ITTC Quality System Manual
Recommended Procedures and Guidelines

Predicting the Power Saving of Wind Powered Ships

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Abstract

Wind propulsion for ships offers significant possibilities for reduction of harmful emissions. This guideline aims at establishing a consistent terminology for evaluating the performance of wind propulsion during the design phase.

Objective: The guideline focuses on methodologies for predicting the power savings achieved by wind-powered vessels along specific routes during the design stage. It compares these savings to corresponding ships that do not utilize wind propulsion.

Method Overview: The guideline provides an overview of suitable methods for different stages of the design process, balancing confidence levels and computational costs. By linking standard indi-cators to prediction procedures of varying confidence levels, the guideline aims to build a shared understanding among all stakeholders.

Target Audience: Organizations engaged in performance predictions for wind-powered ships (such as consultants, shipyards, and technology providers) will find this guideline valuable. Additional-ly, stakeholders involved in discussions about performance indicators—such as ship owners, opera-tors, and investors—can indirectly benefit from its standardised terminology.

Scope: While primarily applicable to cargo vessels equipped with wind assistance technology, the guideline can also be partially adapted for vessels relying primarily on wind propulsion. However, it explicitly excludes sailing yachts, racing boats, and traditional sailing vessels.

Predicting the Power Saving of Wind Powered Ships

1. PURPOSE OF THE GUIDELINE

The industry for wind propulsion for modern cargo vessels has developed from non-existing to a viable industry in a few years and it is expected to expand further the coming decade. The industry has not yet converged to standard performance procedures or performance indicators. This guideline is the first attempt to create a common ground and common terminology for expressing performance of wind powered ships at design stage.

This guideline deals with methodologies for predicting the power saving of a wind-powered ship on a route at design stage, compared to a corresponding ship not using wind propulsion. The guideline gives an overview of the type of methods that are suitable to use at the different stages in the design phase, considering the balance of confidence level and computational cost. However, the guideline does not intend to provide detailed procedures for the performance predictions. It is assumed that the organization conducting the predictions has relevant background knowledge and tools.

The guideline is intended to be used by organizations conducting performance predictions for wind powered ships (e.g. consultants, yards, technology providers). It is also intended to be used indirectly by all stakeholders who need to discuss performance indicators (e.g. ship owners, operators, investors). By providing standard indicators that are linked to prediction procedures of varying confidence levels, the guideline aims to provide a common terminology for all stakeholders.

The guideline is mainly applicable to cargo vessels with wind assistance technology that can maintain its intended speed even when contribution from wind propulsion is small or zero, although it can to some extent be applied to vessels with primary wind propulsion. Sailing yachts, racing boats or traditional sailing vessels are not in the scope of this guideline.

It is expected that the guideline will be updated frequently the coming years as the knowledge and tools in the industry develops.

The reason why the current version of the guideline deals with predicting the power saving and not the absolute power consumption is that the industry today still sees the conventional motorship as the benchmark which novel technologies relate to. This perspective may be changed in future versions.

2. INTRODUCTION

2.1 Definitions

Symbols in this guideline refer to the ITTC Symbols and Terminology List.

Terminology:

- **Primary Wind Powered Ship:** a ship which is designed to maintain service speed the majority of time using wind propulsion only.

- **Wind Assisted Ship:** a motor ship which is adapted such that in favourable wind conditions, the propulsive power to maintain service speed is reduced from using wind powered technology.
- **Wind powered ships:** Primary Wind Powered Ships and Wind Assisted Ships
- **Sailing ship:** a ship that is designed to only occasionally use the engine (e.g. traditional sailing ships).
- **WPS**: Wind Propulsion System. The wind propulsion units and supporting systems.
- **WPT:** Wind Propulsion Technology. Any technology for wind powered ships.
- **WPU**: Wind Propulsion Unit: a single unit of a WPT
- **Tiltable**: Device can be laid down on deck
- **Retractable**: Telescopic
- **Active devices**: WPT that rely on continuous power input for its lift generation principle.
- **DOF**: Degree of freedom
- **PSP**: Power Saving Potential
- **VPP**: Velocity Prediction Program
- **EPP**: Energy Prediction Program
- **PPP**: Power Prediction Program

2.2 Basic principles

The primary focus of the guideline is on how the hydrodynamic properties of hull and propulsion system, aerodynamic properties of the wind propulsion system and the anticipated weather conditions along its route shall be combined to predict the overall powering performance of the wind assisted ship. Since such evaluation requires computations of many combinations of speeds, wind speeds, headings, loading conditions etc, the numerical performance prediction analysis needs to be fast to be applicable in an industrial context. They are therefore typically based on computing the equilibrium of average forces and moments acting on the ship for prescribed conditions. It is acknowledged that this approach represents a simplification of the physics, but to date it is the industry state-of-the-art approach with a feasible balance of accuracy and computational cost for an industrial purpose. Further, aerodynamic and hydrodynamic models used in the computations are often surrogate models such as regressions of underlying data sets, so that all conditions and settings can be covered in a feasible way.

The prediction procedure described here typically follows the four steps below, although it is acknowledged that in practice the approach may not be as linear as outlined here:

1. Generating background data. This includes towing tank tests, wind tunnel experiments, CFD simulations of the different components, alone or in combinations.
2. Generating models from the background data, which describes the sub-systems response to a change of state. This includes aerodynamic force models of sails, hull and superstructure, hydrodynamic force models (e.g. resistance curve and manoeuvring model), propeller and rudder models, and machinery models. Furthermore, it is necessary to model a control system at least to the extent that operational parameters (angle of attack, rotational speed, etc.) is varied as a function of wind conditions.
3. Finding steady state equilibrium. This is commonly done in Velocity Prediction

Programs (VPPs), Energy Prediction Programs (EPPs) or Power Prediction Programs (PPPs).

4. Route studies, where the variation of environmental conditions that the vessel will meet on a route is combined with the static performance model to derive the expected average power or energy saving due to the wind propulsion.

Figure 1 shows a schematic example of the workflow.

2.3 Assessment levels

Predictions of the power savings from wind propulsion systems are relevant in various stages of the design process, from initial assessments to final performance expectation. Therefore, this guideline is structured into various levels of accuracy to meet the specific needs, requirements, and availability of data of each stage. The fidelity and the required efforts increase with increasing level. An overview is given in Table 1

Level 0 gives an indicator of the available power of a single, stand-alone wind propulsion unit (WPU), independent of the ship and route. It can be used when scanning the market and selecting suitable wind propulsion candidates.

Level I provide a simple approach for obtaining an early estimate of the potential of wind propulsion technology for a given ship, but without considering detailed information about the ship, its route, or specifics of the wind propulsion installation (i.e. generic considerations may be applied). It gives an indication of power saving but is not intended to be used for business case decision support. Several physical effects are neglected which will in general give a non-conservative prediction, unless conservative estimates for wind propulsion unit lift/power coefficients are applied.

Level II predictions applicability is "Early business case assessment" studies. At this level of predictions, the intention is to get more reliable estimates of the power saving potential, at a level of effort that still allows for assessing several different options w.r.t. wind propulsion system, hull, propulsion and appendage configurations. In the approach outlined here, most physical effects are accounted for and specific case information is generally used, however with low/medium fidelity methods.

