

Everllence

Two-stroke



New Panamax

Modern two-stroke engine technology for a modern vessel type

Propulsion of 15,500 teu container vessels

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In 2016, commercial operation commenced through the expanded Panama Canal, marking a milestone in maritime transportation. The expansion reinforced the importance and recognition of Neopanamax or New Panamax vessels, the classification of which had already gained significant prominence since the early 2010s. These vessels have become highly popular because of their ability to access the extensive North American market and because of their versatility in navigating various trade routes thanks to the optimal economies of scale. Over the past decades, the growing demand for container transportation and the increase in ship sizes have led to a corresponding rise in orders for New Panamax vessels. With many vessels nearing retirement, it is anticipated that the demand for the New Panamax vessel segment will increase in the future.

1. Introduction

New Panama locks were introduced to accommodate significantly larger and more efficient vessels. Compared to the old locks, the new locks necessitate larger margins between vessels and lock walls. This is an essential change given that tugs guide the vessels into the new locks, rather than being pulled by locomotives running alongside the locks.

In 2018, the maximum permissible breadth for a vessel passing the new Panama locks was extended from the original limit of 49 m to 51.25 m. The permissible breadth of 51.25 m allows for 20 rows of

containers, resulting in an actual vessel breadth of approx. 50.7–51.0 m. Previously, the 49 m limit allowed for 19 rows of containers, and therefore resulted in a vessel breadth of approx. 48.2–48.5 m. Table 1 shows the dimensions of the new Panama locks together with maximum permissible vessel dimensions.

During the 2000s, the maximum container vessel size increased rapidly. As this paper is written, the capacity of the largest container vessels is almost 24,500 teu, and they entered the market in 2023.

The global economic downturn in the late 2000s, coupled with a persistent rise in oil prices, led to a reduction in the speed of the largest vessels. Since then, there has been a swift increase in the industry's focus on optimising vessel performance. The speed reduction led to a design speed of approx. 22 knots for new ultra-large container vessels (ULCV) on the drawing board then. This came hand-in-hand with engines of a longer stroke and lower rpm, such as the super-long-stroke S-type engines and later the ultra-long-stroke G-type engines. An improved engine

	Lock dimensions	Maximum allowed vessel dimensions
Length	427 m	370.30 m
Breadth	55 m	51.25 m
Draught	18.3 m	15.25 m
Height	–	57.9 m
Cargo	–	~15,500 teu

Table 1: Dimensions of new Panama Canal locks and New Panamax vessels

performance and the application of larger propellers ensured significant savings, which intensified the demand for New Panamax vessels, making them one of the most sought-after categories.

By optimising the hull and using alternative fuels like methane, or methanol, ships can achieve a significantly lower EEDI.

While the demand for methanol-fuelled and methane-fuelled engines is growing, the focus on ammonia engine development has increased significantly during the last couple of years because of the potential to achieve zero-carbon emissions and comply with stricter environmental regulations.

For low-sulphur fuels, EcoEGR (exhaust gas recirculation) can reduce EEDI and offer cost savings for shipowners. If a large power take-off (PTO) capacity is desired, the PTO system with Interface option C offers a technological advantage by reducing the number of running hours for the auxiliary engines, while our Asset+ solution 'PTO EEDI PowerMax' also contributes to lowering the EEDI value. Furthermore, 'PTO EEDI PowerMax' enables possibilities of even higher PTO capacities to comply with the stricter EEDI rules. For further information, see the separate paper "Shaft generators for low speed main engines" [1].

This paper outlines two case studies centred on a 15,500 teu New Panamax vessel with

design speeds of 20 and 22 knots, respectively. These case studies aim to demonstrate the economic and environmental advantages of New Panamax vessels using the newest engine technology, specifically, the G-type Mark 10 engine designs, along with an increased propeller diameter. Since the G95ME-C10 engine (Fig. 1) is the most advanced and efficient engine at the time of writing, this engine has been

selected to compare the performance of different fuels and cylinder numbers.

The following sections compare engine performance using different fuels, while maintaining engine dimensions. In these comparisons, it is the intention that the selected engine variants reflect general benefits across ratings and cylinder numbers, independent of specific dot numbers.

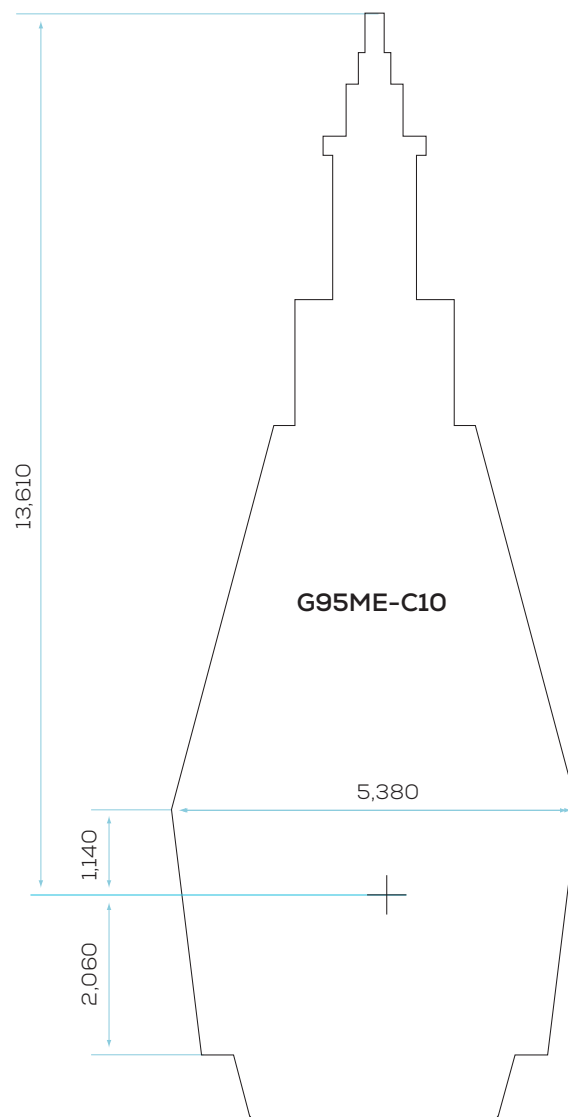


Fig. 1: Main dimensions of G95ME-C10 engine in mm

2. Example of a 15,500 teu New Panamax design

For a 15,500 teu New Panamax vessel equipped with a fixed pitch propeller (FPP), the following case studies illustrate the potential for reducing the fuel consumption by increasing the propeller diameter, introducing modern fuel-efficient dual-fuel main engines, and applying ultra-long-stroke engines (G-type) as the main propulsion system.

Table 1 shows the vessel particulars evaluated in the case studies for power prediction calculations for different design speeds and propeller diameters. The corresponding power at the specified maximum continuous rating (SMCR)

and speed for propulsion of the container vessel are estimated. Table 2 also includes sea, engine, and light running margins.

The two case studies investigate propeller diameters of 10.0, 10.2, and 10.4 m with a 4-bladed design in the 20 knots case, and a 5-bladed design for the 22 knots case. In

both case studies, the change in propeller diameter has been evaluated regarding the constant ship speed coefficient α , which is defined in Eq. 1.

The α -coefficient for container vessels is generally lower than that for tankers and bulk carriers. The difference becomes noticeable when the design speed is reduced to 20

Eq. 1

- $\alpha = 0.05$, for 20 knots

- $\alpha = 0.08$, for 22 knots, based on $P_{M2} = P_{M1} \times \left(\frac{n_2}{n_1}\right)^\alpha$

where P_M is the propulsion power, and n is the rotational speed.

Parameter	Value
Deadweight	164,000 dwt
Scantling draught	16.3 m
Design draught	15.4 m
Length overall	370.0 m
Length between perpendiculars	356.0 m
Breadth	51.25 m
Sea margin	15 %
Engine margin	10 %
Light running margin	5 %

Table 2: Vessel particulars for a typical New Panamax vessel

knots, which leads to a significant decrease of the α -coefficient. The explanation for this phenomenon is that the decrease in speed leads to a corresponding reduction in the thrust loading coefficient (C_{th}), which is the primary reason for the decrease in the α -coefficient. For further information about constant ship speed curves and α -coefficients, see Chapter 3 of the separate paper “Basic principles of ship propulsion” [2].

When reducing the number of propeller blades from 5 to 4 while retaining the propeller

diameter, the optimal propeller speed increases, and the propulsion power needed increases slightly. However, this change can lead to increased vibrations and underwater radiated noise (URN).

Fig. 2 presents potential main engine types, corresponding layout diagrams, and SMCR points for the two design speeds of 22 and 20 knots, respectively.

The main engine operating costs have been calculated and will be described in detail for both cases in later sections.

The design speeds stated refer to the design draught and to a normal continuous rating (NCR) of 85% SMCR, including 15% sea margin. If the design speed was based on calm weather, i.e. without a sea margin, the obtainable vessel speed at NCR of 85% SMCR would be about 1.0 knot higher. If the design speed was based on 75% SMCR, 70% of maximum dwt, calm water, and the hull in sea trial condition, as applied in the calculation of EEDI for container vessels, the vessel speed would be slightly influenced by a minor increase of the engine speed.

