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Report.

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Speed trial and route analysis of m/v Frisian Sea with suction wings



Wind Assisted Ship Propulsion

Interreg North Sea Region WASP

European Regional Development Fund

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Speed trial and route analysis of m/v Frisian Sea with suction wings

A speed trial was performed with m/v Frisian Sea in October 2021. The purpose of the test was to verify the power saving of the suction wings. This report describes the tests conditions, measurements, analysis, and results. The trial test result is extrapolated to annual fuel reduction using voyage analysis and statistical weather distribution.

The work is a part of the Interreg North Sea Region project WASP - Wind Assisted Ship Propulsion.

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Summary and recommendations

A speed trial was performed with m/v Frisian Sea in October 2021. The purpose of the trial was to verify the power saving of the suction wings.

The speed trial result is scaled up to give a prediction of the in-service fuel reduction using a ship simulation model correlated to the actual speed trial measurements, a voyage prediction tool and statistical weather distribution.

At true wind speed 10 m/s and ship's speed 10 knots, the wings give a net power saving for apparent wind angles larger than 17 degrees and the saving reaches up to 90kW at the most favourable wind angle.

It is estimated that the fuel reduction on the vessel's typical routes is between 0.5 and 0.78 kg/nautical miles. For an average year of operation, the fuel saving potential is estimated to be 0.62 kg/nautical miles, which will give approximately 26.8 tons fuel saving per year, corresponding to 84.5 tons CO_2. This assumes that the wings are fully operable at all times when wind permits, and that the additional thrust is used to reduce engine load and keeping the speed constants to 10 knots.

After a longer period of operation, this report may be updated based on weather statistics and other operational data.

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Figure 2	Speed trial evaluation according to ISO 15016
Figure 3	Route analysis results

Symbols and abbreviations

ξ_p	Load variation factor, for power correction according to ITTC (2017)	-
AWS	Apparent wind speed	m/s
AWA	Apparent wind angle	deg
AWS_x	Apparent wind speed in ship longitudinal direction	m/s
AP	Aft perpendicular	
A_T	Transversal wind area	m^2
A_W	Total projected wing area	m^2
B	Beam of hull	m
BL	Baseline	
CL	Center line	
FP	Fore perpendicular	
FS	Full scale	
GWA	Global wind angle	deg
H	Wings height	m
IMO	International Maritime Organization	
ITTC	International Towing Tank Conference	
T	Draught	m
T_F	Draught at fore perpendicular	m
TWA	True wind angle	deg
TWS	True wind speed	m/s
V	Volume displacement	M3
V_s	Ship speed	knots
SOG	Speed over ground	knots
COG	Course over ground	deg
STW	Speed through water	knots

1 Introduction

Boomsma installed the wind assistance solution from Econowind on m/v Frisian Sea in January 2021. On October 11, 2021, a speed trial was performed with the purpose of evaluating the performance of the wings.

The Trial Team present onboard included Ship Master Oleksandr Pasatiuk, Sanne Swaan, engineer at Econowind, and Sofia Werner, SSPA Sweden AB. The trial was planned and conducted by the Trial Team in cooperation.

The speed trial result is scaled up to a predicted annual fuel reduction using a route analysis and statistical weather data. All data processing, analysis and route evaluation is carried out independently by SSPA.

This work is a part of Work Package 5 in the Interreg North Sea Region project WASP. The scope of Work Package 5 is to demonstrate the performance of Wind Propulsion Technologies on five vessels. The first trial, of the ferry Copenhagen, was reported in SSPA report RE40201042-01-00-A and in the proceedings of RINA International Conference on Wind Propulsion (Werner, 2021).

The aim is *not* to compare and rank different wind propulsion technologies. The fuel savings of each installation depend on the ship, speed and route, and therefore the tested cases cannot be compared with each other.

Figure A. m/v Frisian Sea (118m x 13.4m) with two suction wings from Econowind.

2 Speed trial data

2.1 Conventions and definitions

The following coordinate systems are used in this report:

- Used when referring to locations or distances on the ship:
    - Body-fixed, Cartesian, right-handed system "XYZ" with the origin in intersection of AP, CL and BL.
    - X-axis positive forward
    - Y-axis positive to port
    - Z-axis positive upwards

The following definitions of directions and angles are used in this report.

- Global wind angle (GWA): defined in the geographical system
    - GWA=0° means wind coming from north
- True wind angle (TWA): the angle between the wind direction and the course of the ship
    - TWA=0° means head wind
    - TWA=90° means beam wind (starboard side)

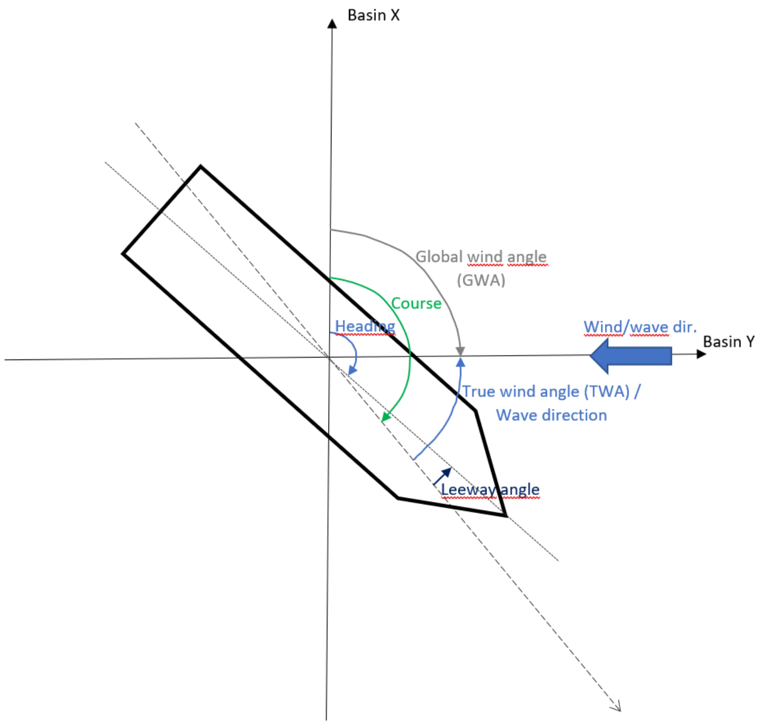

Figure B Definitions of directions and angles

2.2 Ship

The general cargo vessel m/v Frisian Sean (IMO 9534547) operates mainly in the North Sea region and Baltic sea.

The ship data used for the sea trial analysis is listed in Table 1. The ship has a ducted, controllable pitch propeller. The engine is a 4-stroke direct coupled, and with a shaft generator. The ship loading condition during trial is given in Table 2.

Table 1. Ship data

Name	Symbol	Magnitude	Comment
Length over all	Loa	118 m	
Beam over all	B	13.4 m	
Load variation factor for power	ξ_p	-0.15	Based on similar ships in SSPA's database
Hight of anemometer	h	26 m	from waterline at trial
Transversal wind area	A_T	215 m^2	

Table 2. Ship loading condition during trial

Name	Symbol	Magnitude	Comment
Draft forward	Tf	2.6 m	
Draft aft	Ta	3.8 m	
Displacement	Δ	4003 ton	

2.3 Wind propulsion system

The ship is equipped with two suction wings from Econowind with dimensions according to Table 3. The wings are fitted with flat racks and tiltable sideways over the hatch covers. Air suction is created with fans driven by electric motors. Rotation angle is set automatically based on the apparent wind measured in the mast.

Table 3 Wind propulsion system particulars

Name	Magnitude	Comment
Span	10 m	
Chord	3 m	
Thickness	1.8 m	
Area	30 m^2	projected
Position wing 1	74 m	From AP
Position wing 2	56.5	From AP

2.4 Trial location and environmental conditions

The trial was conducted in the Baltic Sea, south of island Gotland (Figure C.). An external weather source (StormGeo) reported conditions as stated in Table 4. Environmental conditions registered onboard are given in Table 5.

Table 4. External weather hind-cast

Wind	WSW	18 knots
Waves	WSW	1.7m / 5s
Swell	SSE	0.3m
Current	NE	0.26 knots

Table 5. Environmental conditions, registered onboard

Name	**Symbol**	**Magnitude**	**Comment**
Temperature sea water	t_{sw}	13°	
Density sea water	ρ_{sw}	1000 kg/m^3	Assumed
Temperature air	t_a	12°	
Air pressure	p	1013 mbar	Was not measured
Density air	ρ_a	1.24 kg/m^3	Derived from temperature

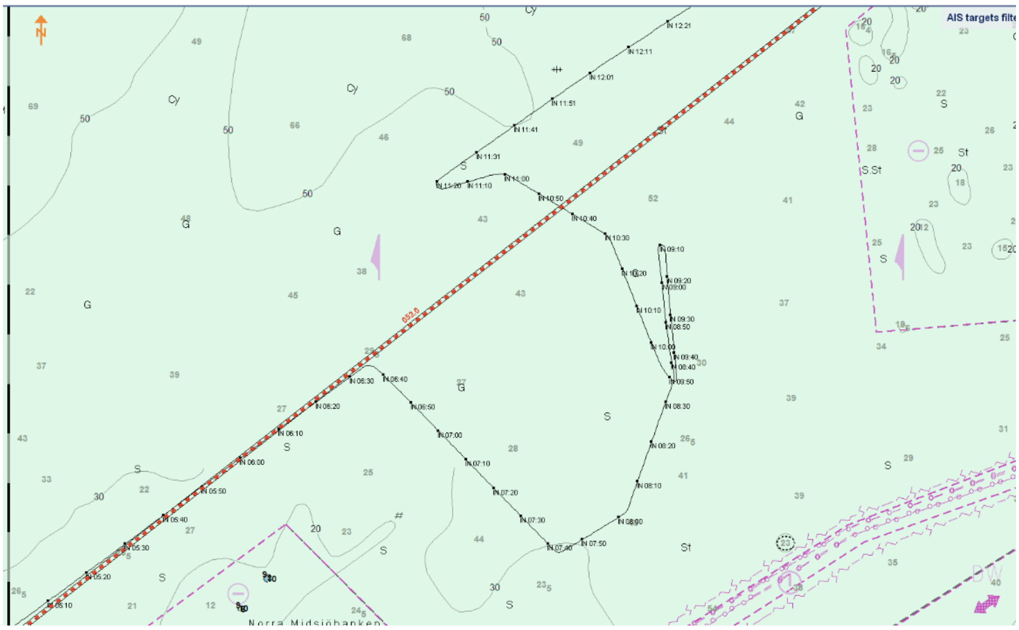

Figure C. Trial area south of Gotland

2.5 Data acquisition

All recorded data is listed in Appendix 1, Figure 1. Data acquisition was performed using the systems given in Table 6.

2.5.1 Power consumption of wings

The suction wing fans were supplied from the ship's shaft generator. PTO was registered in the data logging system. No other mayor consumers were active during the trial.

Table 6. Data acquisition sources

Variable	Instrument	Recording system	Frequency
Shaft power Propeller shaft rate	Eefting torque meter	Eefting data log	3 min running average
Shaft generator	Generator PTO	Eefting data log	3 min running average
SOG, COG	GPS	Eefting data log	3 min running average
STW	Doppler log	Eefting data log	3 min running average
Fuel oil consumption	Flow meters	Eefting data log	3 min running average
Heading (gyro) Rudder angle		Manual reading of displays on the bridge during trial runs	
Relative wind at mast top	Ships Anemometer	Econowind log	3 min running average

2.6 Trial procedure

The trial was conducted according to the principles in ISO 15016/ITTC 7.5-04-01-01.1, with some deviations.

The trial program included 16 single runs according to Table 7. Each run was 10 minutes long. Constant heading was kept during the runs using the ships autopilot.

The following sequence was followed for each heading:

1) Wings were folded down on the deck
2) Steady heading and speed were checked with external GPS by plotting over time.
3) Measurements conducted for 10 minutes
4) While keeping heading, rpm and pitch constant, wings were raised and set in operation mode.
5) Steady heading and speed were checked with external GPS by plotting over time.
6) Measurements conducted for 10 minutes

For some headings, the order was opposite (wings first, without wings second). Additionally, two runs were conducted without the wings straight into and following the wind. All runs were performed at a constant shaft rate and propeller pitch. The rpm of the wings was set automatically by the wings control system. The tracks are shown in Figure D, where the circles mark the start of a run.

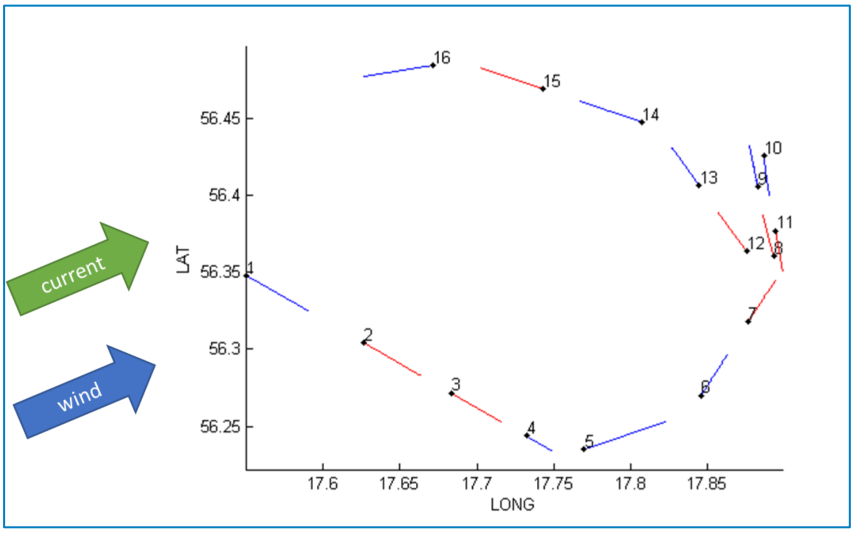

Figure D. Tracks of trial runs. Black dots mark the start of each run. Red=with wings, blue=without wings

Table 7. Trial program (note that actual wind angle deviated somewhat from the targeted)

Run	Target True wind angle	Wings up	Comment
1	120 s.b.		
2	120 s.b.	yes	
3	120 s.b.	1 wing up	
4	120 s.b.		test, not used
5	180		
6	140 port		
7	140 port	yes	
8	110 port	yes	
9	110 port		
10	70 s.b.		
11	70 s.b.	yes	
12	70 port	yes	
13	70 port		
14	35 port		
15	35 port	yes	
16	0		

3 Trial analysis and results

3.1 Current

In standard speed trial analysis, the ship's speed over ground (SOG) is measured with the GPS and corrected to speed through water (STW) using the double runs. The GPS is generally regarded as far more accurate than the speed log. However, this procedure is not possible to follow for WASP sea trials. In the previous WASP trials, the speed is instead measured with the ship's log. For the present ship, after analysing the data it was clear that the speed log precision was too poor to give reasonable trends. Therefore, the analysis is based on GPS speed. In the present sea area, there was a constant ocean current but no significant tidal current. The ocean current could be regarded as constant during the time of two subsequent runs (30 min) and therefore, the current could be neglected in the analysis.

Comparing the SOG and STW readings and combining with the heading shows that the ocean current was about 0.5 knots in direction 55 deg.

3.2 Wind

The true wind during the trial shown in Figure E and Figure F is derived from the apparent wind measured with the ship's anemometer and the ship's speed. The wind was not completely constant during the trial. This could potentially disturb the trial evaluation process, when runs with and without wings are compared. Figure G and Figure H show the derived true wind during the pair of runs that are compared. There are some differences, especially between run 1 and 2. To minimise the disturbance this may have on the comparison, the ship's wind resistance is subtracted from each individual run, according to the ISO 15016 procedure.

According to ISO 15016, the measured wind should be averages between two runs in opposite directions, to reduce the disturbance of the ship's superstructure on the anemometer. In this trial, the runs were however not conducted as reciprocal double-runs and therefore this procedure cannot be followed.

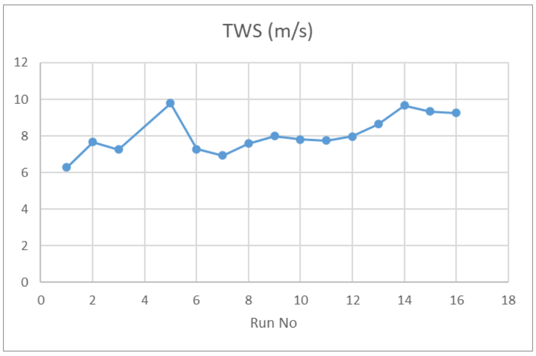

Figure E. True wind speed, at height of anemometer

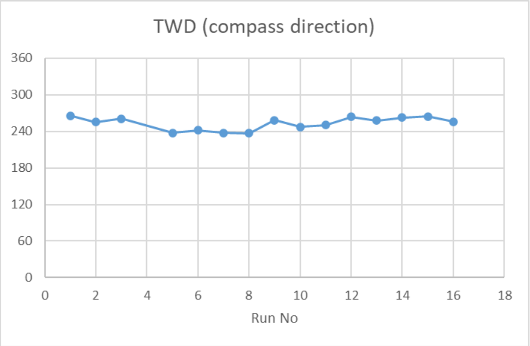

Figure F. Global wind direction, at height of anemometer

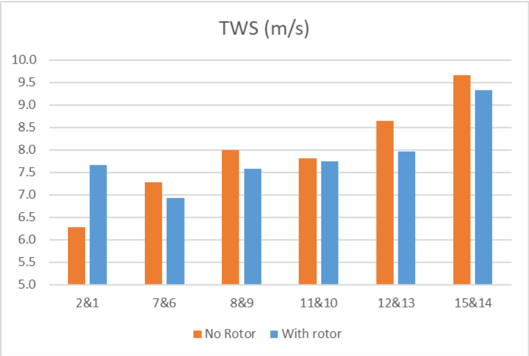

Figure G. True wind speed during speed runs

Figure H. True wind angle during speed runs

3.3 Water temperature, displacement and superstructure resistance

The measured power for each single run is corrected for the wind resistance of the superstructure based on ISO/ITTC standard procedure. The wind resistance coefficient is from SSPA's database.

Correction for water temperature and a correction of displacement to baseline displacement are done according to the procedures.

3.4 Power correction

The correction of propulsive efficiency due to the added resistance corrections is derived using the Direct Power Method according to the ISO standard using the assumed load variation factor stated in Table 1. (See the ISO 15016 standard for a detailed description of the Direct Power Method.)

The corrected power is listed in Appendix 1, Figure 2d.

3.5 Baseline

There were no model test curves available for the ship. Instead, baseline curves were derived based on logging data from the period 2019-01-18 to 2021-12-03. The data is logged with 5 min frequency. Only time periods when the wings were not engaged were included.

A multivariable regression was performed by using the Ordinary Least Squares method. The data points were filtered heavily due to anomalies found between the SOG and STW at speeds larger than approximately 10 knots. Additionally, the speeds under 5 knots were discarded for the regression. In order to make sure that the baseline curves are representative of the deep water conditions, Raven's correction (Raven, 2019) was on the viscous resistance have been calculated. The conditions where the shallow water effects on the viscous resistance is larger than 15% and the difference between the SOG and STW is larger than 0.6 knots were filtered out. The resulting data for the regression analysis was 28% of all of the datapoints and amounted to 22984 points. Several attempts were made with SOG, mean draught and trim as independent variables. However, it was observed that including the trim variable did not significantly contribute to the regression. Instead, Raven's shallow water correction were used together with SOG and mean draught to obtain the baseline curves. This indicates that the shallow water effects were non-negligible. The final baseline curves are intended for the deep water condition, hence, the independent variable for the shallow water correction is set to represent deep waters. Unfortunately, the ship's anemometer was not functioning during this period and therefore no filtering or corrections for wind or waves could be made.

The resulting power curves are shown in Figure I for even keel condition. The uncertainty of the analysis is worse than normal due to the lack of anemometer data. However, these curves are only used to give a reasonable level and shape of the base lines. It is not critical that the absolute level is very accurate.

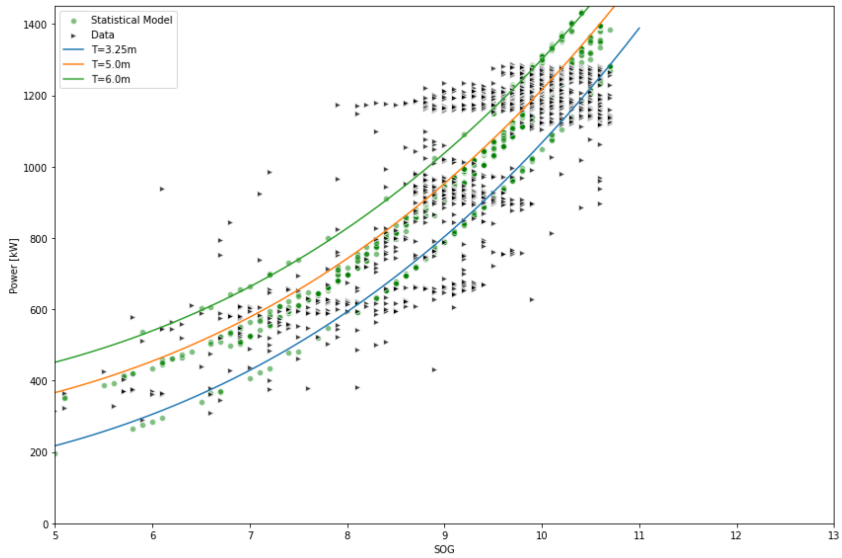

Figure I. Result of multivariable regression analysis of log data without wings.

Figure J shows the derived baseline curve, together with the speed trial runs without the wings and the power corrected according to ISO 15016. The base line curve has been shifted in the vertical direction along with the ISO procedures. The shape of the shifted model test curve is used in the wing evaluation of the performance in the next section.

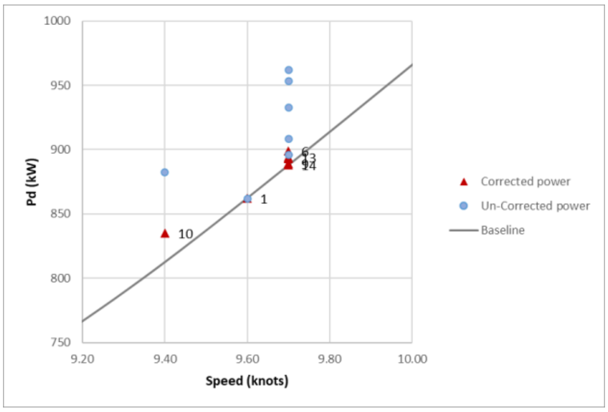

Figure J. Runs without wings, corrected according to ISO 15016.

3.6 Wing evaluation

The principle of the wing evaluation is to compare single runs *with and without* wings at the *same wind angle*. Section 6.1 discusses this approach further. Figure K and Table 8 give a comparison of the speed and corrected power between the runs with and without wings. At all measured wind angles, the speed increases when the wings are employed. Normally, an increased speed due to additional wind thrust gives a slightly reduction of power due to higher efficiency when the propeller is off-loaded. However, this is not observed in all runs. This could be due to measurement uncertainty of the power. In the following wing performance analysis, the speed difference is the dominating factor and the possible errors in the power measurement has less influence, but it adds to the uncertainty of the results.

Th numbers in Figure K and Table 8 are the direct results from the trial, but they are hard to interpret. In Chapter 4, the result is normalised to give representative power savings for a given speed.

Table 8 Speed and corrected power from speed trial.

