TECHNICAL KEY PERFORMANCE INDICATORS FOR WIND-POWERED SHIPS

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SUMMARY

The maritime wind propulsion industry evolves rapidly, and new technologies emerge on the market. This calls for standardised ways to express the technical performance of wind propulsion technologies (WPT) in a transparent manner. The wind propulsion community has not yet agreed on common key performance indicators (KPI). This complicates fair comparison, puts the level playing field at risk, and delays investment decisions.
A number of different KPIs describing the ability of a WPT to save a ships energy consumption are discussed in this paper. These have been gathered through industry workshops and interviews in co-operation with the International Wind Ship Association (IWSA), International Towing Tank Conference (ITTC) and the EU Interreg project WASP.
After an explanation of the underlying assumptions and calculation methods the investigated KPIs are exemplified for a generic ship equipped with different typical wind propulsion systems.
A set of recommended KPIs are suggested by the authors. We hope that this proposal will spark further discussions within the industry and facilitate the process of deriving useful and standardised metrics to assess wind propulsion technologies.

NOMENCLATURE

ρ_A	air density
η_D	total propulsive efficiency of ship
A	Projected area of WPU
C_D	Force coefficient from WPT aligned with to the apparent wind
C_L	Force coefficient from WPT perpendicular to the apparent wind
C_P	Coefficient of power contribution from WPT
C_X	Force coefficient from WPT in the ship's longitudinal direction
C_{X0}	Force coefficient from WPT in the ship's longitudinal direction at head wind
C_Y	Force coefficient from WPT in the ship's transversal direction
AWA	Apparent wind angle, relative course over ground (degrees)
AWS	Apparent wind speed (m/s)
EEDI, EEXI	Energy Efficiency Design Index
ESP	Energy saving potential of a WPT (J)
F_X	Force from WPT in the ship's longitudinal direction
IMO	International Maritime Organisation
ITTC	International Towing Tank Committee
KPI	Key Performance Indicator
P	Ship's propulsion power
PSP	Power saving potential of a WPT (W)
P_{in}	Power input, power consumption of WPT (W)
TWA	True wind angle, relative course over ground (degrees)
TWS	True wind speed (m/s)
V_s	Ship speed
W	wind matrix
WPT	Wind Propulsion Technology
WPU	Wind Propulsion Unit

INTRODUCTION

The maritime wind propulsion industry is evolving rapidly, and many new wind propulsion technologies (WPTs) emerge on the market. Such modern systems have little in common with the canvas sails of the old days and range from rotor sails over kites and suction wings to rigid sails that resemble vertical aircraft wings [1]. All these technologies have their specific strengths and weaknesses, which need to be assessed and quantified when selecting a WPT for a particular application. The wind propulsion community has, however, not yet agreed on common key performance indicators (KPI). Some technologies are described using aerodynamic coefficients, others by e.g. expected fuel savings. Percentage saving figures are commonly used, but it is often unclear what is included in the comparison. This complicates comparing technologies, puts the level playing field at risk, and delays investment decisions.

Before this background the Interreg North Sea region project WASP, the International Wind Ship Association (IWSA), and the International Towing Tank Conference (ITTC) have joined forces to develop and propose KPIs for wind-assisted ships. As part of this effort, several focus group meetings were held during the autumn of 2022. These online workshops were open to all stakeholders from the wind propulsion community and aimed at sharing ideas and discussing implications of various KPI alternatives. Figure 1 summarises and groups the participants.

In the paper we present several possible KPIs. Their advantages and drawbacks are discussed based on the industry workshops, written communication with industry representatives as well as with the authors own experience of wind propulsion applications for commercial ships.

ITTC will publish new Guidelines regarding power prediction for wind assisted ships in 2024. The present work has been conducted in close co-operation with *30th ITTC Specialist Committee for Wind Assisted and Wind Powered Ships*, and the outcome will influence new industry standard ITTC Guidelines.

<u>The authors welcome readers who have additional comments or suggestions to contact us and continue the discussion.</u>

Figure 1. A variety of Key Performance Indicators for wind assisted ships are used in the industry. ITTC, IWSA and the WASP project hosted focus group meetings with the industry aiming for deriving harmonised KPIs. The participants affiliation business types are show in the right graph.

2. KPI CATEGORIES

In this paper, key performance indicators are grouped into several categories and discussed separately. The categories range from A to D as shown in Figure 2. As illustrated, a Category A indicator assesses WPT performance on a general level, while a Category C indicator describes the result of a more (ship) specific assessment. Because the indicators in the four categories serve different purposes, they also need to satisfy different requirements. This is summarised in the right part of Figure 2.

Category A contains indicators that describe the characteristics of wind propulsion units without the presence of a ship. If nondimensionalized correctly, they should enable a fair comparison between technologies on a general level.

Category B consists of indicators that are ship specific and are obtained by “sailing” this ship along a pre-defined standard route. Such indices can be used for regulatory assessments, where easy, transparent, and fair definitions are more important than accurate fuel saving numbers. A typical KPI from this category is the Energy Efficiency Design Index (EEDI), where the influence of installing wind propulsion technologies is assessed by sailing the specific ship along a standard, world-wide, route.

Category C indicators are typically used in the context of analysing business cases for WPTs, or for communicating performance expectation between commercial stakeholders. KPIs in this category must therefore accurately express the expected energy or fuel savings for a particular ship trading in a specific pattern. The current paper pays particular attention to KPIs in this category because the absence of standardised Category C indicators is presently an important issue for shipowners and other stakeholders. Investment decisions often get delayed because it is difficult to compare competing technologies.

Category D comprises indicators of achieved performance during operation. These will not be discussed further in this paper.

As can be seen, indicators in these four categories serve very different purposes and it is of the utmost importance that all stakeholders in the industry understand this. KPIs of category C and D, for example, are based on ship and route specific parameters and cannot be used for comparison and ranking of WPTs in a general way.