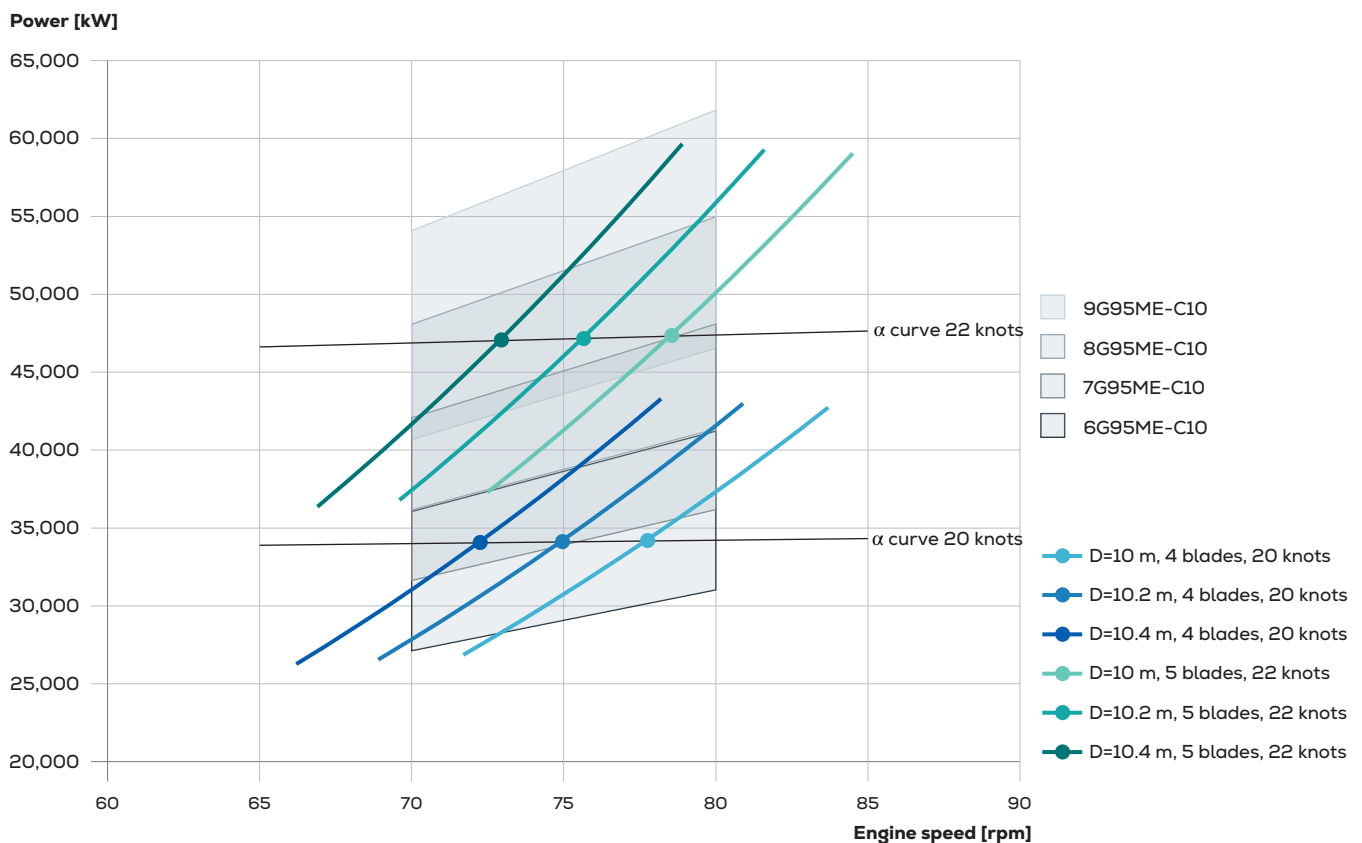


Fig. 2: Propeller and α -factor curves corresponding to engine layout diagrams for 5-bladed and 4-bladed propellers on New Panamax container vessels at design speeds of 22 and 20 knots

3. Energy efficiency, fuel types, propeller, and engine parameters for a New Panamax vessel

EEDI for container vessels

The EEDI guidelines are a mandatory instrument adopted by the International Maritime Organization (IMO). The guidelines ensure compliance with international requirements on CO₂ emissions from new ships. Despite an increase in other greenhouse gases (GHGs) like methane (CH₄) and nitrous oxide (N₂O) as reported in the Fourth Greenhouse Gas Study by IMO [3], these gases have yet to be included in current EEDI regulations. However, the latest revision implies that these will be considered in upcoming regulations. The EEDI (Eq. 2) represents the amount of CO₂ in gram emitted when transporting one dead-weight tonnage of cargo for one nautical mile.

The EEDI calculation is based on cargo capacity, propulsion power, vessel speed, specific fuel oil consumption (SFOC), and fuel type. However, certain correction factors are applicable, and adding a waste heat recovery system (WHRS), for example, may lead to EEDI reductions. Chapter 4 in [2] explains this further.

A reference index for a specific vessel type, considering its scantling condition, is calculated based on data from vessels built in the period 2000–2010. According to the EEDI guidelines implemented on 1 January 2013, the required EEDI for new vessels was reduced in three steps, see Fig. 3. This applies specifically to New Panamax vessels built after April 2022, typically ranging from

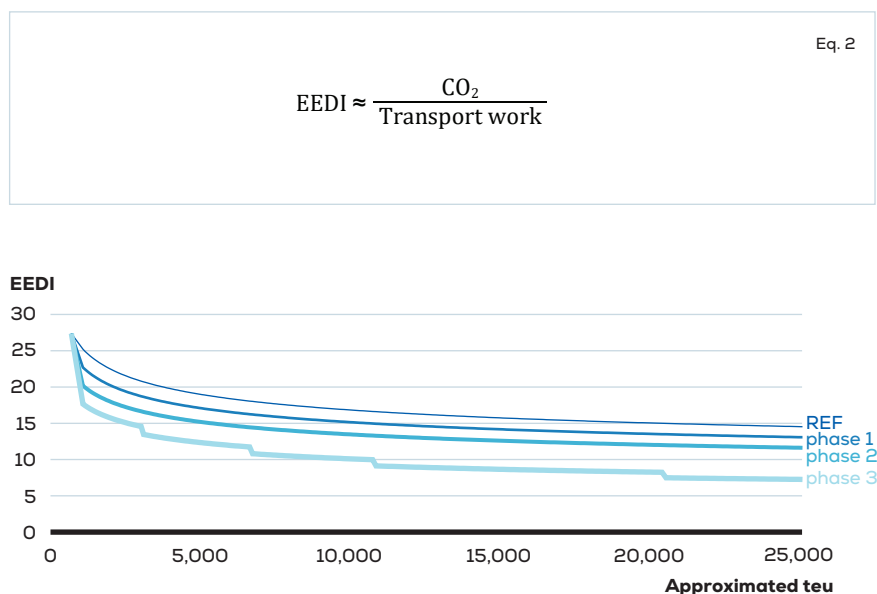


Fig. 3: EEDI reduction in teu across the three defined phases compared to the reference line of 2013

120,000–200,000 dwt, aligning with the New Panamax segment. For this category, the highest current EEDI reduction under Phase 3 requires a 45% decrease compared to the reference value. Looking ahead, potential developments may lead to a Phase 4 in EEDI regulations, or a similar framework aimed at achieving even greater CO₂ reductions from the EEDI baseline. This will depend on future IMO decisions and advancements in environmental standards and technologies.

For a container vessel, the calculation of the reference index is based on 100% utilisation of capacity (in teu) as for all other vessel types. Conversely, the attained EEDI is calculated based on 70% capacity utilisation, a reference speed in consistency with this loading of the vessel at 75% SMCR, and with the hull in sea trial condition. The attained EEDI must not exceed the required EEDI.

There are various methods that can be applied to lower the attained EEDI:

- **Engine derating:** Reducing the mean effective pressure while maintaining a constant maximum (firing) pressure decreases the SFOC.
- **EcoEGR:** Available for most engines with EGR. EcoEGR allows efficiency optimisation of combustion parameters by activating the EGR system even in Tier II mode. This reduces NO_x emissions and optimises fuel efficiency while ensuring NO_x emission compliance at the same time.
- **Power reduction:** The installed power can be reduced, which would also result in a lower vessel speed.
- **Design optimisation:** Improving the hull design to minimise resistance, or optimising propeller design.
- **Energy-saving devices:** Various devices that alter the flow fore or aft of the propeller can be applied to save energy and improve

the efficiency of the overall propulsive system.

- **Green technologies:** Installing systems like WHRS, hull air lubrication, or dual-fuel engines that use fuels such as methane, liquefied petroleum gas (LPG), methanol, or ammonia will also lower the EEDI value thanks to the lower carbon content.
- **PTO:** A shaft generator utilises energy from the main engine to generate electricity, thereby reducing auxiliary engine use and improving efficiency, as the main engine has a high efficiency. This lowers SFOC and reduces the EEDI value.

Eq. 3 outlines the basic structure for calculating the EEDI, where:

P_{ME} :	Main engine power (kW)
$C_{F, ME}$:	Carbon emission factor for the main engine (gCO ₂ /gfuel)
$SFOC_{ME}$:	Specific fuel consumption for the main engine (g/kWh)
P_{AE} :	Auxiliary engine power (kW)
$C_{F, AE}$:	Carbon emission factor for the auxiliary engine (gCO ₂ /gfuel)

$SFOC_{AE}$: Specific fuel consumption for the auxiliary engine (g/kWh)
 Capacity: 70% of the scantling dwt
 V_{ref} : Reference speed of the ship (knots)

At the time of writing, the EEDI regulations only include the greenhouse gas CO₂.

Using alternative fuels is one way to cope with EEDI restrictions. Alternative fuels are not necessarily new fuel types for combustion, but because of emission restrictions these fuels might end up shaping the future of the industry. Methanol and methane are suitable options to lower the EEDI, but they will require dual-fuel engines like the GI-engine for methane, or the LGIM-engine for methanol. Both of these engine designs also have the possibility to operate on conventional fuel or biofuel.

The lower carbon content makes these fuels relevant choices, but methanol offers a low complexity due to storage and handling at ambient temperature in coated tanks. In contrast, LNG requires very low temperatures and specialised storage tanks.

Although alternative fuels can allow for increased speeds due to a lower EEDI from reduced carbon emissions, it is preferable to maintain the same speed and benefit from the lower EEDI, given the high fuel prices, particularly for alternative fuels.

Chapter 4 in [2] provides further information on the calculation of EEDI, and the reduction hereof, and on other environmental regulations.

Fuel types

To reduce GHG emissions, the primary focus naturally shifts to minimising direct emissions from combustion. When calculating CO₂ emissions, marine diesel oil (MDO) is typically used as a reference. However, ships tend to operate on very-low-sulphur fuel oil (VLSFO) because of the lower sulphur content, and properties similar to MDO.

Everllence combustion engines can also operate on fuels like methane, methanol, ethanol, and LPG. In the near future, ammonia will become an option. Table 3 shows the properties of the four fuels compared in this paper: MDO, VLSFO, LNG, and methanol [4].

MDO demonstrates the highest energy density on a volume basis. However, since most ships operate on VLSFO, this fuel represents the highest volumetric energy density for

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

Eq. 3

Fuel	Carbon content	Carbon factor (C _F) [tCO ₂ /tfuel]	Density [kg/m ³]	Energy density [MJ/m ³]	Lower calorific value (LCV) [kJ/kg]
MDO	0.8744	3.206	900	38,430	42,700
VLSFO	0.8493	3.114	991	37,788	40,200
LNG*	0.7500	2.750	450	20,800	48,000
Methanol	0.3750	1.375	791	15,800	19,900

*Fuel quality can vary by season and market, affecting heating values by 5–10%. The values provided apply for fuels with the specified density.
 Table 3: Properties related to carbon content for MDO, VLSFO, LNG, and methanol at 15°C

current ship operations. If a ship uses methanol or methane, it will need more fuel storage space because of their lower energy densities.