AWA [deg]	Δ SOG [knots]	Δ Pd %
76.2	0.07	-1.4%
-93.4	0.02	-1.0%
-73.0	0.16	0.6%
44.5	0.20	0.6%
-45.2	0.17	-1.0%
-23.5	0.15	-0.3%

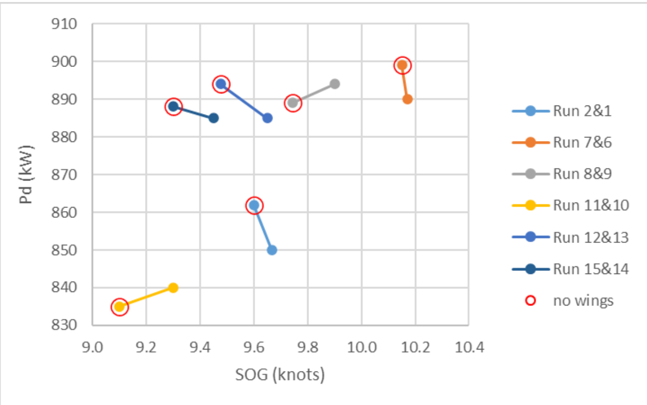

Figure K Speed and corrected power from trial

4 Wing performance analysis

The result of the trial presented in the previous chapter showed that the wings are able to increase the speed. In this chapter, the trial result is normalised such that a power reduction for a given ship speed can be presented. Two alternative normalisation methods are used, and the differences are discussed in Chapter 6.

4.1 Normalisation Method 1

To derive the power difference at a nominal speed V_{ref}, the corrected trial power is interpolated to V_{ref}, using the shape of the ship's baseline curve. (The baseline curve was derived in Section 3.5). This is done by fitting a 3rd order polynomial to the baseline curve and shift it vertically, as Figure L indicates.

The derived power difference is corrected to a nominal wind speed using:

$$\Delta P_{TWS_{ref}} = \Delta P \cdot \frac{TWS_{ref}^{\;2}}{TWS^2} \cdot \frac{\rho_{a\ ref}}{\rho_{a\ trial}} \tag{4}$$

where TWS_{ref} is the reference wind speed and TWS is the true wind speed during the sea trial, at the same height. The wind variation over height is computed according to ISO 15016 using exponent 1/7. $\rho_{a\ ref} = 1.24\ \mathrm{kg/m3}$. TWS_{ref} is set to 8 m/s since it is close to the averaged wind speed during the trial.

The resulting power savings are given in Table 9.

Normalisation Method 1 includes several simplifications, which will be discussed further in Chapter 6.

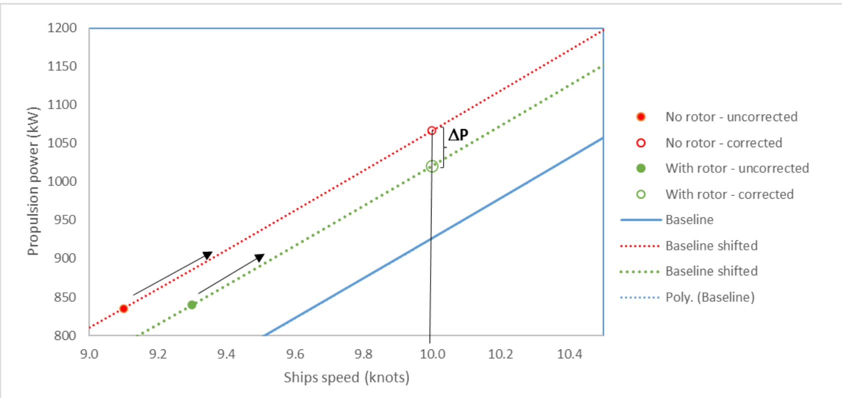

Figure L. Example of how speed trial result is extrapolated to nominal speed using the shape of the Baseline curve.

Table 9. Method 1: Power reduction derived from speed trial and normalized to reference ship's speed 10 knots. "Gross" means without considering power consumption from wings. AWA negative means wind from port.

	Trial wind condition				Ship's speed 10 knots	
Run	**AWA**	**AWS**	**TWA**	**TWS**	**ΔPd Gross** trial wind condition	**ΔPd Gross** TWS=8m/s
	deg	**m/s**	**deg**	**m/s**	**kW**	**kW**
2	76.2	7.1	115	7.66	29	44
7	-93.4	4.2	218	6.93	14	26
8	-73.0	7.3	247	7.58	36	55
11	44.5	10.4	70	7.75	46	68
12	-45.2	10.6	289	7.96	54	75
15	-23.5	13.6	325	9.33	42	42

4.2 Normalisation Method 2

In Method 1, the translation of a speed increase to a power decrease is done by shifting the power curves. This does not fully account for the changed propulsive efficiency when the propeller is unloaded due to the wind propulsion. A second simplification in Method 1 is that the changed apparent wind due to a changed ship speed is accounted for. In order to include these effects, a second normalisation method is introduced. It makes use of a 1DOF speed-power prediction program, which can model the relation between speed, power and the change in propeller efficiency due to changed speed or propeller load. The propeller characteristics of Wagening C 4.40 is used to model the propeller. The process follows the present steps:

1. Ensure that the output of the speed-power prediction program is equal to the Baseline curve (the ship's calm water speed-power curve at the actual loading condition, without wings)

2. Use the speed-power program to find the additional force in the longitudinal direction that matches the change in speed AND corrected power between two runs *with* and *without* wings. That force was the wings thrust, *T* in the run with wings.

3. The thrust coefficient is derived by

$$C_t = \frac{T}{\frac{1}{2}\rho_a \cdot A_W \cdot AWS^2} \qquad (5)$$

   with AWS measured at the trial and translated to mid-hight of the wings and using 1/7 power law.

4. Ct is regressed against AWA by adapting a theoretical Ct curve of a generic suction wing derived by CFD. (See further section 5.1.2) (Figure M).

5. For the nominal condition (ship's speed 10 knots, TWS_{10m}=8m/s, air temperature 15 deg), the apparent wind is computed for a range of wind directions, and the wings thrust *T* is computed using the C_t-polynomial.

6. The speed power prediction program is executed both with and without the wings thrust (entered as a reduction of resistance) and at the nominal speed. The difference in the

resulting power is denoted Gross Power Saving. This represents the hydrodynamic power saving.

7. The wings power consumption, as measured during the trial, is subtracted from the Gross Power Saving to give the Net Power Saving. It is assumed that this number include transmission efficiency.

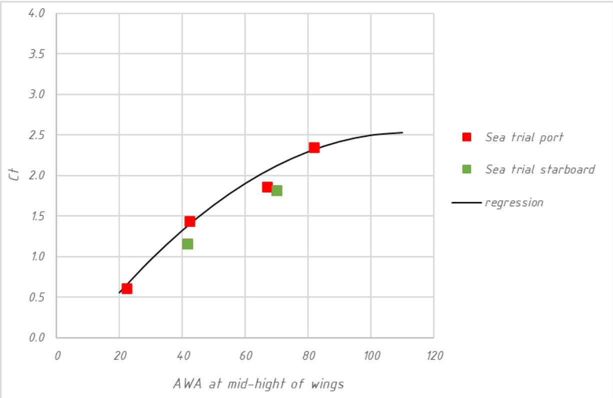

Figure M. Thrust force coefficient derived indirectly from sea trial. Regression found by adapting the Ct curve of a generic suction wing forces predicted by CFD.

4.3 Results

The resulting gross saving (power saving without considering the wings power consumption) from Method 1 and Method 2 are compared in Figure N. (The conclusion on methodology is further discussed in Section 6.2.)

The derived net power saving at the nominal condition is given in Figure O. At true wind speed 10 m/s and ship's speed 10 knots, the wings give a net power saving for apparent wind angles larger than 17 degrees and it reaches up to 6% saving at the most favourable angle. There appears to be a difference in performance between starboard and port tack. Considering that the wings are placed in the ship's port side, it is possible that one tack is favourable over the other. However, the observed differences could well be due to measurements uncertainty and it cannot be concluded that the observed difference is due to a real difference in performance.

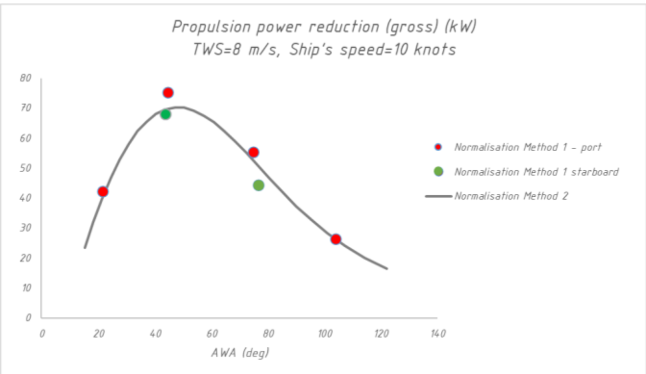

Figure N. Hydrodynamic power savings derived with normalization method 1 and 2 at nominal conditions. Not accounting for power consumption from suction fans. Reference wind speed 8m/s at 10m above sea.

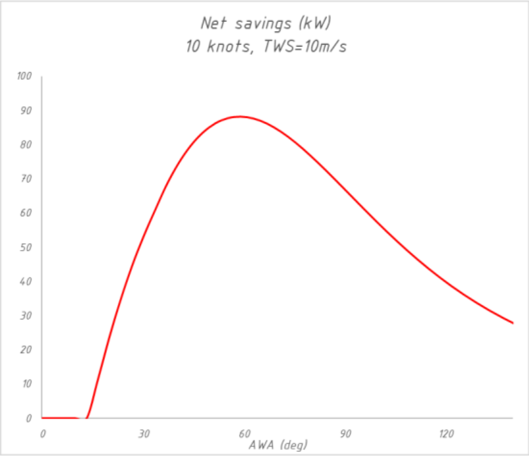

Figure O Power savings derived with normalization method 2 at nominal conditions. Reference wind speed 10m/s at 10m above sea.

5 In-service fuel saving

The following sections describe the methodology applied to estimate the power saving due to the wings for the given routes.

In short, the procedure is outlined as follows:

- Calibrate digital models of the ship, propeller and wings against sea trial.
- Predict the required power to reach the intended speed for a matrix of environmental conditions, using an in-house Velocity Power Prediction (VPP) program. The VPP model is presented in section 5.1.
- Assembly statistics of the environmental conditions that the vessel will encounter along the route over time.
- Perform route simulations using Monte Carlo technique over combinations of environmental conditions along the route to estimate statistical properties of route energy requirement.

5.1 Power prediction

5.1.1 Ship and propeller models

For each unique environmental condition encountered by the vessel it is necessary to predict the power requirement to reach the intended speed. A quasi-static force equilibrium is found at the intended speed, at which the propulsive and rudder forces are in equilibrium with hydrodynamic and aerodynamic forces. This equilibrium equation is set up in 4 DOF (Degrees of Freedom) including surge, sway, roll and yaw as follows:

$$[Fx, Fy, Mx, Mz] = f(n, \delta, \varphi, \psi)$$

Where $[Fx, Fy, Mx, Mz]$ are total force and moment residuals on the vessel in surge, sway, roll, and yaw respectively, n is the propeller rpm, δ is the rudder angle, φ is the heel angle and ψ is the leeway angle. The problem is a multi-dimensional root-finding problem and is solved iteratively, ultimately finding the required input parameters to generate a zero vector as output.

The function f consists of a set of force calculation routines, each one responsible for calculating a subset of the total force acting on the vessel given the current input parameters. The following force calculation routines has been used in this report:

- **Calm water resistance**

The speed-power curve in the actual service condition was first derived as described in Section 3.5 Resistance curves were derived using the propulsive efficiency η_D from the model test of similar ships.

- **Added resistance in waves**

Spectral superposition of R_{AW} (found from model tests in regular waves from SSPA database) and wave spectrum (ITTC) to find mean added resistance in an irregular sea state.

- **Manoeuvring and rudder forces**

Manoeuvring forces based on bis system model in Norrbin (1970). The forces on the hull and rudder due to drift and rudder angles are introduced in the ship simulation tool in terms of manoeuvring coefficients. The manoeuvring coefficients used is extracted from SSPAs database of manoeuvring model tests.

- **Propulsive forces**

The propulsive factors are taken from the model test of similar ships from SSPA's database. The propeller is modelled as a Wagening C 4.40 with constant pitch 0.95. This simplification is assumed not to have any impact on the result, since the propeller model only needs to predict the slope of the propeller efficiency correctly. The chosen propeller model is supposed to represent the actual propeller well in this respect.

The propulsive set-up is checked by comparing the predicted power and shaft rate with the sea trial base line runs.

- **Superstructure aerodynamic forces**
  The wind resistance coefficient is from SSPA's database.

- **Wind propulsor model**

A quasi-static force model of a generic wing sail is used for the route simulations in this report

- Apparent wind is calculated, including effects from the Atmospheric Boundary Layer (ABL) in accordance with ITTC recommended profile (ITTC 1984).
- Wind propulsor force coefficients are derived as detailed in Section 5.1.2.
- Force contribution in vessel coordinate system is calculated based on apparent wind, aerodynamic coefficients and geometry.

5.1.2 Wing model

The wings model is derived with the following process:

A generic suction wing is modelled by RANS CFD simulations with the wing standing on a symmetry plane, i.e without any ship hull. The interaction effect between the two wings is modelled using a lifting line based code (Malmek 2020). The ideal wings model is calibrated to the measured speed trial results, which accounts for the interaction between the ship hull and the wings.

The same correction is applied to the side force, assuming that the ideal wings Cl/Cd is preserved. This is an assumption, but since side forces is not measured at the speed trial, it is the best possible assumption. However, the magnitude of the side force has only a marginal effect on the power gain for the current case.

The suction wing fan rpm is set with respect to apparent wind speed according to a function provided by the wing maker. The power required to operate the wings is a function of the fan rpm, also provided by the maker.

The wings are assumed to be lowered and stored on deck when they do not provide a net saving.

5.1.3 Power saving

The speed power predictions are executed both with and without the wings thrust at the nominal speed. The difference in the resulting power is denoted Gross Power Saving. This represents the hydrodynamic power saving. Including the power consumption from wing fans gives the net power saving.

5.2 Route analysis method

The route simulation tool uses a Monte Carlo technique over combinations of environmental conditions along the route to estimate statistical properties of route energy requirement. The method is described in by Olsson et.al (Olsson 2020).

The methodology entails the following limitations and assumptions:

- No route optimisation with respect to weather or current.
- The wings will be in use whenever wind condition allows.
- When wings are used, main engine power will be reduced to keep the prescribed ship speed.
- The main engine is assumed to always deliver enough power and torque to reach the intended speed, i.e. no involuntary speed reductions.
- Voluntary speed reductions are not accounted for.

The routes are divided into legs, as shown in Figure P. For each leg on the route, a discrete joint weather distribution (True wind speeds and True wind angles) is derived from wind statistics obtained from the ERA5 reanalysis dataset available in the Copernicus Climate Data Store (https://cds.climate.copernicus.eu). Each leg is treated independently, and leg-wise distributions are assumed to be uncorrelated.

5.2.1 Operational conditions for route simulation

The route analysis is carried out for the following conditions:

- Ship's speed 10 knots
- Laden draught: 6m e.k.
- Light Laden: 5m e.k.
- Ballast draught: 3.2m e.k.
- Density air 1.24 kg/m^3
- SFOC=199 g/kWh independent on engine load

The ship does *not* operate on a fixed trade. To be able to estimate a yearly average fuel saving in this study, the route analysis is carried out for six typical routes (Table 10). Route 6 is a generic setting based on the EEDI weather matrix (IMO 2021). The routes are selected based on ship's the most frequent voyages the last years. The distribution between these routes during the full year of 2021 is given in percentage in the table, weighted against their length. The weights are estimated by grouping similar voyages, for example voyages between the Netherland or western Germany to the Baltic region or Finland are counted as Rotterdam-Riga. Voyages that did not fit with any of the routes 1-5 were categorized as EEDI-route.

Table 10. Routes for analysis and their relative frequency of occurrence.

	Share	Outbound	Inbound
Route 1	29%	Rotterdam- Bayonne	Bayonne-Rotterdam
		Laden 6m	Laden 6m
Route 2	42%	Rotterdam – Riga via Skagen	Riga- Rotterdam via Skagen
		Laden 6m	Ballast 3.2m
Route 3	6%	Route 2 but via Kiel	
Route 4	6%	Rotterdam – Bergen	Bergen- Rotterdam
		Laden 6m	Ballast 3.2m
Route 5	12%	Copenhagen - Riga	Riga – Copenhagen
		Ballast 3.2m	Light laden 5m
Route 6	5%	EEDI weather	

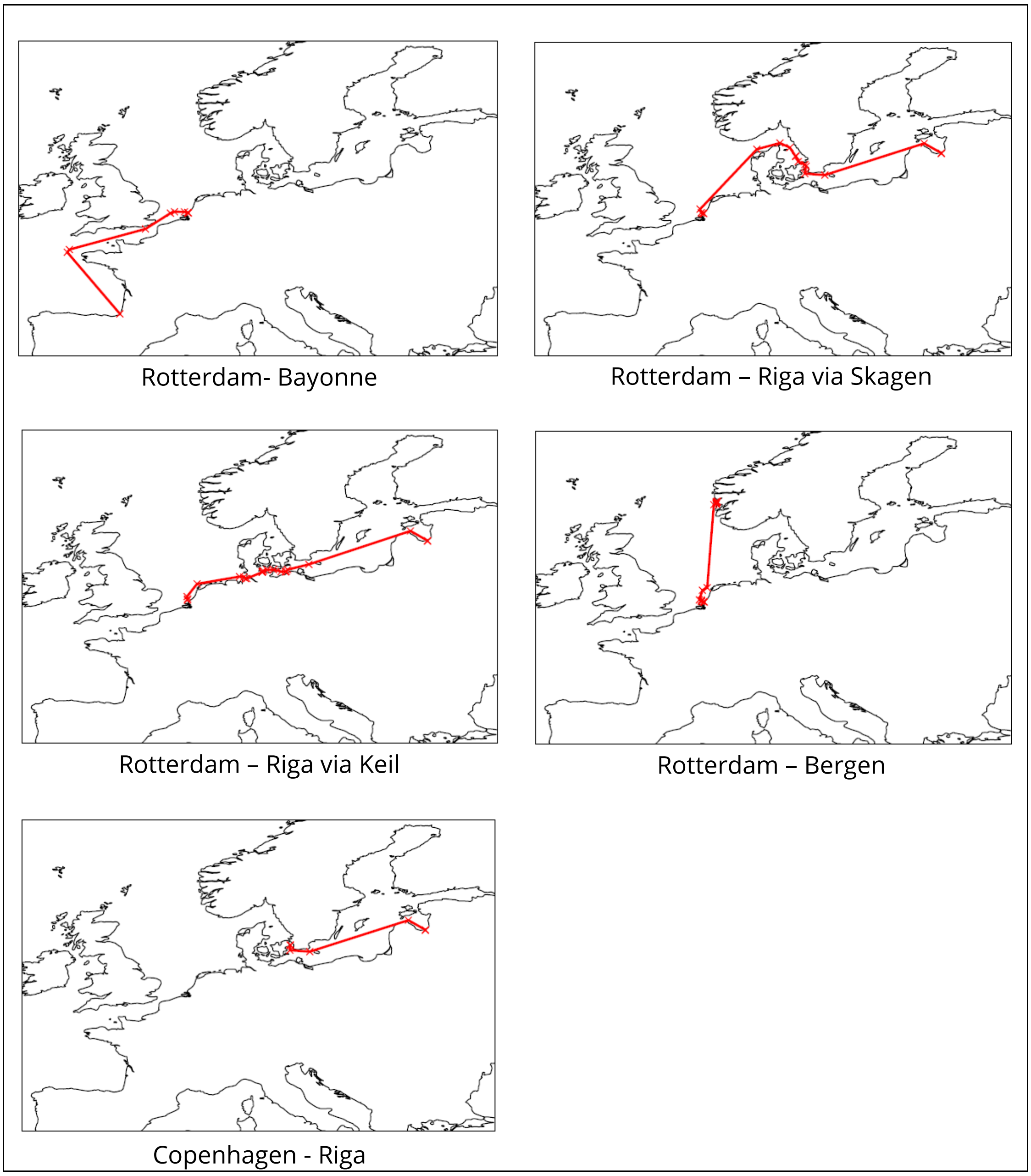

Figure P. Routes

The wind statistics for these routes are presented in Figure Q and Figure R.

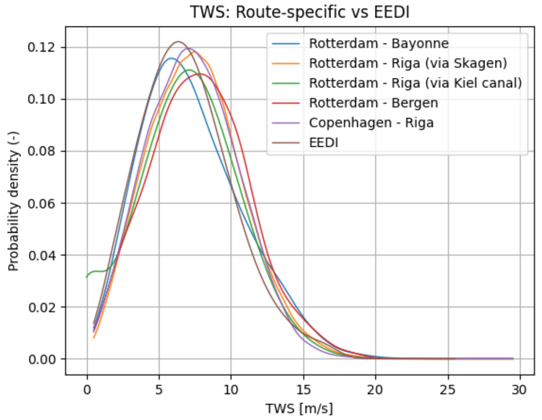

Figure Q. The probability of true wind speed on the routes from external weather source.

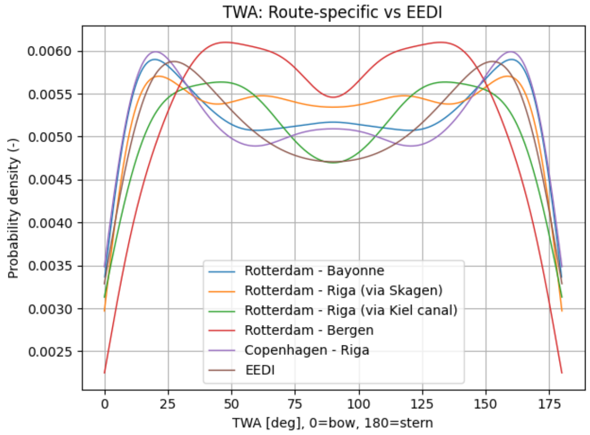

Figure R The probability of true wind angle relative to ship heading, from external weather source.

5.3 Results

5.3.1 Power saving at all wind conditions

The power prediction model is used to derive the power saving at all wind conditions, as presented in Figure S.

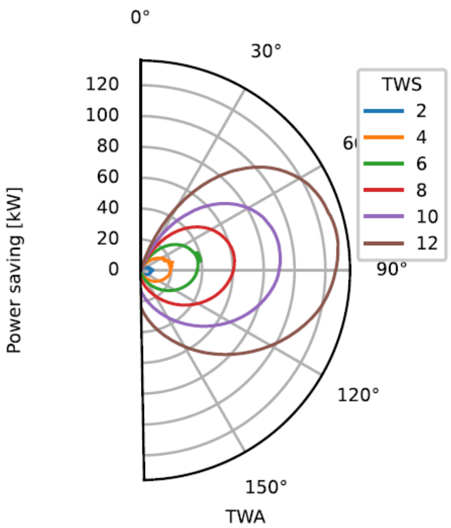

Figure S. Net power saving at various wind speeds.

5.3.2 Power saving on the route

The average power and fuel savings are given in Table 11 and Figure T. This represents the average value of letting the ship sail the route 100 000 times in randomly chosen weather conditions based on weather statistics from the full year of 2019. Some days the weather will be favourable with large power savings, some days it will be adverse. The probability distribution curves are shown in Appendix 1.