					Requirement to a KPI			
	Category	Assesing	Describing	Typical usage	Fair "apple to apple" comparison	Ship specific	Accurate energy saving	Based on logged data
General	CAT A	Wind propulsion Unit (WPU) alone	Unit performance	Comparing technologies, design optimsiation	x	-	-	-
	CAT B	WPU & Ship	Design index	Regulations, financial incentives	x	x	o	-
	CAT C	WPU & ship & route	Energy or fuel saving (compared to same ship without WPT)	Business case, providers performance guarantee	-	x	x	-
Case specific	CAT D	Performance achieved in operation	Energy or fuel saving achieved after some time of operation	Cost-saving splitting, reduced fees, rating	-	-	-	x

Figure 2. Categorisation of KPIs used in this study. To the right, requirements to possible KPIs. Here (x) denotes "required", (0) "optional", and (-) "not required".

3. TEST CASE

Throughout this paper three test cases are used to illustrate the proposed KPIs. They share the same ship hull and propeller but have different wind propulsion systems. It is important to note, that these examples are purely fictive cases. To highlight this, they are "anonymous" and will only be called WPT 1, 2 and 3.

The test cases are designed in such a manner that WPT1 and WPT3 have a rather similar fuel saving potential, whereas WPT 2 has a significantly higher saving potential.

The example ship is a 5000-dwt general cargo / bulk carrier with a length of 90m. The main parameters of the test cases are given in Table 1.

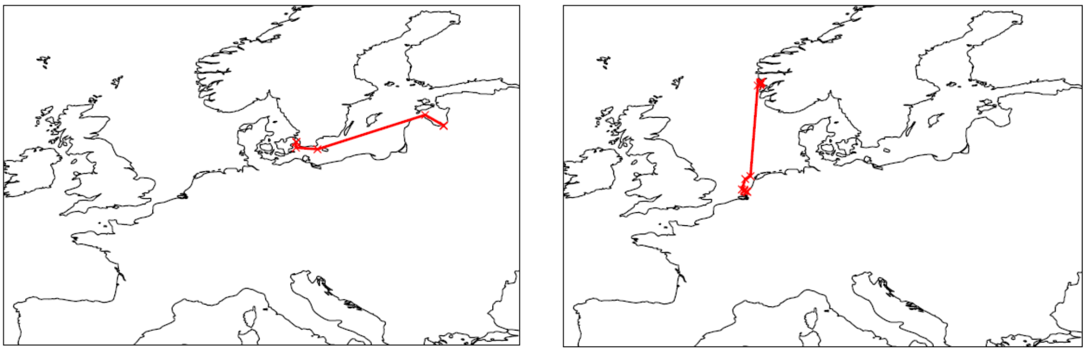
Table 1. The three test cases used throughout this paper

	WPT 1	**WPT 2**	**WPT 3**
Ship	5000 dwt general cargo, L=90m		
Max C_L	9.6	5.8	1.3
Max C_D	3.6	1.9	0.1
Active/passive	Active	Active	Passive
Projected area [m^2]	54	114	200
Deck footprint [m^2]	7	64	136
Foldable /tilting	no	yes	no

KPIs in categories C and D require a route or a trading pattern of the ship. In this paper four example routes are analysed:

- Rotterdam-Bergen (return trip)
- Copenhagen-Riga (return trip)
- New York- English Channel (return trip)
- Worldwide trade according to "EEDI matrix" [2].

The first three routes are illustrated in Figure 3 and a plot of the EEDI route can be found in IMO (2021) [2].



Copenhagen - Riga

Rotterdam – Bergen

Figure 3. Example routes used for KPI calculations.

4. KPI ALTERNATIVES

This section introduces and explains possible performance indicators that have been developed and discussed in close cooperation with industry. The KPIs have also been applied to the three test cases, WPT1, WPT2 and WPT3. The results are summarised in colour-coded tables where the three design are ranked from highest performance (green) to the lowest performance (red) using the KPIs. A more extensive report, containing additional background information and additional KPIs will be published during the spring of 2023 [3].

4.1 CATEGORY A – STAND-ALONE UNITS

Indicators in this category should describe the characteristics of wind propulsion units alone, without considering a ship. “Characteristics” in this context can mean the forces they produce (thrust force, side force, lift, drag) at different wind angles or the propulsive power they are able to provide. Figure 4 provides an illustration of some typical features, which will be discussed in more details below. The results for the test cases are given in Table 2.

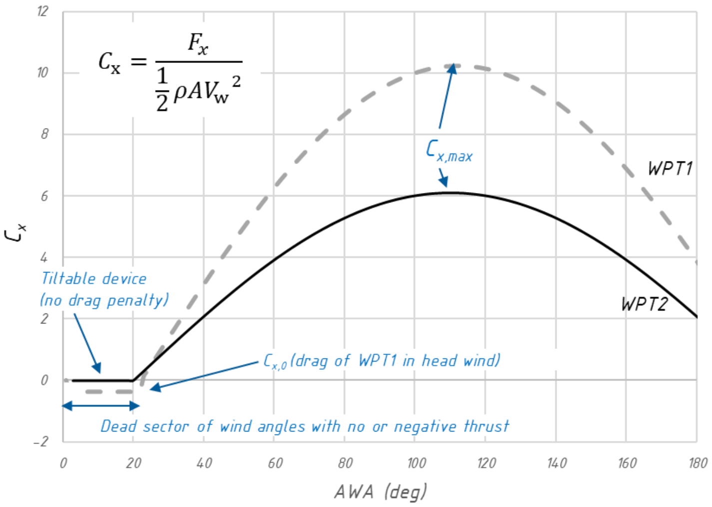


Figure 4. Example characteristics of WPTs, illustrated as thrust force coefficient (C_x) vs. apparent wind angle curves for two different WPTs

4.1 (a) Single, nondimensional KPIs for standalone units

Maximum lift coefficient $C_{L,max}$

The lift force is defined as the aerodynamic force component perpendicular to the flow. The maximum lift coefficient before severe stall, $C_{L,max}$, is commonly used in aeronautics to describe wings and lifting surfaces. It can be obtained by wind tunnel testing or viscous flow computations. Although the parameter has physical significance, it does not describe well how a wind propulsion device works on a ship. A similar KPI that describes the ship-specific situation better is the thrust force coefficient C_x.