Both methane and methanol have a lower carbon content compared to VLSFO, making them attractive options for reducing EEDI. New Panamax vessels more commonly use membrane tanks for storing methane. These tanks are designed to maximise cargo capacity and are well-suited for the larger size, and increased operational demands of New Panamax vessels.

Methanol, like MDO or VLSFO, can be stored at room temperature in coated tanks without cooling. However, keeping LNG on liquid form requires specialised tanks to pressurise and cool the fuel to approximately -162°C. Therefore, integrating LNG tanks in a vessel design needs special considerations and will increase the electrical power consumption.

Table 4 compares the carbon content of the fuels listed in Fig. 4, illustrating how much the EEDI can be reduced by simply changing the fuel type. However, this comparison does not account for the extra challenges for both LNG and methanol, such as the larger storage space, which means less space for cargo goods. Also, the comparison does not include the added power consumption needed to cool the LNG.

Table 4 can be used for calculating the potential EEDI reduction when switching fuel. The example in Eq. 4 shows the calculation for MDO compared to methanol.

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 calculating the EEDI, even though VLSFO is primarily used. However, it is common to use MDO on sea trial and for the EEDI calculation.

Fuel prices

The prices of alternative fuels must also be evaluated. Table 5 provides an estimate of fuel prices as of July 2024. For comparison, the LCV of heavy fuel oil (HFO) is assumed to be 41 MJ/kg, allowing for the calculation of HFO equivalents for various alternative fuels [5].

Our dual-fuel engines offer fuel flexibility. As an example, the GI-engine can switch between main fuels LNG and VLSFO, and operate part-time on these fuels. The engine can run on the fuel preferred in the current market, depending on fuel prices and regulations. As an example of a regulation, the carbon intensity indicator (CII) and FuelEU maritime will be explained later.

Table 4 illustrates an estimation of future fuel prices, highlighting a significant reduction in the prices of alternative fuels. Currently, methanol is considered relatively expensive, but it is expected to undergo

Relative EEDI	MDO as reference point
MDO	100%
Methanol	92%
LNG	76%

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

Fuel	USD/GJ	USD/tonne	HFO equivalent (USD/tonne)
VLSFO	14.28	574	574
LNG	10.40	499	418
Methanol*	34.12	679	1,372

Table 5: Fuel prices for VLSFO, LNG, and methanol as of July 2024
*Produced from fossil fuels

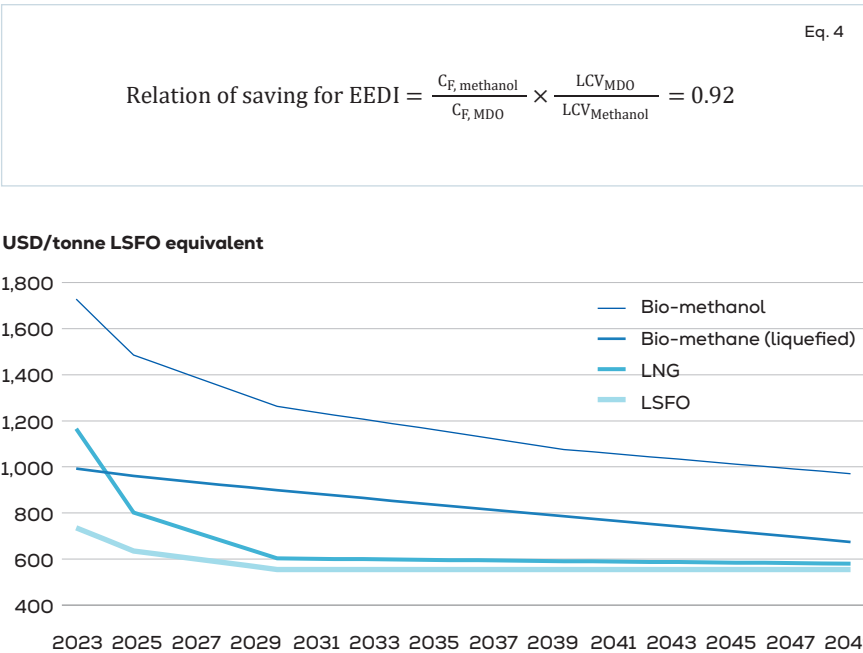


Fig. 4: Predicted fuel prices for VLSFO, LNG, and methanol

a significant price reduction in the future as the infrastructure and market develops. All fuel prices and estimates are from an analysis performed by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) using bottom-up assumptions for the European region. It is important to note that predictions for the Asian and Middle Eastern markets indicate that LNG prices will follow the trends of VLSFO prices [6].

Unlike conventional or 'grey' methanol, which is typically produced from fossil fuels and has even higher GHG emissions than VLSFO in a well-to-wake perspective, e-methanol and bio-methanol are derived from renewable sources. This makes these types of methanol more sustainable options with a smaller carbon footprint on a well-to-wake basis. For this reason, e-methanol and bio-methanol are likely to become more preferable in the future given their significantly lower GHG emissions.

As of April 2025, the methanol engine portfolio includes a variety of options specifically suited for New Panamax vessels. The LGIM engine range, spanning from G45 to G95, offers tailored solutions that align with the operational and efficiency demands of this vessel class. This adaptability has made methanol engines an increasingly attractive choice for the New Panamax segment, driving a notable rise in orders globally in recent months. Notably, the *Laura Mærsk*, although considered a feeder vessel, is the first green methanol vessel to be launched [7]. Following this, methanol-fuelled vessels in larger segments have been introduced, such as the

Ane Mærsk with a capacity of 16,000 teu. The innovative design of *Ane Mærsk*, featuring the bridge at the fore part of the ship to enhance cargo capacity by providing more space for containers, marks a significant step towards greener shipping [8].

Shaft generator/power take-off systems

To reduce GHG emissions further, the latest EEDI phase 3 necessitates a lower propulsion power and, therefore, results in lower ship speeds than earlier trends. The reduced engine load leads to lower SFOC and overall fuel consumption. The latter reduction also means that compliance with CII, FuelEU Maritime, and other operational emission regulations is easier.

New Panamax vessels also face an increased electricity demand, particularly due to the frequent installation of reefer containers, or an increased power consumption for cooling of fuel storage. Therefore, by implementing a shaft generator as PTO, a significant amount of mechanical power from the main engine can be efficiently transformed into electrical power. In this mode, the shaft generator covers the need for electrical power alone, or if a frequency converter is installed, in parallel with gensets. PTO mode not only offers significant fuel savings because of the superior fuel economy of the main engine compared to the gensets, but also decreases maintenance requirements and expenses for spare parts due to the reduced running hours of the gensets. However, even though the main engine can cover the hotel load requirements, auxiliary engines

remain indispensable. They are crucial during port calls, anchoring, or when the main engine must allocate all its power to the propeller, such as during extreme weather conditions.

As part of the Asset+ solutions, the PTO Interface option C can also be applied to improve the governor stability and increase the power capacity of the PTO system, while enhancing load sharing between the engine control system and planned maintenance system. This optimises PTO utilisation, protects the engine from overload, enhances engine stability, and reduces genset running hours. For further information, see the technical specification document PTO Interface Option C [9].

The EEDI guidelines provide two solutions to account for the use of shaft generators and the effect of PTO on the EEDI. Both of these solutions, which are described in options 1 and 2, will lower the EEDI of the design as described in regulations by the IMO [10].

PTO Option 1

Option 1 allows a reduction of the main engine power (P_{ME}) by an amount equal to the PTO's nameplate power (P_{PTO}), provided that $P_{PTO}/0.75$ is sufficient to cover the auxiliary system's power demand (P_{AE}), as estimated by the IMO. This power reduction applies within the EEDI framework and does not reflect a reduction in the engine's actual operational power. In the calculation of EEDI for Option 1, the MCR is the total power of all main engines. The EEDI can be calculated with Eq. 5 when adding

the PTO.

The power capacity of the PTO may exceed the estimated value of P_{AE} but in the calculation, the value of P_{PTO} cannot be greater than P_{AE} . The P_{AE} value is estimated using the equations specified in the EEDI regulations by the IMO, as outlined in the outcome of the Marine Environment Protection Committee, 79 session (MEPC 79) [10].

The effect of the PTO can be estimated along with the auxiliary engine system. For EEDI Option 1, the maximum allowable P_{PTO} deduction is limited to $P_{AE}/0.75$. The main engine power for EEDI Option 1 is calculated as:

$$P_{ME} = 0.75 \cdot (MCR_{ME} - P_{PTO})$$

and EEDI with Eq. 5.

By utilising PTO for EEDI compliance, the vessel's EEDI reference speed will be slightly reduced. All estimates and implementations are described further in [4].

PTO PowerMax

In the alternative PowerMax, the power available for propulsion is limited to:

$$P_{LIM, propulsion} = P_{SMCR} - P_{PTO}.$$

This sets a new propulsion power limit of the main engine power used in the EEDI calculation:

$$P_{ME} = 0.75 \cdot (MCR_{ME} - P_{PTO, name plate}).$$

This limitation allows the PTO to contribute to further EEDI reductions, resulting in substantial power savings regardless of propulsion demands. As in Option 1, this power limit is only used for EEDI calculations and does not restrict actual

engine use unless specifically enforced. Additionally, the implementation of PTO Interface option C is essential for the integration of PTO PowerMax. When applying EEDI PTO PowerMax, the vessel's reference speed is further reduced relative to PTO Option 1. Calculate EEDI for PTO PowerMax with Eq. 6.

Carbon intensity indicator (CII)

On 1 January 2023, the carbon intensity factor was implemented by the IMO 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 from the operation of the vessel. Eq. 6 states an approximate CII calculation.

A grading system is implemented for the carbon intensity indicator, which consists of ratings A, B, C, D, and E.

Grade A represents the highest performance in terms of carbon efficiency, and E the lowest. Following three consecutive years of grade D, as shown in Fig. 5 by the 'attained annual operational CII', or one year of grade E, the owner must submit a corrective action plan to reduce carbon emissions.

