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How updating IMO regulations can promote lower greenhouse gas emissions from ships

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Summary

The International Maritime Organization (IMO) is considering how to update its Energy Efficiency Design Index (EEDI) this year. The EEDI was created to reduce the climate impacts of shipping, but its current design only requires that new ships emit less carbon dioxide (CO_2) over time and it does not cover emissions of other greenhouse gases (GHGs), including potent ones such as methane. The EEDI could be amended to cover all climate pollutants.

To help understand effective ways of revising the EEDI for its upcoming phase 4, we first calculated and compared the attained EEDI of large container and cruise ships using different fuel and engine combinations based on tank-to-wake (TTW) CO_2 emissions, consistent with the existing IMO regulations. We then explored the consequences of reforming the EEDI in two ways: (1) adding carbon dioxide equivalent (CO_2e) emissions using both 100-year (CO_2e100) and 20-year (CO_2e20) global warming potentials (GWPs) for GHGs and black carbon and (2) regulating on a well-to-wake (WTW) basis that accounts for both TTW and well-to-tank (WTT) emissions.

Based on the results, we recommend that the EEDI be amended to regulate TTW CO_2e20, beginning in phase 4. This would encourage the use of liquefied natural gas (LNG) only in low-methane-slip engines or the use of methanol (MeOH). Had all of the ships using dual-fuel LNG engines in 2019 been powered by either low-methane-slip engines or MeOH, their life-cycle WTW CO_2e20 emissions would have been cut by 15 million tonnes (Mt), or more than one third (36%). If the EEDI continues to regulate only TTW CO_2 and not CO_2e, then setting stricter CO_2 intensity standards under phase 4 would reward using LNG, including in high-methane-slip engines, even though lower TTW and WTW CO_2e emissions could be achieved using MeOH or low-methane-slip engines. However, even if amended to cover TTW CO_2e20, additional regulations that directly control WTW emissions, such as an improved Carbon Intensity Indicator (CII) or a Low Greenhouse Gas Fuel Standard (LGFS), would be needed to make sure that fuels with low or zero TTW emissions but high WTT emissions are not encouraged.

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Introduction and background

Adopted in 2011, the International Maritime Organization's (IMO's) Energy Efficiency Design Index (EEDI) was the first carbon intensity regulation to apply globally for any sector. Its goal is to reduce the climate impacts of shipping, but it currently only considers carbon dioxide (CO_2) emissions and not emissions of other greenhouse gases (GHGs). The EEDI requires that ships emit less tank-to-wake (TTW) CO_2 per tonne-nautical mile over time than a baseline of older ships of the same type and size.[1] It applies to ships built in 2013 and afterward and is currently in its third phase. For the largest container ships, EEDI phase 3 requires that ships built in April 2022 or later be at least 50% less carbon intensive than the baseline. For cruise ships, it requires at least a 30% reduction.

Many large container and cruise ships that are being built today are designed to run on liquefied natural gas (LNG) because it emits less CO_2 than conventional marine fuels such as heavy fuel oil (HFO) and marine gas oil (MGO). As of June 2022, by capacity, more than one-third of new container ships and more than half of cruise ships on order were capable of running on LNG (Clarksons, 2022). However, using LNG can result in higher life-cycle GHG emissions than other marine fuels, especially when evaluated using 20-year global warming potentials (GWPs; Pavlenko et al., 2020).

The EEDI could be modified so that it regulates carbon dioxide equivalent (CO_2e) emissions, either on a TTW basis, as CO_2 emissions are currently assessed, or on a well-to-wake (WTW) basis. The different approaches yield different benefits. Controlling TTW CO_2e is important to reduce emissions of non-CO_2 climate pollutants such as methane (CH_4), nitrous oxide (N_2O), and black carbon (BC). Controlling WTW CO_2e emissions is important to ensure that producing fuels to reduce shipping GHG emissions does not increase emissions in other sectors, which would be counterproductive to achieving society's climate goals. Achieving the Paris Agreement's goal of limiting global warming to well-below 2 °C and pursuing efforts to limit it to 1.5 °C is enshrined in the IMO's Initial GHG Strategy.

Existing marine fossil fuels produce both WTT (well-to-tank) and TTW CO_2e emissions, primarily CO_2, CH_4, N_2O, and BC. Future fuels might have no TTW CO_2e emissions, but significant WTT emissions associated with producing the fuel. For example, using hydrogen in a fuel cell would result in zero TTW CO_2e emissions, but if the hydrogen is made from fossil sources such as natural gas, its WTT emissions could mean its total WTW emissions end up being the same or greater than the fuel it replaces (Zhou et al., 2021). Similarly, ammonia is being considered as a zero-carbon fuel for ships because burning it in an internal combustion engine emits no CO_2 emissions. However, like hydrogen, if it is made from fossil sources, it can have high WTT emissions. Moreover, burning ammonia will produce N_2O; this means that burning it will have zero TTW CO_2 emissions, but will have some TTW CO_2e emissions. The N_2O emissions from burning ammonia in a marine engine are still being investigated, as trials of ammonia-fueled engines are just now getting under way. No matter the fuel, the WTT emissions depend on the fuel feedstock and production pathway. It is important to remember that even if the TTW emissions of fuels are the same, their total WTW emissions will vary because their WTT emissions will vary.

1 The EEDI metric is different depending on the ship type. For most ships, tonnes refers to deadweight tonnes (DWT), a measure of the mass of cargo that can be carried. For container ships, 70% of DWT is used in the EEDI calculation. For cruise passenger ships, gross tonnes (GT), a measure of the internal volume of the ship, is used.

There are two new IMO climate regulations that are set to begin in 2023: the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII). The IMO refers to these as short-term measures. The EEXI extends the EEDI concept to the existing fleet and regulates the technical efficiency of a ship based on how much TTW CO_2 it is expected to emit per deadweight tonne- or gross tonne-nautical mile at a given speed and engine power. Because existing ships usually sail slower than they were originally designed to sail, the EEXI is unlikely to result in real-world emissions reductions from the global fleet unless it is strengthened (Rutherford et al., 2020). The current EEXI standards are no more stringent than the EEDI requirements that already apply in 2022. As the EEDI is amended, additional improvements in the technical efficiency of existing ships are likely to be required over time. If the EEDI is changed to regulate CO_2e rather than CO_2, the EEXI could also be amended to cover the same suite of pollutants.