Maximum thrust force coefficient $C_{x,max}$
By resolving "lift" and "drag" (aerodynamic force component in flow direction) into components parallel and perpendicular to the centreline of the ship the "thrust" and "side force" produced by the WPT can be obtained. A useful KPI could be the maximum value of the thrust force coefficient over all wind angles, $C_{x,max}$, see Figure 4.

Dead sector
The wind angles where the WPT does not contribute with power reduction can be called the "dead sector". There are both upwind and downwind dead sectors. However, the upwind sector is more critical since, for modern fast ships, small apparent wind angles occur more frequently than larger ones close to following wind. The size of the dead sector varies significant between different types of WPTs, and it varies also with the ship speed. This is therefore an important characteristic to consider. On the other hand, "weather routing" can reduce the negative effect of a large dead sector and that could possibly make this KPI less relevant. The upwind dead sector is illustrated at the left of Figure 4.

C_L/ C_D
The ratio of lift to drag gives an indication of the "pointing ability" of the WPT. High lift to drag ratios are equivalent to small upwind dead sectors and result in a ship that can sail close to the wind.

Drag of idling WPT in head wind, C_{x0}
Some WPT's can be tilted or folded on deck when the wind is not favourable. The WPTs that are not tiltable create a resistance which is often not negligible. This is an important characteristic which distinguish the differ technologies from each other. Figure 4 exemplifies this for two different WPTs.

Power requirement efficiency
Active devices, such as rotors or suction wings, require some power input (P_{in}) to function. This is of course a significant characteristic of these technologies. A suitable KPI that address this could be the ratio of required power to the power that can be delivered to the ship. Both powers (in and output) vary with the wind as well as with ship speed. A simplified expression which is independent of ship speed it could be:

$$\eta_{WPU} = \frac{P_{\mathrm{in}}}{\left(\max\,(C_x)\,\frac{1}{2}\rho A \cdot AWS^3\right)} \tag{1}$$

where wind speed AWS is 10 m/s, and P_{in} is power consumption at the AWS=10m/s and the AWA where C_x has its maximum. P_{in} should include all losses, mechanical, aerodynamic and others i.e. this should be the power that has to be supplied by the main engine to drive an active WPT.

Looking at the η_{WPU} results from the test cases (Table 2) difference between devices 1, 2 and 3 are clearly visible, with WPT1 consuming the highest power.

KPIs related to geometrical constraints
In the absence of geometrical or financial constraints, the largest device is likely to give the highest fuel saving. In reality, the winning device will be the one that maximises power within the given geometrical limitations. Such limitations can e.g. be deck space, air draft or weight. During a concept development project, it could be relevant to use coefficients based on these parameters. As an example, Table 2 includes $C_{L,max}$ /deck-footprint (i.e the deck area required for the WPUs).

4.1 (b) Combinations of nondimensional KPIs for standalone units

Combinations of single coefficients
As Table 2 shows it is not possible to rank WPTs based on a single KPI, this is because the ranking of the three devices is different for the different KPIs. One way around this could be a to use a combination of several KPIs, including at least: [$C_{x,max}$; C_L/C_D ; C_{x0} ; η_{WPU}].
Alternatively, a graphical representation such as plotting coefficients over wind angles could be useful.

Thrust force coefficient C_x curve over wind angle
The most explanatory way to describe the aerodynamic characteristics of the WPT's is to show the full thrust force coefficient (C_x) vs. apparent wind angle curve. This can either be done in cartesian coordinates (as in Figure 5, lefthand plot) or as a polar diagram. Such curves provide a rather complete picture of WPT performance and many of the other

KPIs discussed above can be obtained from the plots (e.g. width of the dead sector or $C_{X,max}$). The disadvantage of this approach obviously is that this is not a single number but a plot that requires interpretation by an expert.

Net power coefficient $C_{P\text{net}}$

A power coefficient could be one way to include the effect of power demand (PTI) and the power that the WPT can deliver to the ship. This would make it possible to compare "active" and "passive" devices in a fairer way. Ideally, since this is still a stand-alone unit coefficient, it should be independent of ship specific parameters and wind speed. However, this is not possible to derive. The ship's speed affects the ranking between high lift and high efficiency WPT's. Moreover, for a fair comparison between active and passive devices, the ship's propulsive efficiency η_D need to be included. Otherwise, the P_{in} is too large in relation to the power that can be used for propulsion. A standard value of 0.7 could be used for η_D , even though this is also unfair to active device if the real propulsion efficiency is lower.

A standard power coefficient could then be derived as

$$C_{P\text{net}\_V_s} = \frac{\dfrac{C_x \frac{1}{2}\rho A \cdot AWS^2 \cdot V_s}{\eta_D} - P_{\text{in}}}{\frac{1}{2}\rho S \cdot {V_s}^3} \tag{2}$$

where η_D =0.7, S is a typical ship's wetted surface.

The ship's speed should be given as a subscript in the coefficient name, for example $C_{P\text{net}\_10\text{kt}}$ for a ship speed of 10 knots. This coefficient is *not* independent of wind speed, hence a reference true wind speed must be given, for example 10 m/s.

In the same way as for the thrust curve, the most complete picture is given by presenting the $C_{P\text{net}}$ curve over AWA or TWA. Figure 5 (right) shows the curve for the three test cases. The $C_{P\text{net}}$ curve reveals a different relation between the WPT's than the C_x-curve. By including the power consumption, the relative inferior performance in upwind of the active devices WPT2 with the largest power requirement is clearer.

The plots over apparent wind angle can be either polar or cartesian plots. It is the authors opinion that the cartesian plots display the different characteristics in a clearer way.