The percentages in Fig. 5 are based on ship emission statistics from 2019. The data showed that 15% of the vessels would be rated E, 20% would be rated D, etc., according to the current CII definition. Fig. 5 illustrates the current CII restrictions as of April 2025. At MEPC 83, reduction factors for 2027 to 2030 were decided, and a formal work plan was adopted to review the CII methodology by 2028, which may introduce energy-based metrics, segment-specific criteria, and operational incentives. Additional restrictions may be introduced based on the outcome of the 2028 review.

$$\text{EEDI with PTO Option 1} = \frac{((MCR_{ME} - \frac{P_{AE}}{0.75}) \times 0.75 + P_{AE}) \times C_{F, ME} \times SFOC_{ME}}{dwt \times V_{ref}} \quad \text{Eq. 5}$$

where $P_{PTO} < P_{AE}/0.75$

$$\text{EEDI with PTO PowerMax} = \frac{((MCR_{ME} - P_{PTO, name plate}) \times 0.75 + P_{AE}) \times C_{F, ME} \times SFOC_{ME}}{dwt \times V_{ref}} \quad \text{Eq. 6}$$

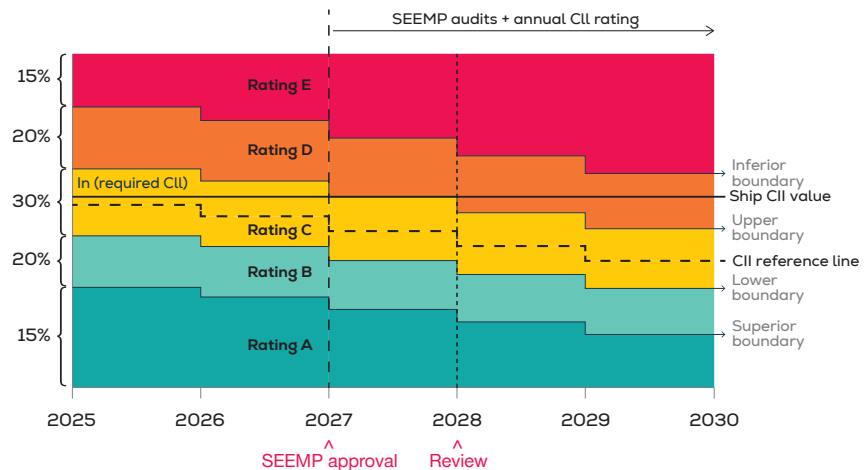


Fig. 5: CII reduction according to annual ratings

To calculate the required CII in Eq. 7, which varies with the year of operation, the reference value (CII_{ref}), known as the attained annual operational CII, must also be considered. Eq. 8 is the expression for calculating CII_{ref} , where $a=1984$ and $c=0.489$ are the coefficients specifically for container ships [11]. The required CII can then be calculated as shown in Eq. 9.

Here Z [%] is the reduction factor implemented in 2023, and Table 6 shows annual changes.

If, for example, a New Panamax vessel complies with the reference value for 2027 requirements, which is a 13.625% CII reduction compared to the reference line of 2019, the vessel will be downgraded to rating D. In this case, the shipowner is responsible for assessing the operational efficiency and taking necessary actions, such as retrofitting the main engine, optimising operational speed, improving maintenance, enhancing voyage planning, installing energy-saving technologies like air lubrication systems and optimising the cargo load. If no corrective CII measures are taken, the ship will be graded D in 2028. It means that within three years, a corrective reduction plan has to be submitted. Fig. 5 illustrates an example of the attained annual operational CII.

Each year, the required emission reduction is lowered compared to the reference line. As of April 2025, the annual reduction figures are only available up to 2030 (see Table 6). The reduction factors for 2027–2030 were decided at MEPC 83, following

$$CII = \frac{\text{Annual fuel consumption} \cdot \text{CO}_2 \text{ factor}}{\text{Annual distance travelled} \cdot \text{capacity}} \cdot \text{Correction factors} \quad \text{Eq. 7}$$

$$CII_{ref} = a \cdot \text{Capacity}^{-c} \quad \text{Eq. 8}$$

$$\text{Required CII} = \frac{100-z}{100} \cdot CII_{ref} \quad \text{Eq. 9}$$

Year	Reduction factor (Z) compared to 2019 as reference [%]
2023	5
2024	7
2025	9
2026	11
2027	13.625
2028	16.250
2029	18.875
2030	21.500

Table 6: Carbon intensity reductions for the coming years

discussions initiated at MEPC 82. Although a review of the short-term CII measure began earlier, its full revision is scheduled to be finalised by 2028, with the aim of aligning future targets with the IMO GHG Strategy. This review may also consider incentives to avoid port waiting and encourage better operational practices.

Dual-fuel engines offer a significant advantage because CO_2 emissions can be controlled by switching fuels. Additionally, the proportion of alternative fuels used during operation can be gradually increased as emission reduction standards become more stringent. This means that the IMO reduces the required CII annually, and it is the shipowner's responsibility to update and comply with the regulatory requirements, as shown in Fig. 5. Furthermore, MEPC 83 approved the development of a new fuel GHG standard

that includes pricing mechanisms for fuels not meeting the reduction targets, which may significantly impact future CII compliance.

FuelEU Maritime

The regulation FuelEU Maritime aims to reduce greenhouse gas emissions in the EU maritime sector by promoting the use of alternative fuels and enhancing energy efficiency. The FuelEU Maritime sets maximum limits on the yearly average greenhouse gas intensity of energy used by ships over 5,000 gross tonnage calling at European ports, regardless of their flag. The regulation targets not only cover CO_2 emissions, but also methane and nitrous oxide emissions across the full lifecycle of fuels on a well-to-wake (WtW) basis [12].

The FuelEU Maritime is fleet based, meaning that it is not

mandatory to change the fuel for all ships to make the entire fleet compliant. The WtW emissions are expressed in $\text{gCO}_2\text{eq/MJ}$. The evaluation is conducted on a WtW basis, and the overall share of a single ship will influence the intensity on a fleet level. Therefore, the larger the emission share from an individual ship, the more it will impact the overall GHG intensity of the fleet.

In Fig. 6, the various WtW intensity values are illustrated in comparison with the upper limits set by the FuelEU Maritime regulation [13]. This overview highlights which fuels will meet compliance requirements and their anticipated duration of compliance, underscoring the importance of dual-fuel engines, as it allows for a flexible shift to compliant fuels.

The FuelEU regulations are only applied when including operation between, and to and from, EU ports and during port stays.

Major propeller and engine parameters

In contrast to the classic approach, where increasing the propeller diameter enhances the efficiency and lowers the optimal propel-

ler speed by maintaining an ideal pitch-to-diameter ratio, modern practices necessitate a comprehensive propeller optimisation analysis.

Reducing the number of propeller blades, for example from five to four blades would result in an approximately 10% higher optimal propeller speed and a slight increase in propeller efficiency. When increasing the propeller pitch for a given propeller diameter with an optimal pitch-to-diameter ratio, the corresponding propeller speed can be reduced. The efficiency will also be slightly reduced depending on the degree of the pitch change. The same applies to a reduced pitch, however, in this case, the propeller speed can be increased to achieve an optimal engine efficiency.

Additional factors, such as wake fraction and thrust deduction factor, influence a vessel's speed and the required thrust. As a result, higher SMCR power is needed to maintain the same speed. The wake fraction factor results from a disturbed water flow around the hull, which affects propeller efficiency. The thrust deduction factor accounts for increased hull resistance caused by the propeller suction force at the stern, which the propulsion system must overcome.

The efficiency of a two-stroke main engine is particularly dependant on the ratio between maximum (firing) pressure and mean effective pressure. The higher the ratio, the higher the engine efficiency, and the lower the SFOC. Furthermore, the higher the stroke-to-bore ratio of a uniflow scavenging two-stroke engine, the higher the engine efficiency, because the scavenging process improves with a higher stroke/bore ratio. Therefore, the ultra-long-stroke G-type engines by design have a higher efficiency than the previous S-type engines applied on container vessels.

Two case studies of New Panamax vessels examine how operation on alternative fuels influences fuel consumption. Engines designed for speeds of 22 knots and 20 knots are used as examples, highlighting the effects of an increased propeller diameter, and changes in the number of blades.

Fig. 2 presents the layout diagrams for the G95ME-C10 engine with cylinder numbers that comply with the different propeller configurations and ship speeds. The diagram shows that, regardless of the

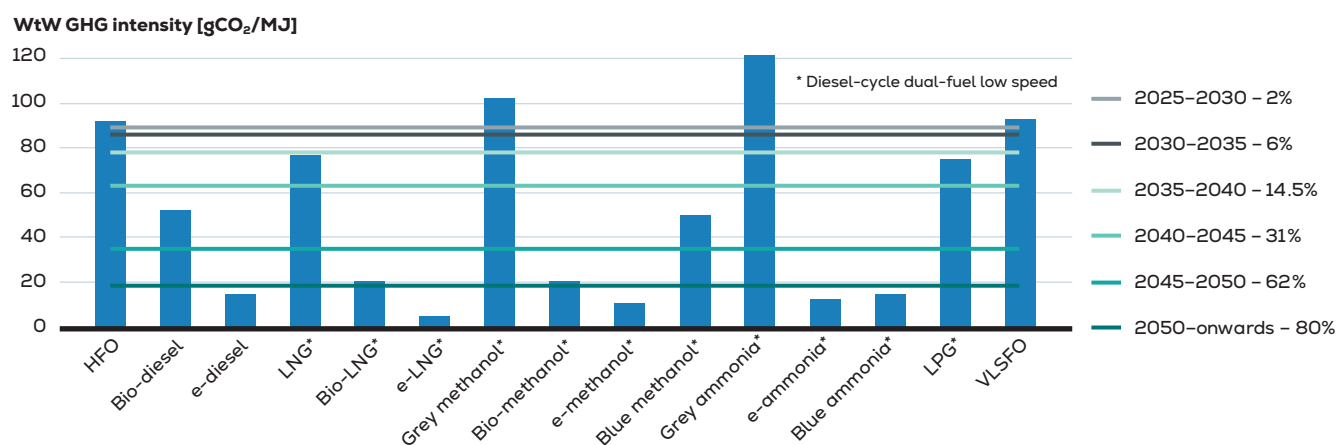


Fig. 6: Different fuel WtW intensity values and an illustration of FuelEU Maritime compliance

cylinder number, the engine speed varies within a specific range to accommodate different propeller setups and ship speeds.

