EEDI/EEXI Verification of Wind-Assisted Propulsion Systems

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1. INTRODUCTION

International shipping is responsible for international transportation and has complicated relationships among ship registry countries, real owners, operators, shippers, *etc*. Therefore, measures to reduce greenhouse gas (GHG) from international shipping do not fit into the framework of national reduction measures under the UNFCCC. As a result, the measures have been left to International Maritime Organization (IMO). On the other hand, GHG emissions from coastal (domestic) shipping are counted in the national emissions under the UNFCCC framework, and measures are being studied by the respective countries.

As part of efforts to reduce GHG emissions, IMO has focused on improvement of the energy efficiency of individual ships from the viewpoint of satisfying both GHG reduction and economic development. Since 2013, IMO has implemented EEDI (Energy Efficiency Design Index) as a fuel consumption regulation for ship design and SEEMP (Ship Energy Efficiency Management Plan) as a fuel consumption regulation for ship operation. Furthermore, IMO adopted Initial IMO GHG Strategy to reduce the GHG emissions from international shipping in 2018. As short-term measures of the GHG Strategy, EEXI (Energy Efficiency Existing Ship Index) and CII (Carbon Intensity Indicator) rating have been also begun since 2023. At MEPC 80 held in July 2023, the GHG Strategy was revised and set an enhanced common ambition to reach net-zero GHG emissions from international shipping by or around, i.e. close to 2050.

As one of elemental technologies to achieve this, the use of wind power as assisted propulsion has attracted renewed interest. In addition to the traditional sails used since antiquity, systems that use large-scale kite connected to ships to capture wind and tow the ship, rotor systems that rotate cylindrical devices mounted on the deck and generate lift force by the Magnus effect, *etc*. have already been put into practical use, and Wind-Assisted Propulsion Systems (WAPS) are progressing daily. In this paper, methods for reflecting and verifying WAPS in the EEDI/EEXI schemes are explained in detail, together with an overview of the EEDI/EEXI regulations, the history of development of IMO-related guidance, the effect of shipping routes on EEDI/EEXI, incentive programs for installation of WAPS and future issues.

2. REPRESENTATIVE WIND-ASSISTED PROPULSION SYSTEMS

IMO has newly adopted the ambitious goal of "reaching net-zero GHG emissions by or around, i.e. close 2050". As a result, there is renewed interest in technologies that use wind power as assisted propulsion as one of the elemental technologies to achieve this goal. Fig. 1 shows representative WAPS. Hard sails are hard wing sails made of FRP or other suitable materials. Due to their wing shape, they are superior to conventional soft sails used in yachts in terms of efficiency in converting wind to thrust. Soft sails can generate the same thrust as hard sails because the soft sail is unfurled along their wing-shaped frames. Towing kite takes advantage of the fact that wind speed increases at higher altitudes and is considered to have a GHG reduction effect of 20% or more since the kite can capture wind at higher altitudes. Although the towing kite has problems with deployment and recovery for the operation, systems are now designed to perform deployment and recovery automatically using the bow mast, and large towing force can be obtained because kite turn in a figure 8 motions and move at high speed acting as a wing. In rotor sail systems, cylindrical rotors are vertically mounted on the ship's deck and generate lift force by the Magnus effect when they capture wind. The principle is the same as that of a curveball in baseball, which curves due to the rotation of the ball. The suction wing has a suction slit in a steel sail with an elliptical horizontal cross section and is capable of generating large lift force using the air suction effect to increase airflow adhesion. In the hull form concept, the ship's hull itself is wing-shaped, so it is possible to convert wind energy to propulsion power even without additional equipment. Propulsion power is maximized using the principle that the wing-shaped hull generates lift force, mainly in the form of leading-edge thrust, when oblique wind strikes the hull above the waterline.

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3. HISTORY OF DEVELOPMENT OF GUIDANCE ON INNOVATIVE ENERGY EFFICIENCY TECHNOLOGIES