The expected fuel savings per year can then be calculated based on the expected number of the various trips.

Largest power saving per mile is achieved on route Bergen-Rotterdam. On this route the prevailing wind directions are further towards the beam then for the other routes and with generally stronger winds speeds.

The route Copenhagen – Riga is east-west bound and the prevailing winds are either head or stern winds. The power savings are therefore smaller.

Table 11 Average power and fuel saving predicted for routes

	Route	power saving (%)	power saving (kW)	energy saving (MWh/trip)	fuel saving (ton/trip)	fuel saving (kg/nm)
1	Rotterdam- Bayonne	2.1	30.3	2.5	0.49	0.60
	Bayonne – Rotterdam	2.3	31.6	2.6	0.51	0.63
2	Rotterdam – Riga via Skagen	2.6	34.7	3.7	0.74	0.69
	Riga – Rotterdam via Skagen	2.6	30.8	3.3	0.65	0.61
3	Rotterdam – Riga via Kiel	2.2	28.6	2.5	0.49	0.57
	Riga – Rotterdam via Kiel	2.1	25.1	2.2	0.43	0.50
4	Rotterdam – Bergen	2.8	39.3	2.1	0.42	0.78
	Bergen – Rotterdam	3.3	37.7	2.0	0.40	0.75
5	Copenhagen – Riga	2.8	30.0	1.4	0.28	0.60
	Riga – Copenhagen	2.0	27.0	1.3	0.26	0.55
6	EEDI weather laden	1.9	27.06			0.54
	EEDI weather ballast	2.4	26.73			0.53

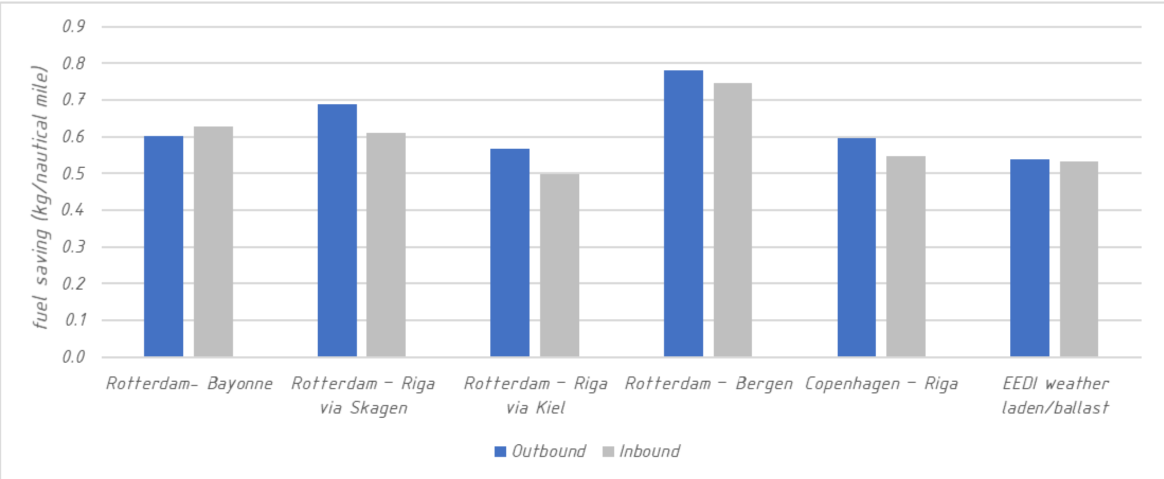

Figure T. Average fuel saving per route

5.4 Yearly average saving

Based on the distribution of the voyages given in Table 10, the average fuel saving is 0.62 kg/nautical miles. With a total sailing distance of 43000 per year (2021) this means 26.8 tons fuel saving per year, corresponding to 84.5 tons CO2.

6 Discussion on evaluation methodology

6.1 Wings evaluation based on single runs

The testing principle employed in this project is that single runs *with and without* wings at the *same wind conditions* are compared. The following list discusses the issues that could disturb the comparison:

- Difference in wind condition for runs that are compared. Figure G and Figure H in section 3.2 show the wind conditions of the runs with and without wings that are compared. The largest difference within a triplet is 1.5 m/s. This means that the ship's windage drag was larger for the run without wings than the one with wings. However, the superstructure resistance is compensated for by a correction of the power (see section 3.3). The air resistance coefficient is taken from the library and is not ship specific, which could introduce an error in the comparison. The possible error from this approximation is conservatively estimated to 10% of the air resistance. However, as can be seen in Appendix 1 Figure 2, the wind resistance correction is maximum 5% of the total resistance. This means that the possible error on the power difference is around 0.5%.

- The added resistance due to waves could potentially differ between the runs, since the speed is changed. The wave resistance was not estimated specifically in this trial, but according to experience is of the magnitude as the wind resistance in head waves. At larger wave directions, like in this trial, it is less. Assuming conservatively that the wave resistance is 10% of the total resistance, and the speed difference between runs is 0.2 knots. Assume further conservatively that wave resistance is proportional to speed squared. This then gives an error in the comparison between the runs of less than 0.5% on the power.

6.2 Normalization methods

The normalization Method 1, described in section 4.1, simplifies the following aspects that Method 2 accounts for:

1) The propulsive efficiency is not necessarily the same when moving along the power curve as when changing the net longitudinal force for a given speed (as when adding a wings).

2) Correcting to a nominal ship speed and true wind speed also means that the apparent wind speed and angle is different.

Method 2 requires that the ship's resistance curve, propulsive factors and propeller characteristics are known or assumed. Based on the model test and tuning against the actual trial, good estimates can be done. A sensitivity check showed that the influence of these assumptions on the end result is small.

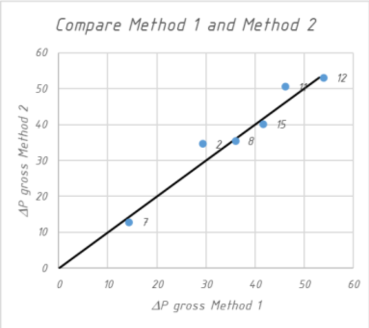

Figure U Normalization methods 1 and 2

A comparison between the two normalisation methods presented in Figure N on page 20 and in Figure U. It shows that the two methods correspond well. The scatter is probably related to the poor precision uncertainty of the measurements.

Method 1 is simple and transparent and does not require any speed-power prediction program as Method 2 does. Therefore, it can be a useful method in praxis but should be limited to cases with small contribution of wind propulsion and when the sea trial wind speed is close to the nominal.

6.3 Speed trial uncertainty assessment

The bias uncertainty of a speed trial is stated in the ISO standard to be 2%. In the present work, the purpose is to derive a power *difference*, and then the bias error can be assumed to cancel out. The exception is the wind. A bias error of the anemometer will strike differently on the run with wings compared to the run without wings.

The precision error of speed trials in general is estimated by Werner (2020) and Insel (2008) to be around 7-8%. However, most of is this uncertainty relates to the fact that there are different sister ships tested, and trials conducted at different occasions.

Here follows an estimate of the uncertainty of the derived power difference, following ITTC 7.5-02-01-01 (Type A). <u>The authors do not claim it to be a complete uncertainty assessment, but rather an indication of the magnitude of the larger error sources.</u>

Variable	Comment, source of uncertainty	Uncertainty of variable (Type A)	Uncertainty of power saving
Heading	Standard deviation of time signal	1 deg	insignificant
SOG	Standard deviation of time signal	0.5 kts	20 kW
power	Standard deviation of time signal	1%	10 kW
AWA	Standard deviation of time signal Disturbance of hull	5 deg	Secondary effects: hull air resistance, regression of thrust function in Method 2
AWS	Standard deviation of time signal Disturbance of hull Atmospheric boundary layer difference from 1/7 power law	0.5 m/s	10 kW (on the normalisation to given wind speed)
	Assumptions in the normalisation method. Assessed by varying the input.		small

The largest source of uncertainty is the standard deviation of the SOG and the power readings. The anemometer also affects the evaluation uncertainty. One part is related to fluctuation of the natural wind and therefore, high frequency logging is preferred. The other part is the disturbance of the hull, which is more problematic as it is very difficult to assess. It is hard to measure the “true” apparent wind hitting the wings sail, as all possible locations to place an anemometer is disturbed by the hull or the wings.

The analysis leads to the 95% uncertainty interval indicated in Figure V.

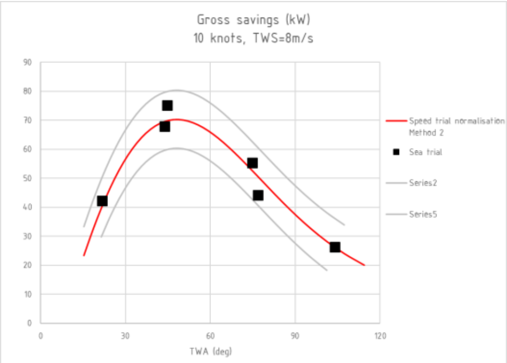

Figure V. Speed trial evaluation with estimated 95% uncertainty interval

6.4 Ship model uncertainty

Simulation models always include assumptions and simplification and cannot mimic the behaviour of complex ship system exactly. This introduces errors in the simulation results.

For the complete generalised model, the manoeuvring coefficients are estimated based on experience and the ducted CPP have been modelled as a conventional propeller, since there was no model test of CFD analysis done to extract the manoeuvring coefficient for the actual vessel. This is believed to have insignificant effect on the fuel saving results as the drift was found to be small even for the high wind speeds at the speed trial.

The process of calibrating the simulation model to the trial tests is believed to result in an accurate ship model for apparent wind angles between 15 and 100 degrees from the bow. The resistance that the wings is assumed to generate in head wind is based on an empirical assumption of resistance of a cylinder. The uncertainty associated with this assumption, in particular the influence of the hull, should be investigated further using numerical tools.

6.4.1 Quality of correlation of the virtual ship model

Figure W compares the power saving predictions from the virtual ship model against the power savings derived from the sea trial using Method 1. There are a few outliers, which probably refers to the uncertainty of the measurements. This diagram indicates the uncertainty that the present analysis can provide.

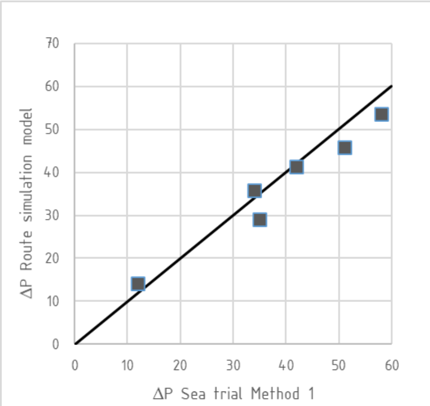

Figure W The power prediction model used on the route analysis against the power saving from the trial

6.5 Route simulation uncertainty

The weather statistics probably contributes to high uncertainty in the route simulation. The weather provider does not state any uncertainty levels for the data, though.

The largest uncertainty relates to the actual operation of the vessel and wings. The annual power saving derived with the route analysis assumes that the wings is used all the time when the wind conditions allow, i.e. no down-time due to maintenance etc. It is also assumed that the speed is kept constant, i.e. that the crew chose to adjust the engine power to keep the fixed speed when the wings is in operation, rather than running at a fixed power and "save" time to port. If the latter happens, no fuel saving will be made.

After a longer period of operation, this report may be updated based on weather statistics and other operational data.

7 Conclusions

7.1 Result

A speed trial was performed on m/v Frisian Sea in October 2021 with the purpose of verifying the power saving of the wings.

At true wind speed 10 m/s and ship's speed 10 knots, the wings give a net power saving for apparent wind angles larger than 17 degrees and the saving reaches up to 90kW at the most favourable wind angle.

The speed trial result is scaled up to give a prediction of the in-service fuel reduction using a ship simulation model correlated to the actual speed trial measurements, a voyage prediction tool and statistical weather distribution.

It is estimated that the power reduction on typical routes is between 0.5 and 0.78 kg/nautical miles. For an average year of operation, the fuel saving potential is estimated to be 0.62 kg/nautical miles, which will give approximately 26.8 tons fuel saving per year, corresponding to 84.5 tons CO_2. This assumes that the wings are fully operable at all times when wind permits, and that the additional thrust is used to reduce engine load and keeping the speed constants to 10 knots.

The mayor uncertainties of the trial result include the wind speed measurement, the ship speed and power measurements. The uncertainty of the wind measurement may disturb the relation between the trial result, which is based on the on-board measurements, and the route analysis that scale up the result to yearly fuel savings, which is based on the natural undisturbed wind on the ocean. Furthermore, the wind statistics introduce large uncertainties in the process. The largest uncertainty is probably the way the wind assistance technology will be handled and operated in reality. If the device is idling due to maintenance, failure, safety or other issues, then the power saving will off course be less. The same applies if crew choose to use the additional thrust from the wind to increase the ship's speed instead of reducing the power. Utilising weather routing adapted to wind propulsion can on the other hand increase the saving.

7.2 Recommendations

It is recommended to log the wind speed on the route, the ship's fuel consumption and operability of the wings for at least one year to complement this study.

8 References

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Run	Time start	Target True wind angle	Wings	Heading	COG	STW (knots)	SOG (knots)	Power (kW)	ShaftGen (kW)	ME rpm
1	6:42	120 s.b.		140	135.0	9.6	9.60	862.0	82.0	148.0
2	7:5	120 s.b.	yes	140	135.0	9.63	9.67	850.3	89.7	148.0
3	7:22	120 s.b.	1 wing up	140	135.0	9.6	9.50	854.0	69.5	148.0
5	7:47	180	baseline	60	58.5	9.7	10.30	853.0	56.0	148.0
6	8:7	140 port		20	19.0	9.7	10.15	896.0	49.0	148.0
7	8:25	140 port	yes	20	20.0	9.7	10.17	888.0	58.7	148.0
8	8:41	110 port	yes	350	353.5	9.7	9.90	897.0	61.5	148.0
9	8:58	110 port		350	354.0	9.7	9.74	908.5	47.0	148.0
10	9:17	70 s.b.		180	176.0	9.4	9.10	882.5	43.5	148.0
11	9:36	70 s.b.	yes	180	175.0	9.5	9.30	885.0	62.5	148.0
12	9:57	70 port	yes	335	337.0	9.7	9.65	932.0	61.0	148.0
13	10:14	70 port		335	339.0	9.7	9.48	932.5	42.5	148.0
14	10:32	35 port		300	301.5	9.7	9.30	953.5	51.0	148.0
15	10:48	35 port	yes	300	301.5	9.7	9.45	950.5	59.0	148.0
16	11:5	0	baseline	255	254.0	9.7	9.27	962.0	44.3	148.0

	at anemometer				
Run	**AWA**	**AWS**	***TWS***	***TWA***	**TWD**
1	75.9	5.3	6.3	125.6	265.6
2	76.2	7.1	7.7	115.3	255.3
3	79.5	6.3	7.2	121.0	261.0
5	174.5	4.5	9.8	177.5	237.5
6	-92.6	4.8	7.3	221.6	241.6
7	-93.4	4.2	6.9	217.7	237.7
8	-73.0	7.3	7.6	247.0	237.0
9	-59.3	9.3	8.0	268.0	258.0
10	43.2	10.5	7.8	67.4	247.4
11	44.5	10.4	7.8	70.1	250.1
12	-45.2	10.6	8.0	288.5	263.5
13	-51.3	10.8	8.6	282.5	257.5
14	-25.3	13.8	9.7	322.5	262.5
15	-23.5	13.6	9.3	324.5	264.5
16	0.7	14.0	9.3	1.1	256.1

0 degrees = head wind
positive = from starboard

Ship particulars		Propulsion particulars	
SSPA hull no.	guess	SSPA propeller no.	x
Length L_{PP} [m]	118.00	Number of propellers	1
Length L_{WL} [m]	118.00	Number of blades (each)	
Beam B [m]	13.43	Propeller diameter [m]	
Cb [-]	0.82	Pitch ratio [-]	
C_p [-]	1.00	C_n [-]	1.000
ESD	no	MCR [kW]	1439

Loading condition	Baseline	Sea trial	Warnings
Displacement [metric tonnes]	3999	4003	
Draft at aft perpendicular (T_A) [m]	3.80	3.80	
Draft at forward perpendicular (T_F) [m]	2.60	2.60	
Transverse projected area‡ (A_T) [m²]	215	215	

Nomenclature of environmental parameters					
TWD	Global wind angle	$H_{W1/3}$	Significant height of local wind driven waves	h	Water depth
AWA	Aparent wind angle	θ_{WT}	True wave direction	ρ_{air}	Density of air
AWS	Aparent wind speed	θ_{SR}	Relative swell direction	ν_{water}	Kinematic viscosity of sea water
TWS	True wind speed	θ_{ST}	True swell direction	ρ_{water}	Density of sea water
TWA	True wind angle	$H_{S1/3}$	Significant height of local swell	T_{water}	Water temperature
T_{Wm}	Mean wave period	T_{Sm}	Swell period	T_{air}	Air temperature
		θ_{WR}	Relative wave direction		
Remarks: Relative directions are defined from bow, positive to s.b. All wave and wind directions are defined as the direction the waves or wind come from. 0º=from the bow.					

Environment			
Air temperature [deg C]	12.0	Water temperature [deg C]	15
Air density [kg/m³]	1.238	Water density [kg/m³]	1026
Water depth [m]	deep		

Onboard measurements					
Run		Heading [deg]	V_S (STW) [knots]	Shaft rate [1/min]	P_d [kW]
2		140	9.63	148.0	842
7		20	9.70	148.0	879
8		350	9.70	148.0	888
11		180	9.50	148.0	876
12		335	9.70	148.0	923
15		300	9.70	148.0	941
1		140	9.60	148.0	853
6		20	10.15	148.0	887
9		350	9.74	148.0	899
10		180	9.10	148.0	874
13		335	9.48	148.0	923
14		300	9.30	148.0	944
5		60	10.30	148.0	844
16		255	9.27	148.0	952

Wind at the height of anemomenter					
Run no.	AWS [m/s]	AWA [deg]	TWS [m/s]	TWA [deg]	TWD [deg]
2	7.13	76	7.65	115	255
7	4.24	-93	6.74	-141	239
8	7.30	-73	7.54	-112	238
11	10.40	45	7.72	71	251
12	10.64	-45	7.96	-72	263
15	13.58	-24	9.22	-36	264
1	5.26	76	6.27	126	266
6	4.84	-93	7.28	-138	242
9	9.28	-59	7.99	-92	258
10	10.54	43	7.81	67	247
13	10.80	-51	8.64	-77	258
14	13.77	-25	9.66	-38	262
5	4.50	175	9.79	177	237
16	14.02	1	9.25	1	256

Wind at reference height					
Run no.	AWS [m/s]	AWA [deg]	TWS [m/s]	TWA [deg]	GWA [deg]
2	6.31	70	6.54	115	255
7	3.65	-82	5.76	-141	239
8	6.49	-67	6.45	-112	238
11	9.41	41	6.60	71	251
12	9.62	-42	6.80	-72	263
15	12.28	-22	7.88	-36	264
1	4.72	67	5.36	126	266
6	4.17	-82	6.22	-138	242
9	8.33	-55	6.83	-92	258
10	9.52	40	6.68	67	247
13	9.69	-48	7.38	-77	258
14	12.40	-24	8.26	-38	262
5	2.83	-161	8.03	-173	247
16	12.77	-5	8.03	-8	247

Corrections					
Run no.	Wind [kN]	Waves [kN]	Depth [knots]	Temp/Dens [kN]	Idling WPU [kN]
2	-1.0	0.0	0.00	0.0	0.0
7	-1.3	0.0	0.00	0.0	0.0
8	-0.7	0.0	0.00	0.0	0.0
11	4.4	0.0	0.00	0.0	0.0
12	4.5	0.0	0.00	0.0	0.0
15	6.7	0.0	0.00	0.0	0.0
1	-1.0	0.0	0.00	0.0	0.0
6	-1.5	0.0	0.00	0.0	0.0
9	1.3	0.0	0.00	0.0	0.0
10	4.8	0.0	0.00	0.0	0.0
13	3.6	0.0	0.00	0.0	0.0
14	7.0	0.0	0.00	0.0	0.0
5	-2.1	0.0	0.00	-0.0	0.0
16	7.5	0.0	0.00	-0.0	0.0

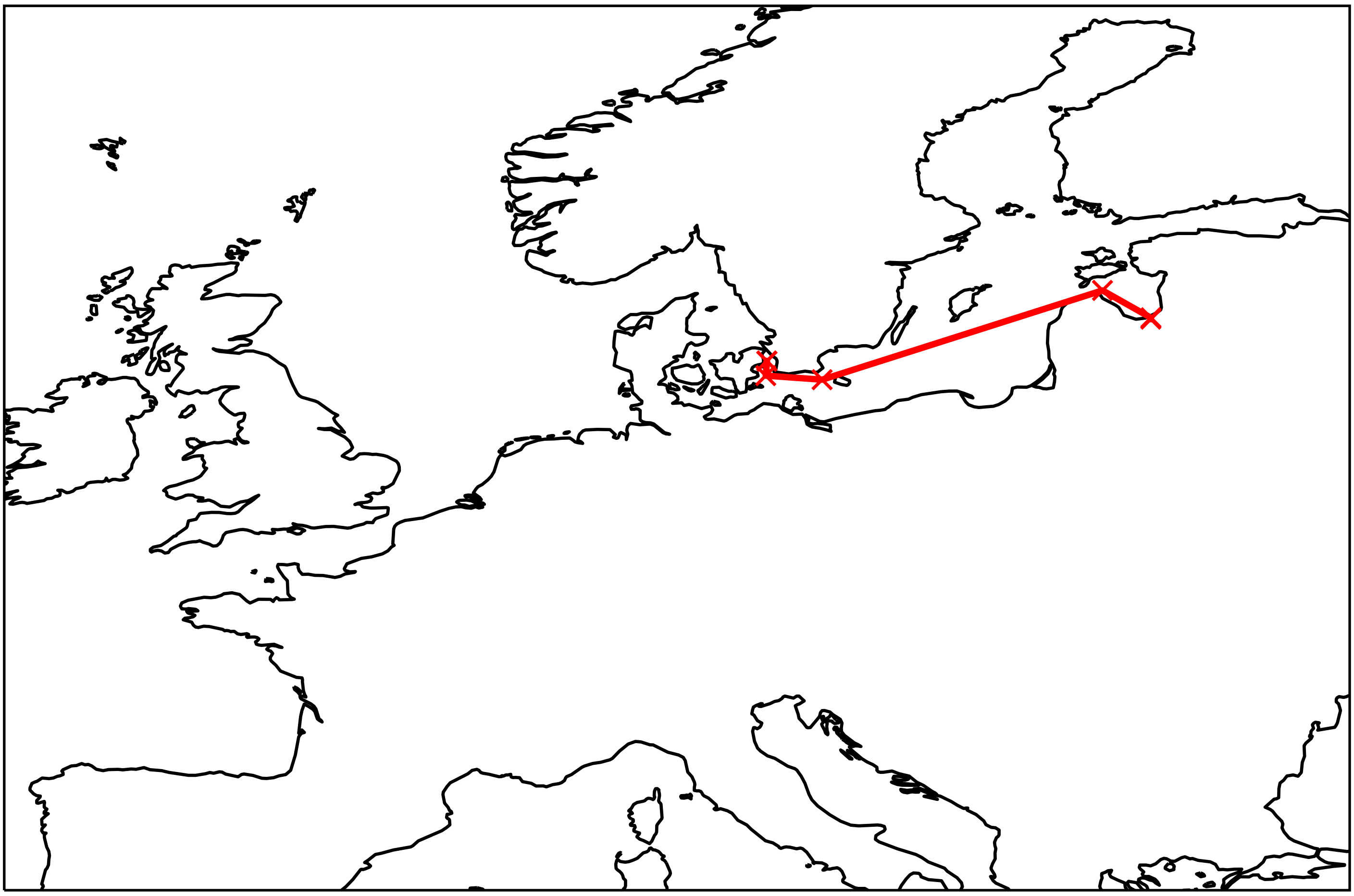
Corrections in percent of total resistance							
Run no.	Wind [%]	Waves [%]	Depth [%]	Temp/dens [%]	Idling WPU [%]	Displ. [%]	Eff. [%]
2	-0.8	0.0	0.0	0.0	0.0	0.0	0.3
7	-1.1	0.0	0.0	0.0	0.0	0.0	0.3
8	-0.6	0.0	0.0	0.0	0.0	0.0	0.3
11	3.8	0.0	0.0	0.0	0.0	0.0	0.3
12	3.7	0.0	0.0	0.0	0.0	0.0	0.3
15	5.5	0.0	0.0	0.0	0.0	0.0	0.3
1	-0.9	0.0	0.0	0.0	0.0	0.0	0.3
6	-1.2	0.0	0.0	0.0	0.0	0.0	0.3
9	1.0	0.0	0.0	0.0	0.0	0.0	0.5
10	4.1	0.0	0.0	0.0	0.0	0.0	0.5
13	2.8	0.0	0.0	0.0	0.0	0.0	0.5
14	5.6	0.0	0.0	0.0	0.0	0.0	0.5
5	-1.8	0.0	0.0	-0.0	0.0	0.0	0.2
16	6.2	0.0	0.0	-0.0	0.0	0.0	0.2