Shaft acceleration through barred speed range for FPP

A barred speed range (BSR) imposed by vibrations must be passed sufficiently quick to prevent excessive vibration-induced stresses that could damage the shafting. What 'sufficiently quick' means depends on how high the stresses are in the shaft compared to the strength of the shaft material. Furthermore, the definition of 'sufficiently quick' depends on how often the BSR will be passed during the expected lifetime of the ship. For example, a feeder containership with many port calls will pass the BSR more frequently than a large crude carrier that mostly performs ocean crossings.

In general, the BSR must be passed within seconds, not minutes. For this reason, it is recommended to lower the 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. However, this is not typically implemented in the New Panamax segment.

A BSR is illustrated in Fig. 7, which shows an example of the BSR at a relatively high location. Usually, the BSR is in the span between 45–60% rpm.

We have established the BSR power margin (BSRrpm) to evaluate the capability of a quick passage, for further information see Chapter 3 in [2]. Some class societies have their own guidelines.

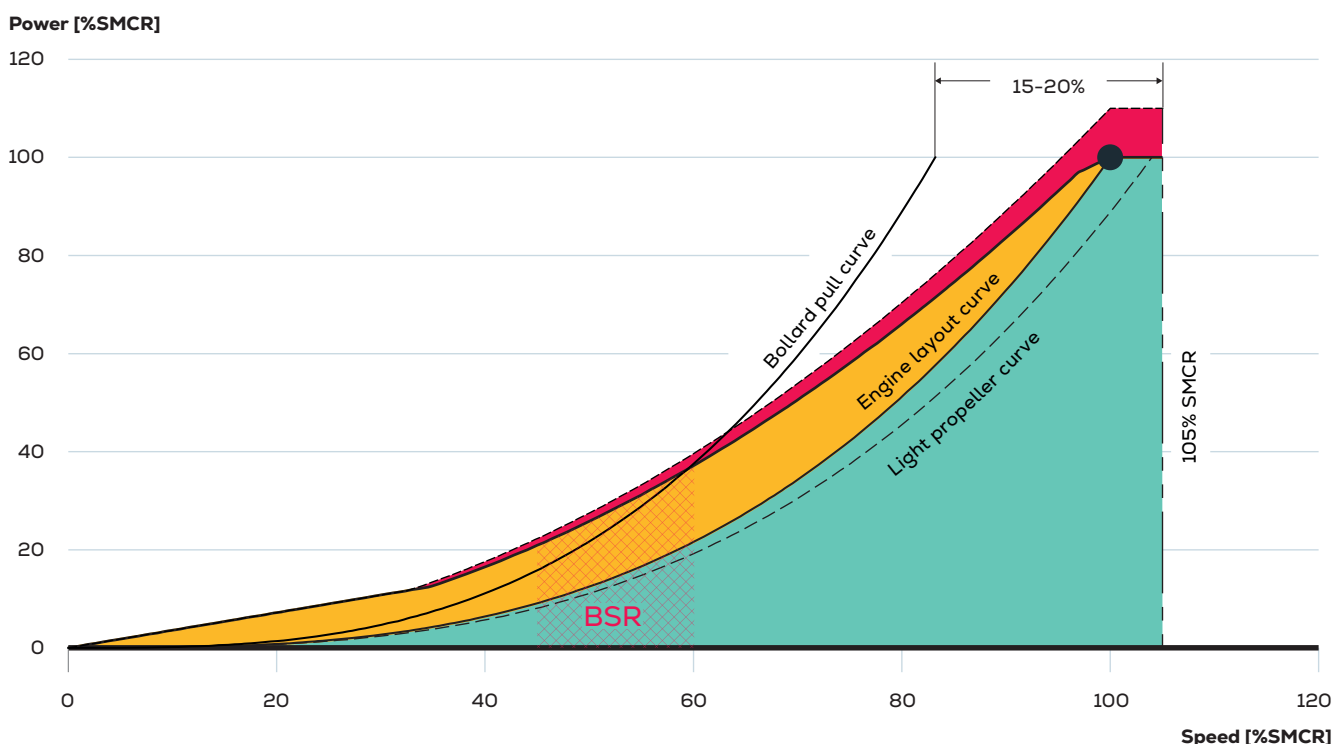


Fig. 7: Bollard pull curve. The two-stroke engine can always quickly accelerate the propeller to about 50% rpm. The BSR in the figure is placed high up in the rpm range, and the BSR passage may not be quick.

4. Main engine operating costs – 22 knots

Fuel consumption

The running costs of an engine are an important factor, particularly since an engine is expected to remain in service for at least 20 years. In recent years, many research institutes have focused on extending the operational lifespan of ships, addressing multiple challenges in the process. One of the most critical challenges is ensuring that engines on older vessels comply with the latest emission regulations.

This section examines two engines operating at three different SMCR points, each maintaining a speed of 22 knots. The results demonstrate how these engines remain compliant with emission regulations and illustrate the impact of three different fuel types – MDO, LNG, and methanol – on the estimated operating expenses (opex).

nol – on the estimated operating expenses (opex).

Table 7 shows the calculated main engine fuel consumption for six propulsion plants operating on MDO at NCR = 85% SMCR, at the relatively high speed of 22 knots.

Table 7 provides several key findings on how changes in propeller diameter and engine type affect fuel consumption and SFOC. The first is that even identical engine types show variations in SFOC due to differing SMCR power and speed requirements. The variations occur because maintaining a constant velocity with the same engines but with different propeller diameters requires a different engine rpm, as the pitch/diameter ratio changes. The optimal propeller configuration will result in an improved

fuel performance, leading to lower SFOC and better engine efficiency. However, optimising for fuel efficiency might decrease the propeller efficiency. See Chapter 2 in [2] for further information on propeller optimisation and other environmental regulations.

Additionally, 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. This highlights the trade-off between propeller diameter and energy consumption, and the potential impact on engine efficiency and operational costs.

Fig. 8 illustrates the daily energy consumption for MDO, LNG, and methanol, and the corresponding savings for each engine case.

Engine type	SMCR [kW]	Shaft speed [rpm]	NCR [kW]	Tier III SFOC [g/kWh]	D _{prop} [m]
8G95ME-C10	47,060	72.9	40,000	157.3	10.4
9G95ME-C10	47,060	72.9	40,000	155.4	10.4
8G95ME-C10	47,140	75.6	40,070	156.8	10.2
9G95ME-C10	47,140	75.6	40,070	154.9	10.2
8G95ME-C10	47,340	78.5	40,240	156.2	10.0
9G95ME-C10	47,340	78.5	40,240	154.4	10.0

Table 7: Specifications for G95ME-C10 engine variants based on cylinder number: SMCR, shaft speed, NCR, SFOC, and propeller diameter for a 5-bladed propeller

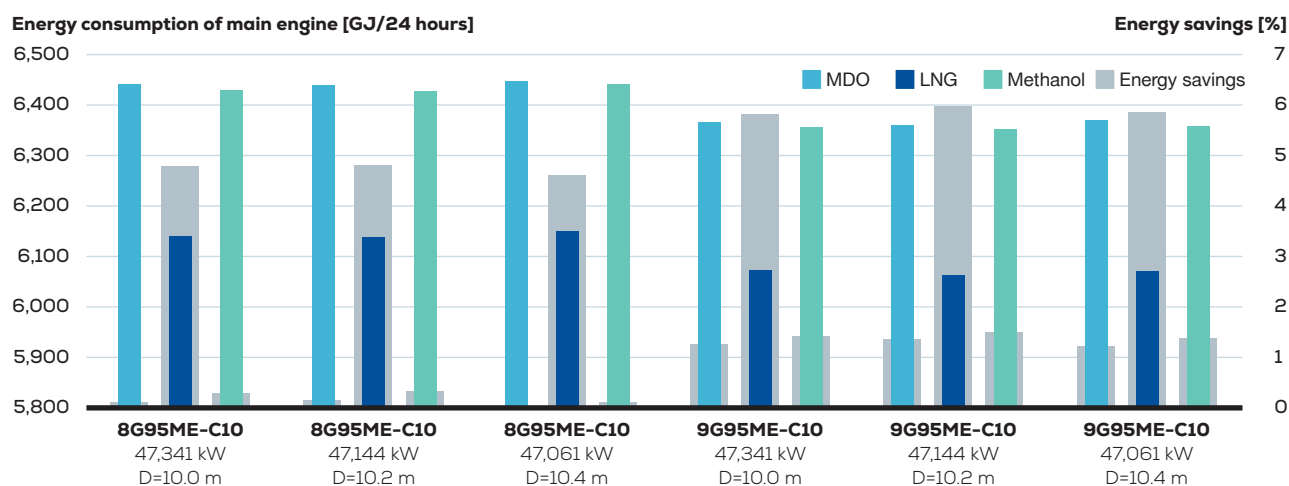


Fig. 8: Daily energy consumption and energy savings for each engine case at 22 knots, using fuel types MDO, LNG, and methanol

However, methanol has roughly half the LCV value of VLSFO and LNG, so to get the same amount of power, nearly twice the mass of fuel must be burned. The values in Table 3 confirm this relationship, which is better visualised in Fig. 9. Both LNG and methanol engines require pilot fuel to ignite the respective main fuels. Generally, the combustion of methanol requires larger shares of pilot fuel compared to LNG, although it depends on the specific engine. Fig. 10 shows the same trend expressed in terms of volumetric consumption, where methanol again stands out with the highest daily volume demand because of the lower energy density.

By analysing Fig. 8, it becomes evident that for both 8G95ME-C10 and 9G95ME-C10 engines, the configurations with the medium propeller size of 10.2 m offer the greatest energy savings.

This challenges the traditional view in shipping that a larger propeller diameter will always lead to a lower fuel consumption for the main engine. A key factor in this observation is the significant speed reduction for the vessels. As a result, the increased SFOC associated with engines using larger propellers is not sufficiently offset by the reduction in propulsion power. Fig. 2 further illustrates this relationship, emphasising that each case should be evaluated individually.

EEDI

Reference and actual EEDI figures have been calculated for a Tier III engine. The calculation

incorporates a 6% tolerance on the SFOC, an SFOC of 210 g/kWh for the auxiliary engines operating on MDO, with no consideration given to WHRS or energy-saving devices. Therefore, the calculated EEDI is regarded as conservative.

The reference value is calculated with Eq. 10 [4]. As mentioned in the section on EEDI, the reference index calculation is based on 100% utilisation of dwt capacity, whereas the EEDI attained is calculated based on 70% capacity utilisation, and a reference speed consistent with this loading of the vessel at 75% SMCR, the hull in sea trial condition, and the use of a PTO of 4,500 kW.

