In this context, the dual fuel engine is a great solution, as it offers the possibility to switch fuel during operation. This is an effective and flexible way to cope with future regulations of greenhouse gas emissions. It would also enable a change of fuel if the market should change in favour of an alternative fuel as the most cost-effective fuel.

The saving in net present value will be lower, compared to the first example as the actual fuel oil consumption is approximately 30% lower for the reduced design speed of the 19 knots.

For this example, it is easy to see the effect of the increased propeller diameter and shipowners will definitely save money if they choose the larger propeller.

Looking at Fig. 19, the 8G60ME-C10.5 engine appears to be the best solution. However, the size should be taken into account as it has 8 cylinders. The 5G70ME-C10.5 engine may appear to be slightly more expensive in operating costs, but its size is smaller and the cost of maintaining 5 cylinders compared to 8 is also lower. However, with only 5 cylinders, torsional vibrations may be an issue depending on the specific layout of the plant. The 5G70ME-C10.5 engine has an optional bearing zero, which allows for the possibility of adding a heavy tuning wheel with added inertia, potentially making it possible to avoid a torsional vibration damper despite the low number of cylinders.

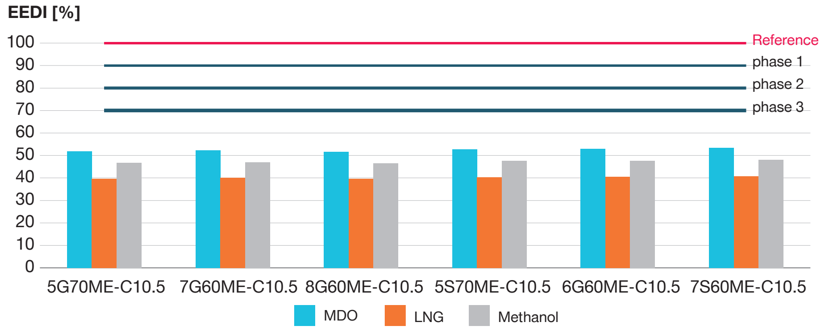

Fig. 17: EEDI values compared to the phase limitations

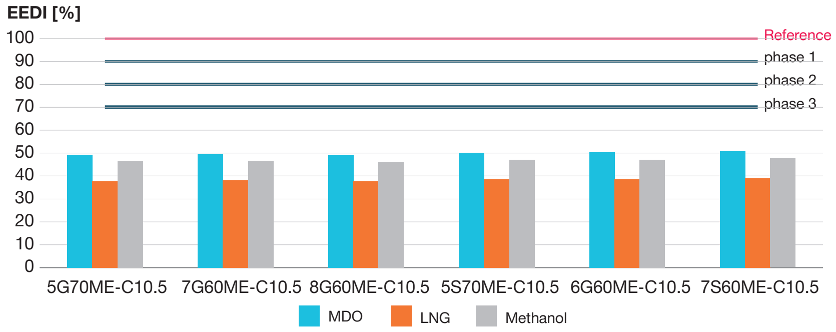

Fig. 18: EEDI values compared to the phase limitations including a PTO

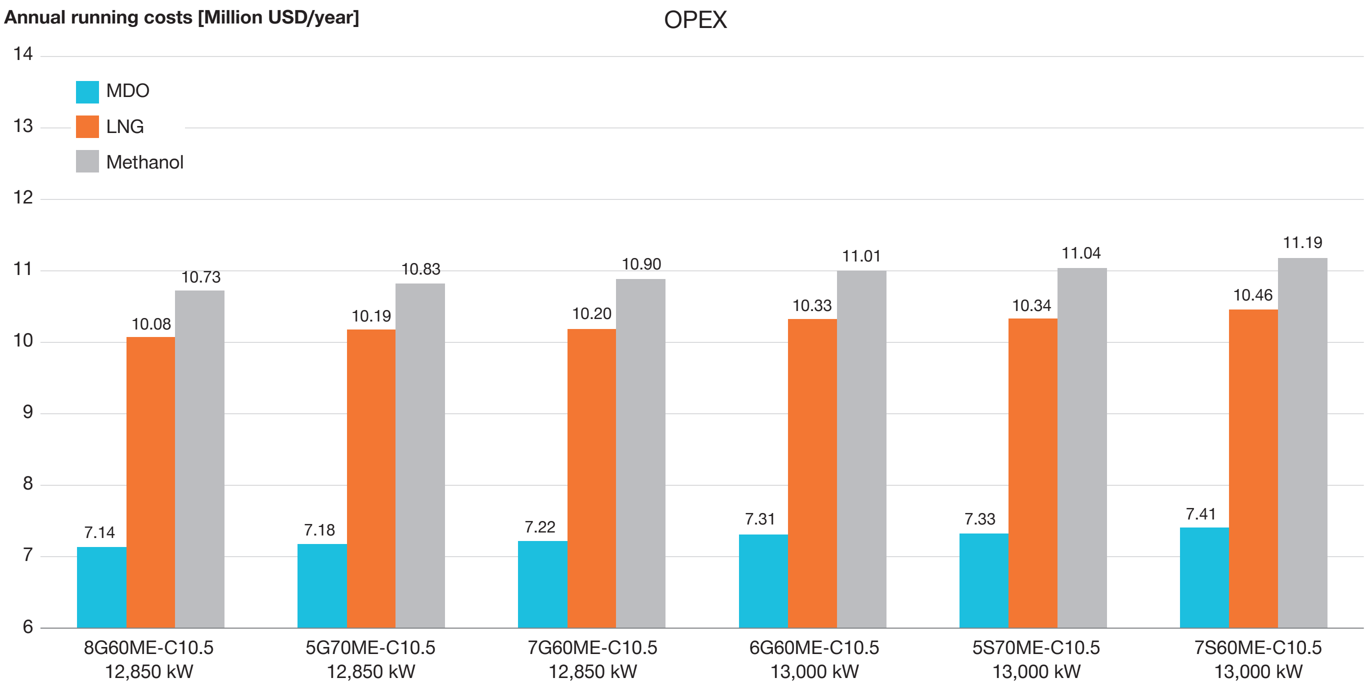

Fig. 19: Comparison of annual running costs for the six engine and all fuels, operating at 19 knots (prices as of April 2022)

Summary

Modern designs of container vessels in the feeder segment offer promising possibilities for the future when it comes to meeting the environmental restrictions set by IMO. And if equipped with a dual fuel engine, compliance with both EEDI and low ratings of the future CII evaluations are ensured together with a high degree of operational freedom.

Modern container vessels with a larger than usual propeller and a fuel efficient S- or G-type engine fulfil the EEDI phase 3 requirements (30% reduction) without further initiatives. If 40% reductions are to be achieved without reducing the speed from 21 knots, a change in fuel to LNG, methanol or possibly ammonia might be necessary. Otherwise, a PTO, various energy saving devices, waste heat recovery, or EcoEGR can be applied. Either way, alternative fuels must be considered.