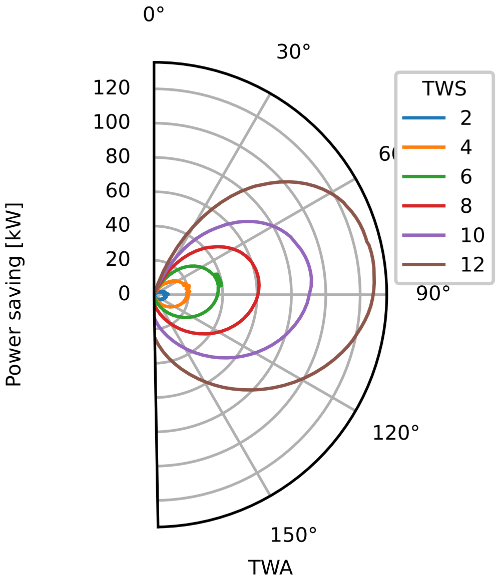
Corrected power		
Run no.	Pdt (ST) [kW]	Nt (ST) [RPM]
2	850	148.3
7	890	148.4
8	894	148.2
11	840	146.6
12	885	146.6
15	885	146.0
1	862	148.3
6	899	148.5
9	889	147.6
10	835	146.5
13	894	147.0
14	888	146.0
5	862	148.7
16	889	145.7

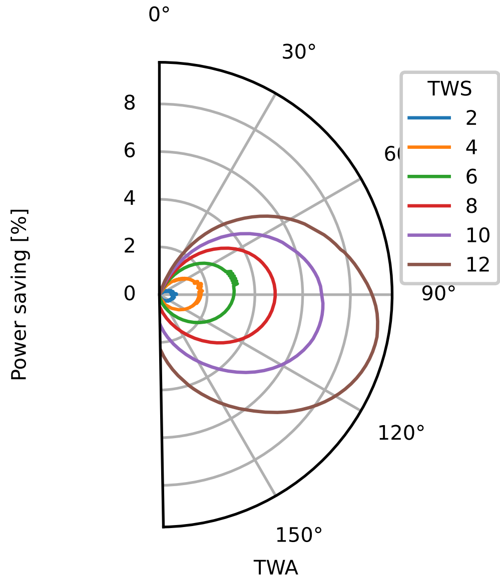
Route analysis report: WPS evaluation

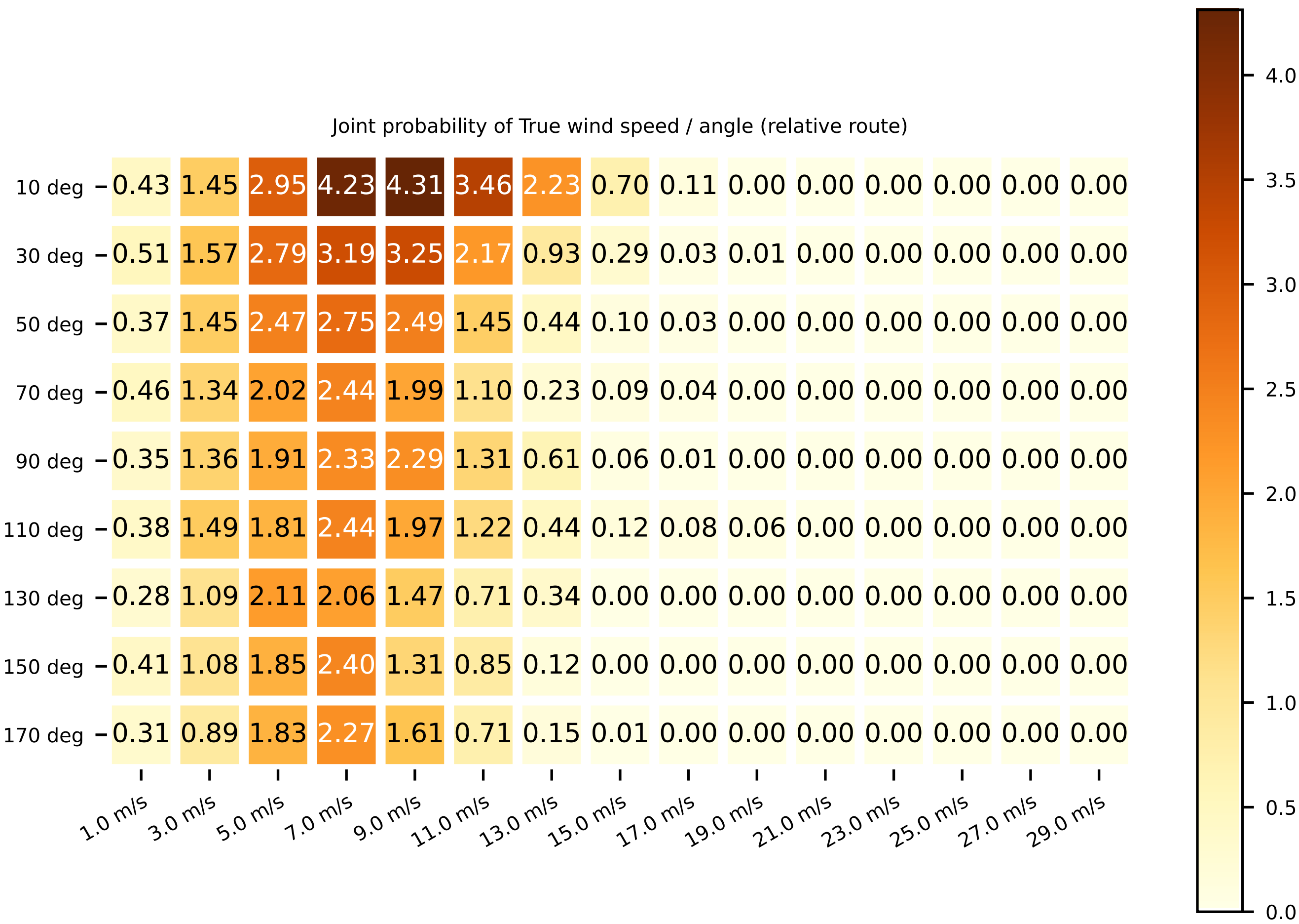
Results for a route analysis for ship: Frisian (light laden) on route: Copenhagen - Riga (inbound) with total distance: 473.9 nm

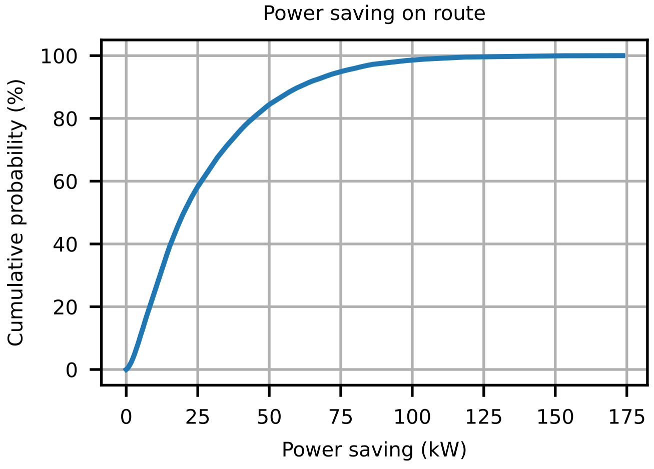
	Average	Min (2.5%)	Max (97.5%)
Power saving (kW)	27.41	1.84	88.41
Energy saving on route (MWh)	1.30	0.09	4.18
Energy saving on route (%)	2.0	0.1	6.4

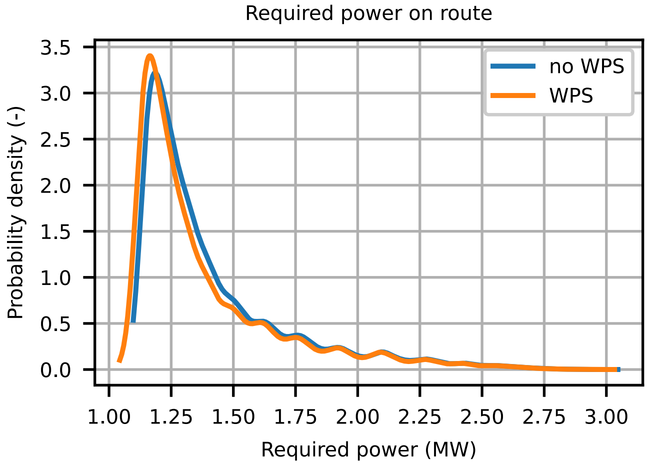



0°
30°
60°
90°
120°
150°
120
100
80
60
40
20
0
Power saving [kW]
TWA
TWS
2
4
6
8
10
12


0°
30°
60°
90°
120°
150°
8
6
4
2
0
Power saving [%]
TWA
TWS
2
4
6
8
10
12


Joint probability of True wind speed / angle (relative route)
10 deg 0.43 1.45 2.95 4.23 4.31 3.46 2.23 0.70 0.11 0.00 0.00 0.00 0.00 0.00 0.00
30 deg 0.51 1.57 2.79 3.19 3.25 2.17 0.93 0.29 0.03 0.01 0.00 0.00 0.00 0.00 0.00
50 deg 0.37 1.45 2.47 2.75 2.49 1.45 0.44 0.10 0.03 0.00 0.00 0.00 0.00 0.00 0.00
70 deg 0.46 1.34 2.02 2.44 1.99 1.10 0.23 0.09 0.04 0.00 0.00 0.00 0.00 0.00 0.00
90 deg 0.35 1.36 1.91 2.33 2.29 1.31 0.61 0.06 0.01 0.00 0.00 0.00 0.00 0.00 0.00
110 deg 0.38 1.49 1.81 2.44 1.97 1.22 0.44 0.12 0.08 0.06 0.00 0.00 0.00 0.00 0.00
130 deg 0.28 1.09 2.11 2.06 1.47 0.71 0.34 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
150 deg 0.41 1.08 1.85 2.40 1.31 0.85 0.12 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
170 deg 0.31 0.89 1.83 2.27 1.61 0.71 0.15 0.01 0.00 0.00 0.00 0.00 0.00 0.00 0.00
1.0 m/s 3.0 m/s 5.0 m/s 7.0 m/s 9.0 m/s 11.0 m/s 13.0 m/s 15.0 m/s 17.0 m/s 19.0 m/s 21.0 m/s 23.0 m/s 25.0 m/s 27.0 m/s 29.0 m/s
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Probability [%]

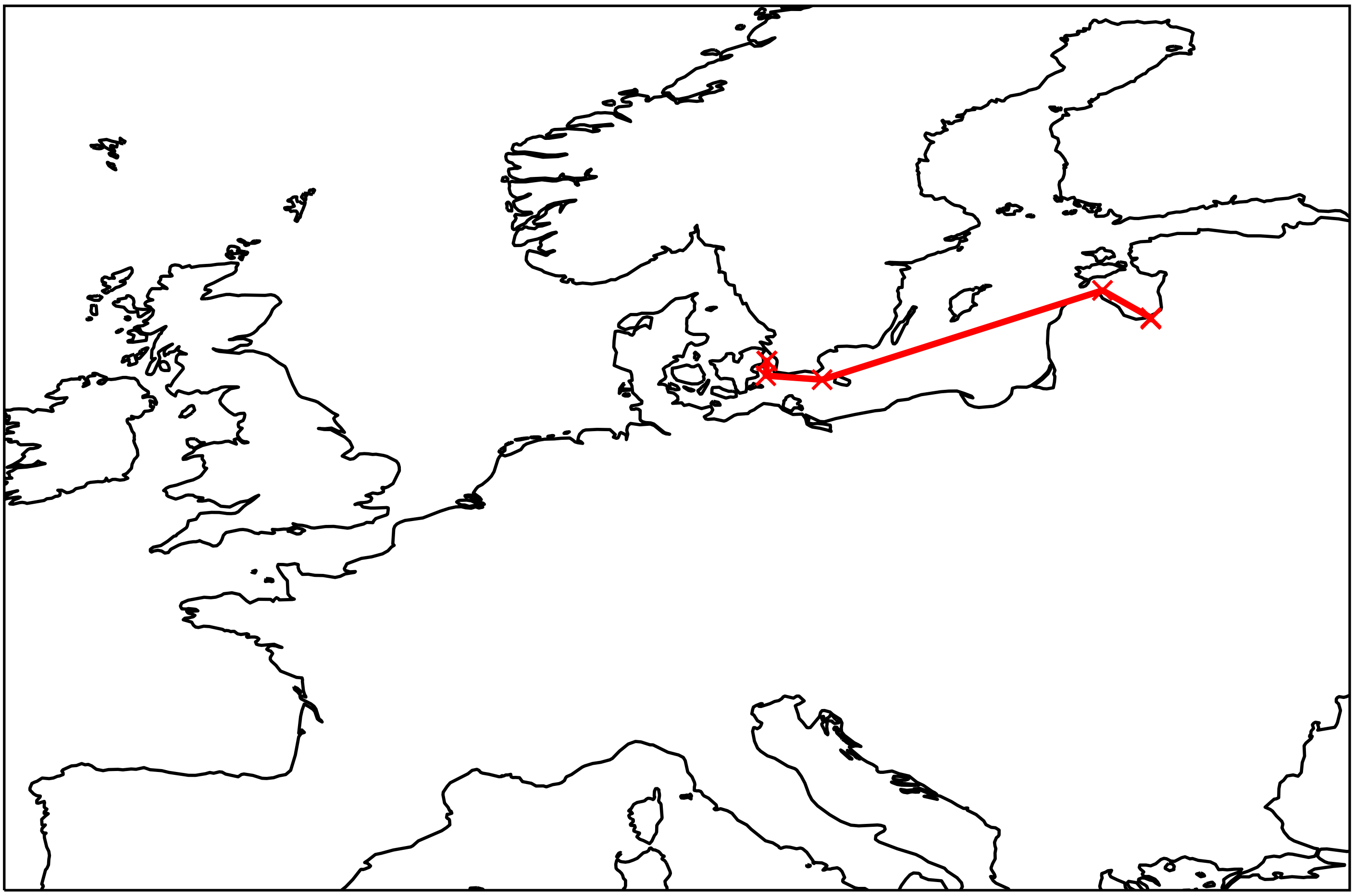

Power saving on route
Cumulative probability (%)
0
20
40
60
80
100
0
25
50
75
100
125
150
175
Power saving (kW)

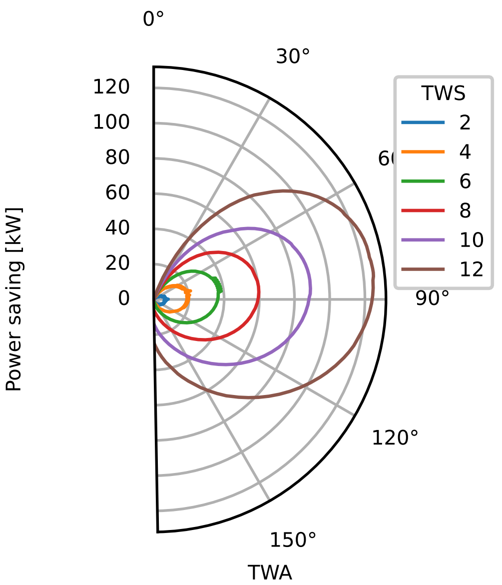

Required power on route
Probability density (-)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
3.00
Required power (MW)
no WPS
WPS

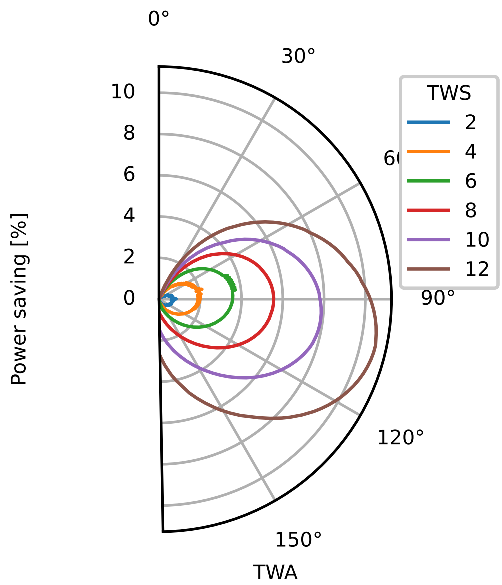
Route analysis report: WPS evaluation

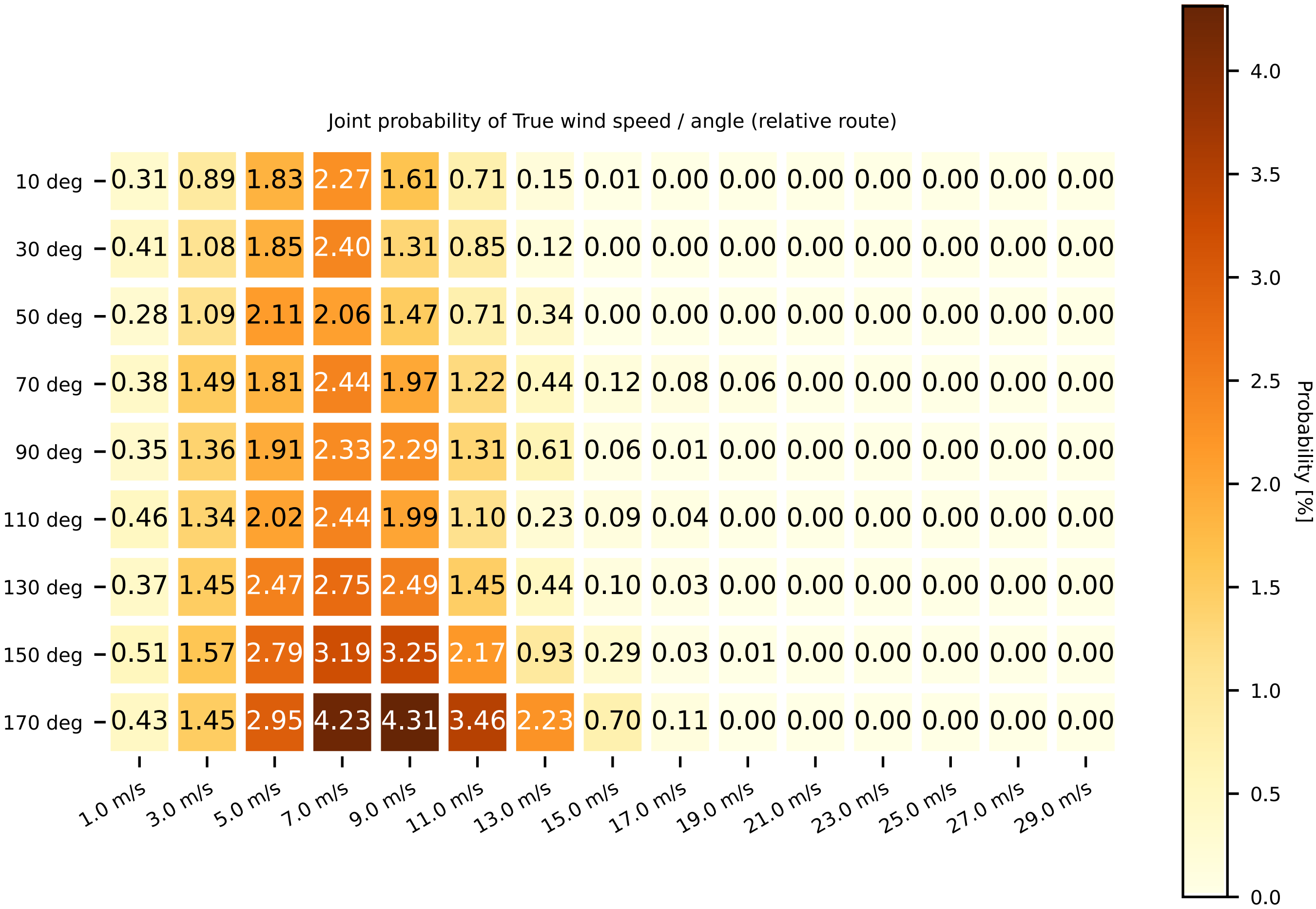
Results for a route analysis for ship: Frisian (ballast) on route: Copenhagen - Riga (outbound) with total distance: 473.9 nm

	Average	Min (2.5%)	Max (97.5%)
Power saving (kW)	29.98	3.30	86.27
Energy saving on route (MWh)	1.42	0.16	4.06
Energy saving on route (%)	2.8	0.3	7.5