Level III is intended to be final level for most wind-assist applications. This level of predictions is intended for evaluating power saving potential to a degree at which performance contracts can be established. As such, it sets requirements to the use of high-fidelity methods for the various modelling approaches and covers all physical effects that at the time of writing is considered to have noticeable influence on the power saving potential.

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 wind propulsion system. 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 transport work.

The guideline states which aspects should be considered for each level (Table 1). It does not mean that all listed aspects must be modelled. For specific cases there may be justified reasons to neglect one or more of the effects listed within a level. This could for example be the case for wind propulsion technologies that provide small forces compared to the ship size. The provider of the analyses should then provide sound justifications for neglecting those aspects.

It is acknowledged that in practise, it may be the case that data and models in a specific prediction are at different fidelity levels, and the governing principle should be to use the best models available at any given time in the design stage.

Level II and III approaches are devoted most attention in the present guideline. Modelling requirements are similar in Levels III and IV, and a level III assessment procedure could as such be extended to IV by introducing weather routing in its basic form. However advanced studies into effects of ship motions, varying wind and adaptations of control systems responses or detailed investigations into for instance combinations of wind propulsion and hybrid power systems are not described, both since it is beyond the scope of the current committee and because it requires methods that are yet on the research forefront and too immature to be included in this guideline.

For model tests and CFD activities it is also referred to other ITTC procedures and guidelines. In particular:

- 7.5-02-03-01.4 1978 ITTC Performance Prediction Method
- 7.5-02-06-02 Captive Model Test Procedure
- 7.5-03-01-02 Quality Assurance in Ship CFD Application
- 7.5-03-02-03 Practical Guidelines for Ship CFD Applications
- 7.5-03-04-01 Guideline on Use of RANS Tools for Manoeuvring Prediction
- 7.5-04-01-02 Conduct and Analysis of Sea Trial for Wind Assisted Ships

Additional information on wind powered and wind assisted ships can be found in the ITTC proceedings and final reports by the 30th Specialist Committee on Wind Powered and Wind Assisted Ships (2024).

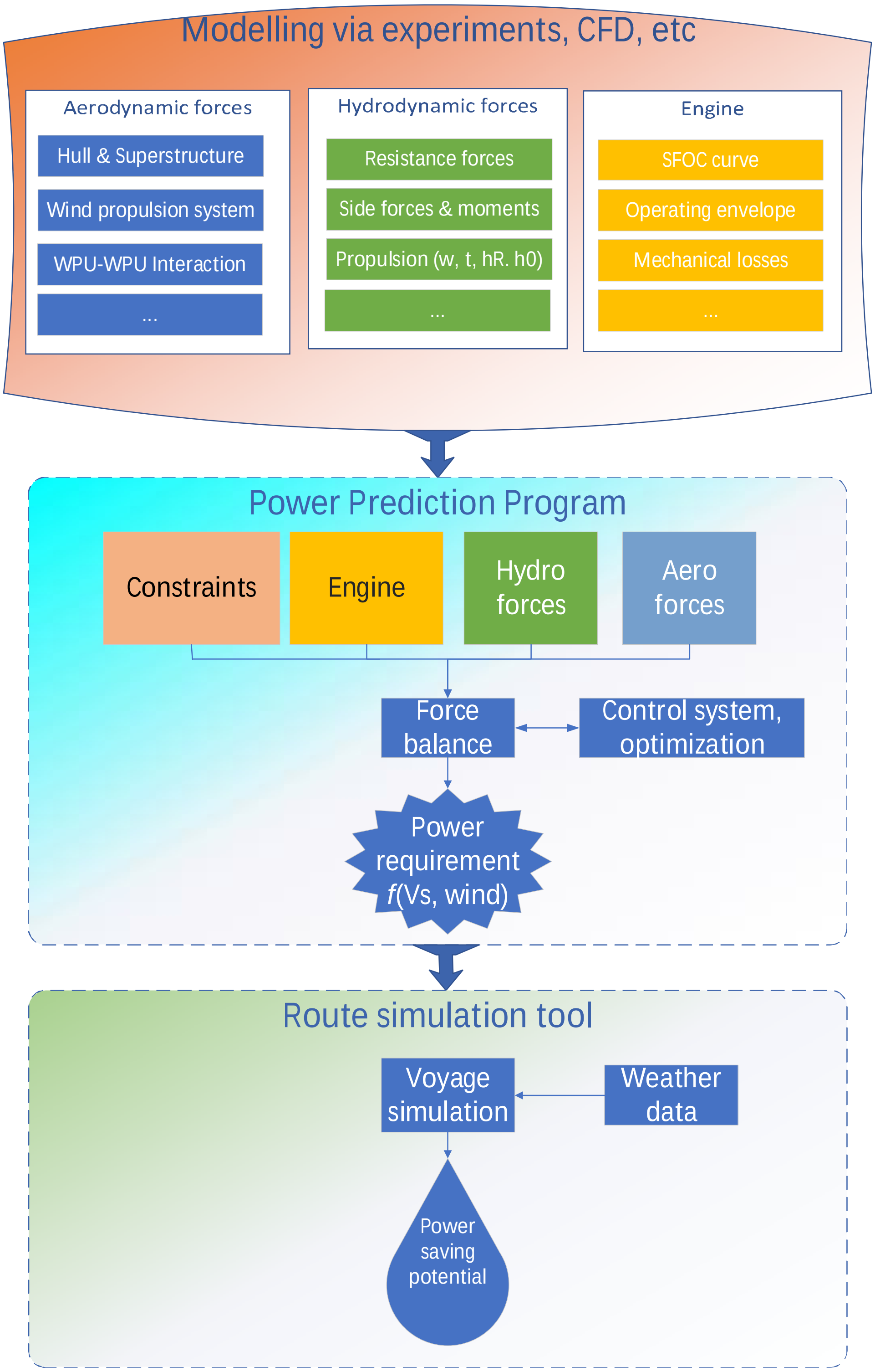

Figure 1, Example of workflow for evaluation of power saving potential of a wind powered ship