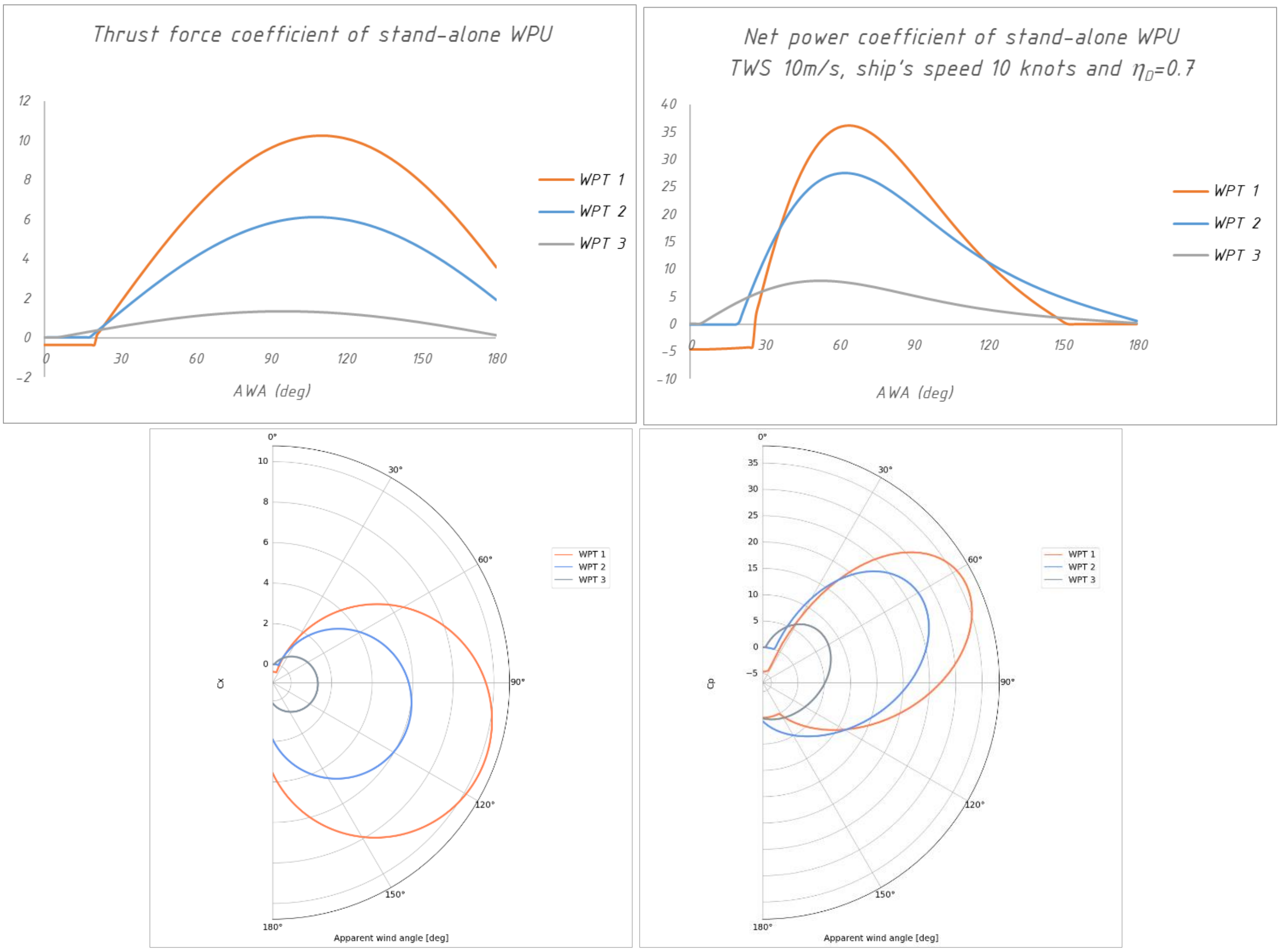


Figure 5. Thrust force coefficient (C_x) and net power coefficient (C_p) for the test cases. With cartesian plots the differences in characteristics may be clearer.

4.1 (c) Dimensional KPIs for standalone units

Rated WPU power [kW]

Wind propulsion units are usually offered in standard sizes. In the early concept phase, when scanning the market and shortlisting possible devices, it could be convenient to have easy, ship independent indicator of a unit size or its power. This could be achieved via a nominal or "rated" power derived in the same way as the "f_{eff}*P_{eff}" in MEPC.1/Circ.815 (2013) [4].:

$$Rated\ WPU\ Power_{10} = \sum_{i,j}^{n,m} \left[\frac{F_x \cdot V_s}{\eta_D} - PTI\right]_{i,j} \text{ x } [\mathrm{W}_{i,j}] \tag{3}$$

where

$\mathrm{W}_{i,j}$ is the EEDI weather matrix (pre-2021)

η_D=0.7

F_x is the force matrix at the corresponding winds

V_s=10 knots

Rated power values for other standard ship speeds (e.g. 15 and 20 knots) can be worked out in a similar way

This KPI is one way to describe a device while including the size. It is a theoretical number and gives an indication of a unit's theoretical potential. It should be understood that it this ignores the effects of aerodynamic side forces and that the propulsive efficiency, η_D at may be different for a specific ship. This expression "punishes" active devices if η_D is larger than the actual for a specific ship, but this flaw is at least smaller then if not including η_D at all.

Wind Route Indices

Another way to produce a dimensional "ship independent" KPI is to use a standard ship on a standard route and show the fuel saving potential. There is, however, a certain risk that such an analysis could be misinterpreted as a ship specific business case. This can lead to misleading conclusions and unfounded decisions.

Table 2. Category A KPI results for the test cases. Green means highest performance, red lowest.