The installation of such equipment will also ensure significant savings on the running costs, but changing completely to alternative fuels might not be cost-beneficial yet.

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 could be sensible, as the main engine can produce electric power at a lower SFOC than the auxiliary engines on board. Applying a PTO would also reduce greenhouse gas emissions thanks to the reduced running time of the auxiliary systems. A shaft generator is especially valuable for alternative fuels such as LNG, thanks to the lower cost of equipment for the auxiliary system.

Besides offering the capability to use different fuels, the MAN B&W S- and G-type dual fuel engines also offer an extensive selection of bore sizes 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 speed of a desired propeller can always be contained within the layout diagram of one of the many possible engine designs. If a duel fuel engine is applied, i.e. a GI for LNG or an LGIM for methanol, these designs also offer the possibility of changing between fuels, such as LNG, methanol, and VLSFO when desired or necessary to save operating costs and attain compliance with environmental restrictions.

For questions on specific cases, contact MAN Energy Solutions at: MarineProjectEngineering2S@man-es.com.

References

[1] Basic principles of ship propulsion, MAN Energy Solutions, Denmark, December 2021

[2] IMO RESOLUTION MEPC.308(73)

[3] VLSFO prices: https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam#VLSFO – of April 2022

[4] LNG prices: https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam#LNG – of April 2022

[5] Methanol prices: https://www.methanex.com/ – of April 2022

[6] Shaft generators for low speed main engines, MAN Energy Solutions, Denmark, April 2021

[7] IMO RESOLUTION MEPC.338(76) (adopted on 17 June 2021)

[8] IMO RESOLUTION MEPC.XXX(78) (adopted on 10 June 2022)

[9] IMO ANNEX 1 DRAFT MEPC RESOLUTION

[10] Fuel parameters: https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html

MAN Energy Solutions
2450 Copenhagen SV, Denmark
P +45 33 85 11 00
F +45 33 85 10 30
info-cph@man-es.com
www.man-es.com

5510-0225-01ppr Mar 2023. Printed in Denmark