https://www.mol.co.jp https://www.neoline.eu https://www.kline.co.jp

(a) Hard Sail (b) Soft Sail (c) Towing Kite

https://www.norsepower.com http://site.craintechnologies.com https://ladeas.no

(d) Rotor Sail (e) Suction Wing (f) Hull Form

Fig. 1 Representative Wind-Assisted Propulsion Systems

At MEPC 65 held in 2013, "GUIDANCE ON TREATMENT OF INNOVATIVE ENERGY EFFICIENCY TECHNOLOGIES FOR CALCULATION AND VERIFICATION OF THE ATTAINED EEDI" [1] was approved to incorporate the effects obtained from innovative energy efficiency technologies such as WAPS, Hull Air Lubrication Systems, Waste Heat Recovery Systems and other innovative energy efficiency technologies into the EEDI framework. However, it was not possible to reflect the effects of WAPS in EEDI because the "probability of occurrence for the respective wind speed and angle encountered in the main global shipping routes" as well as the estimation and verification methods of "wind-assisted propulsion force for the respective wind speed and angle" specified in this guidance were not yet completed. On the other hand, there were several concrete projects to introduce WAPS in Japan, and industry demanded the early development of an environment in which their fuel consumption performance can be officially evaluated. In order to reflect the effects of WAPS in EEDI as quickly as possible, Japan, together with China and Germany, submitted a draft amendment to "GUIDANCE ON TREATMENT OF INNOVATIVE ENERGY EFFICIENCY TECHNOLOGIES" related to WAPS at MEPC 76 held in March 2021 [2]. Although Finland, France, Comoros and RINA also submitted proposals for WAPS at MEPC 76, these proposals were deferred to the next MEPC 77 due to time constraints. At MEPC 77 held in November 2021, a draft amendment [3] based on the proposal by Japan, China and Germany at MEPC 76, which also reflected elements of the proposals by Finland, France, Comoros and RINA was approved. As a result, IMO issued "2021 GUIDANCE ON TREATMENT OF INNOVATIVE ENERGY EFFICIENCY TECHNOLOGIES FOR CALCULATION AND VERIFICATION OF THE ATTAINED EEDI AND EEXI" (hereinafter, "GUIDANCE ON INNOVATIVE ENERGY EFFICIENCY TECHNOLOGIES") [4], and the effects of WAPS technologies could at last be reflected in the EEDI/EEXI schemes.

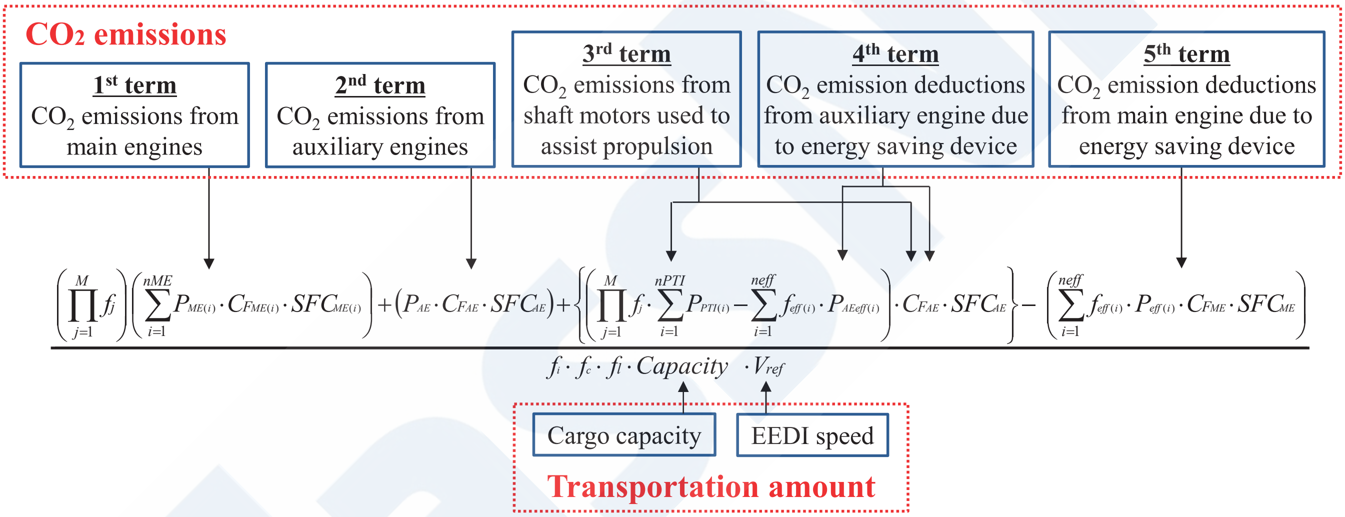
4. OVERVIEW OF EEDI/EEXI REGULATIONS

EEDI and EEXI are one of specifications for newly built ships and are indexes that express "potential efficiency". As the basic concept, as shown in Eq. (1), these indexes are calculated by multiplying the certified specific fuel oil consumption (SFC), CO_2 conversion factor and engine power and dividing the product by the ship’s cargo capacity and speed. The result expresses the expected CO_2 emission (g) when a cargo of one ton is transported one nautical mile. They are applicable only to specified ship types. Ships that exceed the specified size for each type must comply with the required value ("Required EEDI/EEXI") for its type, but required values are not set for ships which is less than the specified size.

$$\mathrm{EEDI/EEXI\ (g/t \cdot mile)} = \frac{\mathrm{CO_2\ conversion\ factor \times SFC\ (g/kWh) \times Engine\ power\ (kW)}}{\mathrm{Cargo\ capacity\ (t) \times Ship\ speed\ (mile/h)}} \quad (1)$$