Eq. 10

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

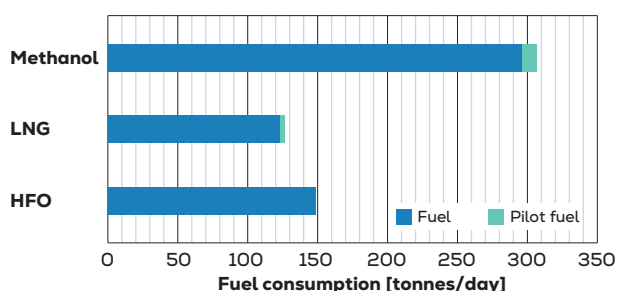


Fig. 9: Daily fuel consumption in tonnes/day for the 9G95ME-C10 engine (D=10.2 m), using methanol, LNG, and HFO

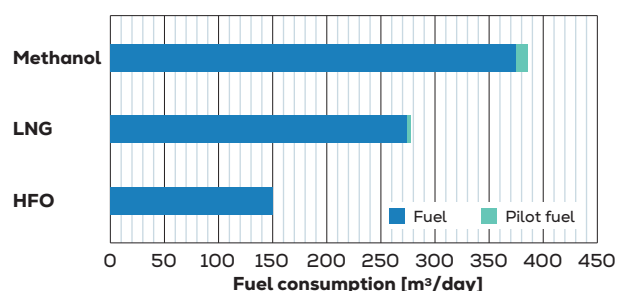


Fig. 10: Daily fuel consumption in m³/day for the 9G95ME-C10 engine (D=10.2 m), using methanol, LNG, and HFO

Table 8, Table 9, Table 10 and Fig. 11 show the calculated EEDI values. These show that all the designs fulfil the EEDI requirements for Phase 3, which mandates a 45% reduction compared to the reference line of 2013. This reduction is a result of the lower design speeds that have been implemented since the 2000s, along with advancements in

propulsion machinery and hull design. The implementation of shaft generators along with the adoption of alternative fuels and hybrid technologies has further improved energy efficiency, leading to a lower EEDI.

Additionally, it can be observed that methanol and LNG engines exhibit lower EEDI values

compared to MDO engines. If a phase 4 reduction exceeding 50% is implemented in the future, MDO engines are likely to either fail compliance, or be right on the limit, even with the installation of a PTO. Either way, ships sailing on MDO would require a vessel speed reduction to comply with the regulation.

Engine type	D _{prop} [m]	Power [kW]	Speed [rpm]	MDO		LNG		Methanol	
				EEDI	%	EEDI	%	EEDI	%
8G95ME-C10	10	40,240	78.5	8.12	51.5	7.2	45.7	7.66	48.6
8G95ME-C10	10.2	40,070	75.6	8.11	51.4	7.19	45.6	7.65	48.5
8G95ME-C10	10.4	40,000	72.9	8.12	51.5	7.2	45.7	7.67	48.6
9G95ME-C10	10	40,240	78.5	8.03	50.9	7.15	45.3	7.58	48.1
9G95ME-C10	10.2	40,070	75.6	8.02	50.8	7.13	45.2	7.57	48
9G95ME-C10	10.4	40,000	72.9	8.03	50.9	7.13	45.4	7.58	48.1

Table 8: EEDI values for MDO, LNG, and methanol **without PTO** at a vessel speed of 22 knots, using propulsion systems with a 5-bladed propeller

Engine type	D _{prop} [m]	Power [kW]	Speed [rpm]	MDO		LNG		Methanol	
				EEDI	%	EEDI	%	EEDI	%
8G95ME-C10	10	40,240	78.5	7.9	50.1	6.7	42.5	7.3	46.3
8G95ME-C10	10.2	40,070	75.6	7.89	50.1	6.69	42.4	7.29	46.2
8G95ME-C10	10.4	40,000	72.9	7.91	50.1	6.7	42.5	7.31	46.3
9G95ME-C10	10	40,240	78.5	7.81	49.5	6.64	42.1	7.22	45.8
9G95ME-C10	10.2	40,070	75.6	7.8	49.5	6.62	42	7.21	45.7
9G95ME-C10	10.4	40,000	72.9	7.81	49.5	6.63	42	7.22	45.8

Table 9: EEDI values for MDO, LNG, and methanol **with PTO Option 1** at a vessel speed of 22 knots, using propulsion systems with a 5-bladed propeller

Engine type	D _{prop} [m]	Power [kW]	Speed [rpm]	MDO		LNG		Methanol	
				EEDI	%	EEDI	%	EEDI	%
8G95ME-C10	10	40,240	78.5	7.67	48.66	6.51	41.27	7.09	44.96
8G95ME-C10	10.2	40,070	75.6	7.67	48.63	6.50	41.22	7.08	44.92
8G95ME-C10	10.4	40,000	72.9	7.68	48.70	6.51	41.27	7.10	45.01
9G95ME-C10	10	40,240	78.5	7.59	48.10	6.45	40.92	7.02	44.48
9G95ME-C10	10.2	40,070	75.6	7.58	48.05	6.44	40.81	7.01	44.43
9G95ME-C10	10.4	40,000	72.9	7.59	48.11	6.44	40.83	7.01	44.46

Table 10: EEDI values for MDO, LNG, and methanol **with PTO PowerMax** at a vessel speed of 22 knots, using propulsion systems with a 5-bladed propeller

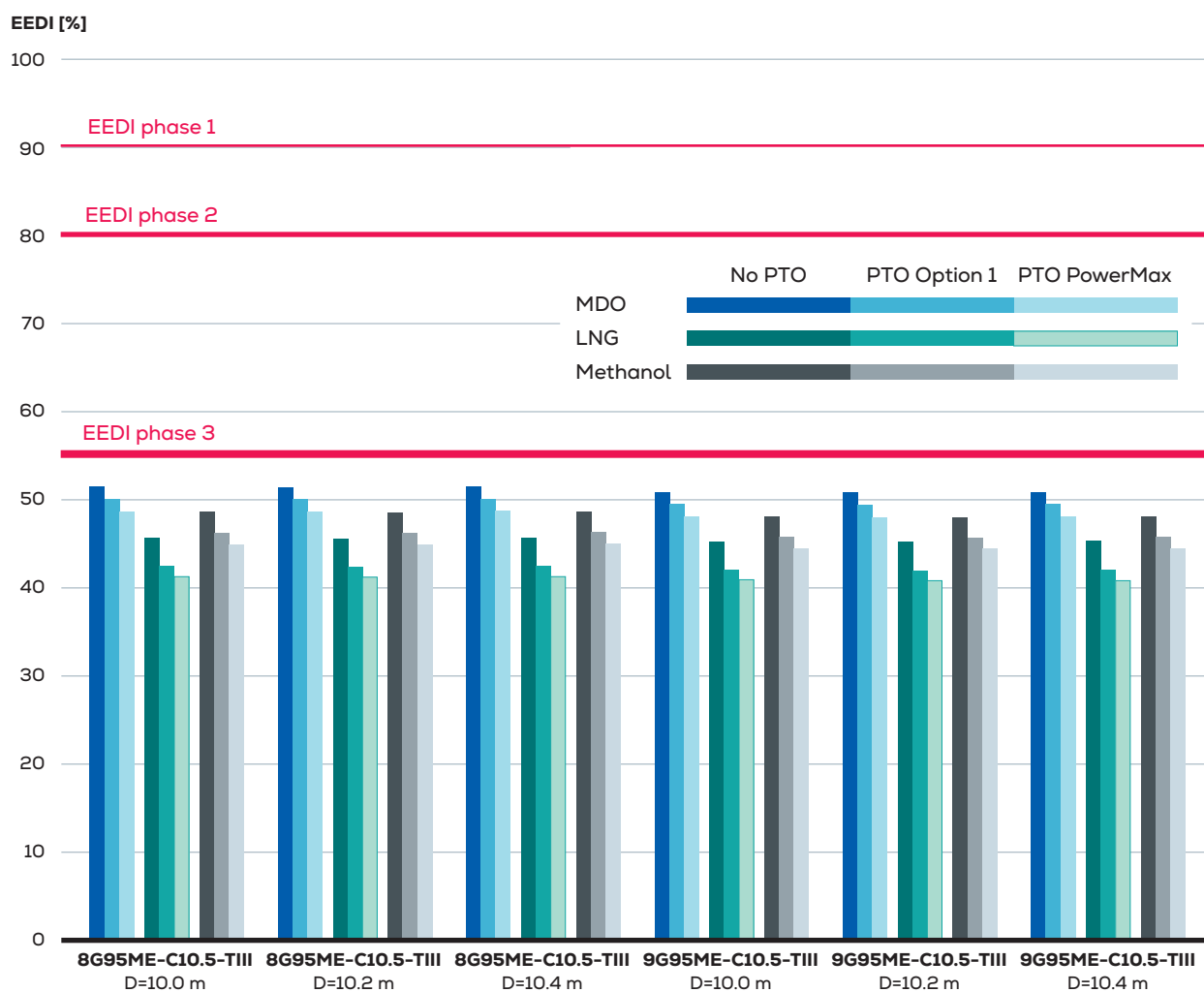


Fig. 11: EEDI values compared to the phase limitations for different PTO configurations, at a vessel speed of 22 knots

Operating costs

While previous comparisons of engine fuel performances are based on a constant engine load of 85% (NCR), the annual operational costs of the engine are influenced by its load profile.

Containerships usually operate on scheduled routes that include transoceanic crossings and subsequent port stops along the coast of a continent, resulting in a fairly predictable load profile. Adhering to the schedule is essential to ensure timely docking with the necessary resources in place, which sometimes require running at high loads to compensate for delays, or overcome harsh weather conditions. Modern containerships are typically equipped with larger engines to maximise shaft generator utilisation and to ensure that the engines remain within the recommended operating area, avoiding the heavy or short-term operating zones.

Fig. 12 illustrates an example of an engine load profile for a New Panamax containership. The load profile has been used to calculate the total main engine operating costs, including yearly lubricating oil consumption, assuming an operating

profile of 275 days/year at sea ($\approx 25\%$ in port). This estimate may seem high for some New Panamax containerships, but it is used for comparing with busy New Panamax containerships that are in operation approximately 75% of the time, reflecting their frequent deployment on long-haul routes.