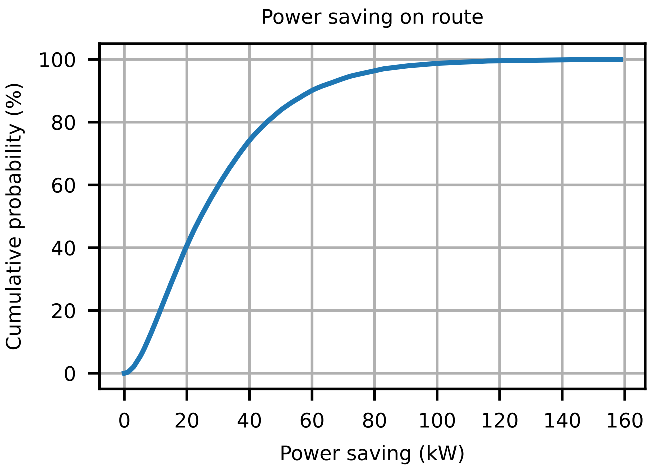


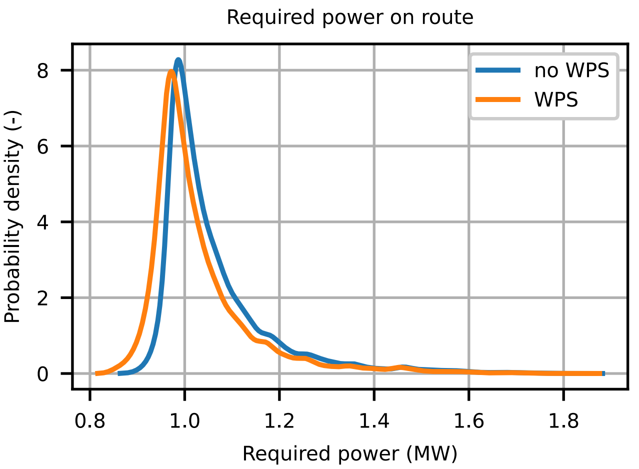






	1.0 m/s	3.0 m/s	5.0 m/s	7.0 m/s	9.0 m/s	11.0 m/s	13.0 m/s	15.0 m/s	17.0 m/s	19.0 m/s	21.0 m/s	23.0 m/s	25.0 m/s	27.0 m/s	29.0 m/s
10 deg	0.31	0.89	1.83	2.27	1.61	0.71	0.15	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30 deg	0.41	1.08	1.85	2.40	1.31	0.85	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50 deg	0.28	1.09	2.11	2.06	1.47	0.71	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
70 deg	0.38	1.49	1.81	2.44	1.97	1.22	0.44	0.12	0.08	0.06	0.00	0.00	0.00	0.00	0.00
90 deg	0.35	1.36	1.91	2.33	2.29	1.31	0.61	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00
110 deg	0.46	1.34	2.02	2.44	1.99	1.10	0.23	0.09	0.04	0.00	0.00	0.00	0.00	0.00	0.00
130 deg	0.37	1.45	2.47	2.75	2.49	1.45	0.44	0.10	0.03	0.00	0.00	0.00	0.00	0.00	0.00
150 deg	0.51	1.57	2.79	3.19	3.25	2.17	0.93	0.29	0.03	0.01	0.00	0.00	0.00	0.00	0.00
170 deg	0.43	1.45	2.95	4.23	4.31	3.46	2.23	0.70	0.11	0.00	0.00	0.00	0.00	0.00	0.00

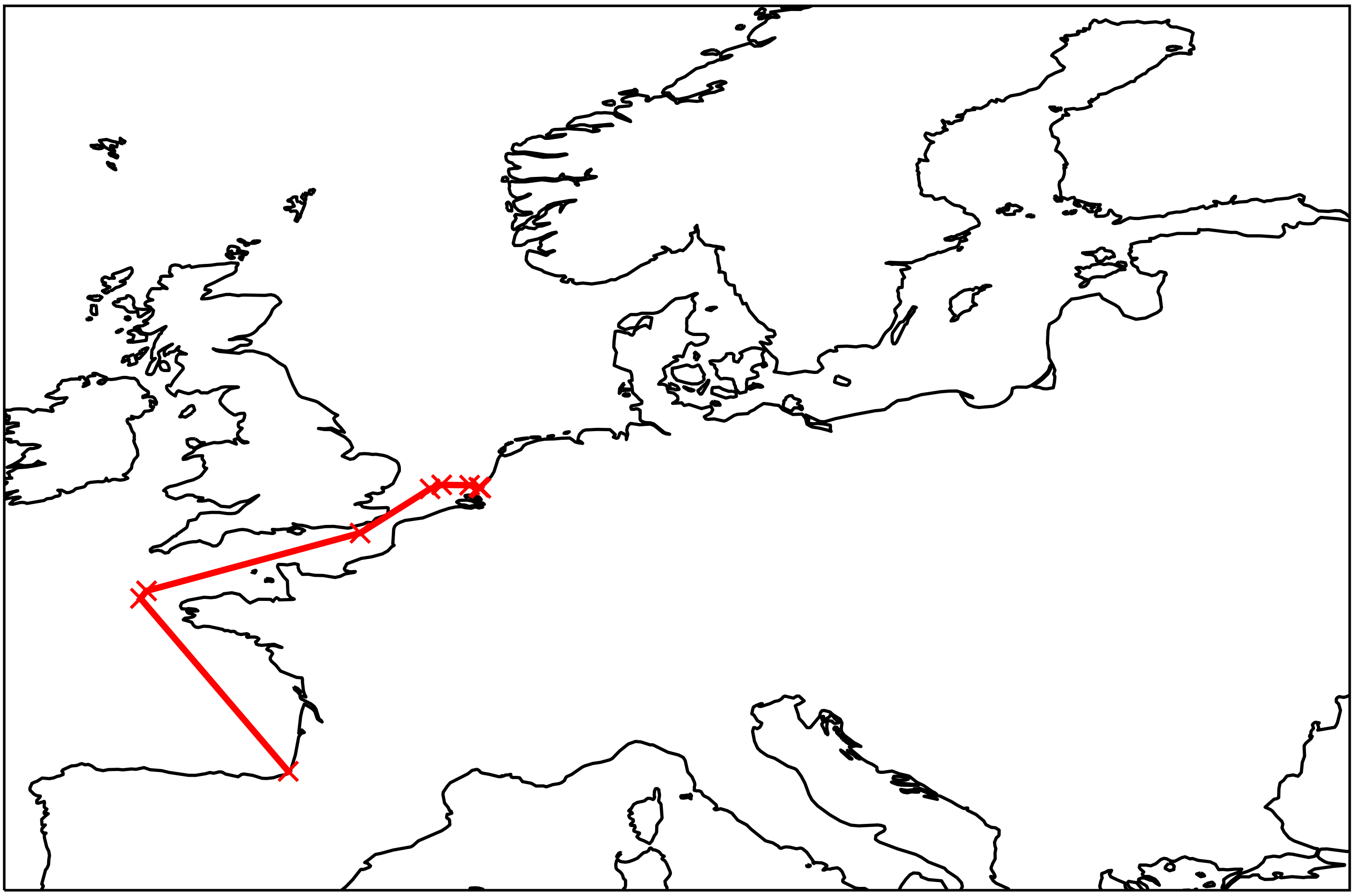

Power saving on route
Cumulative probability (%)
0
20
40
60
80
100
0
20
40
60
80
100
120
140
160
Power saving (kW)

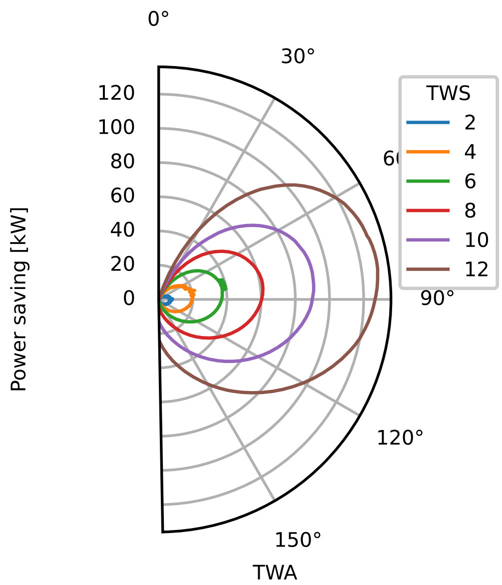

Required power on route
Probability density (-)
0
2
4
6
8
0.8
1.0
1.2
1.4
1.6
1.8
Required power (MW)
no WPS
WPS

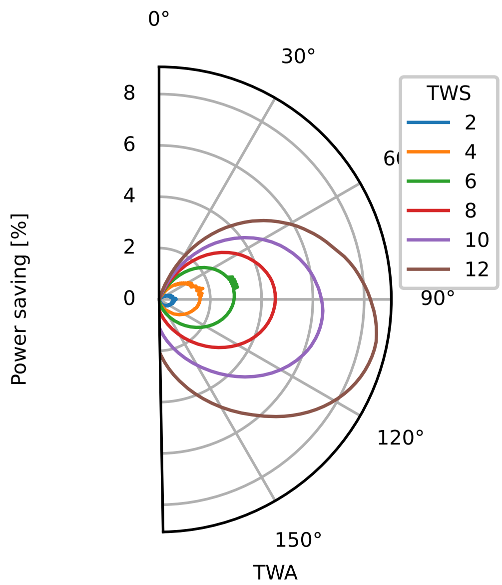
Route analysis report: WPS evaluation

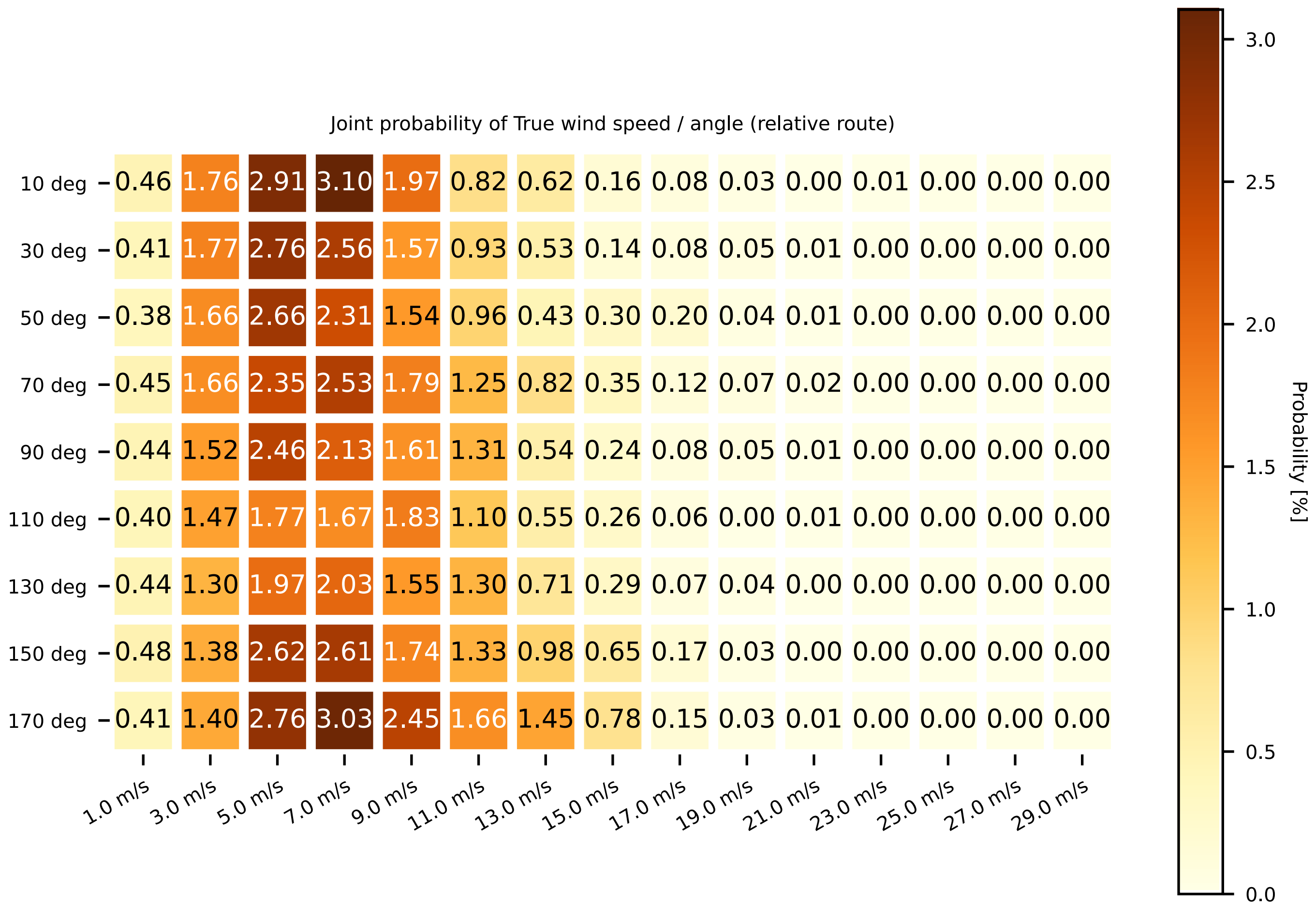
Results for a route analysis for ship: Frisian (laden) on route: Rotterdam - Bayonne (inbound) with total distance: 811.8 nm

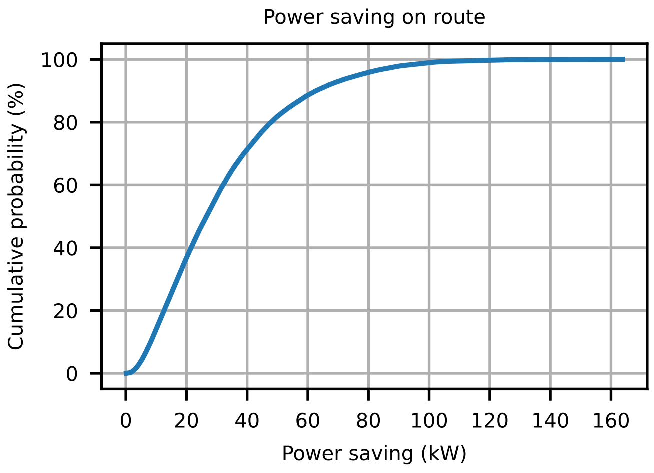
	Average	Min (2.5%)	Max (97.5%)
Power saving (kW)	31.61	4.05	87.91
Energy saving on route (MWh)	2.56	0.33	7.12
Energy saving on route (%)	2.3	0.3	5.8

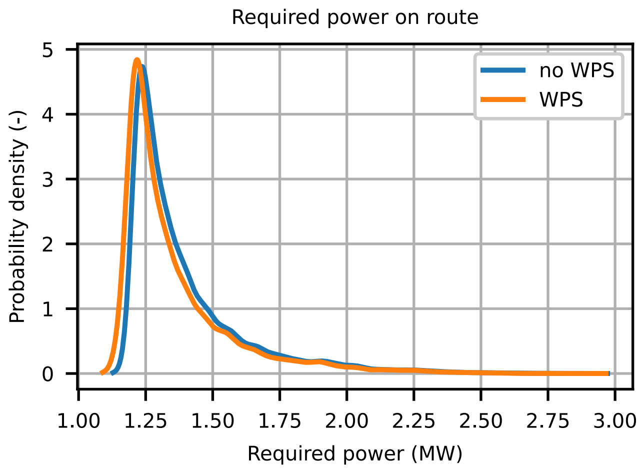



0°
30°
60°
90°
120°
150°
120
100
80
60
40
20
0
Power saving [kW]
TWA
TWS
2
4
6
8
10
12


0°
30°
60°
90°
120°
150°
8
6
4
2
0
Power saving [%]
TWA
TWS
2
4
6
8
10
12


Joint probability of True wind speed / angle (relative route)
10 deg 0.46 1.76 2.91 3.10 1.97 0.82 0.62 0.16 0.08 0.03 0.00 0.01 0.00 0.00 0.00
30 deg 0.41 1.77 2.76 2.56 1.57 0.93 0.53 0.14 0.08 0.05 0.01 0.00 0.00 0.00 0.00
50 deg 0.38 1.66 2.66 2.31 1.54 0.96 0.43 0.30 0.20 0.04 0.01 0.00 0.00 0.00 0.00
70 deg 0.45 1.66 2.35 2.53 1.79 1.25 0.82 0.35 0.12 0.07 0.02 0.00 0.00 0.00 0.00
90 deg 0.44 1.52 2.46 2.13 1.61 1.31 0.54 0.24 0.08 0.05 0.01 0.00 0.00 0.00 0.00
110 deg 0.40 1.47 1.77 1.67 1.83 1.10 0.55 0.26 0.06 0.00 0.01 0.00 0.00 0.00 0.00
130 deg 0.44 1.30 1.97 2.03 1.55 1.30 0.71 0.29 0.07 0.04 0.00 0.00 0.00 0.00 0.00
150 deg 0.48 1.38 2.62 2.61 1.74 1.33 0.98 0.65 0.17 0.03 0.00 0.00 0.00 0.00 0.00
170 deg 0.41 1.40 2.76 3.03 2.45 1.66 1.45 0.78 0.15 0.03 0.01 0.00 0.00 0.00 0.00
1.0 m/s 3.0 m/s 5.0 m/s 7.0 m/s 9.0 m/s 11.0 m/s 13.0 m/s 15.0 m/s 17.0 m/s 19.0 m/s 21.0 m/s 23.0 m/s 25.0 m/s 27.0 m/s 29.0 m/s
Probability [%]
3.0
2.5
2.0
1.5
1.0
0.5
0.0

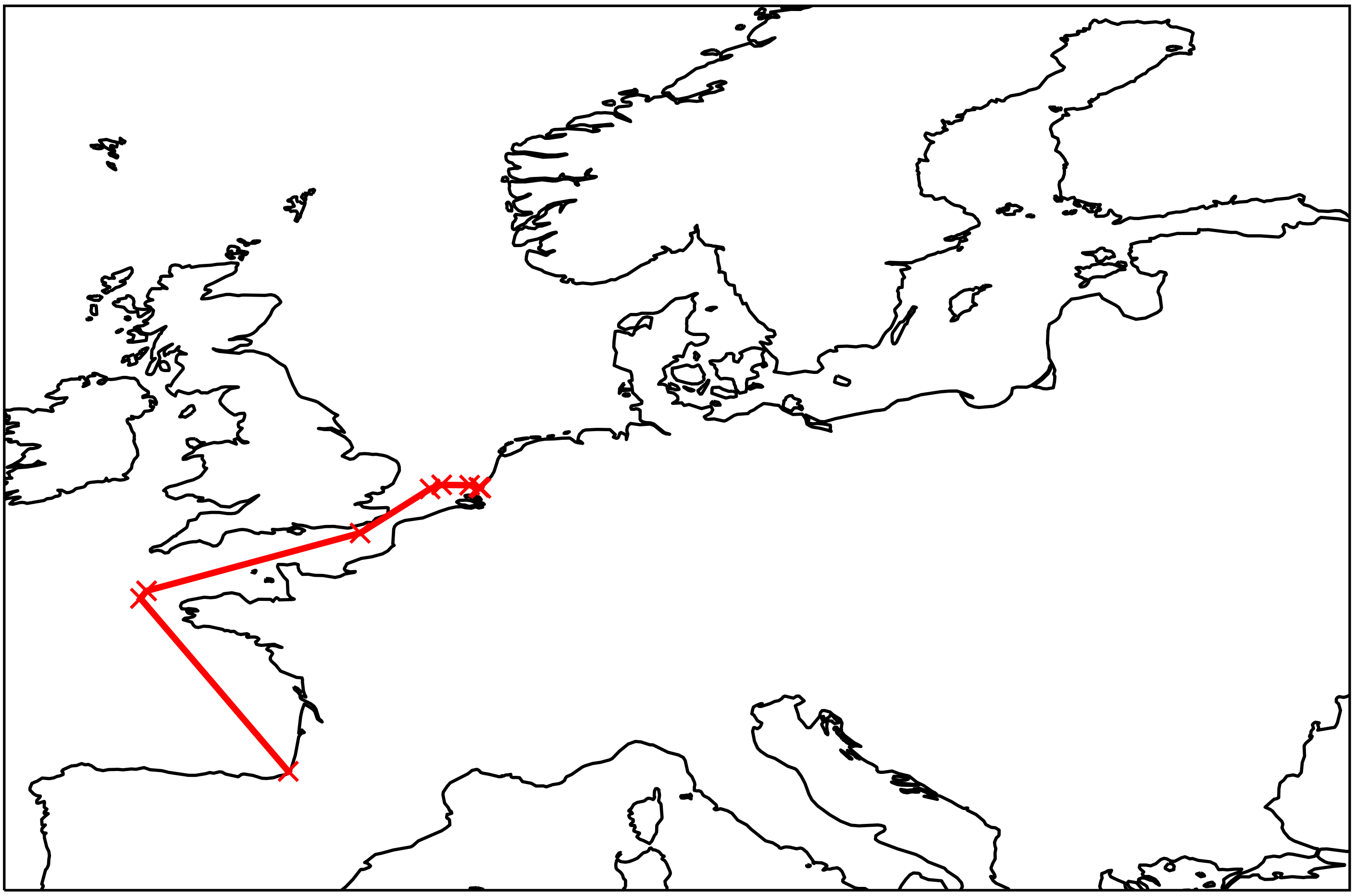

Power saving on route
Cumulative probability (%)
0
20
40
60
80
100
0
20
40
60
80
100
120
140
160
Power saving (kW)

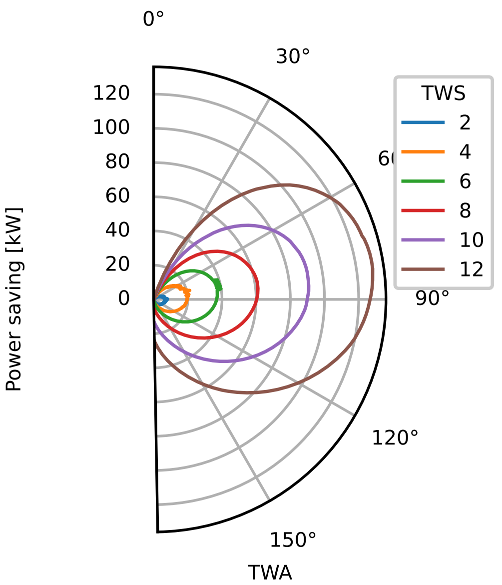

Required power on route
Probability density (-)
0
1
2
3
4
5
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
3.00
Required power (MW)
no WPS
WPS