Suggested KPI	**unit**	**WPT 1**	**WPT 2**	**WPT 3**
Max lift coefficient C_L		9.6	5.8	1.3
Max thrust coefficient C_x		10.3	6.1	1.3
Max C_L/C_D		2.7	3.1	11.1
C_x at AWA=0 (if not tiltable)		-0.4	0.0	0.0
Max C_L / deck footprint		1.4	0.1	0.01
Dead sector upwind, based on C_x	deg	21	19	5
Dead sector upwind, based on C_p (10 knots)	deg	27	19	5
η_{WPU}		15%	4%	0%
Max net power coefficient C_p (10 kn)		3.8	2.9	0.7
Rated WPU power (9 knots)	kW	38	63	44

4.2 CATEGORY B: INDICES – SPECIFIC SHIP CASE ON GENERIC ROUTE

Several indices in this category already exist (e.g. EEDI, EEXI [2,4]) and others are currently being developed. It is anticipated that the EEDI regulations will be revised the coming years. The current paper focuses mainly on the real-life performance indicators of the Category C type, which will be examined in the next section. Below we therefore limit the discussion of Category B indicators to the controversy around the "weather matrix". In the updated EEDI/EEDI Guidance On Treatment Of Innovative Energy Efficiency Technologies from 2021 [2], 50% of the most adverse wind conditions can be deleted from the weather matrix, i.e. ignored for EEDI rating purposes. As can be seen in Table 2, this changes the ranking between WPT1 and WPT3 (due to the different aerodynamic characteristics as described in previous section), even though the differences between them is marginal.

For this reason, some members of the industry criticise the 2021 version of the regulation for being not technologically neutral. Other voices support the change, with the argument that removing unfavourable weather conditions reflects better ship operations using weather routing.

The EEDI formula can also be criticised for not including side force effects, which in theory unable fair treatment of all WPT-types. For moderate wind assisted propulsion this is neglectable, but for more powerful installations and for ships with primary wind propulsion, this simplified equation is not suitable.

Table 3. EEDI/EEXI value for a fictive ship with three different Wind Propulsion Technologies, using the IMO regulations before and after 2021. The 2021-revision can change the ranking between devices of similar performance (like WPT1 and WPT3).

IMO regulation	**unit**	**WPT 1**	**WPT 2**	**WPT 3**
MEPC.1/Circ.896, (IMO, 2021)	g CO2/(t*nm)	10.97	10.57	11.01
MEPC.1/CIRC.815 (IMO, 2013)	g CO2/(t*nm)	11.40	11.16	11.35

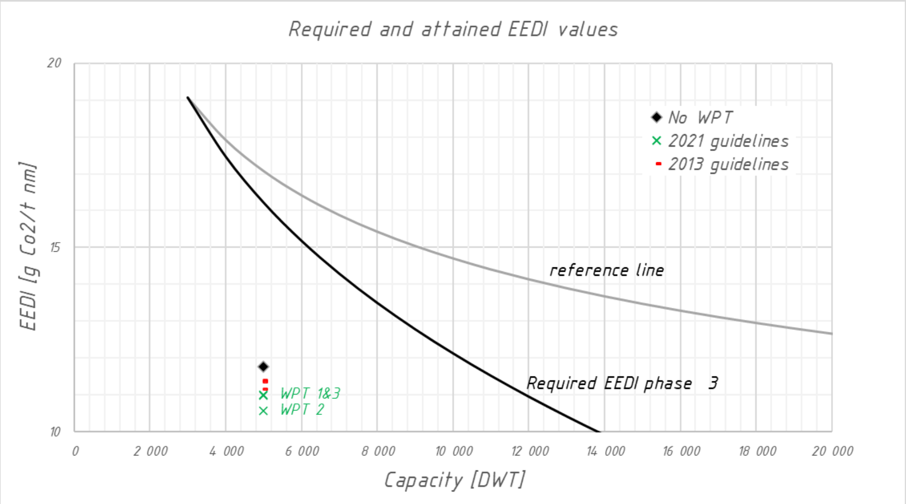


Figure 6. EEDI/EEXI value for a fictive ship with 3 different Wind Propulsion Technologies.

4.3 CATEGORY C – PERFORMANC EEXPECTATIONS FOR SPECIFIC SHIP AND ROUTE

4.3 (a) Power saving, fuel saving, energy saving or CO_2 saving?

The purpose of the indicators in this category is to communicate a realistic expectation of the saving potential from a WPT. They are typically used as decision support for business cases, or for agreements between commercial stakeholders

The saving due to a WPT in absolute terms can be expressed either as power, fuel, energy, or CO_2 saving. While this choice will not affect the ranking between the WPTs for the same ship it can make a difference in how far a KPI resonates with different stakeholders of the shipping industry. Owners and operators tend to think in tonnes of bunker per day, engineers are more familiar power or energy-based numbers, lawmakers will mostly focus on CO_2 savings.

If we consider ships with conventional diesel engines and power saving for constant operational speeds, then there is an almost linear relation between the predicted power, fuel, and energy savings. This allows for an easy conversion between the savings expressions by simply post-processing route simulation results. For hybrid propulsion systems, and if routing and speed optimisation are included, the relation is not that so straight forward and must be modelled within in the voyage simulations. Some of the advantages and disadvantages of the various units for savings are summarised below. These points were raised during discussions with industry stakeholders.

Fuel saving

- Ship owners can relate to fuel (tons/day and kg/h).
- Tons/miles makes it easier to scale to different routes.
- Can be used in a transition period when HFO is still the standard in shipping.
- Need modelling of machinery efficiency, or stipulate fixed specific fuel oil consumption (SFOC).
- Not easy for hybrid propulsion systems.

Energy saving

- Using propulsion energy instead of fuel allows to leave out engine efficiency.
- For specific cases ship owners can translate to fuel themselves.
- More future proof considering future fuels.

CO_2 savings/ CO_2s avoided

- Parameter assessed in EEDI, CII and emission trading schemes like EU-ETS.
- Of interest to the wider society.