4.1 EEDI/EEXI Calculation Formula

As shown in Fig. 2, at a glance, the EEDI/EEXI calculation formula appears to be complicated, but its idea is based on the fundamental concept described above. The first term in the numerator of the formula is used to estimate the CO_2 emissions from the main engines, and the CO_2 emissions are calculated by multiplying the engine power, specific fuel oil consumption (SFC) and CO_2 conversion factor. The second term is used to estimate the CO_2 emissions from the auxiliary engines, and the basic idea is the same as that of the main engines. The third term is used to estimate the CO_2 emissions from shaft motor(s) used to assist propulsion. The fourth and fifth terms are CO_2 emission deductions from the auxiliary engine and main engine emissions when an energy saving device (ESD) is installed. In this case, the CO_2 emissions from the auxiliary engine or main engine can be reduced by an amount equivalent to the energy-saving effect of the ESD. The cargo capacity in the denominator is the deadweight (DWT) at the maximum summer load draft, except for passenger ships, and the EEDI speed V_{ref} is the ship speed at the maximum summer load draft at 75% of MCR (Maximum Continuous Rating).



P_{ME} : Main engine power $0.75 \times (MCR_{ME} - P_{PTO})$ [kW]
P_{AE} : Auxiliary engine power $0.025 \times MCR_{ME} + 250$ [kW] ($0.05 \times MCR_{ME}$, if $MCR_{ME} < 10{,}000$ kW)
P_{PTI} : 75% of output power by shaft motor [kW]
SFC : Specific fuel oil consumption [g/kWh]
C_F : CO_2 conversion factor corresponding to fuel type
Capacity : DWT (70% DWT for container ships and GT for passenger ships)
V_{ref} : Ship speed at P_{ME} at maximum summer load draft (draft at 70% DWT for container ships) in calm seas [knots]

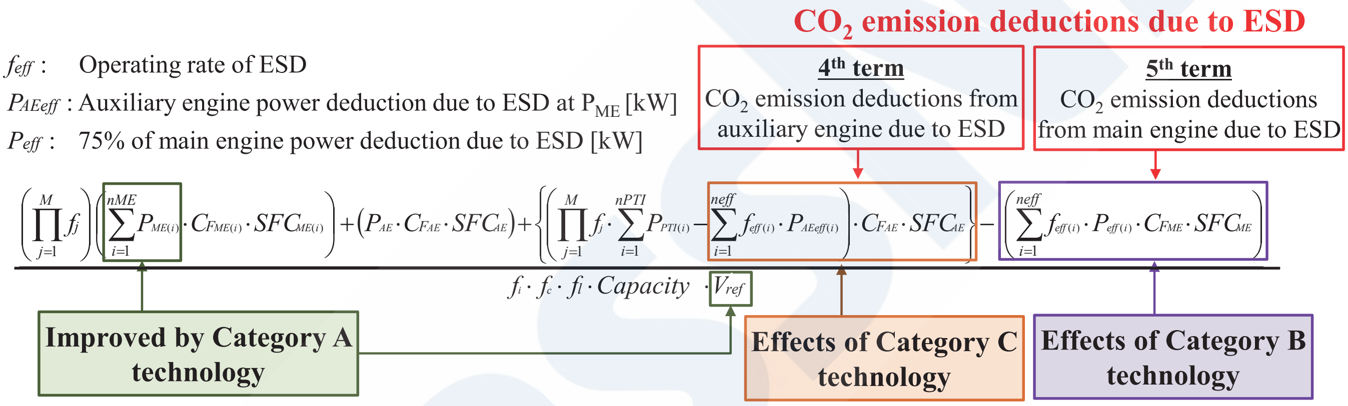
Fig. 2 EEDI/EEXI calculation formula

4.2 Method for Reflecting Energy Efficiency Technologies in EEDI/EEXI

As shown in Table 1, "innovative energy efficiency technologies" are classified into three categories in EEDI/EEXI. The first is Category A and includes technologies that affect propulsion efficiency and total resistance, as reflected in the speed-power curve. Additional devices such as ducts and fins installed on the stern and improvement of the hull form fall under this category. As shown in Fig. 3, the effect of Category A technologies is reflected in the main engine power and the ship speed. The second is Category B technologies, which reduce main engine power by activating the device. Hull Air Lubrications Systems fall under Category B-1, while WAPS are classified as Category B-2 because the operation depends on the ambient environment. Their effects are reflected in the 5th term of the numerator. The third is Category C, which reduces the power of auxiliary engines or motors by activating the device. Waste Heat Recovery Systems are classified as Category C-1, and Photovoltaic Cells are classified as Category C-2 because their operation depends on the ambient environment. Their effects are reflected in the 4th term of the numerator. The concrete EEDI/EEXI calculation and verification methods for the Energy Saving Devices (ESD) in Category B and Category C are specified in the IMO's GUIDANCE ON INNOVATIVE ENERGY EFFICIENCY TECHNOLOGIES.