The CII ranks ships based on their operational efficiency according to their TTW CO_2, which is based on the fuel consumption they report annually to the IMO's Data Collection System (DCS). Currently, the CII is based solely on TTW CO_2 emissions. Additionally, while it ranks ships from A (best) to E (worst), it does not contain penalties, except that a shipowner or operator must draft and implement a plan of corrective actions if the ship is rated D for three consecutive years or E in any year (IMO, 2021). Stronger incentives and penalties could be added in the revision of the CII that is due to be completed by January 1, 2026. Additionally, once the IMO finalizes its life-cycle assessment (LCA) guidelines, which are expected to be completed in 2023, it will be possible to rate ships based on their WTW CO_2e intensity by using the factors developed under the guidelines in combination with the fuel consumption reported under the IMO's DCS. This would enable ships to use blends of certified-low-CO_2e fuels to comply with the CII.

The IMO is also considering mid-term climate measures, those that can be agreed and implemented between 2023 and 2030. One proposed measure is a Low GHG Fuel Standard (LGFS) that would limit the operational WTW CO_2e intensity of ships based on the mix of fuel consumption they report to the DCS (Austria et al., 2022). This requires WTT and TTW CO_2e emission factors for current and future marine fuels and engines, and those are being developed as part of IMO's abovementioned LCA guidelines.

This paper explores the consequences of reforming the EEDI. We first model and compare the attained EEDI scores of large container and cruise ships using different fuel and engine combinations. These attained EEDI scores are based on TTW CO_2, consistent with the existing IMO regulations. We then consider the impacts of altering the EEDI in two ways: (1) adding CO_2e using both 100-year (CO_2e100) and 20-year (CO_2e20) GWPs for GHGs and BC; and (2) regulating on a WTW basis (thus accounting for both TTW and WTT emissions). Following that we discuss the implications for EEDI phase 4 and how the IMO could adjust its existing and proposed climate regulations to ensure that new ships are built with lower total GHG emissions, not simply lower CO_2 emissions.

Methods

This work focuses on container ships and cruise ships for several reasons. They are among those with the largest EEDI reduction requirements for phase 3 and are among the group of ship types that had their EEDI phase 3 requirements moved up from 2025 to 2022; the latter means that their EEDI phase 4 requirements will likely begin sooner than other ship types. Additionally, large container ships and cruise ships are ordering dual-fuel engines at a higher rate than other ship types (Clarksons, 2022). Lastly, large LNG-fueled container ships use engines with low and medium methane slip, whereas large LNG-fueled cruise ships use engines with high methane slip. The focus on both ship types allows us to analyze and compare emissions from these three engine types. The characteristics of the ships analyzed are shown in Table 1.

Table 1. Ship characteristics.

Ship type	Capacity	Max speed (knots)	Main engine type	Maximum installed main engine power (kW)	Auxiliary engine type	Auxiliary engine power demand while underway (kW)
Container	220,000 DWT	28	HPDF 2-stroke	75,570	LPDF 4-stroke	2,300
Container	220,000 DWT	28	LPDF 2-stroke	75,570	LPDF 4-stroke	2,300
Cruise	183,200 GT	19	LPDF 4-stroke	57,600	LPDF 4-stroke	11,500

Note: DWT is deadweight tonnes; GT is gross tonnes; HPDF is high-pressure injection dual-fuel; LPDF is low-pressure injection dual-fuel; kW is kilowatts.

We compare LNG to methanol (MeOH) for most of the study. Today, very few ships use MeOH as a fuel, but that is beginning to change as companies like Maersk have ordered more than a dozen MeOH-fueled container ships, and CMA CGM recently announced that six of the 16 newbuild dual-fuel-engine container ships it is ordering will be MeOH-fueled (the rest will be LNG-fueled). As of June 2022, there were only 16 MeOH ships, 15 of them methanol carriers; the other is the 1,300-passenger Stena Germanica car ferry that sails between Gothenburg, Sweden, and Kiel, Germany. In total, there are 40 MeOH-fueled ships that are either in service or being built as of June 2022. Compare that to the more than 1,500 LNG-fueled ships that are now or will soon be on the water.[2]

EEDI reference line

The current EEDI standards apply to ships 400 GT and above that were built in 2013 or later, and they vary based on ship type and size (IMO, 2019). The EEDI works by first establishing a reference line, which reflects the estimated TTW carbon intensity of a baseline of ships 400 GT and above that were operating, with some exceptions, between January 1, 1999 and January 1, 2009.[3] Then, an "attained EEDI" is calculated for ships built in 2013 or later and compared to the "required EEDI," which is a percentage reduction from the reference line. The EEDI currently has three phases, and the required EEDI becomes more stringent over time. The reduction factors that determine the required EEDI vary by ship type and size.

The EEDI reference line is calculated according to Equation 1. The values in Table 2 are from MARPOL Annex VI Regulation 24: *Required EEDI*. The reference line is set based on the Estimated Index Value of the ships covered by the reference scenario. The assumption was that HFO was used by these ships, with a carbon factor (Cf) of 3.114 g CO_2/g fuel. When we evaluated potential compliance with the EEDI if it were regulated based on TTW or WTW CO_2e100 or CO_2e20, we adjusted the reference lines to account for additional TTW or WTW emissions by multiplying the EEDI reference value by the ratio of HFO TTW or WTW CO_2e Cfs to the HFO TTW CO_2 Cf. The relevant HFO CO_2e Cfs are provided in Table 4, below.

2 According to Clarksons World Fleet Register (https://www.clarksons.net/wfr/) accessed June 6, 2022.

3 See paragraph 9 of the 2013 guidelines for calculation of reference lines for use with the Energy Efficiency Design Index (EEDI): https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.231(65).pdf

Equation 1. EEDI reference lines

$$EEDI_{reference} = a \cdot b^{-c}$$

Table 2. Parameters for determining the EEDI reference line.

Ship type	a	b	c
Containership	174.22	DWT of the ship	0.201
Cruise passenger ship having non-conventional propulsion[a]	170.84	GT of the ship	0.214

[a] Nearly all new cruise ships have what the IMO would call "non-conventional propulsion." Most cruise ships have diesel-electric propulsion whereby they use a series of engines for both propulsion and auxiliary power.