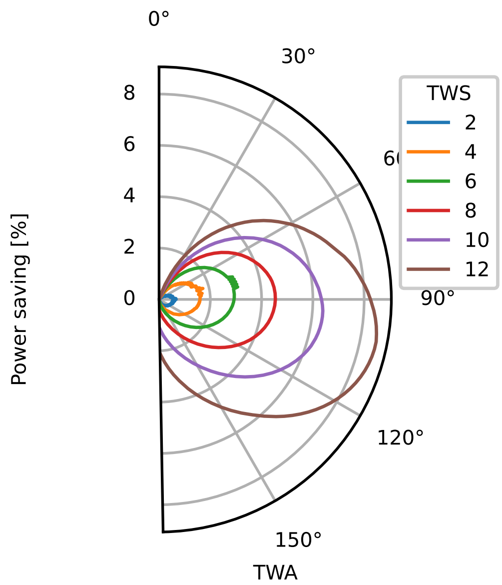
Route analysis report: WPS evaluation

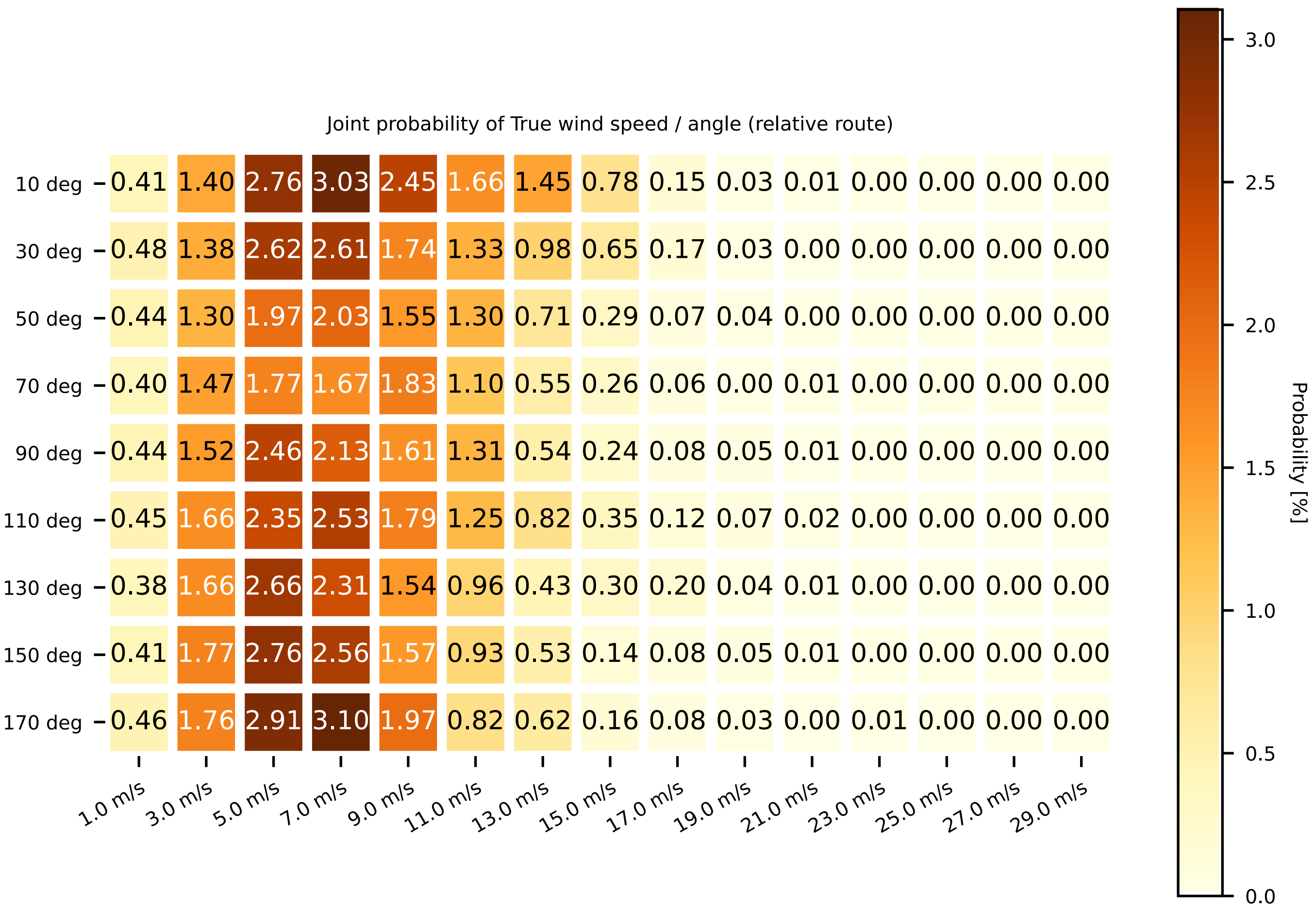
Results for a route analysis for ship: Frisian (laden) on route: Rotterdam - Bayonne (outbound) with total distance: 811.8 nm

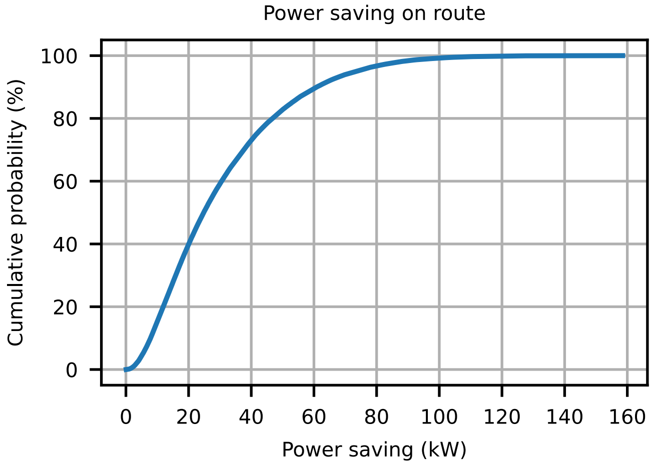
	Average	Min (2.5%)	Max (97.5%)
Power saving (kW)	30.26	3.81	84.09
Energy saving on route (MWh)	2.45	0.31	6.81
Energy saving on route (%)	2.1	0.3	5.6

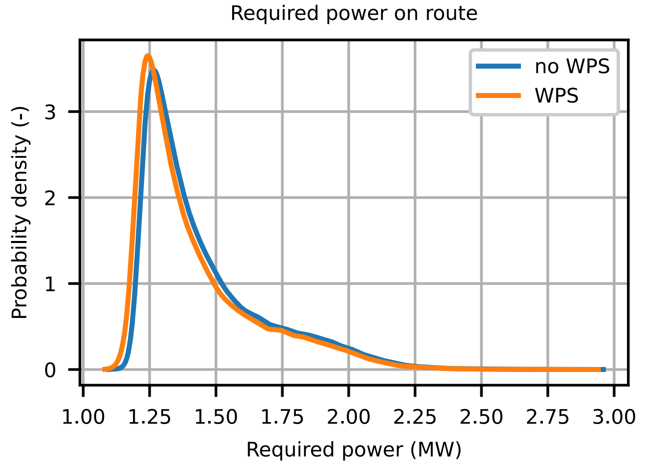



0°
30°
60°
90°
120°
150°
120
100
80
60
40
20
0
Power saving [kW]
TWS
2
4
6
8
10
12
TWA


0°
30°
60°
90°
120°
150°
8
6
4
2
0
Power saving [%]
TWS
2
4
6
8
10
12
TWA


Joint probability of True wind speed / angle (relative route)
10 deg 0.41 1.40 2.76 3.03 2.45 1.66 1.45 0.78 0.15 0.03 0.01 0.00 0.00 0.00 0.00
30 deg 0.48 1.38 2.62 2.61 1.74 1.33 0.98 0.65 0.17 0.03 0.00 0.00 0.00 0.00 0.00
50 deg 0.44 1.30 1.97 2.03 1.55 1.30 0.71 0.29 0.07 0.04 0.00 0.00 0.00 0.00 0.00
70 deg 0.40 1.47 1.77 1.67 1.83 1.10 0.55 0.26 0.06 0.00 0.01 0.00 0.00 0.00 0.00
90 deg 0.44 1.52 2.46 2.13 1.61 1.31 0.54 0.24 0.08 0.05 0.01 0.00 0.00 0.00 0.00
110 deg 0.45 1.66 2.35 2.53 1.79 1.25 0.82 0.35 0.12 0.07 0.02 0.00 0.00 0.00 0.00
130 deg 0.38 1.66 2.66 2.31 1.54 0.96 0.43 0.30 0.20 0.04 0.01 0.00 0.00 0.00 0.00
150 deg 0.41 1.77 2.76 2.56 1.57 0.93 0.53 0.14 0.08 0.05 0.01 0.00 0.00 0.00 0.00
170 deg 0.46 1.76 2.91 3.10 1.97 0.82 0.62 0.16 0.08 0.03 0.00 0.01 0.00 0.00 0.00
1.0 m/s 3.0 m/s 5.0 m/s 7.0 m/s 9.0 m/s 11.0 m/s 13.0 m/s 15.0 m/s 17.0 m/s 19.0 m/s 21.0 m/s 23.0 m/s 25.0 m/s 27.0 m/s 29.0 m/s
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Probability [%]

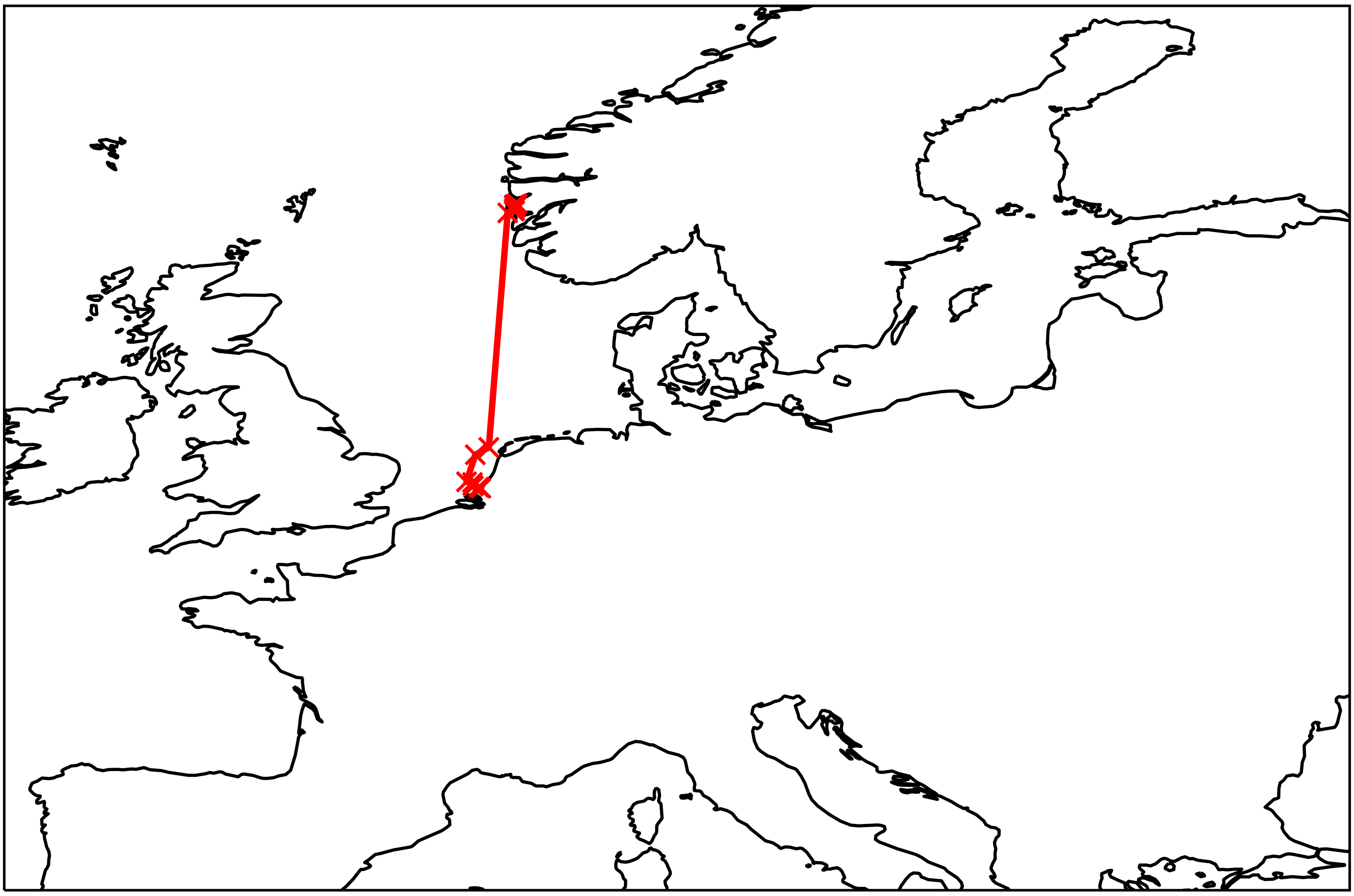

Power saving on route
Cumulative probability (%)
100
80
60
40
20
0
0
20
40
60
80
100
120
140
160
Power saving (kW)

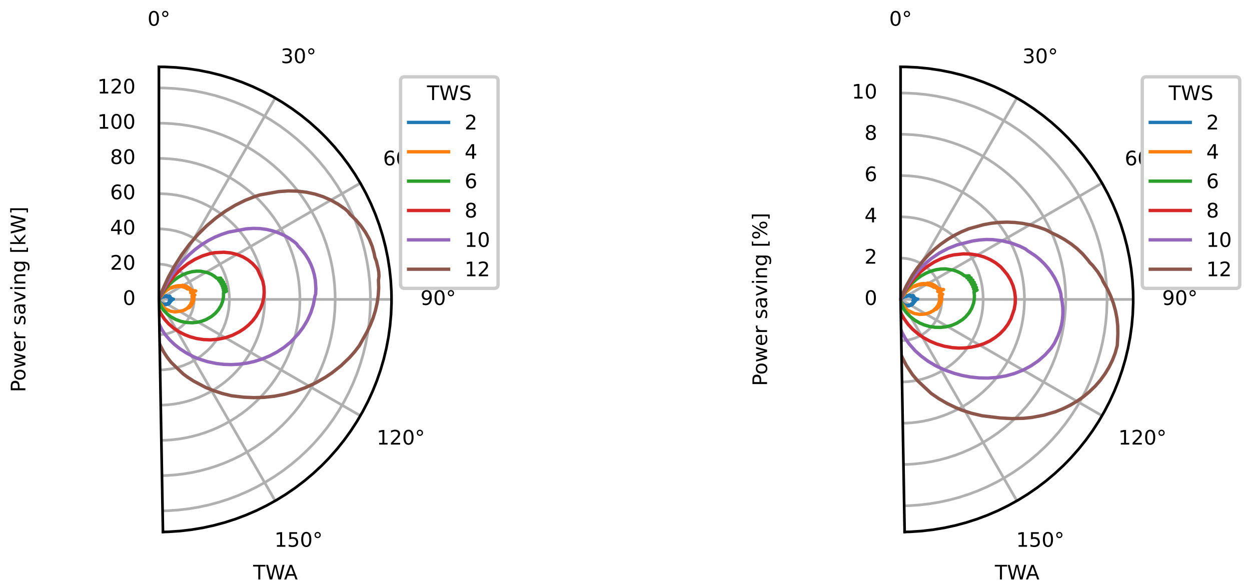

Required power on route
Probability density (-)
3
2
1
0
no WPS
WPS
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
3.00
Required power (MW)

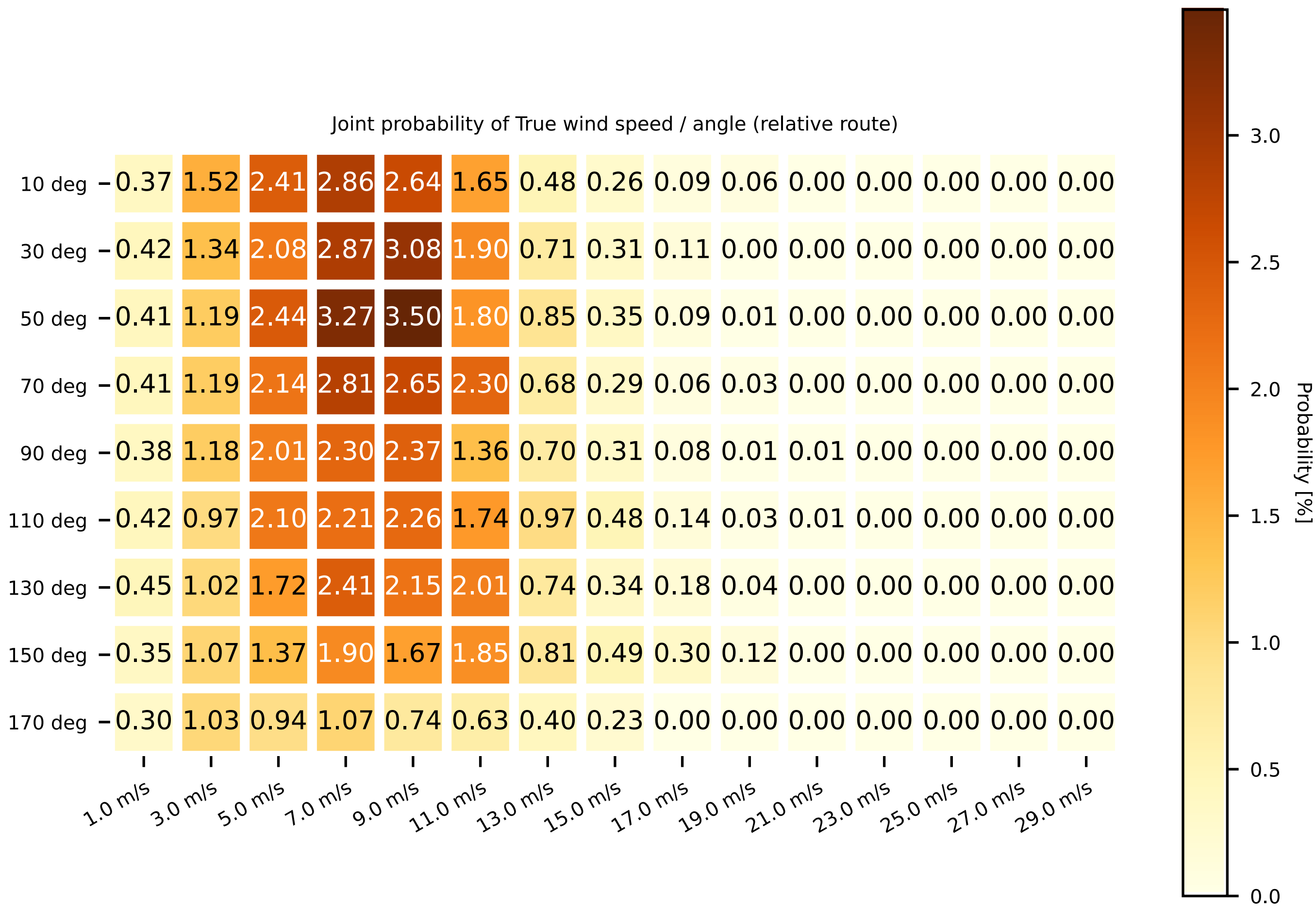
Route analysis report: WPS evaluation

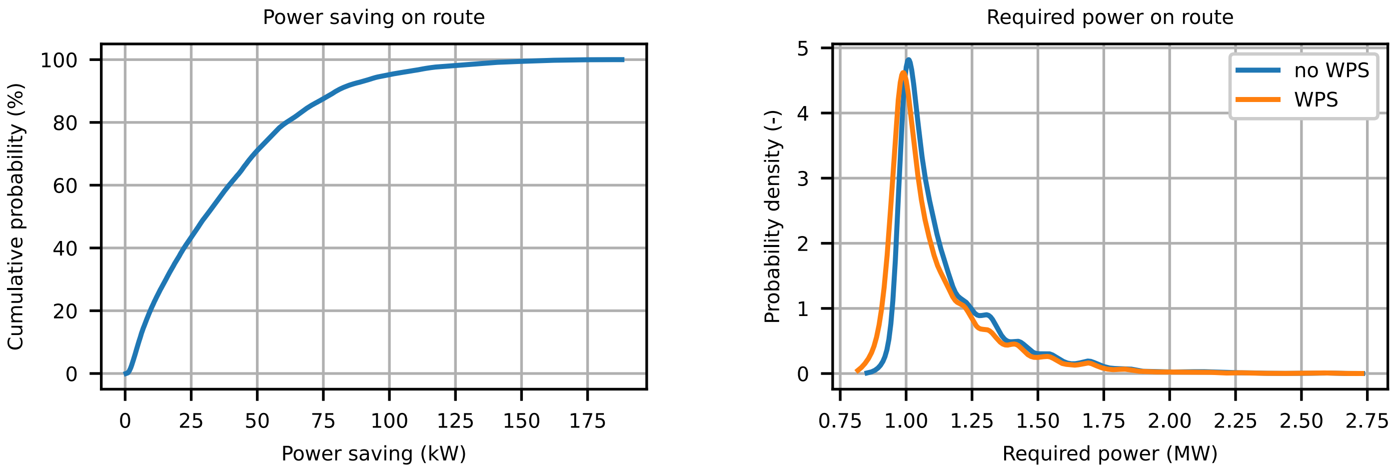
Results for a route analysis for ship: Frisian (ballast) on route: Rotterdam - Bergen (inbound) with total distance: 532.6 nm

	Average	Min (2.5%)	Max (97.5%)
Power saving (kW)	37.65	2.41	116.18
Energy saving on route (MWh)	2.00	0.13	6.15
Energy saving on route (%)	3.3	0.2	9.8




0°
30°
60
90°
120°
150°
TWA
Power saving [kW]
120
100
80
60
40
20
0
TWS
2
4
6
8
10
12
Power saving [%]
10
8
6
4
2
0

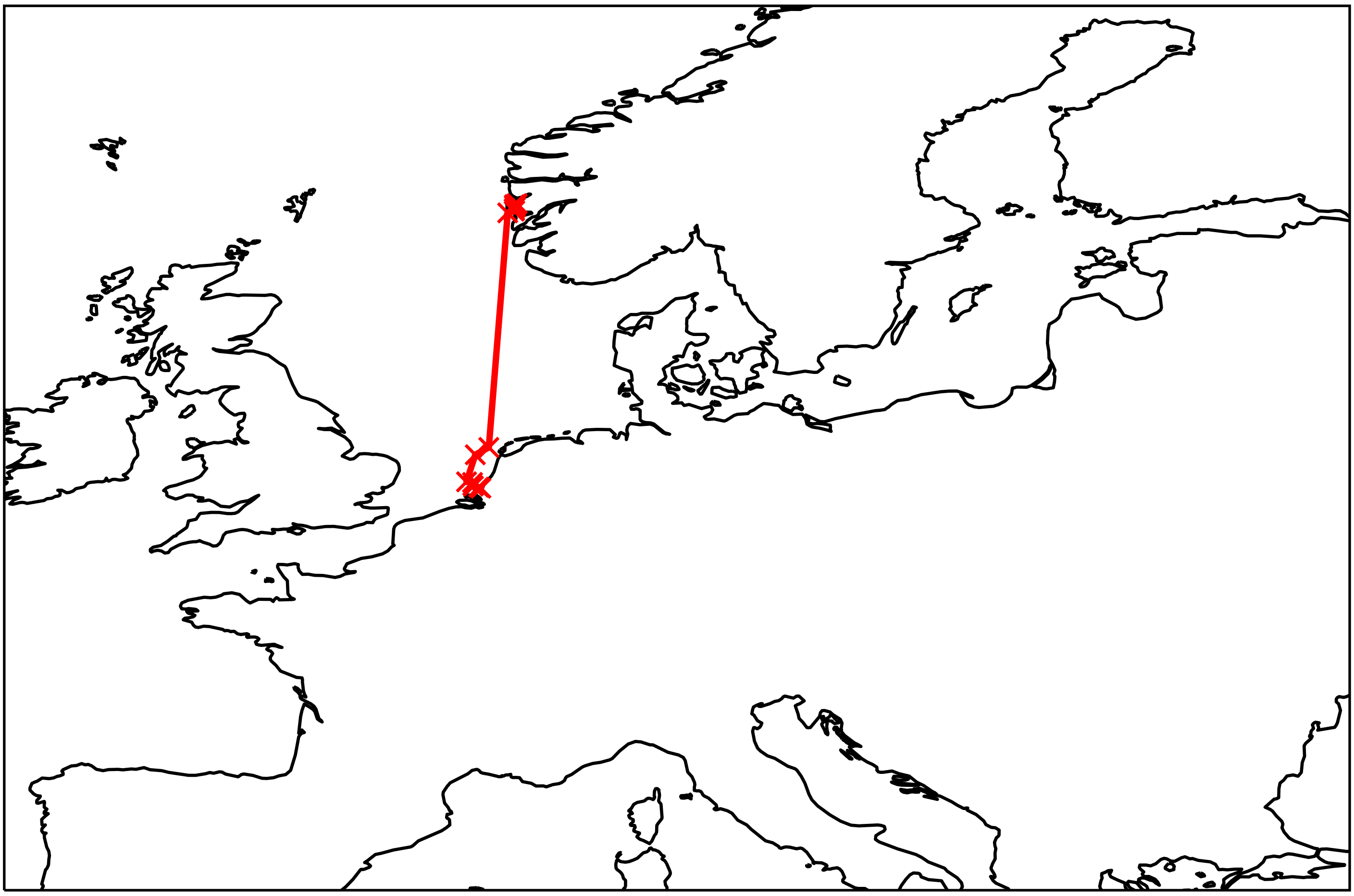

Joint probability of True wind speed / angle (relative route)
10 deg 0.37 1.52 2.41 2.86 2.64 1.65 0.48 0.26 0.09 0.06 0.00 0.00 0.00 0.00 0.00
30 deg 0.42 1.34 2.08 2.87 3.08 1.90 0.71 0.31 0.11 0.00 0.00 0.00 0.00 0.00 0.00
50 deg 0.41 1.19 2.44 3.27 3.50 1.80 0.85 0.35 0.09 0.01 0.00 0.00 0.00 0.00 0.00
70 deg 0.41 1.19 2.14 2.81 2.65 2.30 0.68 0.29 0.06 0.03 0.00 0.00 0.00 0.00 0.00
90 deg 0.38 1.18 2.01 2.30 2.37 1.36 0.70 0.31 0.08 0.01 0.01 0.00 0.00 0.00 0.00
110 deg 0.42 0.97 2.10 2.21 2.26 1.74 0.97 0.48 0.14 0.03 0.01 0.00 0.00 0.00 0.00
130 deg 0.45 1.02 1.72 2.41 2.15 2.01 0.74 0.34 0.18 0.04 0.00 0.00 0.00 0.00 0.00
150 deg 0.35 1.07 1.37 1.90 1.67 1.85 0.81 0.49 0.30 0.12 0.00 0.00 0.00 0.00 0.00
170 deg 0.30 1.03 0.94 1.07 0.74 0.63 0.40 0.23 0.00 0.00 0.00 0.00 0.00 0.00 0.00
1.0 m/s 3.0 m/s 5.0 m/s 7.0 m/s 9.0 m/s 11.0 m/s 13.0 m/s 15.0 m/s 17.0 m/s 19.0 m/s 21.0 m/s 23.0 m/s 25.0 m/s 27.0 m/s 29.0 m/s
Probability [%]
3.0
2.5
2.0
1.5
1.0
0.5
0.0