Table 1　Categories of innovative energy efficiency technologies

Category		Contents		Energy Saving Devices
Category A		Influence on propulsive efficiency and total resistance, and consequently reflected in the speed-power curve.		Stern duct, rudder bulb, Hull form optimization
Category B	(B-1)	Main engine power is reduced at any time during the operation of the system.	$f_{eff} = 1.0$	Hull Air Lubrication Systems
	(B-2)	Main engine power is reduced depending on the ambient environment.	$f_{eff} < 1.0$	Wind-Assisted Propulsion Systems
Category C	(C-1)	Auxiliary engine/motor power is reduced at any time during the operation of the system.	$f_{eff} = 1.0$	Waste Heat Recovery Systems
	(C-2)	Auxiliary engine/motor power is reduced depending on the ambient environment.	$f_{eff} < 1.0$	Photovoltaic Cells



$$\frac{\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE}\right) + \left\{\left(\prod_{j=1}^{M} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right\} - \left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}\right)}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot V_{ref}}$$

Fig. 3　Calculation method of EEDI/EEXI for each category of innovative energy efficiency technology

5.　METHOD FOR REFLECTING EFFECT OF WAPS IN EEDI/EEXI

WAPS reduce main engine power, but they depend on the ambient environment. Therefore, they are classified as Category B-2, their reduction effect is reflected in the 5th term of the numerator. The concrete calculation method for WAPS is specified in the GUIDANCE ON INNOVATIVE ENERGY EFFICIENCY TECHNOLOGIES. As shown in Fig. 4, the propulsion power generated by WAPS is calculated by multiplying the Wind Force Matrix, which gives the wind-assisted propulsion force for the respective wind speed and angle, and the Global Wind Probability Matrix, which gives the probability of occurrence for the respective wind speed and angle encountered in the main global shipping routes. The reduction of propeller propulsion power is calculated by dividing the propulsion power obtained from the WAPS by the ship's propulsion efficiency, and the CO_2 emission deductions from the main engines is then calculated based on this reduction of propeller propulsion power and the electric power demand of the WAPS.

$$\frac{\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE}\cdot C_{FAE}\cdot SFC_{AE}\right) + \left\{\left(\prod_{j=1}^{M} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) \cdot C_{FAE}\cdot SFC_{AE}\right\} - \left(\sum_{i=1}^{neff} f_{eff(i)}\cdot P_{eff(i)} \cdot C_{FME}\cdot SFC_{ME}\right)}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot V_{ref}}$$

$$(f_{eff} \cdot P_{eff}) = \left(\frac{1}{\sum_{k=1}^{q} W_k}\right) \cdot \left(\left(\frac{0.5144 \cdot V_{ref}}{\eta_D} \sum_{k=1}^{q} F(V_{ref})_k \cdot W_k\right) - \left(\sum_{k=1}^{q} P(V_{ref})_k \cdot W_k\right)\right)$$

with $F_1 - F_k \geq 0 \wedge F_{k-1} - F_k \geq 0$

(sorting all force matrix elements in descending order)

and $\sum_{k=1}^{q-1} W_k < \frac{1}{2} \wedge \sum_{k=1}^{q} W_k \geq \frac{1}{2}$

(defining q: the number of elements added in the formula)

$F(V_{ref})_k$: Matrix which represents the wind-assisted propulsion force for the respective wind speed and angle (Wind Force Matrix)

W_k : Matrix which represents the probability of occurrence for the respective wind speed and angle encountered in the main global shipping routes (Global Wind Probability Matrix)

$P(V_{ref})_k$: Matrix which represents electric power demand for the operation of the WAPS

Fig. 4 Method for reflecting effect of WAPS in EEDI/EEXI

5.1 Wind Force Matrix

As shown in Table 2, Wind Force Matrix represents a matrix of the wind-assisted propulsion force for the respective wind speed and angle. GUIDANCE ON INNOVATIVE ENERGY EFFICIENCY TECHNOLOGIES specifies that the Wind Force Matrix is to be obtained from wind tunnel model tests, CFD and other numerical calculations and full-scale tests, depending on the type of WAPS. For example, in the case of towing kite, numerical calculations such as CFD validated by full-scale tests can also be accepted since it is difficult to conduct the wind tunnel model tests. In any case, it is necessary to create the Wind Force Matrix by an appropriate estimation method corresponding to the type of WAPS.