Attained EEDI

While the detailed formula can be found in IMO Resolution MEPC.308(73), for this analysis, we simplified the attained EEDI formula and used Equation 2, below. The assumptions for each variable are in Table 3. When we analyzed the impacts of using MeOH instead of LNG, we modeled a 2-stroke dual-fuel MeOH main engine for the container ships and a 4-stroke dual-fuel MeOH engine for the cruise ship. For auxiliary engines, we assumed that the LNG-fueled ships used a 4-stroke low-pressure injection dual-fuel (LPDF) engine and that the MeOH-fueled ships used a 4-stroke dual-fuel MeOH engine. The specific fuel consumption (SFC) assumptions are from the Fourth IMO GHG Study (Faber et al., 2020), with a few exceptions. The LPDF 4-stroke pilot fuel SFC is from Sphera (2021) because no pilot fuel was listed in the Fourth IMO GHG Study for this engine. The SFC for the 2-stroke MeOH engine and the MGO pilot fuel for that engine are based on MAN's engine calculator tool.[4] The SFC for the 4-stroke MeOH engine starts from the Fourth IMO GHG Study's assumption of 370 g MeOH/kWh and applies an assumption from MAN (2021) that 95% of fuel consumption is from MeOH and 5% is from pilot fuel.

Equation 2. Simplified attained EEDI

$$Attained\ EEDI = \frac{(P_{ME} * (SFC_{ME,i,j} * Cf_j + SFC_{ME_{pilot,i,j}} * Cf_{pilot}) + P_{AE} * (SFC_{AE,i,j} * Cf_j + SFC_{AE_{pilot,j}} * Cf_{pilot}))}{Capacity * V_{ref}}$$

Where:

P_{ME} = 75% of maximum main engine power in kW

SFC_{ME} = g fuel/kWh, which varies by engine *i* and fuel *j*

Cf = gCO_2/g fuel, which varies by fuel type *j*

$SFC_{MEpilot}$ = g MGO/kWh, which varies by engine i and main engine fuel type *j*

Cf_{pilot}= gCO_2/g fuel, which is assumed to be 3.206, representing MGO pilot fuel

P_{AE} = auxiliary engine demand at cruising speeds, which varies by ship class and size, in kW

SFC_{AE} = g fuel/kWh, which varies by engine *i* and fuel *j*

$SFC_{AEpilot}$ = g MGO/kWh, which varies by main engine fuel type *j*

4 Tool is available at https://www.man-es.com/marine/products/planning-tools-and-downloads/ceas-engine-calculations. Assumption based on the MAN 11G95ME-C10.5-LGIM engine.

Capacity = deadweight tonnage, except for containerships where it is equal to 70% of DWT, and cruise ships where it is 100% of GT

V_{ref} = speed associated with P_{ME}

Table 3. Parameters used to calculate attained EEDI.

Parameter	Unit	Container ship (HPDF 2-stroke)	Container ship (LPDF 2-stroke)	Cruise ship (LPDF 4-stroke)
P_{ME}	kW	56,678	56,678	43,200
$SFC_{ME\ HFO}$	g fuel/kWh	175	175	185
$SFC_{ME\ MGO}$	g fuel/kWh	165	165	175
$SFC_{ME\ LNG}$	g fuel/kWh	135	148	156
$SFC_{ME\ MeOH}$	g fuel/kWh	324	324	352
$SFC_{MEpilot\ LNG}$	g MGO/kWh	6	0.8	3.8
$SFC_{MEpilot\ MeOH}$	g MGO/kWh	9.8	9.8	8.75
P_{AE}	kW	2,300	2,300	11,500
$SFC_{AE\ HFO}$	g fuel/kWh	185	185	185
$SFC_{AE\ MGO}$	g fuel/kWh	175	175	175
$SFC_{AE\ LNG}$	g fuel/kWh	156	156	156
$SFC_{AE\ MeOH}$	g fuel/kWh	352	352	352
$SFC_{AEpilot\ LNG}$	g MGO/kWh	3.8	3.8	3.8
$SFC_{AEpilot\ MeOH}$	g MGO/kWh	8.75	8.75	8.75
Capacity	70% of DWT for Container or 100% GT for Cruise	154,000	154,000	183,200
V_{ref}	nautical miles per hour	25.4	25.4	17.3
Cf HFO	g CO_2/g fuel	3.114		
Cf MGO	g CO_2/g fuel	3.206		
Cf LNG	g CO_2/g fuel	2.750		
Cf MeOH	g CO_2/g fuel	1.375		

When analyzing the impacts of regulating EEDI based on TTW or WTW CO_2e accounting for CO_2, CH_4, N_2O, and BC, the Cfs in Equation 2 were replaced by those in Table 4, which are from Comer and Osipova (2021). That study used TTW values from Faber et al. (2020) and WTT values from the U.S. Argonne National Laboratory's GREET 2020 model. We emphasize that the emission factors in Table 4 use default factors that are especially sensitive to assumptions about methane slip. The ICCT is leading a project to measure real-world methane slip from LNG engines and fugitive methane emissions from LNG fuel tanks and cargo tanks on ships as part of a project called FUgitive Methane Emissions from Ships (FUMES).[5] These emission factors might change as data from that and other projects add to our understanding.

5 For more information about FUMES, please visit https://theicct.org/maritime-shipping-fumes-march2022-statement/

Table 4. Carbon factors when calculating attained EEDI using TTW or WTW CO_2e.

		TTW			WTW		
Fuel	**Engine**	**CO_2**	**CO_2e100**	**CO_2e20**	**CO_2**	**CO_2e100**	**CO_2e20**
LNG	HPDF 2-stroke	2.750	2.864	2.965	3.280	3.940	5.008
	LPDF 2-stroke	2.750	3.308	4.244	3.280	4.385	6.288
	LPDF 4-stroke	2.750	3.854	5.758	3.280	4.930	7.801
MeOH	2-stroke or 4-stroke	1.375	1.375	1.375	1.738	1.825	1.976
MGO	2-stroke	3.206	3.284	3.357	3.782	4.007	4.340
	4-stroke	3.206	3.408	3.802	3.782	4.130	4.785
HFO	2-stroke	3.114	3.316	3.710	3.545	3.874	4.495
	4-stroke	3.114	3.457	4.219	3.545	4.015	5.004

Required EEDI

The required EEDI is a percentage reduction from the EEDI reference line. For the largest container ships, EEDI phase 3 requires a 50% reduction. The largest cruise ships are subject to a 30% reduction. These reduction factors are established by MARPOL Annex VI Regulation 24.