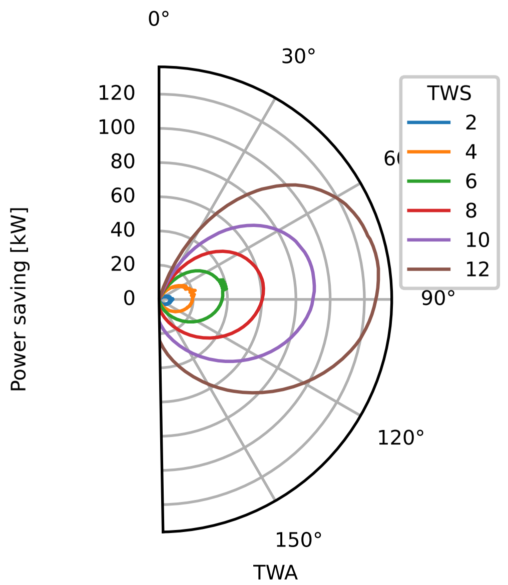

Power saving on route
Cumulative probability (%)
0
20
40
60
80
100
0
25
50
75
100
125
150
175
Power saving (kW)
Required power on route
Probability density (-)
0
1
2
3
4
5
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
Required power (MW)
no WPS
WPS

Route analysis report: WPS evaluation

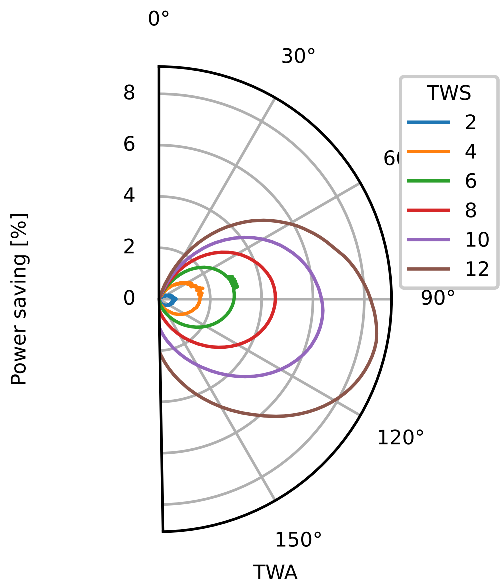
Results for a route analysis for ship: Frisian (laden) on route: Rotterdam - Bergen (outbound) with total distance: 532.6 nm

	Average	Min (2.5%)	Max (97.5%)
Power saving (kW)	39.31	3.60	122.24
Energy saving on route (MWh)	2.09	0.19	6.49
Energy saving on route (%)	2.8	0.2	7.7

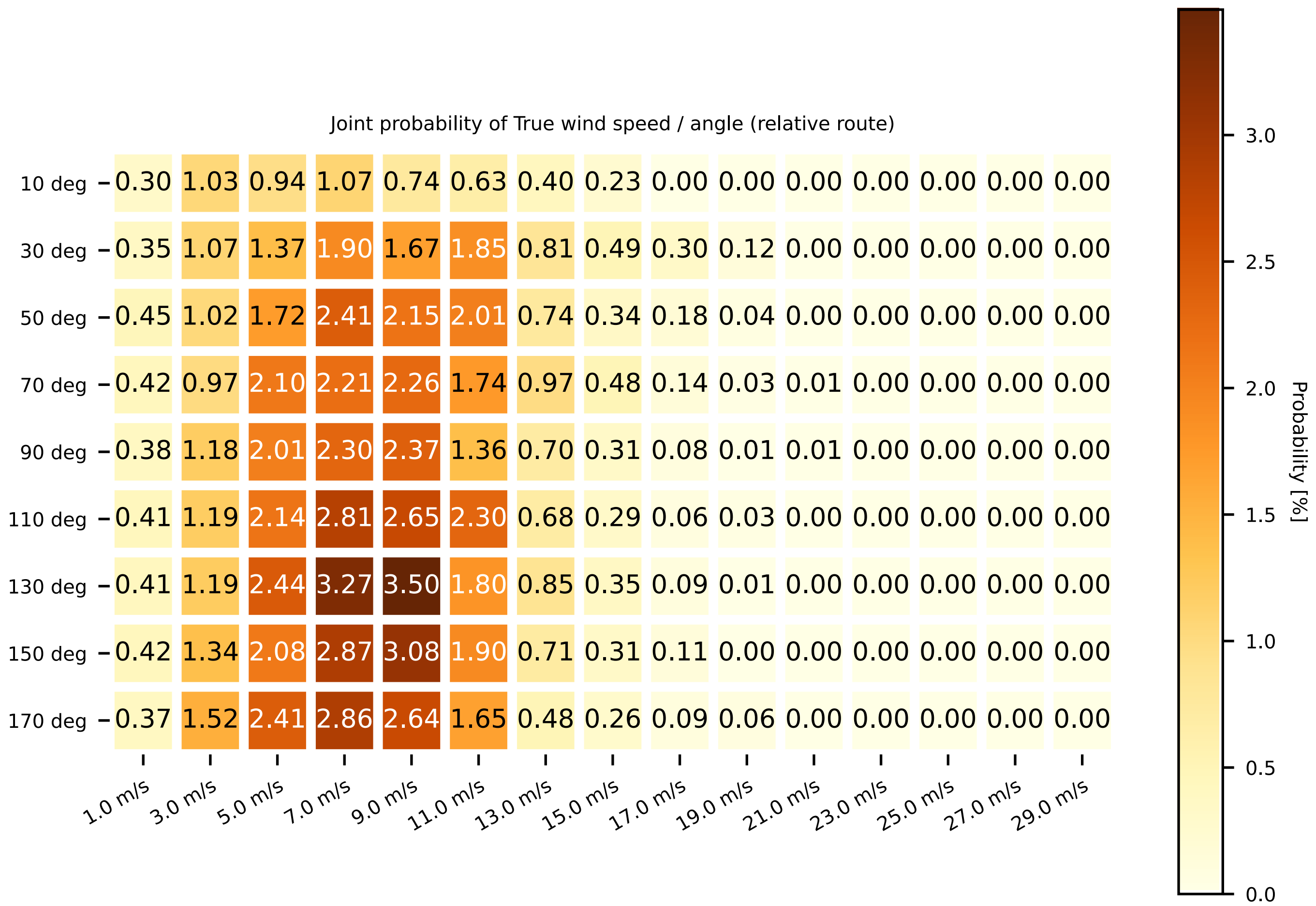




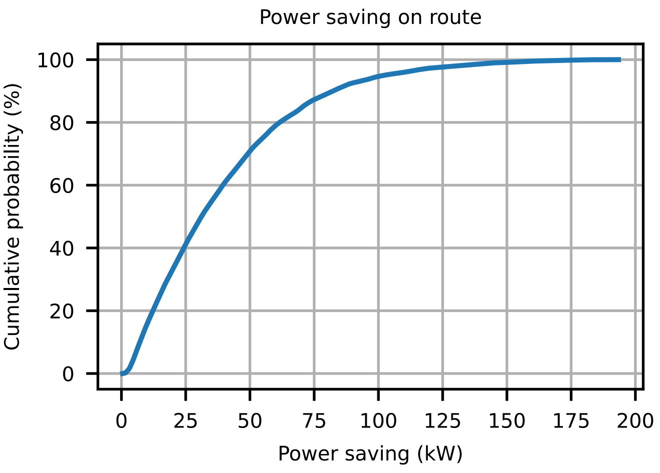
0°
30°
60°
90°
120°
150°
120
100
80
60
40
20
0
Power saving [kW]
TWA
TWS
2
4
6
8
10
12

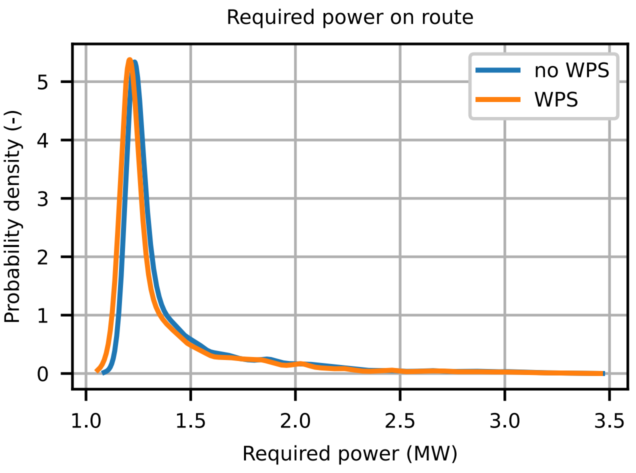


0°
30°
60°
90°
120°
150°
8
6
4
2
0
Power saving [%]
TWA
TWS
2
4
6
8
10
12



Joint probability of True wind speed / angle (relative route)
10 deg 0.30 1.03 0.94 1.07 0.74 0.63 0.40 0.23 0.00 0.00 0.00 0.00 0.00 0.00 0.00
30 deg 0.35 1.07 1.37 1.90 1.67 1.85 0.81 0.49 0.30 0.12 0.00 0.00 0.00 0.00 0.00
50 deg 0.45 1.02 1.72 2.41 2.15 2.01 0.74 0.34 0.18 0.04 0.00 0.00 0.00 0.00 0.00
70 deg 0.42 0.97 2.10 2.21 2.26 1.74 0.97 0.48 0.14 0.03 0.01 0.00 0.00 0.00 0.00
90 deg 0.38 1.18 2.01 2.30 2.37 1.36 0.70 0.31 0.08 0.01 0.01 0.00 0.00 0.00 0.00
110 deg 0.41 1.19 2.14 2.81 2.65 2.30 0.68 0.29 0.06 0.03 0.00 0.00 0.00 0.00 0.00
130 deg 0.41 1.19 2.44 3.27 3.50 1.80 0.85 0.35 0.09 0.01 0.00 0.00 0.00 0.00 0.00
150 deg 0.42 1.34 2.08 2.87 3.08 1.90 0.71 0.31 0.11 0.00 0.00 0.00 0.00 0.00 0.00
170 deg 0.37 1.52 2.41 2.86 2.64 1.65 0.48 0.26 0.09 0.06 0.00 0.00 0.00 0.00 0.00
1.0 m/s
3.0 m/s
5.0 m/s
7.0 m/s
9.0 m/s
11.0 m/s
13.0 m/s
15.0 m/s
17.0 m/s
19.0 m/s
21.0 m/s
23.0 m/s
25.0 m/s
27.0 m/s
29.0 m/s
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Probability [%]

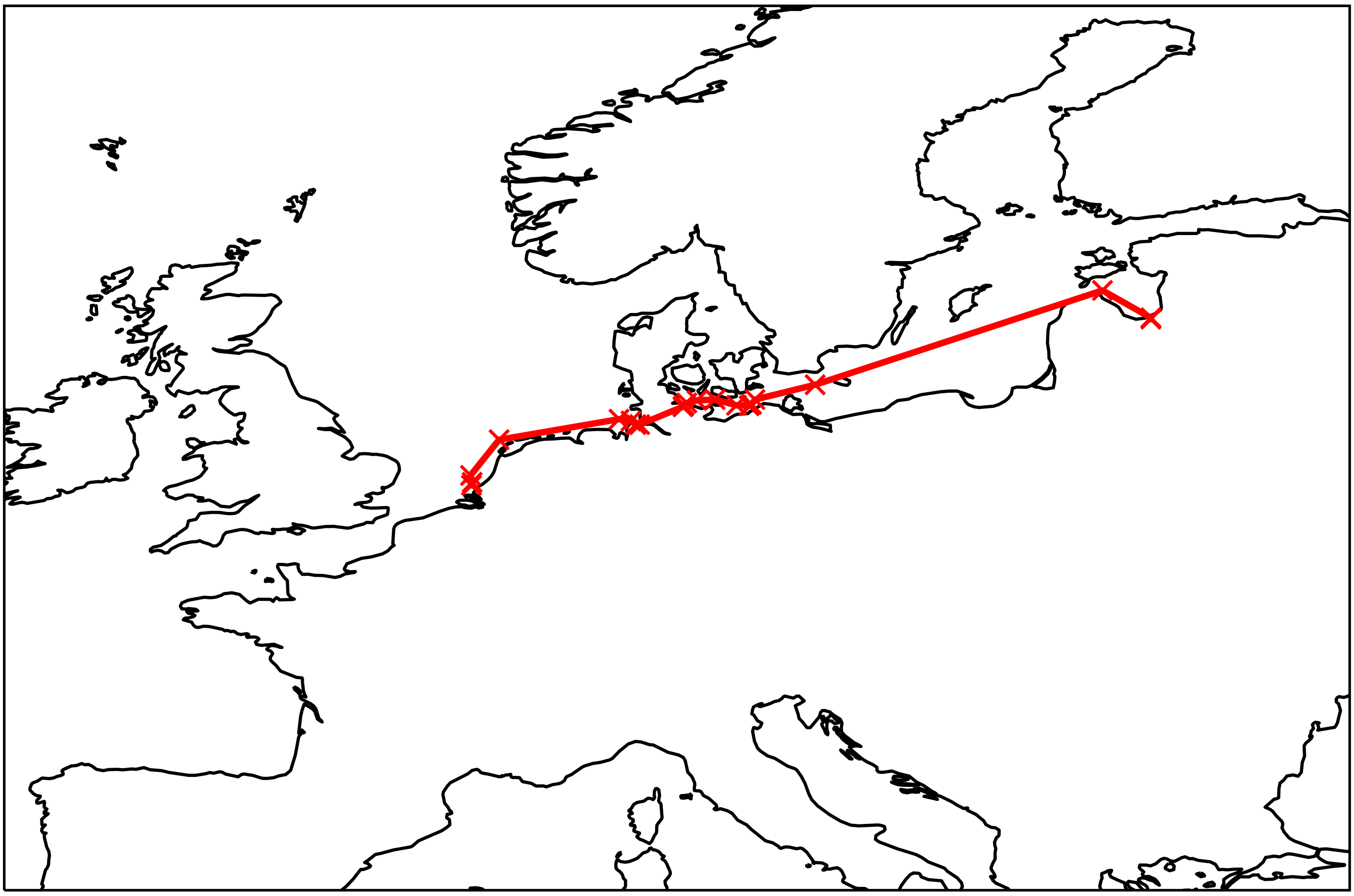

Power saving on route
Cumulative probability (%)
0
20
40
60
80
100
0
25
50
75
100
125
150
175
200
Power saving (kW)

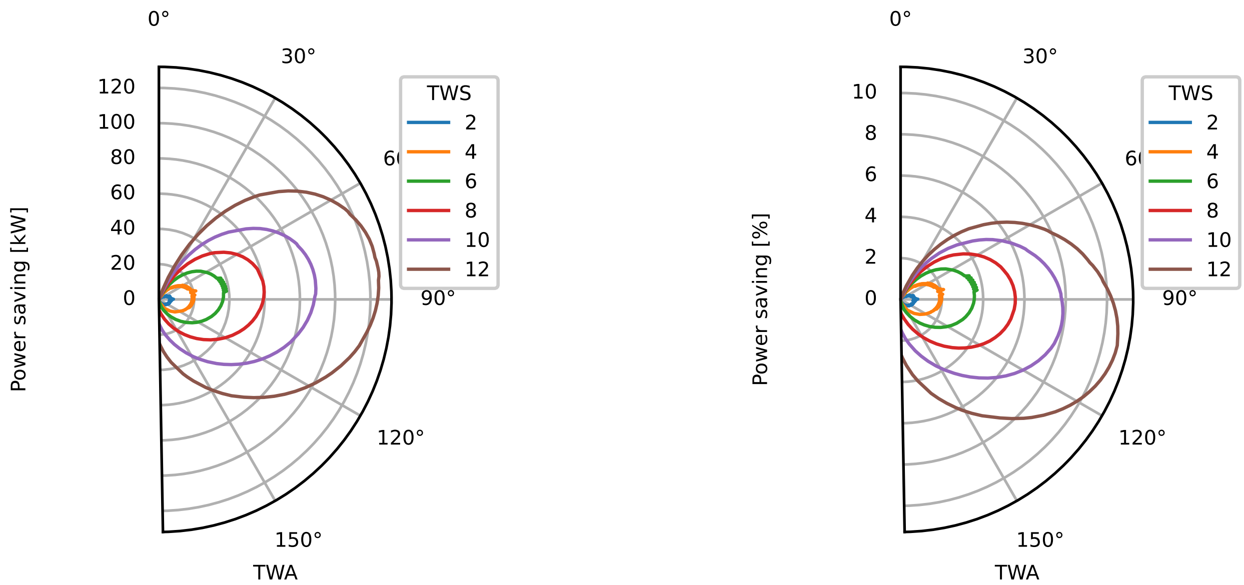

Required power on route
Probability density (-)
0
1
2
3
4
5
1.0
1.5
2.0
2.5
3.0
3.5
Required power (MW)
no WPS
WPS

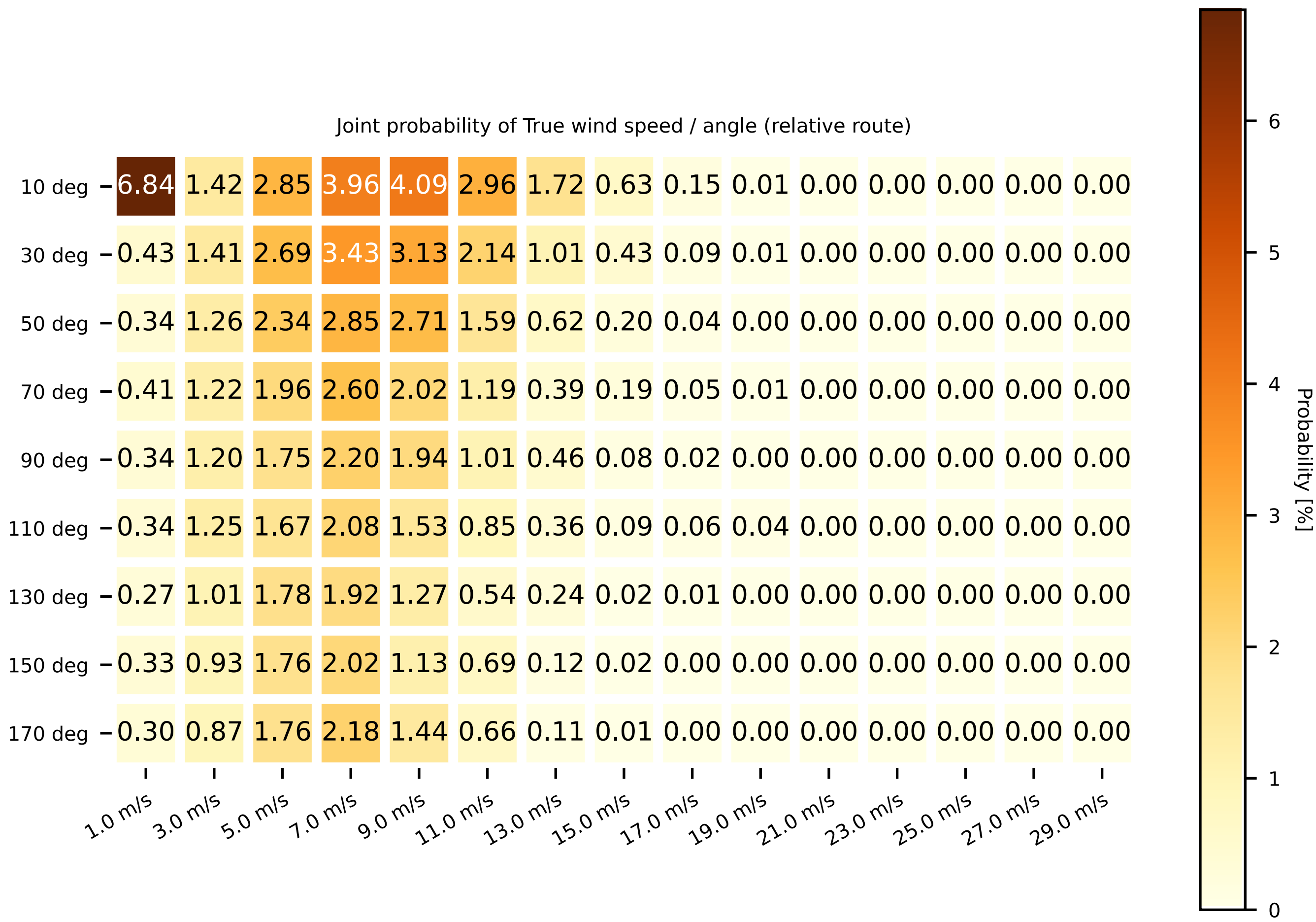
Route analysis report: WPS evaluation

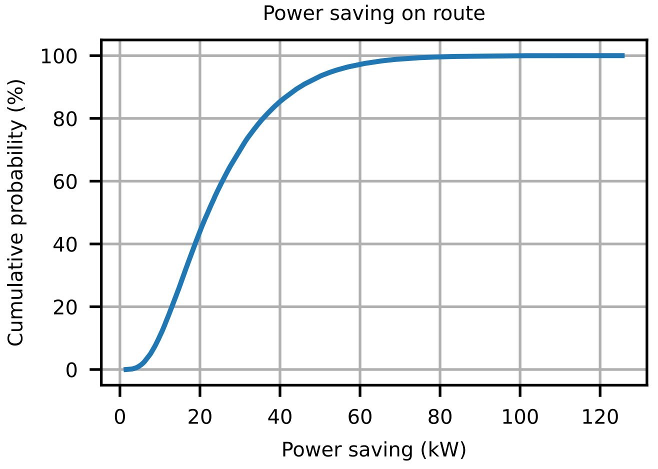
Results for a route analysis for ship: Frisian (ballast) on route: Rotterdam - Riga (inbound) with total distance: 858.8 nm