Table 2 Matrix of wind-assisted propulsion force for the respective wind speed and angle (Wind Force Matrix)

Wind Angle(°) / Wind speed(m/s)	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115
<1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	3.7	5.0	6.0	6.5	6.7	6.6	6.2
<4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.5	9.3	13.3	16.6	19.1	21.0	22.1	22.6	22.6	22.0	21.0	19.6
<5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.4	13.5	20.6	26.5	31.4	35.1	37.7	39.2	39.6	39.1	37.8	35.8	33.3	30.5
<6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.3	19.9	30.1	38.8	45.9	51.4	55.1	57.2	57.7	56.8	54.8	51.8	48.1	43.9	39.4
<7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.3	22.2	36.5	48.9	59.2	67.2	72.9	76.3	77.4	76.6	74.1	70.3	65.6	60.2	54.5	48.6
<8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.6	37.9	55.1	69.8	81.6	90.3	95.9	98.5	98.5	96.1	92.0	86.6	80.4	73.6	66.5	59.2
<9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.1	32.5	55.6	75.8	92.7	105.9	115.1	120.4	122.1	120.7	116.8	111.2	104.4	96.8	88.7	80.2	71.4
<10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.1	48.1	75.1	98.5	117.6	132.0	141.6	146.4	147.0	144.3	139.1	132.1	124.0	115.1	105.6	95.5	85.3
<11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	30.4	65.3	96.5	123.1	144.5	160.1	169.8	174.0	173.6	169.6	163.1	154.9	145.6	135.3	124.2	112.6	101.0
<12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	44.0	84.1	119.7	149.7	173.4	190.0	199.8	203.3	201.9	196.8	189.2	179.8	169.2	157.4	144.7	131.6	119.2
<13	0.0	0.0	0.0	0.0	0.0	0.0	9.1	58.9	104.5	144.7	178.3	204.1	221.8	231.6	234.5	232.1	225.9	217.3	206.8	194.8	181.4	167.0	152.8	140.4
<14	0.0	0.0	0.0	0.0	0.0	0.0	18.8	75.1	126.5	171.6	208.8	236.8	255.5	265.2	267.6	264.3	257.2	247.5	235.8	222.4	207.3	191.4	176.5	165.0
<15	0.0	0.0	0.0	0.0	0.0	0.0	29.4	92.6	150.2	200.3	241.1	271.5	291.1	300.8	302.6	298.5	290.5	279.8	266.9	251.9	235.1	218.0	203.1	193.3
<16	0.0	0.0	0.0	0.0	0.0	0.0	40.8	111.4	175.4	230.8	275.4	308.1	328.6	338.4	339.6	334.8	325.9	314.3	300.0	283.4	265.0	247.0	232.6	225.3
<17	0.0	0.0	0.0	0.0	0.0	0.0	53.2	131.5	202.3	263.1	311.7	346.6	368.1	377.9	378.6	373.1	363.5	350.8	335.2	316.9	297.0	278.5	265.4	261.2
<18	0.0	0.0	0.0	0.0	0.0	0.0	66.5	152.9	230.7	297.2	349.8	387.1	409.6	419.4	419.8	413.7	403.3	389.5	372.4	352.4	331.2	312.6	301.4	301.1
<19	0.0	0.0	0.0	0.0	0.0	0.0	80.8	175.6	260.8	333.1	389.8	429.5	453.0	463.0	463.0	456.3	445.2	430.3	411.7	390.0	367.7	349.4	340.6	344.8
<20	0.0	0.0	0.0	0.0	0.0	0.0	95.9	199.6	292.4	370.8	431.8	473.9	498.5	508.6	508.3	501.1	489.3	473.2	453.0	429.6	406.5	389.1	383.3	392.5
<21	0.0	0.0	0.0	0.0	0.0	0.0	111.9	224.8	325.7	410.4	475.6	520.3	546.0	556.3	555.7	548.1	535.5	518.2	496.4	471.4	447.6	431.5	429.5	444.1
<22	0.0	0.0	0.0	0.0	0.0	0.0	128.9	251.4	360.5	451.7	521.4	568.7	595.5	606.0	605.3	597.3	583.9	565.4	541.8	515.4	491.2	476.9	479.0	499.6
<23	0.0	0.0	0.0	0.0	0.0	0.0	146.8	279.3	396.9	494.7	569.1	619.0	647.0	657.8	657.0	648.6	634.4	614.6	589.4	561.5	537.3	525.2	532.0	558.8
<24	0.0	0.0	0.0	0.0	0.0	0.0	165.6	308.4	434.9	539.6	618.7	671.3	700.6	711.8	710.8	702.0	687.1	665.9	639.0	609.9	585.9	576.4	588.4	621.9
<25	0.0	0.0	0.0	0.0	0.0	19.4	185.3	338.8	474.5	586.3	670.2	725.7	756.2	767.8	766.8	757.7	741.9	719.3	690.7	660.4	636.9	630.5	648.3	688.8
≥25	0.0	0.0	0.0	0.0	0.0	23.5	195.5	354.6	494.9	610.3	696.7	753.6	784.7	796.6	795.6	786.3	770.1	746.8	717.4	686.6	663.4	658.7	679.5	723.6

5.2 Consideration of Effect of Altitude on Wind Speed

In comparison with the wind speed at higher altitudes, the wind speed near the ground or sea surface decreases due to the effect of friction, as shown in Fig. 5. There is a "power law" as an expression for the variation of wind speeds with height from the ground or sea (vertical distribution of wind speed). In the GUIDANCE ON INNOVATIVE ENERGY EFFICIENCY TECHNOLOGIES, the 1/9 power law based on the wind speed at 10m above the sea level has been adopted in accordance with the ITTC recommended procedures so that the effect of altitude on wind speed can be considered, as shown in Eq. (2).