Table 1 Usage and methods compliant for each level

		Level 0	Level I	Level II	Level III	Level IV
	Applicability *) ->	***WPU rated power***	***Early idea***	***Early business case assessment***	***Business case & Performance expectation***	***Advanced Business case & Performance expectation***
	Performance Indicator	*PSP-0*	*PSP-I*	*PSP-II*	*PSP-III*	*ESP-IV*
Force balance	Degree of freedom	*1DOF (Surge)*	*1DOF (Surge)*	*3-4DOF (Surge, Sway, Yaw – Heel)*	*3-4DOF (Surge, Sway, Yaw – Heel)*	*3-4 DOF*** (Surge, Sway, Yaw - Heel)*
Aerodynamic	WPU thrust	*Specific*	*Generic*	*Low/Mid fidelity* **)	*High fidelity* **)	*High fidelity*
	WPU power consumption	*Specific*	*Generic*	*Specific*	*Specific*	*Specific*
	WPU-WPU interaction			*Low/Mid fidelity*	*High fidelity*	*High fidelity*
	WPU-superstructure interaction			*Low/Mid fidelity*	*High fidelity*	*High fidelity*
Hydrodynamic	Ship resistance			*Low/Mid fidelity*	*High fidelity*	*High fidelity*
	Ship added resistance in waves			*Low/Mid fidelity*	*High fidelity*	*High fidelity*
	Propeller efficiency		*fixed* η_D	*Specific or adapted propeller series*	*Specific*	*Specific*
	Propulsive coefficients		*fixed* η_D	h_0 *varies with propeller load. Fixed* η_H, η_R	*Include also effect of leeway on propeller*	*Include also effect of leeway on propeller*
	Hydrodynamic effects of side force			*Low/Mid fidelity*	*High fidelity*	*High fidelity*
	Parasitic resistance from added weight etc			*Low/Mid fidelity*	*High fidelity*	*High fidelity*
Engine	Machinery interaction			*Generic SFOC + limitations*	*Specific SFOC + limitations*	*Specific SFOC + limitations*
Voyage	Weather modelling		*EEDI or intended route*	*Intended route*	*Intended route*	*Intended route or weather routing*
Constraints	Operational constraints and limitations	*Example: Limiting wind speed*		*Examples: Limiting wind speed, Reasonable rudder and heel*	*Examples: Limiting wind speed, Reasonable rudder and heel*	*Examples: Limiting wind speed, Reasonable rudder and heel*
Mix	Effects of ship motions and varying wind, incl control systems response time					*optional*
Mix	Hybrid-propulsion (diesel electric) with energy management optimisation					*optional*

**) Suggested design stage where the different levels can considered appropriate.*

***) Distinctions between Low/Mid and high fidelity methods are discussed in the following sections of the guideline*

****) Although force balance can be limited to 3-4 DOF, 6-DOF seakeeping models for evaluating motions are generally required for routing purposes*

3. PREDICTION OF POWERING PERFORMANCE AND FUEL CONSUMPTION OF A SHIP WITH WIND PROPULSION.

3.1 Aerodynamic modelling

Covering all possible wind- and operational conditions in the power prediction process with high fidelity methods is in practise impossible. The aerodynamic modelling will in most cases therefore be a surrogate model based on an underlying data set, so that all conditions and settings can be covered in a feasible way. The underlying data set should then be ascertained to cover the relevant range of conditions with sufficient resolution and with variation of the parameters important for the study. The difference between the fidelity levels lays in which physical phenomena are neglected and to what extent the models are validated for the specific case using high fidelity methods.

High fidelity methods can be considered to be wind tunnel model tests, CFD/numerical calculations and full scale tests, and the appropriate choice of method depends on the type of wind propulsor, but also size limitations and proven methodologies shown in literature.

In this section, general considerations for wind modelling, wind tunnel testing and CFD are given, followed by modelling recommendations for the various performance prediction levels.

3.1.1 Air density

Unless otherwise specified and reasoned for, the standard air density at sea level and temperature 15°C of ρ_A =1.225 kg/m^3, should be used.

3.1.2 Wind modelling

Studies have shown that the modelling of the wind field can have substantial impact on the predicted performance of wind propulsion applications, and appropriate modelling of the vertical profile originating from the atmospheric boundary layer is considered important. For wind tunnel tests, CFD simulations and computations as relevant, an exponential profile for open-sea conditions without obstacles is suggested as a default. Deviations from this profile may be prudent in specific studies, but should be accompanied with reasonable arguments and relevant documentation:

$$v_{Zref} = v_{10m}\left(\frac{z_{ref}}{10}\right)^{\alpha}, for\ z_{ref} < 300m \qquad (1)$$

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

$$\alpha = \frac{1}{9} \qquad (3)$$

3.1.3 Wind tunnel testing of wind propulsion systems

The intention of this section is not to provide a detailed guideline on wind tunnel testing of wind propulsion systems, but rather to highlight some important aspects of such studies.

For wind propulsion devices appropriate for wind tunnel testing, various options may be considered:

- Test of a wind propulsor as a single unit alone. In this case, interaction effects between units and between ship and WPS must be added separately.
- Test of the complete wind propulsion system on a flat plate In this case, interaction effects between ship and WPS must be added separately
- Test of the complete wind propulsion system on a complete ship model.

The choice of setup depends on the application and feasibility in the wind tunnel. For large rigs such as on sailing yachts, where interaction effects play a major role, it is common to test the complete system in order to capture such effects directly.

There are significant Reynolds number dependent scale effects related to the performance of WPS measured in wind tunnel. Therefore, wind tunnels with small test section or low wind speed may not be appropriate for testing WPS.

- Wing sails operate close to maximum lift and therefore the stall angle is an important result of the wind tunnel test However, laminar separation will occur on wings sections for low Reynolds number, affecting heavily the stall angle and maximum lift. The critical Reynolds number depend on the geometry. It should firstly be considered when selecting the wind tunnel and designing the experiment. Secondly, the test program should include tests at different Reynolds numbers (several velocities or different scaled models) to explore the WPU behaviour in the different conditions, and to confirm supercritical Reynolds number. Appropriate turbulence stimulators including trip wires may be used to minimise this scale effect.
- Rotor lift and drag curves are reported in literature to be Reynolds number dependent. Also here, the test program should include tests at different Reynolds numbers (several velocities or different scaled models) to explore the WPU behaviour in the different conditions, and to confirm supercritical Reynolds number. Furthermore, velocity ratio (.e. the ratio between the tangential velocity of the rotor and the velocity of the incoming wind) effects and end plate effects must be considered. Not enough knowledge is available on the magnitude of the scale effect on rotors compared to full scale. Further research is recommended.

Furthermore, for tunnels with closed test sections, the blockage ratio calculated by the transverse projected area of the model divided by the cross-sectional area of wind tunnel should not exceed 5% according to common practise (Perzon, S., 2001), and if interaction between models is investigated, also the effects of wall proximity must be considered. It is otherwise referred to the expertise of the wind tunnel test laboratory for choice of appropriate method, setup and test matrix.

It is further recognized that for active devices, it might not be appropriate to determine the input power to the system by direct measurements.

3.1.4 CFD simulations for wind propulsion systems

Simulation for wind propulsion systems is essentially all about aerodynamics of lifting bodies and their mutual interaction, as well as their interaction with superstructure and ship. The main goal is to determine the thrust, side force, yaw moment and roll moment generated by the wind propulsion units (WPU). The following guidelines are applicable in general.