Power saving

- Propulsion power is a measure that both yards, designers, ship owners and operators are familiar with.
- It does not require any modelling of engine efficiency or assumptions of fuels and hybrid propulsion.
- WPT providers do not always have information on the details of the propulsion system or engine efficiency. In this case the power makes for safe option for the saving prediction.

Considering these pro and cons, it appears that "power savings" are the most feasible way of expressing WPT performance and are also a concept that is familiar to owners and operators. In this paper we will therefore in the following focus on power-based KPIs.

4.3 (b) KPIs for power saving

A number of possible KPIs are suggested below, and again corresponding results for the test cases are given in Table 4. It is assumed that a power saving ΔP has been computed using a numerical model or formula. We will not discuss the prediction *methods* as such here but focus on how the results could be *presented*.

Table 4. KPI expressing power saving expectation for test fictive cases. EEDI means pre-2021 weather matrix. Green means highest performance, red lowest.

	unit	**Route**	**Ship Speed (knots)**	**WPT 1**	**WPT 2**	**WPT 3**
Rated WPU power / Ship Propulsive power	%	EEDI	9	4.3%	7.1%	4.9%
ΔP Sea legs only, calm water	%	EEDI	9	6.0%	9.7%	6.0%
	%	Rot-Bergen	9	8.6%	13.2%	8.0%
	%	Rot-Bergen	13	4.5%	7.3%	4.4%
	%	Cop-Riga	9	6.1%	9.7%	6.0%
	%	NY- UK	9	10.2%	16.1%	9.5%
ΔP Sea legs only, incl S.M.	%	EEDI	9	5.3%	8.7%	5.4%
	%	Rot-Bergen	9	7.4%	11.6%	7.1%
ΔP vs. Total fuel consumption	%	EEDI	9	4.5%	7.2%	4.5%
	%	Rot-Bergen	9	6.2%	9.7%	5.9%
ΔP max, TWS=10m/s	%		9	27%	37%	19%
ΔP max, TWS=10m/s	kW		9	258	345	180
ΔP design	kW		9	170	233	160
ΔP most likely weather	kW	Rot-Bergen	9	92	104	100
ΔP most likely weather	kW	Cop-Riga	9	-7	11	0
ΔP yearly average, Sea legs only, incl. waves	kW	EEDI	9	57	91	56
	kW	Rot-Bergen	9	80	124	76
	kW	Rot-Bergen	13	102	165	99
	kW	Cop-Riga	9	57	91	56
	kW	NY- UK	9	95	151	90

Percentage

The percentage fuel saving is the most common KPI in communications around wind propulsion today. One could think that a percentage saving is a clear KPI that can be used for comparison between different installations, since it is nondimensional. Very often, percentage saving claims are published without any further description of the specific cases. This is, however, a problematic approach.

The first issue is to *what* the savings have been related , i.e. what number to have in the denominator. The left graph in Figure 7 shows the percentage power saving of the three test cases computed in different ways. First, the fuel saving is predicted for the sea legs in calm water. The ship's propulsion power when employing the WPT is compared to the propulsion power when there is no WPT, for the same sea leg and same speed:

$$\Delta P\% = \frac{P_{no\ WPT} - P_{with\ WPT}}{P_{no\ WPT}} \tag{4}$$

Secondly, the sea margin, or added resistance in waves, is included in the prediction. This is the standard procedures for some organisations, whereas others do not include it. It has minor effect on the predicted fuel or power saving in absolute terms (tons, kW), but it has a significant effect on the percentage, since it increases the denominator in eq (4). For WPT2, as an example, it makes the saving to decrease from 13% to 11.5%.

For the third group of numbers in Figure 7, the comparison is done against the ship's *total* fuel consumption, i.e. not only the fuel used for propulsion on the same sea legs. The denominator hence includes port manoeuvres, hotel load etc. That makes the saving to decrease further still, to 10% for WPT2. It should be noted that the trends between the WPTs are preserved: in all cases WPT 2 is still the "winner".

Finally, the %-saving is also shown for a higher ship speed, 13 knots, to illustrate how much this can affect the saving number. The saving is now down to 7%. The trends are still the same, but this is not a general conclusion since some technologies work better for higher speeds than others.

The righthand graph in Figure 7 shows that the power savings differ considerable between different routes. For WPT2, as an example, the fuel saving is 10% for the least favourable route and 16% for the most favourable. The trends between the three WPTs are preserved, although the advantage of WPT1 over WPT3 differs between the routes.

These examples illustrates that a percentage saving number, taken out if its context, may be misleading. A percentage number gives the false impression that it can be universally compared with other percentage saving predictions. For the reasons addressed here, many of the industry partners participating in the study are sceptical of using this KPI.

It could, however, be useful as limits, for example when a rule is applicable or not.

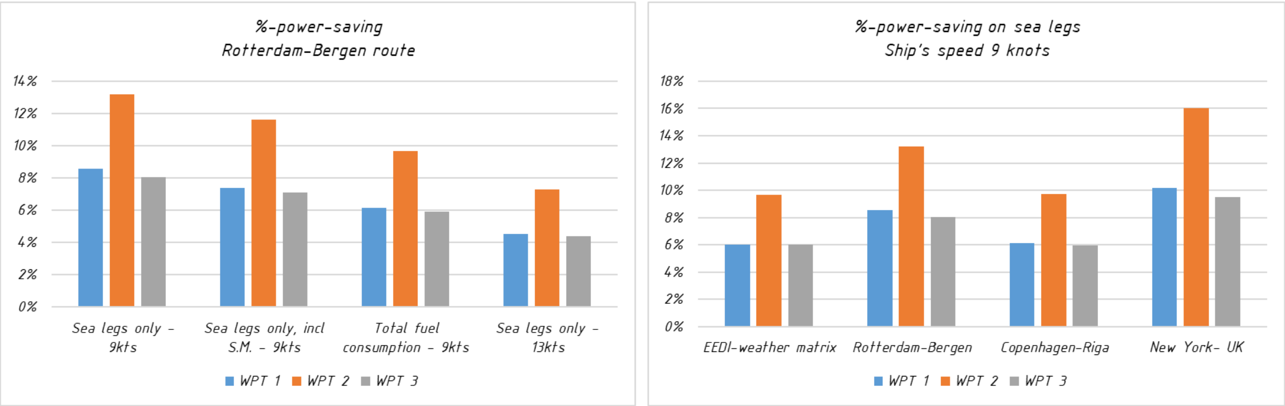


Figure 7. Percentage power saving can be computed in different ways, and for different conditions, which results in different performance expectations.