The estimation of annual opex assumes:

- 275 days per year at sea ($\approx 25\%$ in port)
- Fuel prices in Table 5
- Lubricating oil price of 1,500 USD/tonne
- A price of 350 USD/tonne is assumed for NaOH (in a 50% solution) required for EGR operation
- A price for handling the discharged sludge of 100 USD/tonne.

Additionally, a PTO would slightly reduce operating costs. While the 9G95ME-C10 outperforms the 8G95ME-C10 engine at the same power output, it is important to consider the additional maintenance costs associated with an extra cylinder.

As this paper is written, and for the configurations mentioned, methanol shows the highest operating costs. A comparison of the

9G95ME-C10 engine equipped with a 10.2 m propeller in diameter across three fuel types reveals that operating the engine on methanol results in daily costs more than twice as high as those for LNG and VLSFO, based on the fuel prices listed in Table 5.

Specifically, VLSFO costs approximately \$ 85,510 per day, while LNG (including pilot fuel) costs \$ 63,440 per day. In contrast, methanol, including pilot fuel, costs around \$ 207,320 per day. However, the use of methanol is expected to become essential, since the other examined fuels may no longer meet future EEDI and related regulatory standards. Furthermore, Fig. 4 indicates a significant projected decrease in methanol prices, which is expected to enhance the viability and competitiveness. LNG proved to be the most economical during operations, factoring in engine power variations according to the engine load diagram. An exact comparison based on current market prices is not particularly important, as these prices are highly dynamic and can shift rapidly over time, making precise cost assessments challenging because of the volatile and unpredictable nature of fuel markets. Additionally, the comparison does not include compliance with regulations or the penalties for non-compliance.

It is important to consider the engine and propeller in combination when evaluating the overall system efficiency.

For 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.

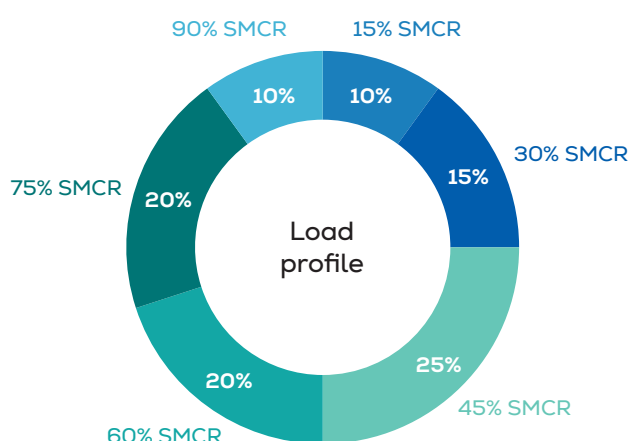


Fig. 12: Load profile for New Panamax vessels showing the engine load distribution

5. Main engine operating costs – 20 knots

Fuel consumption

As for the previous example of 22 knots, the running costs of an engine are an important factor. The following sections provide examples of selected engines that can maintain a speed of 20 knots while complying with emission regulations and remaining cost-efficient on three different kinds of fuels: MDO, LNG, and methanol.

Table 11 shows calculations of main engine fuel consumption, EEDI, operating costs at NCR = 85% SMCR, and SFOC for Tier III for five propulsion plants operating at a reduced service speed of 20 knots. The impact of the three different fuels on the EEDI at service speed, including the sea margin, is also estimated. Additionally, Table 11 highlights the corresponding SFOC and the effect on the main engine efficiency for the

five plants. Consequently, this variation in propeller diameter leads to SFOC savings because the optimal propeller configuration improves fuel efficiency.

While the engines considered are designed for operation on all three fuel types, the required SMCR point for the 7-cylinder G95ME-C10 engine designed for a 10 m propeller diameter does not fit within the engine layout diagram. Furthermore, including an engine with a different propulsion power would compromise the fairness of the comparison.

The significantly lower power required to propel the vessel at 20 knots allows for a more derated engine. This reflects in a lower SFOC (approx. 2 g/kWh) compared to the SFOC for the 22 knots example, where a more derated engine would be of an impractical size. The lower SFOC at reduced service

speed results from decreased wave-making resistance and a more favourable engine-propeller matching, which enhances the overall efficiency. It is evident that the reduced power leads to a corresponding decrease in overall fuel consumption across all engine configurations.

For the dual-fuel engines, the consumption of the main fuel (e.g., LNG, methanol) decreases due to the reduced power demand. However, since the amount of pilot fuel used is minimal compared to the main fuel, the overall fuel efficiency still shows a substantial reduction. The daily fuel consumption was obtained by multiplying the propulsion power demand at NCR (85%) by the corresponding SFOC (Table 10). Therefore, the daily energy consumption in Fig. 13 was calculated as the product of the daily fuel consumption and

Engine type	SMCR [kW]	Shaft speed [rpm]	NCR [kW]	Tier III SFOC [g/kWh]	D _{prop} [m]
6G95ME-C10	34,070	72.2	28,960	156.9	10.4
7G95ME-C10	34,070	72.2	28,960	154.5	10.4
6G95ME-C10	34,120	74.9	29,000	156.3	10.2
7G95ME-C10	34,120	74.9	29,000	154.0	10.2
6G95ME-C10	34,190	77.7	29,060	155.8	10.0

Table 11: Specifications for G95ME-C10 engine variants based on cylinder number: SMCR, shaft speed, NCR, SFOC, and propeller diameter for a 4-bladed propeller

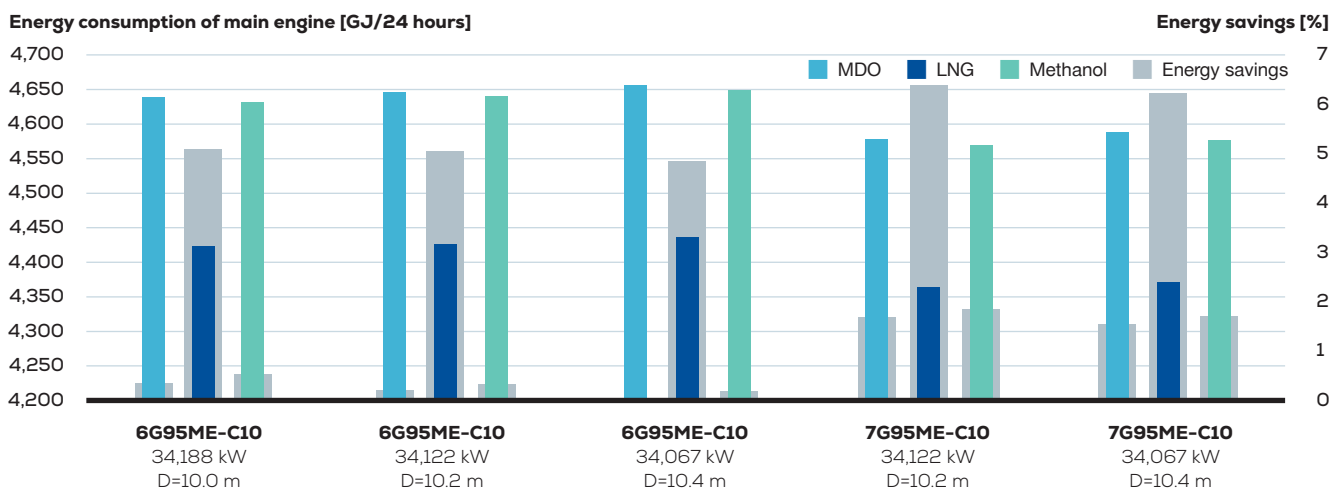


Fig. 13: Daily fuel consumption and energy savings for each engine case at 20 knots, and fuel types MDO, LNG, and methanol

the LCV of each fuel concept. Similar to the 22 knots case, the methanol consumption is nearly twice that of VLSFO and LNG for the same power output, including pilot fuels, across all dual-fuel engine types. This difference arises from the fuel properties listed in Table 3, where methanol's LCV is approximately half that of MDO and LNG.

As mentioned previously, the engine efficiency is nearly independent of the fuel type.

However, the extra space necessary to store methanol and LNG with lower densities must also be considered. A comparison between the 20 and 22 knots cases reveals approximately 25% power reduction at 20 knots, which reflects in a similar reduction of the fuel consumption. Nevertheless, the extended working hours for the crew, the extended delivery times, and the associated increase in operational costs should also be considered.

EEDI

Reference and actual EEDI figures have been calculated for a low-load optimised engine, including 6% tolerance on SFOC, and an SFOC of 210 g/kWh for the auxiliary engines, all operating on MDO. Table 12, Table 13, Table 14 and Fig. 14 show the results of the calculations.

When comparing with the EEDI of the 22 knots example, see Fig. 11 compared to Fig. 14,

Engine type	D _{prop} [m]	Power [kW]	Speed [rpm]	MDO		LNG		Methanol	
				EEDI	%	EEDI	%	EEDI	%
6G95ME-C10	10	34,190	77.7	6.44	40.82	5.73	36.36	6.08	38.58
6G95ME-C10	10.2	34,120	74.9	6.45	40.88	5.73	36.34	6.09	38.63
6G95ME-C10	10.4	34,070	72.2	6.46	40.96	5.74	36.39	6.1	38.68
7G95ME-C10	10.2	34,120	74.9	6.36	40.31	5.67	35.98	6.01	38.12
7G95ME-C10	10.4	34,070	72.2	6.37	40.36	5.68	36	6.02	38.17

Table 12: EEDI values for MDO, LNG, and methanol **without PTO** at a vessel speed of 20 knots, using propulsion systems with a 4-bladed propeller

Engine type	D _{prop} [m]	Power [kW]	Speed [rpm]	MDO		LNG		Methanol	
				EEDI	%	EEDI	%	EEDI	%
6G95ME-C10	10	34,190	77.7	6.25	39.66	5.31	33.66	5.78	36.65
6G95ME-C10	10.2	34,120	74.9	6.26	39.72	5.31	33.66	5.79	36.71
6G95ME-C10	10.4	34,070	72.2	6.28	39.8	5.32	33.71	5.8	36.77
7G95ME-C10	10.2	34,120	74.9	6.17	39.14	5.25	33.29	5.71	36.19
7G95ME-C10	10.4	34,070	72.2	6.18	39.2	5.25	33.31	5.71	36.24

Table 13: EEDI values for MDO, LNG, and methanol **with PTO Option 1** at a vessel speed of 20 knots, using propulsion systems with a 4-bladed propeller

Engine type	D _{prop} [m]	Power [kW]	Speed [rpm]	MDO		LNG		Methanol	
				EEDI	%	EEDI	%	EEDI	%
6 G95ME-C10	10	34,188	77.7	5.94	37.64	5.04	31.95	5.49	34.78
6 G95ME-C10	10.2	34,122	74.9	5.94	37.69	5.04	31.94	5.49	34.83
6 G95ME-C10	10.4	34,067	72.2	5.96	37.76	5.04	31.98	5.50	34.88
7 G95ME-C10	10	34,122	74.9	5.86	37.14	4.98	31.58	5.42	34.34
7 G95ME-C10	10.4	34,067	72.2	5.86	37.19	4.98	31.61	5.42	34.38

Table 14: EEDI values for MDO, LNG, and methanol **with PTO PowerMax** at a vessel speed of 20 knots, using propulsion systems with a 4-bladed propeller

it is clear that a speed reduction greatly influences the EEDI. On average, the attained EEDI is reduced by an index of approx. 21%. This significant reduction is achieved because the wave-making resistance on the relatively short hull decreases significantly when the vessel speed is reduced, resulting in a lower Froude number. See Chapter 1 in [1] for more information.