Since towing kite flies at higher altitudes, their towing force should be obtained using the wind speed at the flight altitude. Moreover, the Wind Force Matrix for towing kite need to be created considering the vertical distribution of wind speed. The wind speed at 300m above sea is 1.46 times greater than at 10m above sea, and 100m above sea it is 1.29 times greater, as shown in Fig. 6.

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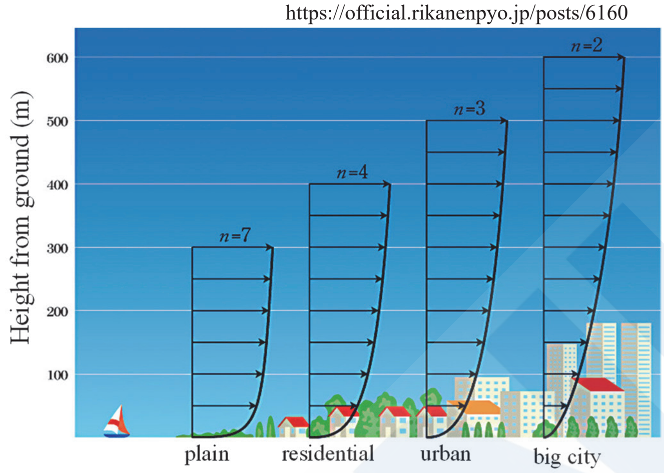


Fig. 5　Vertical distribution of wind speed

$$v_{Zref} = v_{10m}\left(\frac{Z_{ref}}{10}\right)^{\alpha} \quad for \;\; z_{ref} < 300m$$
$$v_{Zref} = v_{10m}\left(\frac{300}{10}\right)^{\alpha} \quad for \;\; z_{ref} \geq 300m \qquad (2)$$

Z_{ref}: reference height above the sea level (m)
v_{10m}: wind speed at 10m above the sea level (m/s)
v_{Zref}: resulting wind speed at the reference height (m/s)
α: taken as 1/9 conforming to the ITTC recommended procedures

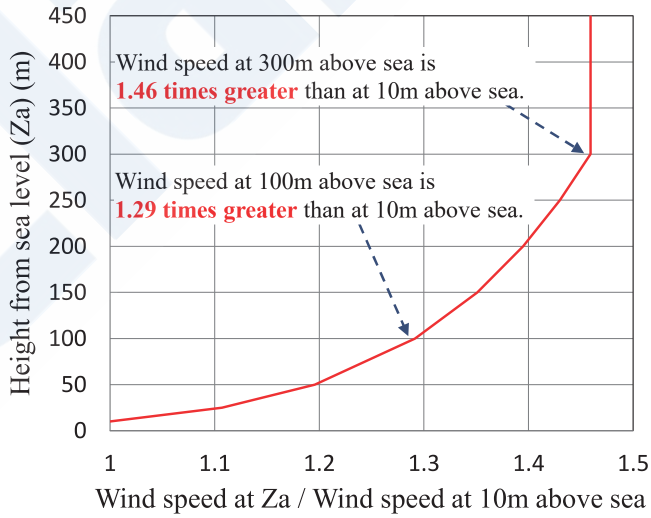
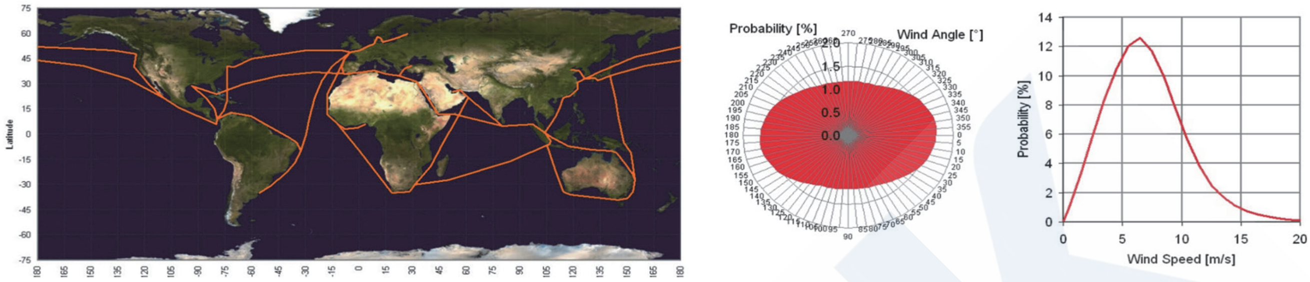