Emissions comparison by fuel and engine

We calculated and compared emissions from using LNG or MeOH for ships that used LNG dual-fuel engines in 2019. We first estimated energy demands from main engines and auxiliary engines for each ship using the ICCT's Systematic Assessment of Vessel Emissions (SAVE) model (Olmer et al., 2017), which has been updated to use assumptions that are consistent with the Fourth IMO GHG Study (Faber et al., 2020). We then used the methods described above to estimate TTW and WTW CO_2e100 and CO_2e20 emissions from using LNG or MeOH in these ships. While we recognize that these existing ships could not use MeOH without engine modifications, the analysis demonstrates how the emissions profile of the ships would have been different had they used similar MeOH-fueled engines rather than LNG-fueled engines.

Results and discussion

The largest container ships use 2-stroke, slow-speed engines and therefore can use HPDF or LPDF 2-stroke engines. These engines have methane slip on the order of 0.15% and 1.7%, respectively, according to the Fourth IMO GHG Study (Faber et al., 2020) and Pavlenko et al. (2020). The largest cruise ships use LPDF 4-stroke engines that have methane slip of approximately 3.5% (Faber et al., 2020; Pavlenko et al., 2020).[6] We refer to HPDF 2-stroke, LPDF 2-stroke, and LPDF 4-stroke engines as low-, medium-, and high-methane-slip engines, respectively.

As large container ships and cruise ships shift away from HFO, their options are MGO, LNG, or, more recently, MeOH. Using HFO or MGO, without the adoption of innovative technologies such as wind-assisted propulsion or hull air lubrication, these ships would not comply with EEDI phase 3 because of the relatively high carbon intensity of these fuels, as shown in Figure 1. Using MeOH, the ships would comply, and the attained

6 Note that Pavlenko et al. (2020) explained that LPDF engines might also have crankcase emissions that can add an additional 1 g/kWh of methane emissions from these engines. If so, that would equate to 4.5% methane slip for LPDF 4-stroke engines.

EEDI would be nearly exactly the required EEDI. Using LNG, the example ships would comply by a margin of 10 percentage points because of the lower CO_2 intensity of LNG compared to the other fuels. In fact, using LNG, the container ships would be able to achieve a 60% reduction from the EEDI baseline and the cruise ship could achieve a 40% reduction. If EEDI phase 4 requires any greater reductions and continues to only focus on TTW CO_2, Figure 1 shows that the only fuel that could comply would be LNG.

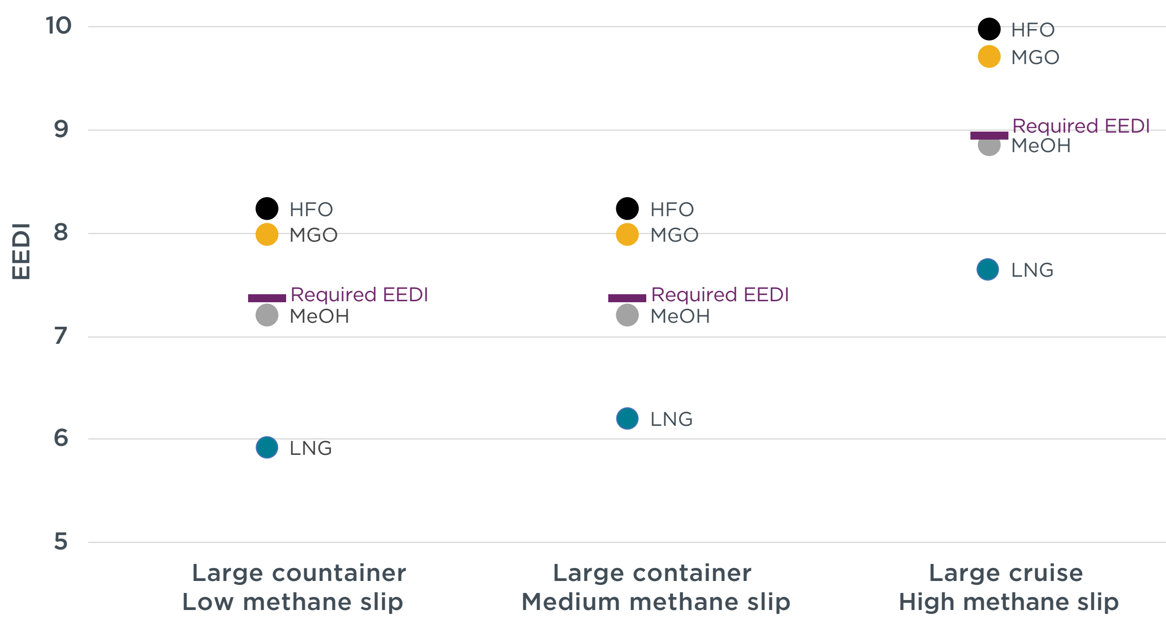

Figure 1. Comparing required EEDI phase 3 and attained EEDI for three ship-engine combinations using HFO, MGO, MeOH, and LNG.

TTW CO_2e emissions

If the EEDI were modified to regulate TTW CO_2e, we find that MeOH would continue to comply with EEDI phase 3 (Figure 2) but using LNG would not guarantee compliance because of methane slip. The LPDF 2-stroke engine would need to cut its methane slip by 28% to comply with EEDI phase 3 if regulated on CO_2e20. The LPDF 4-stroke engine would need to reduce its methane slip by 25% if regulated on CO_2e100 or 47% if regulated on CO_2e20. As shown in Figure 2, methane's contribution to CO_2e emissions is larger when applying its GWP20 (82.5) compared to its GWP100 (29.8). Using GWP100 spreads out the warming impacts of methane emissions over 100 years even though methane has an atmospheric lifetime of only about 9–12 years (Intergovernmental Panel on Climate Change, 2021). Calculating attained EEDI based on CO_2e20, instead, would require deeper reductions in emissions of short-lived climate pollutants with shorter atmospheric lifetimes such as methane.