At 20 knots, all the designs fulfil EEDI phase 3 (30% reduc-

tion), and all engine configurations would even fulfil a 40% reduction with and without PTO, respectively. In the estimation of operational costs, the load profile is estimated to be consistent with that at 21 knots, see Fig. 12.

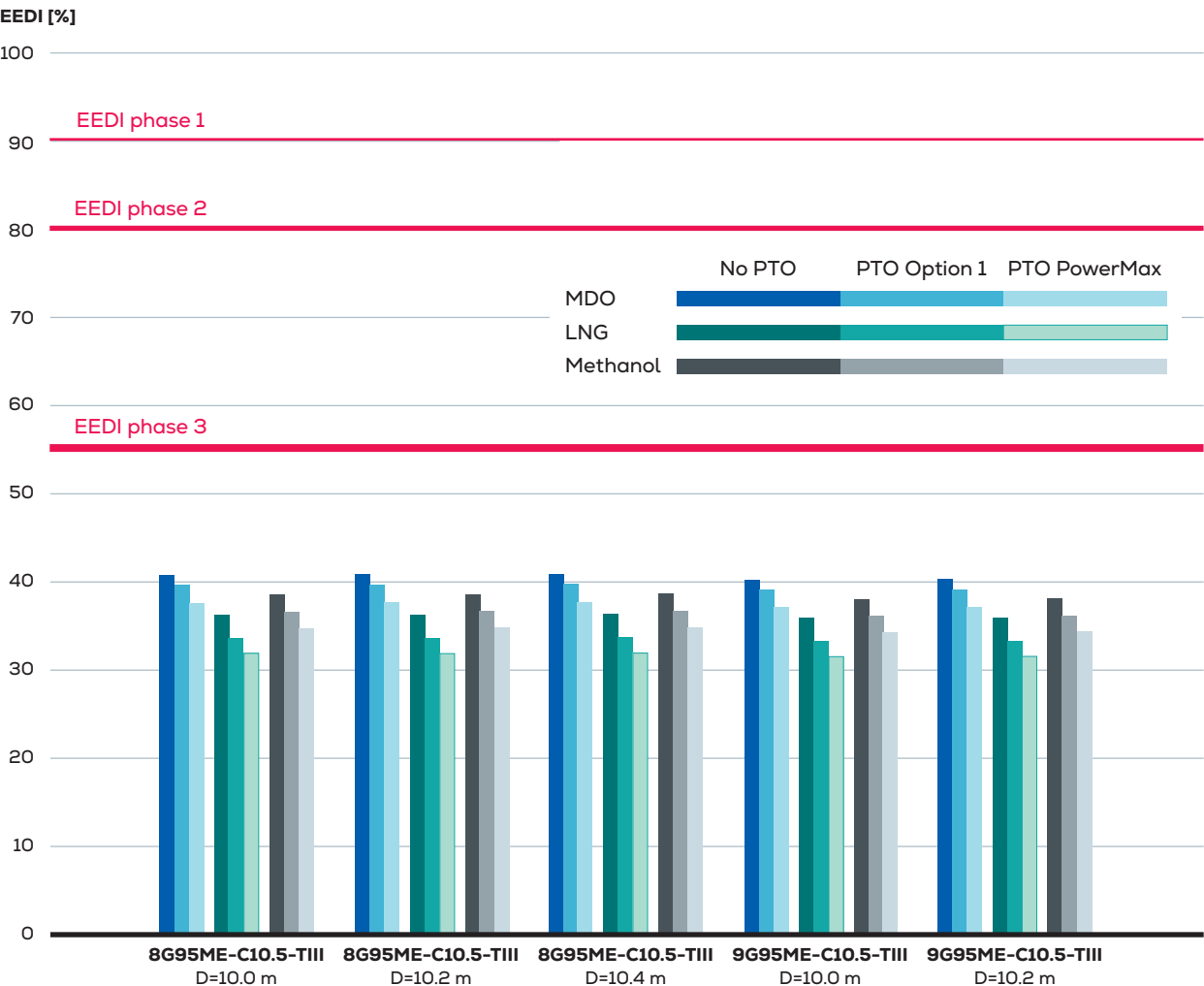


Fig. 14: EEDI values compared to the phase limitations, including PTO PowerMax, at a vessel speed of 20 knots

Operating costs

Whereas the previous comparisons of engine fuel performance are based on a constant engine load of 85% (NCR), Fig. 12 illustrates that the annual operating costs of the engine largely depend on the engine load profile.

The estimation of annual opex assumes:

- 275 days per year at sea (≈25% in port)
- Fuel prices in Table 5
- Lubricating oil price of 1,500 USD/tonne
- A price of 350 USD/tonne is assumed for NaOH (in a 50% solution) required for EGR operation
- A price for handling the discharged sludge of 100 USD/tonne.

The savings in annual main engine operating costs mainly depend on the fuel market. In the current market as of July 2024, LNG is cheaper than VLSFO and methanol, when comparing the prices per tonne in Table 5. This makes LNG the most cost-effective fuel currently, with slightly lower operating costs compared to VLSFO.

In this context, the dual-fuel engine is a great solution, since 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. If the market changes in favour of an alternative fuel as the most cost-effective fuel, the dual-fuel engine also enables a change of fuel. Additionally, PTO PowerMax can be considered for this scenario, since a New Panamax vessel with potentially increased demands for refrigerated cargo and ongoing cooling of natu-

ral gas during transport will require a larger amount of energy from the PTO system. The use of PowerMax could lead to an additional EEDI reduction compared to the previous Option 1, and to even higher reductions when compared to the initial EEDI value without PTO.

The savings in net present value will be lower compared to the first case of 22 knots, as the actual fuel oil consumption is approximately 25% lower at the reduced design speed of 20 knots. In this scenario, the benefits of the optimised propeller diameter are clear, providing ship-owners with the potential for significant cost savings. For this case, the 7G95ME-C10 engine emerges as the optimal solution. However, it is important to consider the engine size which can reduce cargo space, and also the additional costs associated with the extra cylinder.

6. Summary

Modern designs of New Panamax containerships present significant opportunities for the future in terms of adhering to environmental regulations set by the IMO. When equipped with dual-fuel engines, these vessels can achieve compliance with both EEDI standards and future low ratings in CII evaluations, while also providing a high level of operational flexibility.

Additionally, the container carrier market has widely adopted ultra-long-stroke G-type engines, driven by the benefits of increased propeller diameters, reduced design speeds, and higher efficiencies compared to smaller engines, all of which align with current efficiency optimisation trends. If stricter reductions, such as a 40% cut compared to the reference EEDI line, are required without lowering the speed from 22 knots, a switch to alternative fuels like LNG, methanol, or possibly ammonia may become essential. This shift would likely be mandatory in the transition from EEDI phase 3 to phase 4. Otherwise, PTO Interface option C, energy saving devices, waste heat recovery, or EcoEGR can be applied.

However, from both environmental and economic perspectives, implementing fuel-saving measures remains highly relevant. While installing such equipment can lead to significant savings on running costs, a complete shift to alternative fuels may not yet be cost-effective.

Modern container vessels carry a large number of reefer containers, and have a large electricity consumption at sea. The

inclusion of a power take-off/shaft generator on the main engine could be sensible, since the main engine can produce electric power at a lower SFOC than the auxiliary engines. Applying a PTO would also reduce greenhouse gas emissions thanks to the reduced running time of the auxiliary engine systems. A shaft generator is especially valuable for alternative fuels, such as LNG, thanks to the lower cost of equipment for the auxiliary system and the increased fuel efficiency of the two-stroke engine.

Besides offering the capability to use different fuels, the S- and G-type dual-fuel engines also offer an extensive selection of bore sizes and stroke lengths for the New Panamax segment. This ensures that an optimal fit can always be achieved for each individual project, and that the optimal speed of a desired propeller can always be contained within the layout diagram of one of the many possible engine designs.

If a dual-fuel engine is employed, such as a GI-engine for LNG, or an LGIM-engine for methanol, the design offers the flexibility to switch to VLSFO whenever necessary. This capability helps optimise operating costs and ensures ongoing compliance with environmental regulations. Although ammonia engines have not yet been developed, their future potential for New Panamax containerships remain highly promising.

For questions on specific cases, contact Everllence at: Marine-ProjectEngineering2S@everllence.com.

7. Acronyms

BSR	Barred speed range
CII	Carbon intensity indicator
EEDI	Energy efficiency design index
EGB	Exhaust gas bypass
EGR	Exhaust gas recirculation
FPP	Fixed pitch propeller
GHG	Greenhouse gas emission
GI	Gas injection
GT	Gross tonnage
HFO	Heavy fuel oil
HPT	High-pressure tuning
IMO	International Maritime Organization
LCV	Lower calorific value
LGIM	Liquid gas injection methanol
LNG	Liquified natural gas
LPG	Liquefied petroleum gas
LSFO	Low-sulphur fuel oil
MCR	Maximum continuous rating
MDO	Marine diesel oil
MEPC	Marine Environment Protection Committee
NCR	Normal continuous rating
Opex	Operating expenses
PTO	Power take-off
SFOC	Specific fuel oil consumption
SMCR	Specified maximum continuous rating
teu	Twenty-foot equivalent unit
ULCV	Ultra-large container vessel
URN	Underwater radiated noise
VLSFO	Very-low-sulphur fuel oil
WHRS	Waste heat recovery system
WtW	Well-to-wake

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