- The CFD result is highly sensitive to turbulence model, grid quality, and other settings. For example, incorrect setting can delay stall of wings, such that the performance is over-predicted heavily. Therefore, validation against wind tunnel data of the actual case, or similar shapes should always be carried out by the organisation conducting the CFD computations. This can be applied on a scaled model and a validation study with the wind tunnel data shall be carried out first, fine tune the solution strategy before it is applied for full scale configurations.
- The flow around superstructure and wind propulsion units (WPU) is highly turbulent and unsteady in nature, therefore URANS solver should be used in the first place. Steady RANS solver can be used only if a preliminary URANS simulation shows that the integral forces are not varying substantially with time in certain wind conditions.
- Make a proper balance in geometry representation between preserving the crucial parts in full detail and simplifying the unimportant parts. Ensure that the final geometry representation of configuration is well defined (no gaps, holes, intersecting patches). A water-tight solid geometry is preferable.
- The computational domain should be large enough in all directions so that the blockage coefficient of the configuration is below 5% in the x- and y-direction (Abdolrahim, R. et. al, 2017).
- Choose a turbulence model available in CFD software that can reliably predict flow separation, wake flow and tip-vortices. Menter’s SST k-ω turbulence model may be considered as it has been seen to have relatively better performance than other two-equation models in predicting separation, wake flow and vortices.
- Hexahedral mesh is preferred over tetrahedra mesh. It is impossible to align all the mesh lines with the inflow direction when a twisted velocity profile is assigned at the velocity inlet boundary, polyhedral mesh can be considered in such cases.
- Pay attention to the difference in turbulence length scale and hence the difference in Reynolds number between WPU and ship. The y+ value and the first prism-layer height should be determined using their respective characteristic length and Reynolds number.
- The mesh should be refined extensively on the suction side of WPU and in wake regions, as the WPU may be working in stalling and post-stall angles where massive flow separation occurs.
- Sufficient mesh refinement should be applied in the wall-normal direction towards body surface (wall). This is usually achieved by generation of a set of prism layers near body surfaces. A y+ value around 1.0 is

preferred for WPU. This is however not always affordable especially for a full-scale configuration with multiple installation of WPUs where the total cell count of mesh would have become unrealistically large, in such cases a y+ value falling in the log-law region is used for WPU and a wall-function boundary layer model should be selected in the turbulence model for WPU.

- The far-field velocity relative to ship is the vector sum of Atmospheric Boundary Layer (ABL) velocity and a reversed ship velocity. This vector is used to specify a velocity inlet Boundary Condition (BC) on parts of the domain.
- Depending on the apparent wind direction, the Velocity Inlet BC may need to be applied on more than one side of the CFD domain. The same principle applies for the Pressure Outlet BC. The top side of the domain is either defined as Slip BC or Symmetry BC. The bottom of the domain is defined as a No-slip wall BC.
- At least a 2nd order discretization scheme should be used for all the convective terms in the transport equations. A 2nd order temporal scheme is preferred to use.
- The time history of solution residuals should be monitored all the time. Convergence is considered to have reached when all the residuals have decreased by three orders of magnitude from their initial values. In addition to residual monitoring, the integral forces are normally also monitored to check the convergence of solution.

3.1.5 Wind forces on hull and superstructures

Depending on the approach taken for modelling the aerodynamic forces of the wind propulsion system, the aerodynamic forces on hull and superstructure may have to be modelled separately. The following should be taken into account w.r.t. modelling of wind forces on hull and superstructures:

- Side forces, yaw moments and heeling moments should be taken into account as well as the resistance component, since it will affect the equilibrium states of leeway, heel and rudder angle.
- The previous point is equally important when evaluating the baseline case without WPS in a power saving study.
- Any additional forces from wind propulsors not represented in the WPS modelling should be included, such as e.g. inactive rotors/suction sails, additional structures (masts etc)
- It is common practice that the ship hull resistance curves include air resistance (in zero wind). If that is the case, then that resistance component should be corrected for.

Low-fidelity alternatives to CFD or wind tunnel tests are available in literature, e.g. Brix (1993) Blendermann (1996) Fujiwara et al (1998).

3.1.6 Modelling for Level I predictions

The following are examples of appropriate simplified methods for Level I investigations:

- Lift and drag coefficients for similar installations from literature, with appropriate inclusion of 3D effects if coefficients are based on 2D sections.
- Data from previous inhouse studies on similar installations.

(See section "CFD" or "WT" for discussion on requirement to judge the quality of the available sources in literature)

Further, any required power input to the WPU can be estimated in a simple manner or from experience. Interactions between WPU's and between WPU and hull/superstructure/cargo can be neglected.

3.1.7 Modelling for Level II predictions

For a Level II investigation, simplified methods can still be applied in the aerodynamic modelling. However, the methods and models shall be adapted specifically to the case to be analysed, and estimates shall where relevant also include:

- Interactions between WPU's by best estimates (e.g. generalized models from 3D CFD simulations, lifting line approaches and similar)
- Interactions between Hull/superstructure/cargo and WPU's; by e.g. estimate shadow effects from best guess, literature (p.t. limited relevant literature is available) or earlier similar studies.
- Effect of wind profile (e.g. twisted inflow requiring section-based coefficients)
- Specific estimate of the power input to the WPU(s), including mechanical losses, actuation of control surfaces and flow-manipulation techniques (if any).

(See section "CFD" or "WT" for discussion on requirement to judge the quality of the available sources in literature)

3.1.8 Modelling for Level III & IV predictions

For Level III & IV investigations, high fidelity methods for the specific case shall be applied for generating and/or validating the aerodynamic surrogate models. In this context, high fidelity methods are considered to be primarily wind tunnel tests and validated 3D CFD simulations carried out according to best practices. It is however recognized that such methods are not rational to apply for certain wind propulsion types. A relevant example are kites in which cases combinations of land-based prototype tests and numerical computations may be more prudent.

Furthermore, the validation of the aerodynamic surrogate model shall be ensured to appropriately cover the settings that the WPU will operate within.

In the case of the installation of multiple wind assisted propulsion units, the method applied to account for interaction effects between wind propulsors and between the ship and the wind propulsors should be validated by spot checks using e.g. CFD or wind tunnel tests for the actual installation for a certain number of conditions.

Interaction between WPU(s) and hull/superstructure/cargo shall be included by appropriate models validated and tuned to results from high fidelity methods

The aerodynamic modelling of the WPU's should allow for incorporating the effect of wind profile in power predictions, for instance by sectional lift and drag coefficients with sufficiently small sections.

(See sections 3.1.3 and 3.1.4 for discussions on requirements to judge the quality of the available sources in literature)

3.2 Hydrodynamic modelling

Performance predictions for conventional vessels are commonly produced by evaluating the equilibrium between one degree of freedom straight line resistance forces and propulsion forces. Also for ships with WPS, the performance prediction typically starts with a resistance curve for the vessel under ideal conditions, i.e. calm water, no wind, and a straight course. However due to the forces inherently generated by WPS, the force balance is now in principle a 6 DOF problem. In the following sections, guidance on modelling of hydrodynamic effects for different levels of fidelity is provided.

In addition to the specific hydrodynamic effects originating from the forces from the WPS, increased hull resistance due to increased displacement stemming from the weight of the WPS including subsystems, structural support and, if applicable, systems or ballast for heel compensation, should be accounted for.

3.2.1 Modelling for Level I predictions

For the purpose of early concept studies falling under the definition of Level I, hydrodynamic effects from leeway, heel and use of rudder may be omitted in what is a 1DOF-approach. This will lead to an overly optimistic estimate of the power saving from the wind propulsor systems, increasingly so for larger portions of wind propulsion.