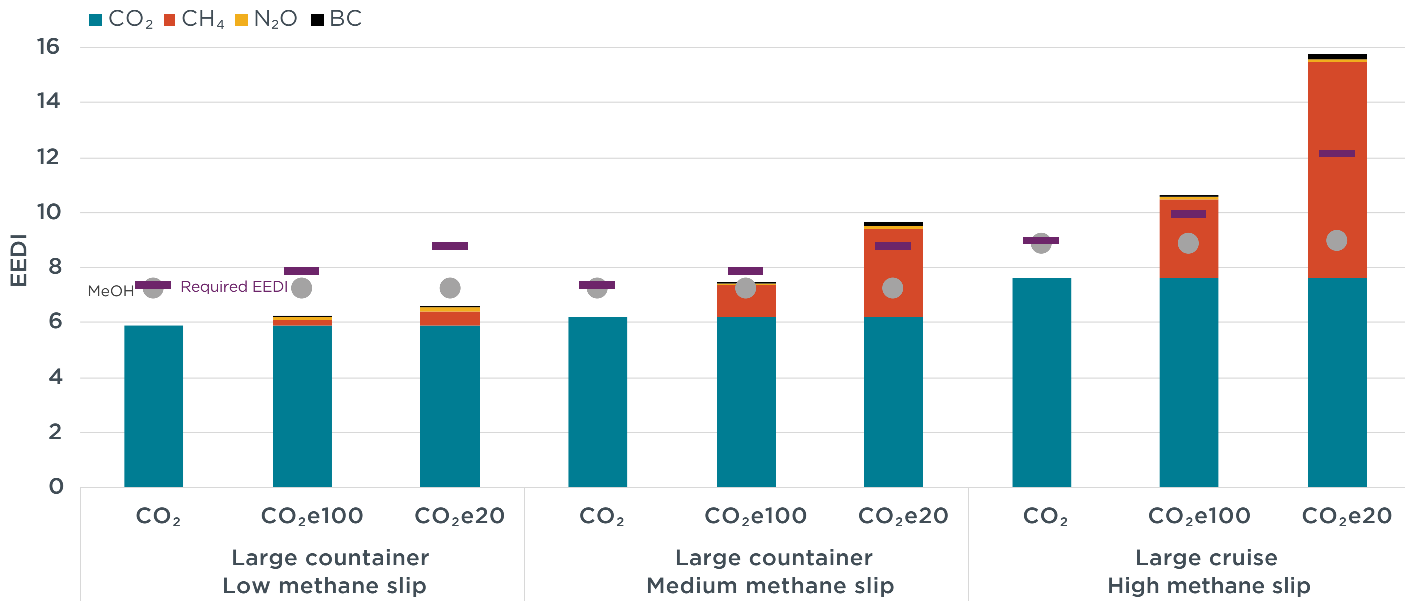

Figure 2. Comparing estimated attained EEDI using LNG (stacked bars) and MeOH (dots) to required EEDI phase 3 using TTW CO_2e100 and CO_2e20 for three ship-engine combinations.

Using MeOH would not only eliminate the TTW methane slip issues associated with LNG, but MeOH is liquid under ambient conditions. Therefore, unlike LNG, which starts as a gas but is cooled to liquefy it, there is no need for cryogenic storage for MeOH. One downside of MeOH, though, is that using it reduces the maximum range of the ship by about one-third compared to LNG; this is because MeOH has lower volumetric energy density.[7] Also, unlike LPDF LNG engines, MeOH will require aftertreatment to comply with IMO Tier III nitrogen oxides (NO_X) regulations, which apply to ships built in 2016 or later when they operate in the North American and U.S. Caribbean Emission Control Areas (ECAs) and ships built in 2021 or later when they operate in the Baltic and North Sea ECAs. Still, MAN (2021) has suggested that it is possible to mix MeOH with 20%–45% water and achieve Tier III standards without aftertreatment. For LNG engines, the HPDF engine requires NOx aftertreatment, but the LPDF engines do not. The tradeoff is higher methane slip for the LPDF engines.

Figure 2 also shows that for LNG, the ship using the low-methane-slip HPDF engine would continue to comply with EEDI, despite some methane slip emissions, and TTW CO_2e emissions are lower than when using MeOH. The ship using the medium-methane-slip LPDF 2-stroke engine would only barely comply when using LNG if EEDI were regulated on TTW CO_2e100 and would no longer comply if regulated on TTW CO_2e20. For the ship using the high-methane-slip LPDF 4-stroke engine, it would no longer comply with EEDI phase 3, even if regulated on CO_2e100, due to its high methane emissions. In this case, the only existing fuel that would consistently meet EEDI phase 3 for all dual-fuel engine types would be MeOH.

7 Assuming LNG is approximately 22 MJ/L and MeOH is approximately 15 MJ/L and assuming similar engine efficiency using either fuel.

Alternate compliance options

Another compliance option for the shipowner would be to choose a smaller engine to reduce installed main engine power and associated speed.[8] Other options that would allow ships to continue to use LNG in this instance include using some combination of more efficient hull designs, better antifouling paint, wind-assisted propulsion, hull air lubrication, batteries, fuel cells, and other zero-emission technologies.

Engine manufacturers are also working to reduce methane slip, and the IMO has collected information on ways to reduce methane emissions from marine engines as part of its EEDI phase 4 correspondence group. Options include developing 4-stroke HPDF engines; retrofitting 4-stroke and 2-stroke LPDF engines to be HPDF (but this would also require installing NO_x aftertreatment systems, in most cases); and methane oxidation catalysts (MOCs). Engine manufacturers like MAN have stated that converting engines to HPDF can reduce methane slip by 90% and MOCs can reduce slip by 70%. MAN offers options for converting 2-stroke diesel engines to HPDF and is also developing a 4-stroke HPDF engine.[9]

MOCs, which could be useful in reducing methane slip from LPDF engines that have medium and high methane slip, work best on mono-fuel LNG engines (e.g., LBSI), but these engines are spark-ignited, rather than dual-fuel, and dual-fuel engines are the most common LNG-fueled technology. Unfortunately, the pilot fuel that is required for dual-fuel engines and lubricating oil both contain contaminants like sulfur that can render MOCs ineffective (Lott et al., 2020; Ottinger et al., 2015). MOCs also increase capital costs, operating costs, and maintenance costs. Therefore, unless there is an incentive or requirement to use them, shipowners would be expected to continue to use unabated LPDF engines.