Early estimation

In the previous section on Category A KPIs, a "Rated WPU power" was defined for the purpose to be used in very early estimation of saving potential. By comparing the Rated WPU power with the ship's propulsive power at the same ship speed, we can get a rough estimate of the power saving potential. For the three test cases this indicates a saving of around 7%. The more accurately predicted average saving for the EEDI weather showed around 10%. The Rated WPU power could hence be used as a first rough approximation for fuel saving.

Power reduction

The performance of WPT could also be expressed as power reduction in kW, $\Delta P = P_{no\,WPT} - P_{with\,WPT}$. Several options for a standardised KPI related to ΔP were suggested by the industry partners involved in this study:

i. Max ΔP for TWS=10m/s (at the best wind direction)
ii. ΔP at a specified "design point" which could be for example TWS 10 m/s, TWA=60 deg
iii. ΔP at the most frequent weather
iv. ΔP on a given route, averaged over a year to include all season's weather
v. ΔP from the EEDI equation (pre or post 2021), but using weather statistics for an actual route

Figure 8 shows these options for the test cases. The advantage of option i) – iii) is that the prediction does not require any routing/voyage analysis tool. However, selecting one point where ΔP is extracted can give large over or under predictions of the power reduction (left graph in Figure 8) compared to the average saving on a route (righthand graph in Figure 8). For example, the maximum power reduction of WPT 2 is 345kw (37%), whereas the yearly average power reduction on a favourable route is about a third of that, (124kW, 12%). Communicating these two numbers would result in rather different expectations and business cases. The maximum ΔP gives also a misleading comparison between high lift versus high lift/drag devices, as explained above regarding maximum C_x. The same drawback is true for the option to derive ΔP at a specified "design point".

Selecting the most frequent weather as the design point is completely misleading. The most frequent weather could well be head wind, where WPTs cannot even be employed.

Some industry partners suggest ΔP to be derived for a given route, including route optimisation. This would give a more favourable KPI for all WPTs, but it would especially favour high lift/drag devices versus high lift devices. It can be argued that including route optimisation would reflect the real operation better. It can, on the other hand, be argued that the KPI should reflect the technical performance and not operational measures. Successful routing depends on factors like the skill of the crew, safety, logistics requirement etc. These are very hard to incorporate in a standardised KPI.
The solution could be to clearly distinguish between KPIs including and not including routing.

Power Saving Potential (PSP)

No matter how accurate we try to model the power saving on a route, it is still a theoretical value. The real saving achieved in operation will depend on many practical aspects which cannot be foreseen in the predictions, such as maintenance time, changed route and speed, changed hull efficiency due to fouling, crew skill, function of the automated WPU control system, icing and wear. For this reason, it would be wise to denote the predicted ΔP the "Power Saving Potential". This will indicate that it is an ideal number derived under certain conditions. The PSP should be possible to verify during a short, controlled sea trial. After that, it is up to the owner, operator, and crew to use this potential in the best way.

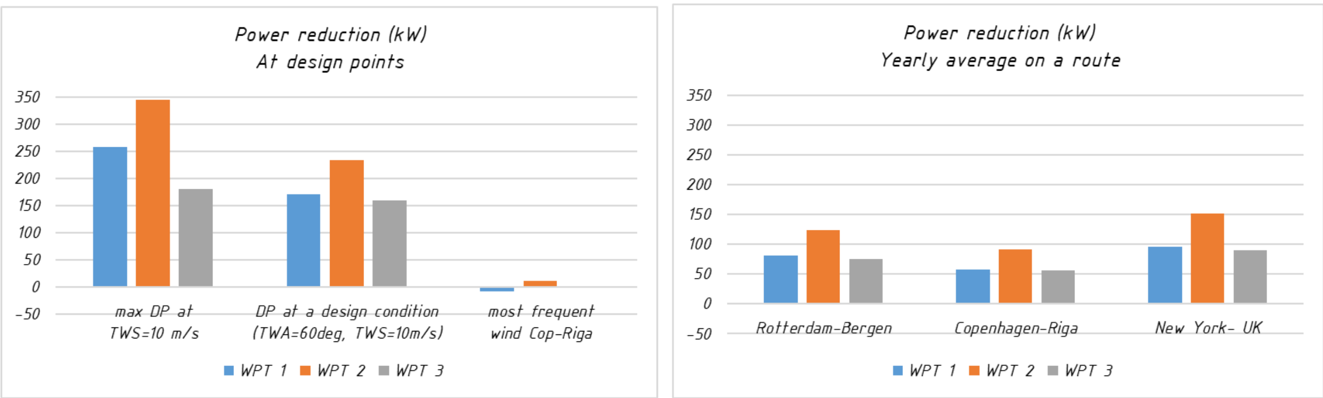


Figure 8. Power saving can be computed in different ways, and different conditions, which results in different performance expectations.

4.3 (c) Other KPIs

Other indicators that could be expressed in a description or offer of WPT includes:

- Operability range, such as limitation in top wind speed. Could be expressed as percentage of the EEDI matrix.
- Deck area footprint, air draft, weight and centre of gravity
- Noise and vibration
- CAPEX OPEX, LCC/LCA
- Crew training requirement

5. CONCLUSIONS AND RECOMMENDATIONS

Key performance indicators (KPI) for wind assistance ships have been discussed in a wide group of industry stakeholders. The need from the industry can be summarised as:

- It would be helpful to have a set of agreed KPIs, especially for expressing ship specific fuel saving potential in the business case and procurement phase.
- KPIs that will be communicated to ship owners and operators should be tangible to their business.
- It would be useful if the KPIs reflect the prediction method used to derive the value.
- It would be useful to have a set of KPI definitions that is consistent and can accompany the ship design process from early concept stage to operation stage, gradually adding more and more complexity.