In a Level I investigation the propulsion efficiency, η_D, may be assumed unaffected and constant. If unknown for the specific case, a standard value of 0.7 can be used for conventional open propellers.

3.2.2 Modelling for Level II predictions

In a Level II investigation, hydrodynamic effects from the forces imposed by the WPS shall be included in the power predictions. While simplified empirical methods can be utilized, they must be tailored to the specific case and their validity towards the case considered.

Hull and appendages

Under Level II, the calm water resistance curve may be derived from established empirical methods valid for the case in hand, e.g. Holtrop & Mennen (1982), Hollenbach (1998) or other. For retrofit case studies, calm water resistance curve can often be made available from earlier model test or sea trial reports, and in such cases these data should be applied.

Hull forces can be derived from mathematical manoeuvring models which as a minimum account for surge, sway and yaw (3-DOF models). The mathematical models in Level II can be based on data base from earlier CFD or model tests of similar ships, regression equations from data base or potential flow methods with corrections for viscous forces. The chosen approach should be validated against a similar ship to ensure its applicability, and surge forces predicted by the model for zero leeway angle shall be made sure to correspond to the calm water resistance curve. It is important to consider the similarity of the ship's hull (similarity needs to be evaluated specifically depending on case, but some examples of parameters to consider are fullness, number and type of propulsors, non-dimensional characteristics L/B, B/T, $L/V^{1/3}$), appendages, and other characteristics towards the basis of the empirical model, as such models typically have limited validity envelopes.

Significant appendages, such as drop keels or fins can be modelled for instance by lift and drag coefficients for representative shapes.

Rudder modelling

In Level II, rudder models can be based on best estimates from what may be limited available data. In practise, this implies using generic lift/drag coefficients from literature for the rudder, for example from Molland & Turnock (2007).

Propeller and propulsive coefficients modelling

In level II, propeller series data or open water curves from similar propellers may be used. Case specific propeller open water curves may be available for e.g. retrofit studies and should then be applied. For Level II studies, it is adequate to apply the same values for thrust deduction t, wake fraction w (and as such hull efficiency $\eta_H = \frac{(1-t)}{(1-w)}$) as for the vessel without wind propulsion, and the values can be based on empirical data. The same applies for relative rotative efficiency η_R. In other words, corrections for e,g, changes in inflow due to leeway and hull straightening effects on the propeller etc can be omitted. Although several studies show that these effects are not in principle negligible (Sauder & Alterskjær (2022), Schot & Eggers (2019)), and empirical formulas to calculate straightening coefficients and modulation of wake fraction with leeway can be found in Yasukawa & Yoshimura (2014), the application for wind powered ships which are also affected by reduced propeller loading is not well established.

Rudder and propeller interaction

The modelling shall allow for incorporating changes in inflow due to leeway, reduced flow speed over the rudder due to lower propeller loading, and for hull straightening effects. All these effects are shown to have significance for the performance prediction, and approaches for such modelling for conventional propeller-rudder systems are available in literature, for instance in the description of the MMG method (Yasukawa & Yoshimura, 2014)

Added resistance due to waves

For Level II studies, it is adequate to include an appropriate sea margin for the sake of a fairer relative comparison of power consumption with and without wind propulsion. Note then however, that the prediction model will not be suitable for routing purposes, as it will give unrealistically high rewards for routing the vessel with wind propulsion into severe weather conditions.

3.2.3 Modelling for Level III&IV predictions

Hull and appendages

For predictions at Level III, it is expected that the hydrodynamic model is based on CFD simulations or model tests of the particular vessel, and that the simulations or tests are conducted in accordance to 7.5-03-04-01 or 7.5-02-06-02, respectively. When conducting and analysing the simulations/tests, sufficient attention must be given to the forces and moments for relatively small leeway angles, compared to standard manoeuvring models. Alternatively, standard/empirical manoeuvring models may be applied if tuned and validated to results from hybrid model tests, i.e. hydrodynamic model tests with free running model and where real-time simulated wind forces are applied to the physical model by means of wire/winch system (Sauder & Alterskjær (2022)), or fans.

Significant appendages that are not considered part of the hull in the above-described manoeuvring model, such as keels or stabilizer fins that shall be adjustable or retractable shall be modelled based on dedicated CFD simulations or model tests.

A 4 DOF (surge, sway, yaw, heel) manoeuvring model is generally advised. If a 3 DOF model is applied (neglecting heel angle) the choice must be justified since in principle heel angle can have non-negligible affects on forces in surge, sway and yaw. Note that even in cases where heel is neglected in the manoeuvring model, it may still be necessary to impose maximum allowable heel thresholds in performance predictions and route studies.

Rudder and propeller

For Level III&IV predictions, it is expected that the propeller open water curve for the particular propeller is available from CFD or model tests.

Although CFD or model tests data for the rudder are preferred, established rudder model representative and validated for the particular rudder type may be applied. Rudder models shall include corrections for changes in inflow due to leeway and lower propeller loading, and for hull straightening effects.

Propulsion coefficients

For Level III&IV predictions, it is expected that CFD simulations or model tests are conducted to investigate the effect of leeway and reduced propeller loading on effective wake fraction, thrust deduction and relative rotative efficiency. It is clear that simulations or model tests for deriving these quantities for every conceivable operation point is too comprehensive, so the most important operation points should be chosen, and rational models established as required for power predictions and route studies.

Added resistance due to waves

For predictions under Level III & IV, added resistance due to waves is expected to be modelled through ship-specific rational approaches capable of considering waves from all headings through added resistance quadratic transfer functions. Model tests or CFD simulations or validated potential theory codes are advised but published and recognized empirical methods such as SNNM (Wang, et al., 2021) or SPA (Grin, R., 2015) may also be used keeping in mind the validity limits of these methods.

3.3 Machinery modelling

3.3.1 Modelling for Level I predictions

Machinery modelling may be neglected in a Level I study.

3.3.2 Modelling for Level II predictions

Level II predictions should account for the fact that reduced loading may lead to reduced efficiency in engine and drive trains (e.g. gearboxes). Characteristic efficiencies and SFOC-curves (Specific Fuel Oil Consumption) representative for the configuration to be studied may be applied.

For cases with significant portion of wind propulsion, it is important that the machinery modelling takes into consideration the lower loading limits in terms of RPM and torque, typical for the machinery type relevant for the ship investigated.

3.3.3 Modelling for Level III&IV predictions

Level III & IV predictions should account for the fact that reduced loading may lead to reduced efficiency in drive train and engine. Efficiencies and SFOC-curves for the specific case to be studied shall be applied.

For cases with significant portion of wind propulsion, it is important that the machinery modelling takes into consideration the lower loading limits in terms of RPM and torque, specifically for the ship investigated.

3.4 Power requirement in all wind conditions

This section describes methods for predicting the power requirement of a wind powered vessel in a range of wind conditions. The tool for these computations is commonly denoted Power Prediction Programs (PPP). The process involves, but not necessarily in this order:

- Finding the static force and moment equilibrium, where the forces are derived from the various input models described in earlier sections.
- Computing the propeller power requirement to maintain the ship’s speed given the static force.