Fig. 6　Vertical distribution of wind speed above the sea level

5.3　Global Wind Probability Matrix

Since IMO develops regulations based on the assumption that a ship may operate on any shipping route in the world, ships must be evaluated for not specific shipping routes but all routes worldwide. Therefore, as shown in Fig. 7, Global Wind

Probability Matrix is defined as a matrix of the probability of occurrence for the respective wind speed and angle encountered in the main global shipping routes. Due to the route effect, there is some divergence between the effects of WAPS in the EEDI/EEXI (which are based on the global average of wind conditions) and their actual effects, but this is a limitation of the concept as a design index. Therefore, the actual effect is reflected in the Carbon Intensity Indicator (CII), which is an operational index.



Wind Angle [°] / Wind Speed [m/s]	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115
<1	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
<2	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
<3	0.0009	0.0009	0.0009	0.0009	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008
<4	0.0013	0.0013	0.0013	0.0013	0.0012	0.0012	0.0012	0.0012	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0010	0.0010	0.0010	0.0010	0.0011	0.0011	0.0011	0.0011	0.0011
<5	0.0017	0.0017	0.0017	0.0016	0.0016	0.0015	0.0015	0.0015	0.0014	0.0014	0.0013	0.0013	0.0013	0.0012	0.0012	0.0012	0.0012	0.0012	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013
<6	0.0021	0.0020	0.0020	0.0019	0.0018	0.0018	0.0017	0.0016	0.0016	0.0015	0.0015	0.0014	0.0014	0.0014	0.0014	0.0013	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0015	0.0015
<7	0.0022	0.0022	0.0021	0.0020	0.0020	0.0019	0.0018	0.0017	0.0017	0.0016	0.0015	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0015	0.0015	0.0015	0.0015
<8	0.0020	0.0020	0.0020	0.0019	0.0019	0.0018	0.0017	0.0016	0.0016	0.0015	0.0014	0.0014	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0014	0.0014	0.0014
<9	0.0017	0.0017	0.0017	0.0016	0.0016	0.0016	0.0015	0.0014	0.0014	0.0013	0.0013	0.0012	0.0012	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0012	0.0012
<10	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0012	0.0012	0.0011	0.0011	0.0010	0.0010	0.0010	0.0009	0.0009	0.0009	0.0009	0.0009	0.0009	0.0008	0.0008	0.0008	0.0009	0.0009
<11	0.0010	0.0010	0.0010	0.0010	0.0009	0.0009	0.0009	0.0009	0.0009	0.0008	0.0008	0.0008	0.0008	0.0007	0.0007	0.0007	0.0007	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006
<12	0.0007	0.0007	0.0007	0.0007	0.0007	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
<13	0.0004	0.0005	0.0005	0.0005	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002
<14	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
<15	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
<16	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
<17	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
<18	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
<19	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
<20	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
<21	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
<22	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
<23	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
<24	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
<25	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
>=25	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Fig. 7 Matrix of probability of occurrence for the respective wind speed and angle encountered in the main global shipping routes (Global Wind Probability Matrix)

5.4 Effect of Shipping Route on EEDI/EEXI

According to China [5], it has been reported that the EEDI improvement effect was only 1.6% when a Wind Probability Matrix for all routes worldwide was used to evaluate the VLCC equipped with two hard sails shown in Fig. 8, but when a Wind Probability Matrix based on routes limited to the Middle East/Far East was used, the improvement in EEDI was 16%. This remarkable difference is thought to have occurred because the Middle East-Far East Routes are an ideal environment for WAPS, in that ships are frequently sailing with beam winds.

Fig. 8 VLCC equipped with two hard sails (Dalian Shipbuilding Industry Company; China)

5.5 Incentives for Installation of WAPS

Since the effect of WAPS calculated for EEDI/EEXI and the actual effect diverges due to the route effect, Germany and Finland, which were concerned about the effect on popularization of WAPS, submitted an additional draft amendment to IMO with the aim of incentivizing the installation of WAPS [6)], and as a result of deliberations, this proposal was accepted. Since it is assumed that wind-assisted ships will operate mainly on routes with favorable strong winds, the two countries proposed using only the top half of wind speeds in Global Wind Probability Matrix, and disregarding the remainder as an incentive to encourage installation of WAPS. However, this approach simply applies the idea of the 1/3 significant wave height (mean value of the highest 1/3 of waves, which are considered "significant"), and is not based on clear physical grounds. In the proposal by Germany and Finland, the countries reported that the EEDI/EEXI improvement of the 8,660 DWT RO-RO cargo ship equipped with rotor sails shown in Fig. 9 was 15% without this incentive and 30% with the incentive (this calculation used only the top half of the highest wind speeds). Although the results will differ case by case, at least in the example studied here, the EEDI/EEXI improvement effect was doubled by utilizing this incentive.