Based on these discussions and the case study in this paper, the authors present here their recommendations. These will be further processed by ITTC Specialist Committee for Wind Assisted and Wind Powered Ships for a future inclusion in ITTC's Guidelines. Readers who have additional comments or suggestions are most welcome to contact the authors.

5.1 Recommended KPIs for Stand-alone wind propulsion units

The authors recommendations:

- Nondimensional stand-alone coefficients are useful to understand the characteristics of a WPT but not directly the fuel saving potential. This is relevant for experts working with the design or assessment of wind powered ships. However, it should not be the first choice when communicating performance with community in general.
- There is no single nondimensional coefficient that describes all the important characteristics of a WPT. The best demonstration of the complete picture is a power coefficient curve over apparent wind angle (eq. 2).
- The "Rated WPU power" could be a standard way to express the potential power for a single device in marketing and for short-listing suitable WPUs during early concept phase.

It is important that Standard conditions for nondimensional KPIs are defined by for example ITTC. That could be:

- Uniform/rectangular wind profile
- Area A defined as projected/planform area of WPT
- Standard air density of 1.204 kg/m3

5.2 Recommended KPIs for Performance expectation and business case input

The contribution of the WPT to the ship's propulsion can be expressed as power reduction, fuel saving, energy saving or CO2-saving. We recommend power saving to be used as standard. However, nothing prevents showing them all in a prediction report.

Some industry partners request that KPIs derived by different organisations should be truly comparable with each other also in terms of the derivation method. To ensure that all actors in the industry derive indicators that are truly comparable would require that some organisation could derive detailed procedures prescribing methods for CFD simulations and wind tunnel test. This is not a feasible solution. A true "apple to apple" comparison can only be achieved if the same simulation platform is used for the cases to be compared. However, we believe that it would be an improvement compared to today's situation if the industry agreed on a number of KPIs that are linked to certain levels of confidence. In this section we present a suggestion for how this could be achieved.

A Power Saving Potential (PSP) is derived by comparing the power requirement for a ship with WPT against the same ship without WPT on the same route and same speed. This can be done with a matrix multiplication of a weather matrix or by voyage simulations, in both cases using hind-cast weather covering all year around weather conditions. The power prediction should include the power consumption by the WPT if active, the drag from idling device if non-tiltable, and the operability range. The PSP is the ideal performance, assuming 100% operability within the operation range. The real saving may be lower due real life practicalities such as repairs, logistics etc. It can also be higher, of smart routing and energy management is used onboard.

The PSP can be derived using methods and input of different confidence levels. In the early stage of a concept development or feasibility study for a retro-fit, low fidelity methods and input based on estimations is sufficient. As the project advances, more accurate predictions are required for the business case support and performance expectations between provider and ship owners. Table 5 presents a system of KPIs for different confidence levels. An overview description of the corresponding power modelling methods are presented in Table 6. The details should be given in for example the coming ITTC's Guidelines.

Table 5. Recommended KPIs for Performance expectation and business case input

KPI	Unit	Usage	Power modelling*)	Weather modelling
Rated WPU power	kW	General comparing, scanning the market	Stand-alone WPU power	EEDI
PSP-I	kW	Early idea	Level I	EEDI or the ship's intended route
PSP-II	kW	Early business case assessment	Level II	The ship's intended route
PSP-III	kW	Business case & Performance expectation	Level III	The ship's intended route
ESP-IV	kW	Advanced Business case & Performance expectation	Level IV	The ship's intended route (incl. possible weather routeing, speed optimisation)

*) See table 6.

Level I-III are recommended for wind assisted ships that do not use weather routing or speed optimisation.

Level IV is recommended for ships that use extensive weather routing, primary wind powered ships, and ships with advanced hybrid propulsion systems. Modelling can include different speed profiles and different routes for the case with and without WPT. For this level, it is feasible to derive the *energy* saving rather than average power saving. For primary wind powered ships, the comparison can even be against other ship sizes and ship speeds. The energy saving should then be related to a constant cargo flow.

Table 6. Suggestion for specification of methods to derive Power Saving Potential or Energy Saving Potential at various confidence levels. Details to be given in for example the ITTC's Guidelines.

	Level I	**Level II**	**Level III**	**Level IV**
Degree of freedom	*1DOF*	*4DOF*	*4DOF*	*4-6DOF*
WPT forces	*Generic*	*Low/Mid fidelity**)	*High fidelity***)	*High fidelity*
Power requirement of active WPU	*Generic*	*Specific*	*Specific*	*Specific*
Ship propulsive efficiency	*fixed* η_D	*POW Propeller open water curves*	*POW +effect of leeway on prop*	*POW +effect of leeway on prop*
WPU-WPU interaction		*Low/Mid fidelity*	*High fidelity*	*High fidelity*
WPU-hull interaction		*Low/Mid fidelity*	*High fidelity*	*High fidelity*
Hydrodynamic effect of side force		*Low/Mid fidelity*	*High fidelity*	*High fidelity*
Heel		*Low/Mid fidelity*	*High fidelity*	*High fidelity*
Effects of ship motions and varying wind, incl. control systems response time				*optional*
Hybrid-propulsion (diesel electric) with energy management optimisation				*optional*

*) **Low/Mid fidelity** methods can be for example high fidelity data or regression models from similar cases, or case specific lifting line methods

) **High fidelity refers to case specific CFD, model test or full-scale test.

It is recommended not to use %-savings as KPI. If used, the standard way should be to compare propulsion power with device including power consumption, against power without WPT, both derived with the same numerical tool for the same route, same speed, and including wave added resistance or a suitable sea margin.

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