The net propulsion power required from the ship’s engine for the case with WPS is found from

$$P_{with\ wps} = \frac{T_P \cdot V_S}{\eta_D} + P_{WPU-in} \qquad (4)$$

where

T_P is the hydrodynamic propulsion force in the ships longitudinal direction

V_s is the ship's speed

η_D is the total propulsive efficiency, modelled differently in the different Levels as described in section 3.3.

P_{WPU-in} is the power consumption of the WPU, also taking into account losses in producing this power.

For comparison, the power requirement for the case without WPS is derived as

$$P_{no\ wps} = \frac{T_P \cdot V_S}{\eta_D} \tag{5}$$

For the wind conditions where the WPS do not produce any thrust, and the WPS is not tiltable or retractable, a resistance of the idling WPU must be added to the force balance.

The input models are typically smooth mathematical descriptions of the physics each model represents, making it possible to use common optimization/solver techniques.

The equilibrium is usually obtained for constant ship speed, for constant propeller power or for constant propeller RPM.

Given a ship sailing with constant speed in a set environmental condition, there exist in principle a continuous number of force equilibriums depending on the commanded states of the WPS and conventional propulsion system. It is not necessarily so that maximizing the thrust from the WPS yields the best net performance, due to undesirable effects from e.g. side forces from the WPS. Consequently, if the underlying models and the control system of WPS allows, the PPP should ideally identify the force equilibrium with best performance considering all modelled effects. Further, The PPP should detect and, by for example reduce WPS loading, handle when power, torque or RPM limitations, or other constraints, are exceeded.

Allowances for e.g. margins towards stall, control system limitations etc should be included either in the underlying WPS models or in the logics of the PPP. Preferably the actual algorithms, or control strategy, from WPS provider should be used, but if these are not known, the control system should be assumed realistic, not ideal.

The two steps are conducted for a range of TWA and TWS in sufficient resolution.

3.4.1 Degrees of Freedom in the powering predictions

In Level I the force balance comprises 1 DOF; Surge. The forces in the longitudinal direction to consider are calm water resistance, propeller thrust, and WPS thrust.

In Level II the force balance comprises 3 DOF or 4 DOF: surge, sway, roll and yaw. Roll can be neglected for moderate wind assistance installations.

In Level III the force balance comprises 4 DOF: surge, sway, roll and yaw.

Roll is for many ship types small and can be omitted if justified.

In Level IV the force balance comprises at least 4DOF. Since the steady forces from WPS in pitch and heave are typically small compared to the ship’s restoring force/moment, these degrees of freedom can normally be neglected for the purpose of power predictions. However, where the intention is to conduct route optimization, 6 DOF models are necessary in order to include constraints on ship motions/accelerations. Moreover, 6 DOF simulations can be valuable to quantify the effect of changed inflow to the WPS due to the ship’s motions in waves.

3.5 Constraints, settings

Operational considerations may impose limitations on the output of the WPS, and such constraints can be taken into account either implicitly in the PPP or in route simulations. Examples of relevant constraints are:

- Excessive rudder angle
- Excessive heeling
- Excessive local forces on WPS or its foundation
- Reduced engine loading below minimum continuous operating point

Reasonable quantifications of constraints should be identified together with owner/operator for the specific case, taking into consideration that since the predictions are based on steady state assumptions, sufficient margins towards dynamic effects should be included.

In lack of better estimates in early design stages, an upwards limitation for static rudder angle for a conventional vessel may be in the order of 10 degrees.

Similarly, the upwards limiting static heel will be highly case dependent and, in many cases, dictated by stability requirements, but 5 degrees for cargo ships and 2 degrees for passenger ships may be used in early-stage assessments in lack of better information. In case heel compensation by means of ballast tanks, anti-heeling tanks or stabilizing fins is applied, any contribution to the total resistance should be accounted for.

Voyage simulations in a level II, III & IV prediction shall account for limitations due to excessive heel angles, excessive rudder use and excessive WPU forces in conditions with especially strong winds, unless such conditions are shown to be so rare that they are statistically insignificant. The conditions can be accounted for by setting WPS contribution to zero and, where relevant, including the drag of the inactive devices if thresholds for abovementioned parameters are exceeded (conservative approach) or depowering to such a degree that that values are below thresholds.

Furthermore, in level IV predictions WPS control system should be set according to supplier's specifications, incorporating limitations such as stall margins.

3.6 Route studies

3.6.1 Weather data

Since the predicted power savings from WPS applications are very dependent on the wind conditions, weather data should be retrieved from reliable sources. The choice of source may depend on specific requirements, but the following are often considered for open ocean studies:

- EEDI Global Wind Probability Matrix (https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.1-Circ.896.pdf). Note: Area of applicability is limited to the main global shipping routes
- ECMWF ERA5 reanalysis data set available at the Copernicus Climate Data Store (https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5, u.d.)
- CFSR: The Climate Forecast System Reanalysis (CFSR) dataset is generated by the National Centers for Environmental Prediction(NCEP) (https://climatedataguide.ucar.edu/climate-data/climate-forecast-system-reanalysis-cfsr, u.d.)
- MERRA-2: The Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2), is produced by NASA's Global Modeling and Assimilation Office (https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/, u.d.)
- Global Wind Atlas: free, web-based application developed through of a partnership between the Department of Wind Energy at the Technical University of Denmark (DTU Wind Energy) and the World Bank Group (https://globalwindatlas.info/en)
- Globus: Global winds and waves statistics of multiple sea area, produced by National Maritime Research Institute, Japan (NMRI) https://www.nmri.go.jp/archives/db/globus/namikaze_main_e.html

These data sources will generally have higher uncertainty and too large spatial resolution for routes close to shorelines and sheltered areas, in which case it is advised to investigate whether regional weather centres have data of higher quality and resolution.

Where added resistance due to waves are included in the assessments, the wave conditions may be determined from an appropriate wave-follow-wind formulation as defined in for instance Bales (1983) or recommendations such as IMCA (2000) or DNV (2021). However, such a relationship can realistically only consider wind sea and it neglects swell, yielding relatively short waves. For longer ships, this may lead to an underprediction of the added wave resistance. Thus, both wind waves and swells should be considered by use of suitable weather data sets.

An alternative option for specific use cases and routes is to use wind logged on board a representative ship, provided a trustworthy data set of sufficient recording time can be obtained and when it has been ascertained that the measured wind sensor is calibrated, corrected for height and made sure that it is not affected by nearby obstructions.

Irrespective of approach, it is of importance that the duration of the data sets, and the route study itself, is sufficient to provide statistically representative results which implies studying several years of operation.

3.6.2 Level I predictions

In Level I, the route study is carried out using the **Aggregate route wind statistics**

approach. The wind variation on one or several routes is represented by a matrix of true wind speed, true wind angle and their aggregated probabilities. The average propulsion power demand is obtained by:

$$\overline{P_{with\ wps}} = \sum_{i,j}^{n,m} \left[\frac{T_P \cdot V_S}{\eta_D} + P_{WPU-in} \right]_{i,j} \times \left[\mathrm{W}_{i,j} \right] \qquad 6)$$

where

T_P is the hydrodynamic propulsion force in the ships longitudinal direction

V_S is the ship’s speed

η_D is the total efficiency at the main drive(s) including shaft losses, 0.7 if unknown

P_{WPU-in} is the power consumption of the WPU.