Fig. 9 8,600 DWT RO-RO cargo ship equipped with rotor sails

6. EEDI/EEXI VERIFICATION OF WAPS

EEDI/EEXI verification of WAPS is conducted in accordance with the GUIDANCE ON INNOVATIVE ENERGY EFFICIENCY TECHNOLOGIES. Various documents including the grounds for setting the Wind Force Matrix (wind tunnel test results, CFD and other numerical calculation results, full-scale test results, *etc*.) are confirmed in the preliminary verification, and the EEDI/EEXI values is finally verified by confirming the configuration and installation of the WAPS in the final verification.

7. REVIEW

Since early reflection of the effects of WAPS in EEDI was prioritized in the revision of the GUIDANCE ON INNOVATIVE ENERGY EFFICIENCY TECHNOLOGIES, there was remaining room for improvement, for example, in the validity of incentives, *etc*. Therefore, in the near future, revisions (improvements) that enable more accurate evaluation of the effects of WAPS is desired. The items that are considered to require improvement are as follows.

1) Although EEDI/EEXI is evaluated under the ship speed at 75% of MCR, slow steaming has now become the usual practice. However, as a result, the EEDI/EEXI ship speed deviates from the actual speed now. The effect of WAPS increases as the ship speed decreases, which means the actual effect of WAPS is under-estimated in EEDI/EEXI. Therefore, it is desirable to develop and adopt a formula for correcting the ship speed.
2) Since a ship may be used on any route in the world, ships are evaluated under not specific shipping routes but the main global shipping routes in the revision guidance. Although this results in a deviation between the effect of WAPS in EEDI/EEXI and the actual effect, this is a limitation of the concept of design index. Therefore, the actual effect is reflected in CII, which is an operational index. Even on the main global shipping routes, a route with the optimum wind speed and angle for WAPS exists. Therefore, it is desirable to develop and adopt a Wind Probability Matrix based on those optimum routes.
3) Accurate prediction (evaluation) of the effects of WAPS on specific shipping routes is helpful for business discussions among

manufacturers, ship owners and other related parties. Therefore, although it is not related to IMO, if Wind Probability Matrix for specific shipping routes is specified in the IMO's Guidance as reference information, it will be extremely beneficial for the related parties, and can also be used effectively in performance appraisals by third parties.

4) Since the Revised GUIDANCE has not considered the effects of oblique sailing and counter-steering caused by WAPS, it will be necessary to investigate these effects, and if necessary, develop and adopt correction formulae for their effects.
5) To incentivize the installation of WAPS, a method of considering only the top half of wind speeds in the Global Wind Probability Matrix and disregarding the remaining half has been adopted, but this is analogous to the idea of the 1/3 significant wave height (mean value of the highest 1/3 of waves), and does not have clear physical grounds. Therefore, the validity of this approach should be verified, and it should be improved if necessary.
6) It is desirable to specify the details on methods for implementation and verification of wind tunnel tests, CFD and other numerical calculations, full-scale tests and sea trials in the near future.

8. CLASS NK GUIDELINES FOR WIND-ASSISTED PROPULSION SYSTEMS

In 2019, ClassNK released "Guidelines for Wind-Assisted Propulsion Systems for Ships (First Edition)" as a guideline for the safe design of Wind-Assisted Propulsion Systems to conduct plan approval, and it became possible to understand the design elements that should be taken into account in the design of WAPS by referring to the Guidelines. The Guidelines were substantially updated in Edition 2.0 in 2023, reflecting the knowledge gained in actual projects and the results of recent research and development. In Edition 2.0, the composition of the entire Guidelines has been reviewed to enable easier understanding by both Wind-Assisted Propulsion System designers and ship designers, and has been organized into three parts: "Wind-Assisted Propulsion Systems", "Base Ships", and "Surveys", and requirements have been refined and clarified. As a result, a comprehensive check of the points that should be considered when designing and installing WAPS on ships is now possible.

Edition 2.0 specifies that the effects of WAPS can be reflected in EEDI/EEXI in accordance with the IMO's GUIDANCE ON INNOVATIVE ENERGY EFFICIENCY TECHNOLOGIES, and also states that evaluations can be conducted by other methods deemed appropriate by Society, including evaluations of the effects of WAPS on specific shipping routes.

9. CONCLUDING REMARKS

In revision (improvement) of the IMO's GUIDANCE ON INNOVATIVE ENERGY EFFICIENCY TECHNOLOGIES to enable more accurate evaluation of the effects of Wind-Assisted Propulsion Systems, ClassNK will be happy if we can contribute to the maritime industry by continuing to provide positive support in the technological aspect. We also hope that we can continue to contribute to various third-party certification activities in connection with GHG, beginning with the EEDI/EEXI verification for WAPS, and also including performance appraisals for specific shipping routes and certifications of actual GHG emission reductions.

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