WTW CO_2e emissions

If the EEDI regulated WTW CO_2e (Figure 3), ships could comply using MeOH with some minor engine power reductions or by using the technologies mentioned earlier to reduce fossil fuel consumption. For LNG, the ship using the low-methane-slip HPDF engine can comply using LNG. No matter the GWP time frame, neither the ship using the medium-methane-slip LPDF 2-stroke nor the ship using the high-methane-slip LPDF 4-stroke engine could comply. .

8 For example, to comply with EEDI phase 3 if regulated on TTW CO_2e20, the container ship using the LPDF 2-stroke engine would need to reduce its installed main engine power by more than 15%, which would reduce its maximum speed by 5%. For the cruise ship, complying with EEDI phase 3 if regulated on TTW CO_2e20 would require reducing its installed main engine power by nearly 50%, which would reduce its maximum speed by 20%.

9 https://www.man-es.com/docs/default-source/man-primeserv/sustainability/man_ps_retrofit_dual_fuel_conversion.pdf?sfvrsn=d24d69fa_4

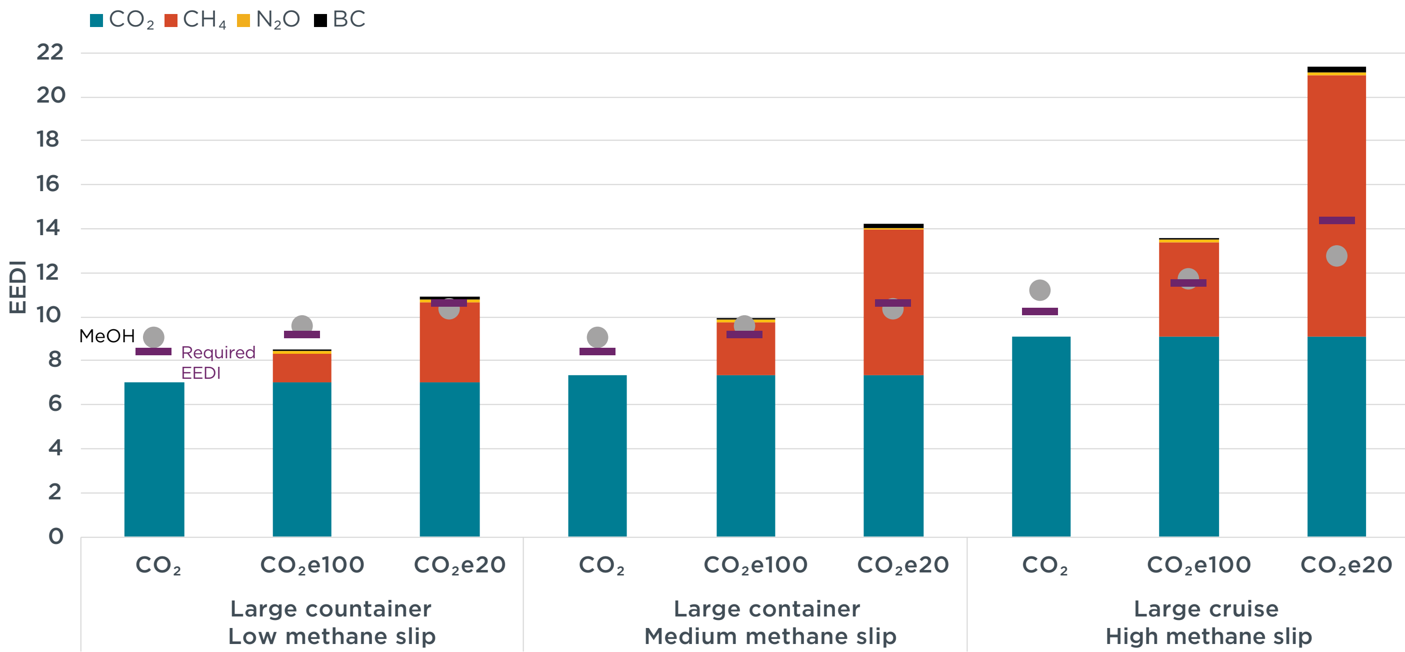

Figure 3. Comparing estimated attained EEDI using LNG (stacked bars) and MeOH (dots) to required EEDI phase 3 using WTW CO_2e100 and CO_2e20 for three ship-engine combinations.

Note that the analysis shown in Figure 3 relies on our WTT assumptions for the upstream emissions associated with LNG and MeOH. In reality, there will be a range of WTT emission factors based on each fuel's feedstock and production pathway. Pavlenko et al. (2020) presented a range of WTT CO_2e100 emission factors in the appendix to their study and it showed a range of 8.8 to 31 gCO_2e100/MJ. Applying that range results in the WTW EEDI values presented in Figure 4, which illustrates that variability in WTT emissions can sometimes change whether a ship would comply with the EEDI if it were regulated based on WTW CO_2e. Moreover, a ship is unlikely to source its fuel from the same place over its lifetime and the emissions from a given fuel supplier can change over time. Figure 4 also illustrates that even using the engine with high methane slip, there could be a scenario where the reported WTT emissions are low enough that the use of that high methane slip engine with minor modifications to the engine or the ship could result in compliance if regulated on GWP100. As demonstrated earlier, using GWP20 instead of GWP100 to calculate CO_2e emissions creates an incentive to use best-in-class technologies that have the lowest methane slip, whereas using GWP100 does not.