$\mathrm{W}_{i,j}$ is a weather matrix, for example the complete EEDI weather matrix as given in IMO (2021).

The wind matrix may be derived for a specific route using reliable weather data sources, see section 3.7.1.

The corresponding value for the case without WPS is computed in the same way with everything else unchanged apart from the WPS.

3.6.3 Level II-III predictions

In Level II, the route study can be carried out with two different approaches:

- **Statistical route simulation**. Typically using Monte Carlo simulations where joint weather distributions for TWS and TWA are aggregated based on weather statistics for the route. Sample weather conditions are drawn based on its probability of occurrence, and the performance for this specific weather condition is found through interpolation in pre-processed polar curves for the parameters of interest. The simulations are repeated for a predetermined number of iterations.
- **Discrete-event voyage simulations.** Simulations where a simulation is typically set to start at a predefined historic time and date and runs for a specified amount of time (often throughout the length of the available historic weather data set). Equilibrium conditions are found either by the PPP or pre-processed polar curves for each point along the route in the occurring environmental conditions.

Each of the above methods have advantages and disadvantages. While the Monte Carlo simulation approach will require less computational effort, the discrete-event simulations may be preferred for investigating varying different parameters along the route such as ship speed, displacement, etc.

For either of the approaches, it is essential to divide the legs on the route in sufficient detail. The spatial resolution will often relate to the available weather data. For discrete-event simulations also the temporal resolution is of importance, also here typically guided by the weather data.

From both approaches, probability distributions for relevant parameters are important outputs, in addition to most probable power/energy consumption numbers.

The result of the route study is the average power requirement $\overline{P_{wps}}$ and $\overline{P_{no\ wps}}$ for the ship with and without WPS respectively, for the same ship's speed and same route.

3.6.4 Level IV predictions

Level IV is intended for extensive weather routing studies, primary wind powered ships, and ships with advanced hybrid propulsion systems. In most aspects, Level IV follow the same approaches as Level III. However, more detailed modelling and studies are required to enable including effects such as ship motions, realistic constraints, varying wind control system behaviour and response time. Further descriptions are not provided in this guideline, as the approaches will be highly case-dependent.

Studies at this level will typically also include optimisation of both speed and track to get the minimum energy consumption for a given transport time. For route optimization studies, it should be realized that desktop studies using weather hindcast data may give too optimistic results compared to real-life routing situations that deal with the uncertainties in forecasted data (Eggers, R. et al, 2022).

3.7 Presentation of results

3.7.1 Performance Indicator for Level I-IV

The indicators should be indexed by the level number with which it was derived. Level I predictions results in PSP-I, Level II results in PSP-II etc.

The indicators express *potential* savings. The word "potential" indicates that the result is the technical potential that the installation can deliver. During operation, many practical aspects may affect the real saving, such as maintenance, damage, operating in confined waters. The saving may also be larger than predicted, if the ship is routed with respect to the wind in a favourable way.

Propulsion power saving indicators

Power Saving Potential is derived as:

$$PSP = \overline{P_{no\ wps}} - \overline{P_{wps}}$$

where

$\overline{P_{\text{no wps}}}$ is the yearly average power on a given route for the ship without WPS

$\overline{P_{with\ wpt}}$ is the yearly average power on a given route for the same ship with WPS, for the same ship speed.

In some cases, one will want to compare only the propulsion power with and without WPS. In other cases, it is more relevant to quantify the savings WPS contributes to compared to the ship's total power consumption. This should be reflected in the percentage saving indicators. The PSPp includes the propulsion power only, and the route includes the sea legs only (pilotage to pilotage).

$$PSPp = \frac{(\overline{P_{no\ wps}} - \overline{P_{with\ wps}})}{\overline{P_{no\ wps}}} \tag{7}$$

The PSPt relates the fuel saving to the ships total fuel consumption including auxiliary power, harbour manoeuvres etc:

$$PSPt = \frac{(\overline{FOC_{no\ wps}} - \overline{FOC_{with\ wps}})}{\overline{FOC_{no\ wps}}} \tag{8}$$

Fuel saving indicators

The Percentage Total Fuel Saving requires that the fuel consumption is derived for both cases with and without WPS. The fuel consumption should include the total consumption including auxiliary power, harbour manoeuvres etc.

Energy saving indicator

For Level IV prediction, the indicator is denoted Energy Saving Potential (ESP). The ESP is derived by comparing the average energy consumption to transport the same transport work between the same ports. This means the ship speed may vary.

Energy saving potential is derived as

$$ESP = E_{no\ wps} - E_{wps} \tag{9}$$

where

$E_{\text{no wps}}$ is the yearly energy consumption for a given transport mission for the ship without WPS

$E_{with\ wps}$ is the yearly energy consumption for the same ship with WPS, carrying out equivalent transport work.

3.7.2 Performance Indicator for Level 0

The performance indicator for stand-alone wind propulsion units, PSP-0 (kW) is derived in the following manner:

$$PSP - 0_{[kn]} = \sum_{i,j}^{n,m} \left[\frac{F_{x,wpu} \cdot V_s}{\eta_D} - P_{WPU-in}\right]_{i,j} \times [\mathrm{W}_{i,j}] \tag{10}$$

where:

$\mathrm{W}_{i,j}$ is the complete EEDI weather matrix as given in IMO (2021).
η_D =0.7
$F_{x,wpu}$ is the WPU thrust force matrix at the corresponding winds as the weather matrix (kN)
V_s is the ship speed (m/s)
P_{WPU-in} is the power consumption of the WPU (kW)
Kn is the V_s in knots

3.7.3 Expected outputs and documentation

A list of outputs and documentation expected to accompany power saving predictions at different levels is presented in Table 3. Furthermore, the following should be made available where relevant:

- Origin of lift and drag coefficients with source

- Source of data, or description of procedure and assumptions applied to determine input power for WPU.
- Description of the modelling and its validation, also stating with which level each part of the analysis adheres to, with reference to Table 1.
- Source of weather data in case of voyage simulations
- Presentation of weather data statistics in case of voyage simulations, in the form of for example histograms of TWA, TWS, AWA and AWS.