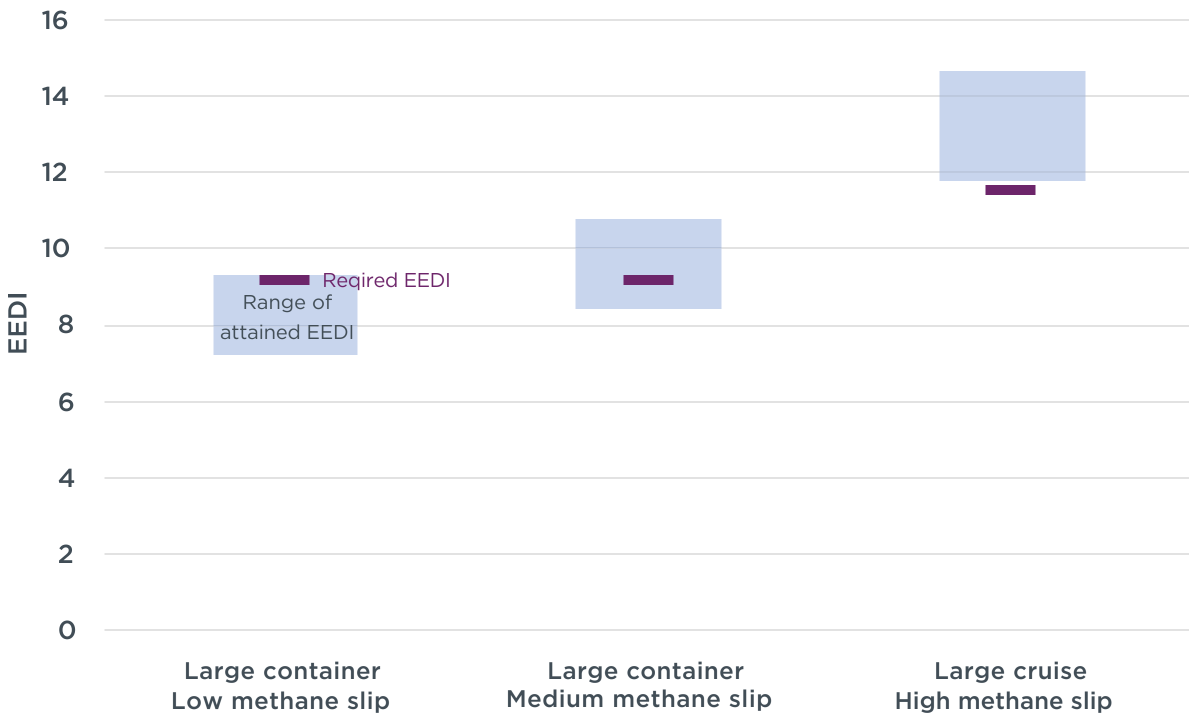

Figure 4. Potential attained EEDI of ships using LNG dual-fuel engines if EEDI were regulated on WTW CO_2e100, accounting for a range of WTT values for LNG.

Emissions comparison using 2019 data

Figure 5 compares our estimates of the TTW emissions from ships using LPDF 4-stroke, LPDF 2-stroke, and HPDF engines in 2019 when using LNG compared to if they had used MeOH instead. Emissions from LNG-fueled ships using these engines in 2019 totalled approximately 16 Mt CO_2, 21 Mt CO_2e100, and 30 Mt CO_2e20, respectively, according to ICCT's SAVE model. As shown in Figure 5, using LNG emits 14% less CO_2 but 14% more CO_2e100 and 62% more CO_2e20 than MeOH. Similarly, as shown in Figure 6, on a WTW basis, using LNG emits 19% less CO_2 but 11% more CO_2e100 and 57% more CO_2e20 than MeOH. Overall, compared to MeOH, using LNG in these engines resulted in excess TTW emissions of 2.5 Mt CO_2e100 (11 Mt CO_2e20) and WTW emissions of 2.7 Mt CO_2e100 (15 Mt CO_2e20).

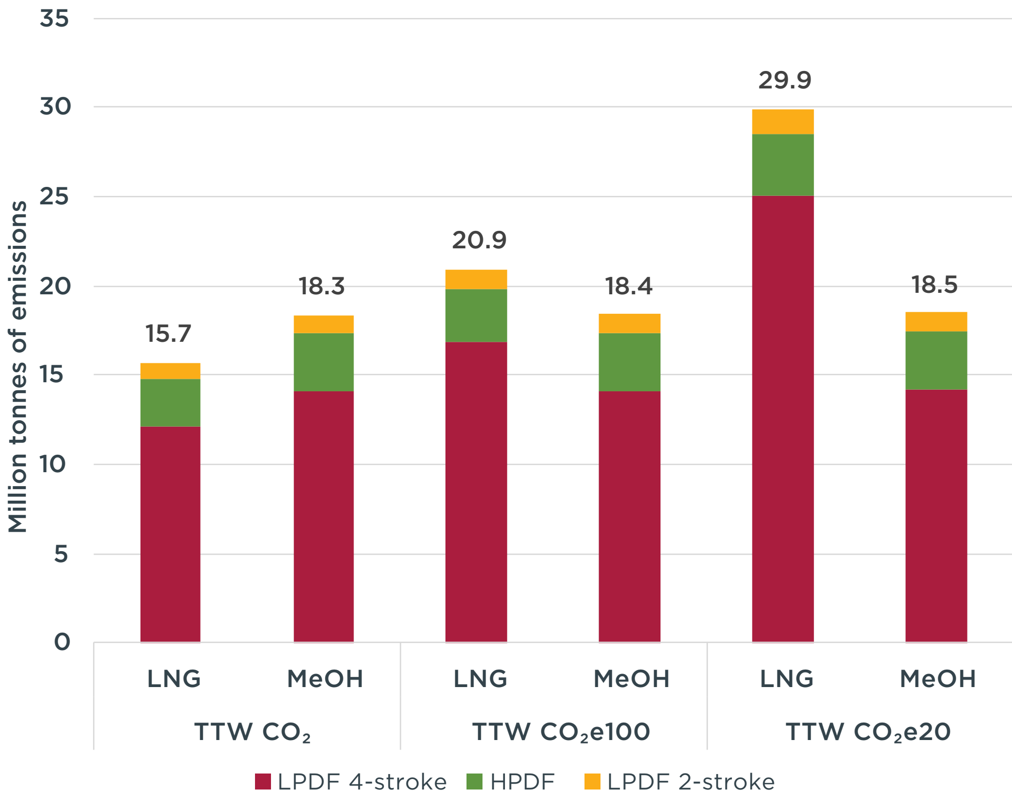

Figure 5. Comparing estimated 2019 TTW emissions from LNG-fueled ships using LPDF and HPDF engines to what they would had been if they had been fueled by methanol.