Table 2 Recommended KPI's

		Level 0	Level I	Level II	Level III	Level IV
Preferred	Rated power (kW)	*PSP-0*				
	Power Saving Potential (kW)		*PSP-I*	*PSP-II*	*PSP-III*	
	Energy Saving Potential *(MWh)*					*ESP-IV*
Optional	Percentage Saving Potential – Propulsion power (%)			*PSPp-II*	*PSPp-III*	*PSPp-IV*
	Percentage Saving Potential – Total fuel (%)			*PSPt-II*	*PSPt-III*	*PSPt-IV*

Table 3 Expected output/documentation

Quantity	Description	Unit	Level I	Level II	Level III	Level IV
CL and CD charts	*Charts illustrating lift and drag coefficients for WPU as function of angle of attack as applied in the predictions*	*[-]*	X	X	X	X
Thrust force coefficient	*Chart illustrating the thrust force coefficient as function of TWA for the WPU at different TWS*	*[-]*	X	X	X	X
Power coefficient	*Chart illustrating power coefficient (WPU power demand) as function of TWA for the WPU at different TWS (for devices that require power input to produce lift)*	*[-]*	X	X	X	X
Fraction of wind assist	*Chart(s) illustrating fraction of total required thrust provided by WPS for given ship speed(s) as function of TWA at different TWS*	*[-]*	X	X	X	X
F(Vref)	*Wind Propulsion force matrix as applied for EEDI calculation*	*[kN]*	X			
P(Vref)	*Power demand matrix for operation of the WPS as applied for EEDI calculation*	*[kW]*	X			
η_D	*Total efficiency of main drive as assumed for EEDI calculation*	*[-]*	X			
Leeway angle	*Chart(s) showing equilibrium leeway angle for given ship speed(s) as function of TWA at different TWS*	*[deg]*		X	X	X
Rudder angle	*Chart(s) showing equilibrium rudder angle for given ship speed(s) as function of TWA at different TWS*	*[deg]*		X	X	X
Heel angle	*Chart(s) showing equilibrium heel angle for given ship speed(s) as function of TWA at different TWS*	*[deg]*		(X)	(X)	X
RPM, Thrust, Torque, Power	*Chart(s) showing equilibrium propeller RPM, thrust, torque and power for given ship speed(s) as function of TWA at different TWS*	*[-], [kN], [kNm], [kW]*	X	X	X	X
η_D	*Chart(s) showing equilibrium propulsion efficiency for given ship speed(s) as function of TWA at different TWS*	*[-]*		X	X	X
w, t, η_0, η_R,	*Chart(s) showing equilibrium propulsion coefficients for given ship speed(s) as function of TWA at different TWS*	*[-]*			X	X
Voyage simulation statistics	*Relevant statistical output from the voyage simulations, such as distribution of TWA, TWS, wave conditions, leeway angle, rudder angle, heel angle and propulsion parameters*			X	X	X
PSP	*Chart of Power Saving Potential as function of TWA at different TWS*	*[kW]*	X	X	X	X

4. VALIDATION

4.1 Uncertainty analysis

Uncertainty analysis of the underlying experimental or numerical investigations used for deriving the models can be performed in accordance with *Uncertainty analysis in EFD, Uncertainty assessment Methodology*, as described in QM 7.5-02-01-01, and: *Quality Assurance in Ship CFD Application*, as described in QM 7.5-03-01-02.

4.2 Verification of predictions

Presently, no experimental or CFD standards are available for a complete verification of the power saving prediction. However, hybrid model tests or sea trials according to 7.5-04-01-02 can be viewed as the procedures producing highest fidelity level at present and as such should be used for verification of predictions and for producing data for validation of models and methods.

5. PARAMETERS; SYMBOLS

β	Leeway (also referred to as drift) angle, angle between heading and course	(deg)
ρ_A	density air	(kg/m^3)
AWA β_{WA}	Apparent wind angle	(deg, rad)
AWS V_{WR}	Apparent Wind Speed	(m/s)
C_D	Drag coefficient of WPT	
C_L	Lift coefficient of WPT	
TWA β_{WT}	True wind angle relative to ship's course	(deg, rad)
TWD	True wind direction, relative to	(deg, rad)
TWS V_{WT}	True Wind Speed	(m/s)
P_{WPU-in}	Power cons. of WPU	(kW)
U_{10}	Reference mean wind speed	(m/s)
${U_z}^A$	Average wind speed, at elevation z above the sea surface	(m/s)
V_s	Ships speed	(knots)

6. REFERENCES

Abdolrahim, R., Kalkman, I., Blocken, B., 2017, “CFD simulation of a vertical axis wind turbine operating at a moderate tip speed ratio: Guidelines for minimum domain size and azimuthal increment”, Journal of Renewable Energy, Vol. 107, pp. 373-385

Bales, L.S., 1983, “Designing Ships to the Natural Environment”, Naval Engineering Journal, Vol. 92(2)

Blendermann, W., 1996, “Wind loading of ships—collected data from wind tunnel tests in uniform flow”, Report 574, Institute of Naval Architecture, University of Hamburg.

Brix, J. E., 1993, “Manoeuvring Technical Manual”, Seehafen-Verlag.

DNV, G. L. DNV-ST-0111, 2021, "Assessment of station keeping capability of dynamic positioning vessels"

Eggers, R., Dell’Acqua, A., Akker, J., Wisse, J., 2022, " Exploration of Wind Propulsion: Performance and economical assessment for a NewcastleMax Bulk Carrier", 15th International Symposium on Practical Design of Ships and Other Floating Structures

(PRADS) Dubrovnik, Croatia, October 9th – 13th 2022

Fujiwara, T., Ueno, M., Nimura, T., 1998, “Estimation of Wind Forces and Moments acting on Ships.”, Journal of the Society of Naval Architects of Japan, pp. 77-90.

Grin, R., 2015, “On the Prediction of Wave-added Resistance with Empirical Methods.”, Journal of Ship Production and Design, Vol. 31.

Hollenbach, K. U., 1998, “Estimating Resistance and Propulsion for Single-Screw and Twin-Screw Ships”, Ship Technology Research, Vol. 45.

Holtrop, J. & Mennen, G.G.J., 1982 “An approximate power prediction method”, International Shipbuilding Progress, Vol.29, No. 335,

IMCA, 2000, "Specification for DP Capability Plots." M. 140 Rev. 1 IMCA, London, 2000.

International Maritime Organisation, 2021 "Guidance on treatment of innovative energy efficiency technologies for calculation and verification of the attained EEDI and EEXI", MEPC.1/Circ.896

Molland, A. F, & Turnock, S. R., 2007 "Marine Rudders and Control Surfaces". Elsevier.

Perzon, S., 2001 "On blockage effects in wind tunnels – a CFD study", in: SAE 2001 World Congress, Detroit, Michigan.

Sauder, T. & Alterskjær, S. A., 2022 "Hydrodynamic Testing of Wind-Assisted Cargo Ships Using a Cyber-Physical Method". Journal of Ocean Engineering, Volume 243.

Schot, J. & Eggers, R., 2019 "The Effect of Leeway Angle on the Propeller Performance. RINA Wind Propulsion Conference, Oct 15, 2019.

Wang, J., Bielicki, S., Kluwe, F., Orihara, H., Xin, G., Kenichi Kume, K., Oh, S., Liu, S., Feng, P., 2021, "Validation study on a new semi-empirical method for the prediction of added resistance in waves of arbitrary heading in analyzing ship speed trial results", Ocean Engineering vol. 240, 109959

Yasukawa, H., & Yoshimura, Y., 2014. "Introduction of MMG standard method for ship maneuvering predictions." JASNAOE, pp. 37-52.

7. KEYWORDS

Wind propulsion, Performance prediction, Emissions reduction, Wind Propulsion Technology (WPT), Sustainable maritime operations