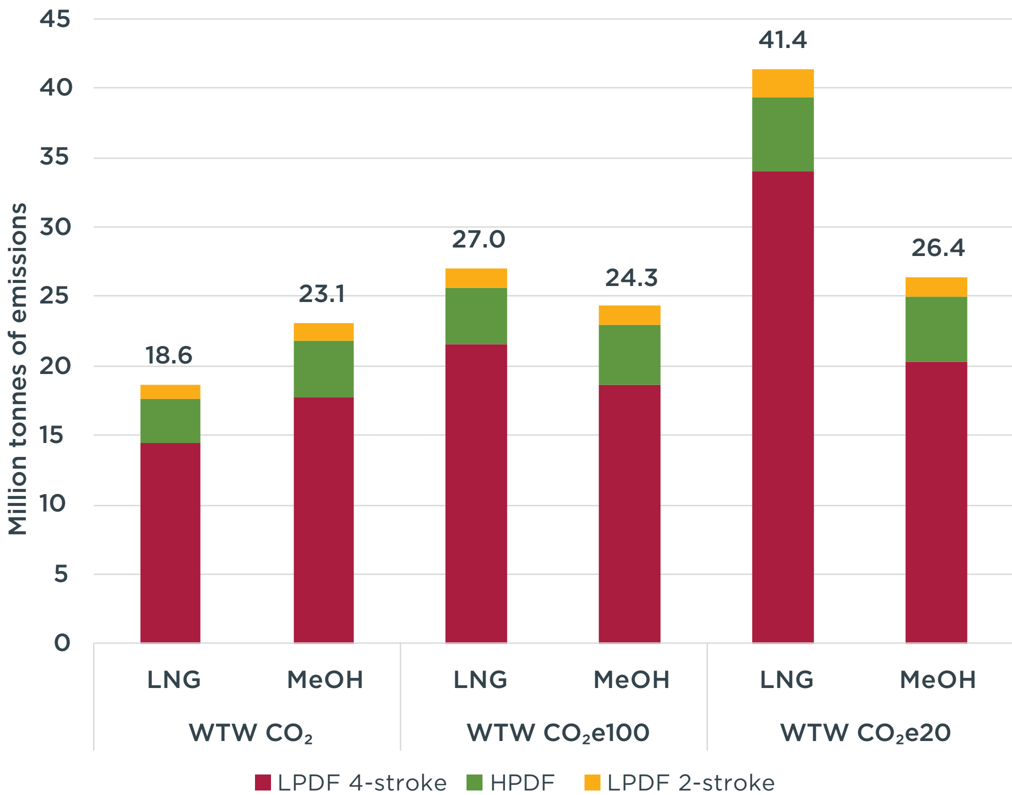

Figure 6. Comparing estimated 2019 WTW emissions from LNG-fueled ships using LPDF and HPDF engines to what they would had been if they had been fueled by methanol.

Implications for EEDI phase 4

We have shown that any dual-fuel LNG engine technology can meet EEDI phase 3 standards, and that the largest container and cruise ships could have complied with an EEDI standard 10 percentage points stricter than phase 3 using LNG, meaning a 60% or 40% reduction, respectively, from the EEDI baseline. We discussed that the EEDI is best suited for regulating TTW emissions, given the variability in WTT emissions, but these results also show that controlling WTW emissions is important for achieving climate goals. If the EEDI were amended to regulate TTW CO_2e100, it would encourage the use of LNG in engines with low or medium methane slip or the use of MeOH. If EEDI were instead amended to regulate TTW CO_2e20, it would encourage the use of LNG only in low-methane-slip engines or the use of MeOH. We estimated that using LNG in dual-fuel engines resulted in 41.4 Mt of WTW CO_2e20 emissions in 2019. Had all of the ships using dual-fuel LNG engines been powered by either low-methane-slip engines or MeOH, their life-cycle WTW CO_2e20 emissions would have been approximately 26.4 Mt, a reduction of 15 Mt, or 36%. Thus, regulating TTW CO_2e20 can help reduce WTW CO_2e20 emissions, especially those associated with methane. For these reasons, we recommend that the EEDI begin to regulate TTW CO_2e20, beginning with phase 4. Additional regulations that directly control WTW emissions will be needed so that fuels that have low or zero TTW CO_2e, but high WTT CO_2e, are not rewarded.

Note that if the EEDI continues to regulate TTW CO_2 and not CO_2e, there is a risk that strengthening it in phase 4 could reduce CO_2 emissions but increase GHG emissions. This is because the stricter CO_2 intensity standards would reward using LNG, including in high-methane-slip engines, even though lower TTW and WTW CO_2e emissions could be achieved using MeOH or low-methane-slip engines.

Conclusion

We explored how the IMO's EEDI could be modified to ensure that new ships are built with lower total GHG emissions, not simply lower CO_2 emissions. We modeled the attained EEDI of large container ships and cruise ships using different fuel and engine combinations and then analyzed the consequences of regulating TTW or WTW CO_2e using both 100-year (CO_2e100) and 20-year (CO_2e20) GWPs for GHGs and BC instead of regulating strictly TTW CO_2.

Based on our analysis, we recommend that beginning with phase 4, the EEDI regulate TTW CO_2e20. If the EEDI continues regulate TTW CO_2, setting stricter CO_2 intensity standards under phase 4 would encourage the use of LNG, even in high-methane-slip engines, even though lower TTW and WTW CO_2e emissions could be achieved using MeOH or low-methane-slip engines. Continuing to regulate only TTW CO_2 under the EEDI would therefore be counterproductive to phasing out GHG emissions.

Regulating TTW CO_2e20 would encourage the use of LNG only in low-methane-slip engines or the use of MeOH. Had all of the ships using dual-fuel LNG engines in 2019 been powered by either low-methane-slip engines or MeOH, their life-cycle WTW CO_2e20 emissions would have been approximately 15 Mt lower, a 36% reduction. However, additional regulations that directly control WTW emissions, such as an improved CII or a LGFS, will be needed so that fuels with low or zero TTW emissions, but high WTT emissions, are not encouraged.

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