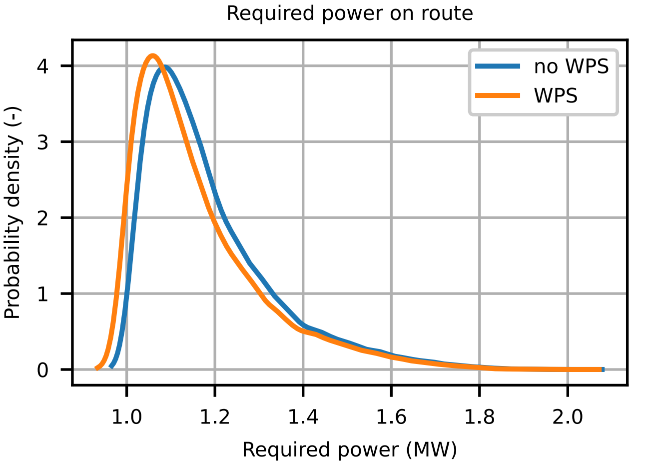
	Average	Min (2.5%)	Max (97.5%)
Power saving (kW)	25.12	6.12	61.12
Energy saving on route (MWh)	2.15	0.52	5.22
Energy saving on route (%)	2.1	0.5	5.2




0°
30°
60°
90°
120°
150°
120
100
80
60
40
20
0
Power saving [kW]
TWS
2
4
6
8
10
12
TWA
0°
30°
60°
90°
120°
150°
10
8
6
4
2
0
Power saving [%]
TWS
2
4
6
8
10
12
TWA


Joint probability of True wind speed / angle (relative route)
10 deg 6.84 1.42 2.85 3.96 4.09 2.96 1.72 0.63 0.15 0.01 0.00 0.00 0.00 0.00 0.00
30 deg 0.43 1.41 2.69 3.43 3.13 2.14 1.01 0.43 0.09 0.01 0.00 0.00 0.00 0.00 0.00
50 deg 0.34 1.26 2.34 2.85 2.71 1.59 0.62 0.20 0.04 0.00 0.00 0.00 0.00 0.00 0.00
70 deg 0.41 1.22 1.96 2.60 2.02 1.19 0.39 0.19 0.05 0.01 0.00 0.00 0.00 0.00 0.00
90 deg 0.34 1.20 1.75 2.20 1.94 1.01 0.46 0.08 0.02 0.00 0.00 0.00 0.00 0.00 0.00
110 deg 0.34 1.25 1.67 2.08 1.53 0.85 0.36 0.09 0.06 0.04 0.00 0.00 0.00 0.00 0.00
130 deg 0.27 1.01 1.78 1.92 1.27 0.54 0.24 0.02 0.01 0.00 0.00 0.00 0.00 0.00 0.00
150 deg 0.33 0.93 1.76 2.02 1.13 0.69 0.12 0.02 0.00 0.00 0.00 0.00 0.00 0.00 0.00
170 deg 0.30 0.87 1.76 2.18 1.44 0.66 0.11 0.01 0.00 0.00 0.00 0.00 0.00 0.00 0.00
1.0 m/s
3.0 m/s
5.0 m/s
7.0 m/s
9.0 m/s
11.0 m/s
13.0 m/s
15.0 m/s
17.0 m/s
19.0 m/s
21.0 m/s
23.0 m/s
25.0 m/s
27.0 m/s
29.0 m/s
6
5
4
3
2
1
0
Probability [%]

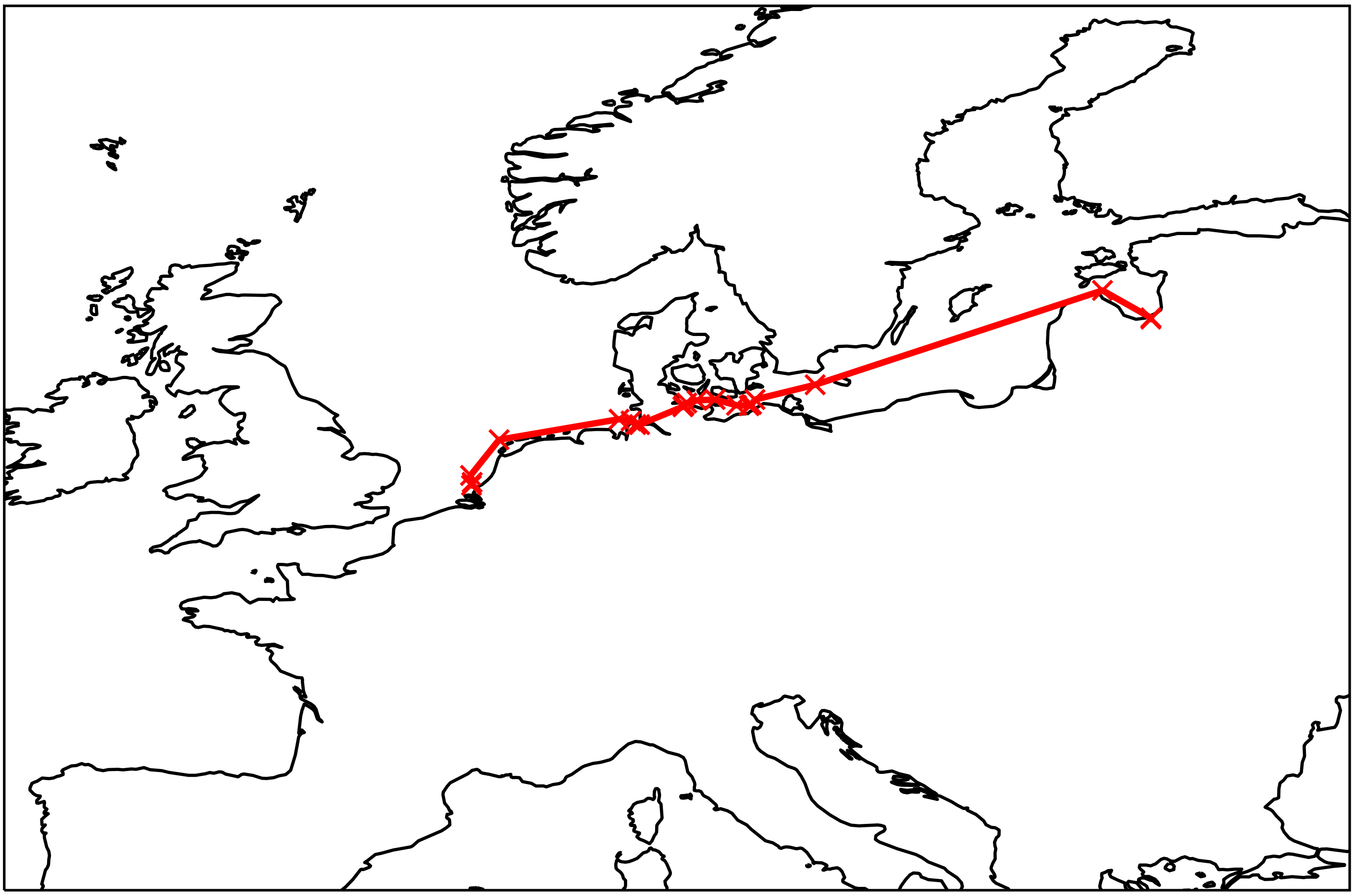

Power saving on route
Cumulative probability (%)
Power saving (kW)
0
20
40
60
80
100
120

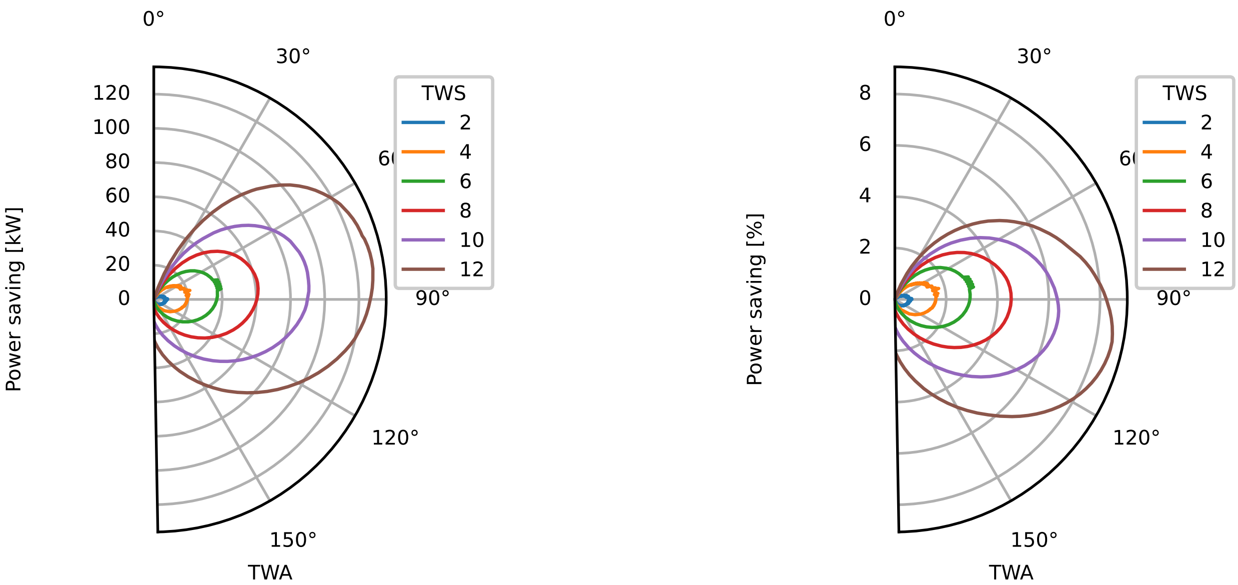

Required power on route
Probability density (-)
Required power (MW)
no WPS
WPS
1.0
1.2
1.4
1.6
1.8
2.0

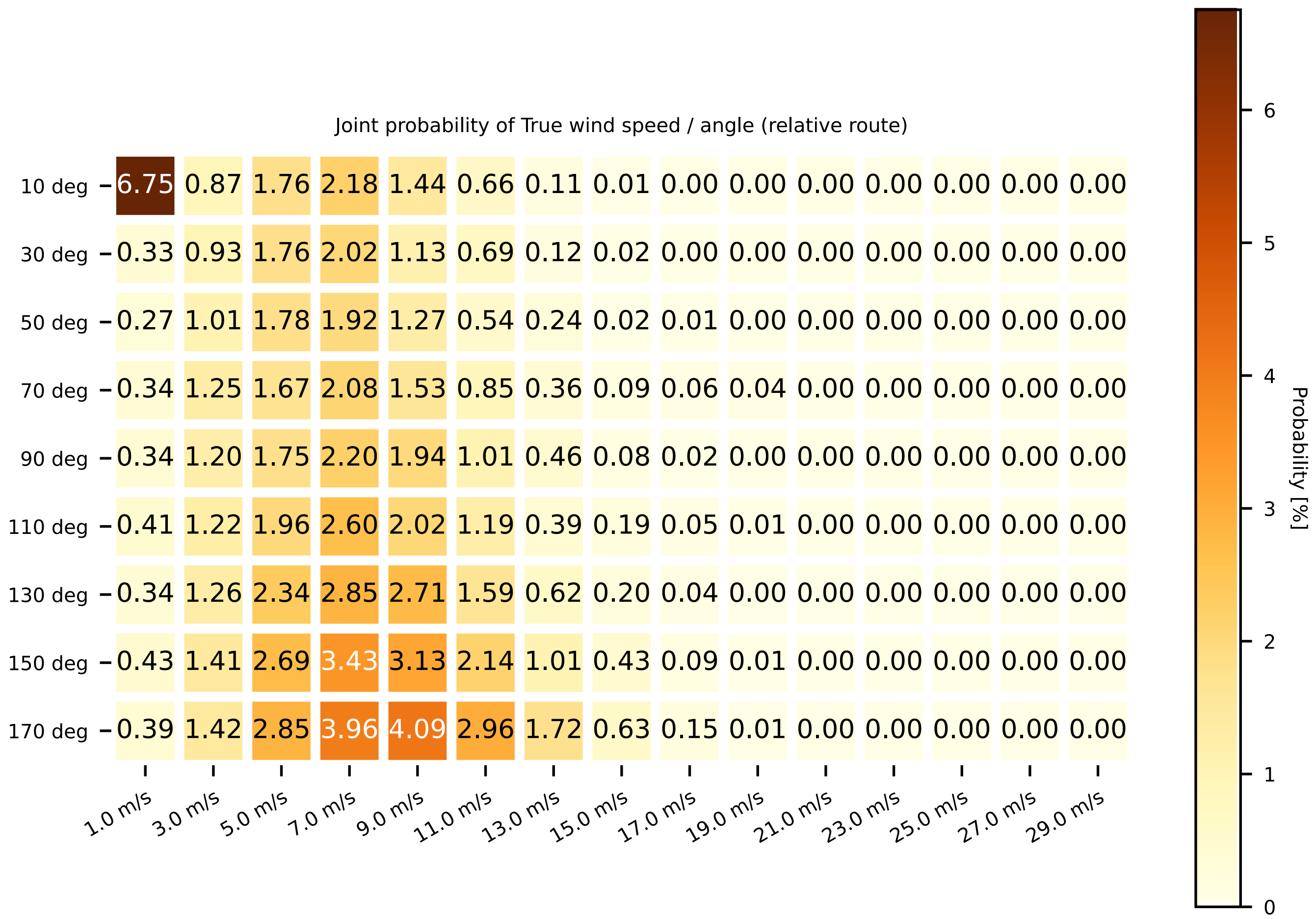
Route analysis report: WPS evaluation

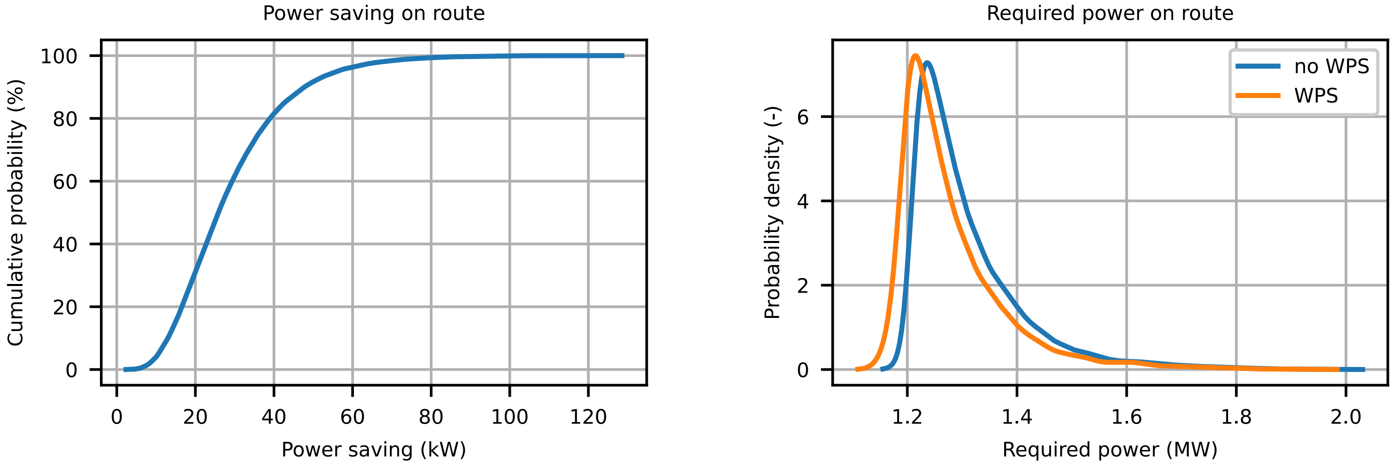
Results for a route analysis for ship: Frisian (laden) on route: Rotterdam - Riga (outbound) with total distance: 858.8 nm

	Average	Min (2.5%)	Max (97.5%)
Power saving (kW)	28.61	8.79	64.34
Energy saving on route (MWh)	2.45	0.76	5.52
Energy saving on route (%)	2.2	0.7	4.6




0°
30°
60°
90°
120°
150°
120
100
80
60
40
20
0
Power saving [kW]
TWA
TWS
2
4
6
8
10
12
8
6
4
2
0
Power saving [%]

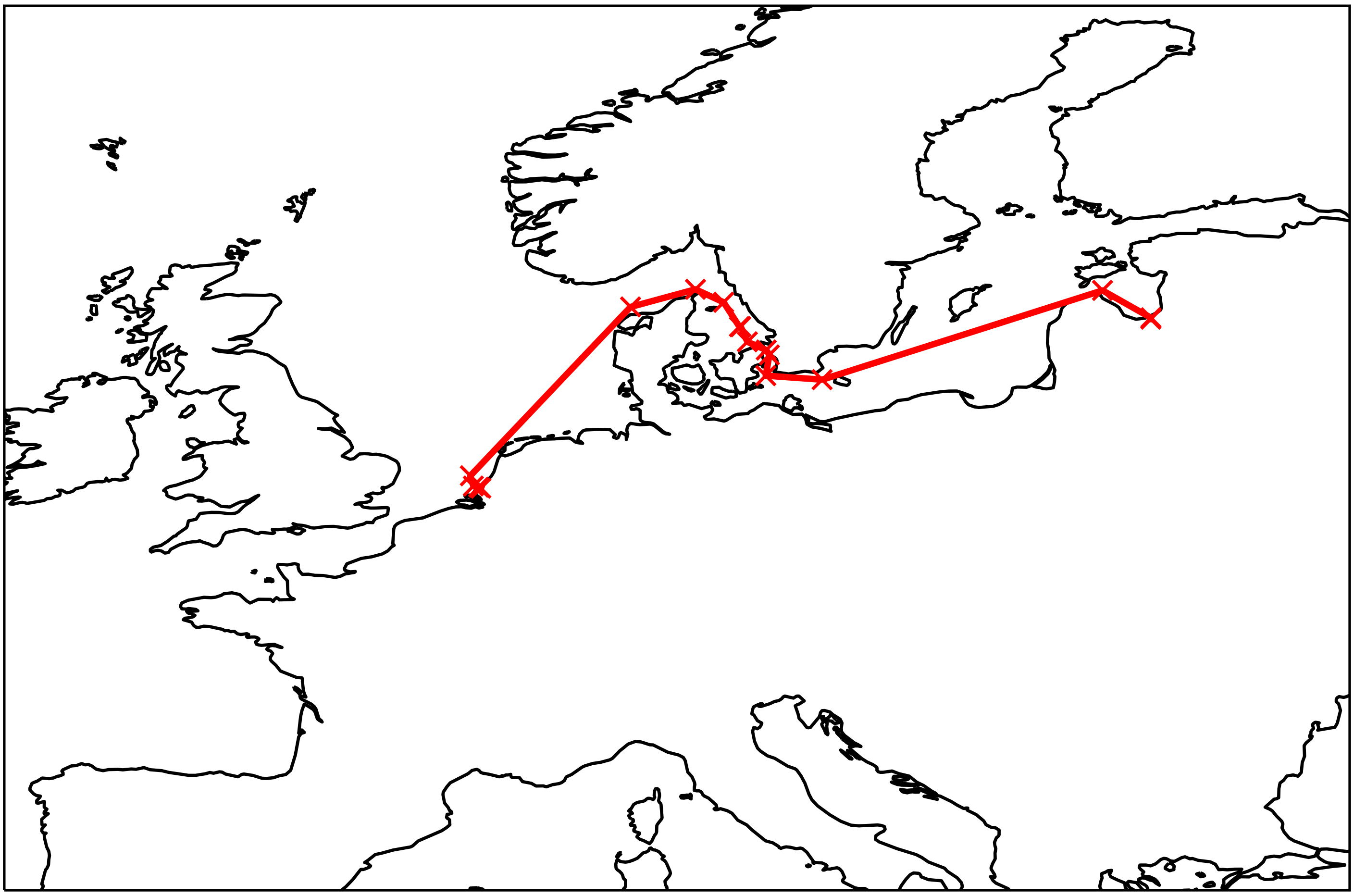

Joint probability of True wind speed / angle (relative route)
10 deg 6.75 0.87 1.76 2.18 1.44 0.66 0.11 0.01 0.00 0.00 0.00 0.00 0.00 0.00 0.00
30 deg 0.33 0.93 1.76 2.02 1.13 0.69 0.12 0.02 0.00 0.00 0.00 0.00 0.00 0.00 0.00
50 deg 0.27 1.01 1.78 1.92 1.27 0.54 0.24 0.02 0.01 0.00 0.00 0.00 0.00 0.00 0.00
70 deg 0.34 1.25 1.67 2.08 1.53 0.85 0.36 0.09 0.06 0.04 0.00 0.00 0.00 0.00 0.00
90 deg 0.34 1.20 1.75 2.20 1.94 1.01 0.46 0.08 0.02 0.00 0.00 0.00 0.00 0.00 0.00
110 deg 0.41 1.22 1.96 2.60 2.02 1.19 0.39 0.19 0.05 0.01 0.00 0.00 0.00 0.00 0.00
130 deg 0.34 1.26 2.34 2.85 2.71 1.59 0.62 0.20 0.04 0.00 0.00 0.00 0.00 0.00 0.00
150 deg 0.43 1.41 2.69 3.43 3.13 2.14 1.01 0.43 0.09 0.01 0.00 0.00 0.00 0.00 0.00
170 deg 0.39 1.42 2.85 3.96 4.09 2.96 1.72 0.63 0.15 0.01 0.00 0.00 0.00 0.00 0.00
1.0 m/s
3.0 m/s
5.0 m/s
7.0 m/s
9.0 m/s
11.0 m/s
13.0 m/s
15.0 m/s
17.0 m/s
19.0 m/s
21.0 m/s
23.0 m/s
25.0 m/s
27.0 m/s
29.0 m/s
Probability [%]
0
1
2
3
4
5
6

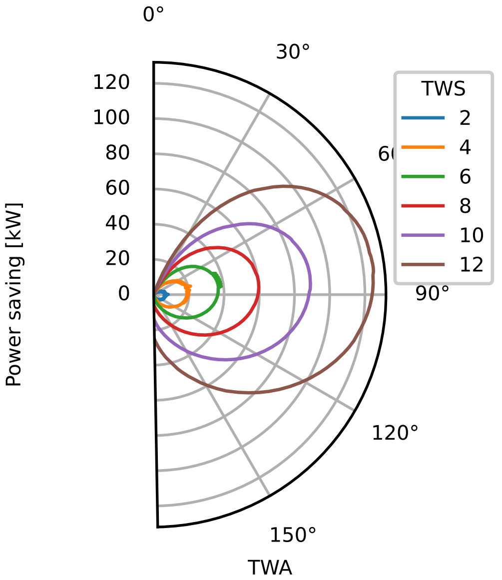

Power saving on route
Cumulative probability (%)
0
20
40
60
80
100
Power saving (kW)
0
20
40
60
80
100
120
Required power on route
Probability density (-)
0
2
4
6
Required power (MW)
1.2
1.4
1.6
1.8
2.0
no WPS
WPS

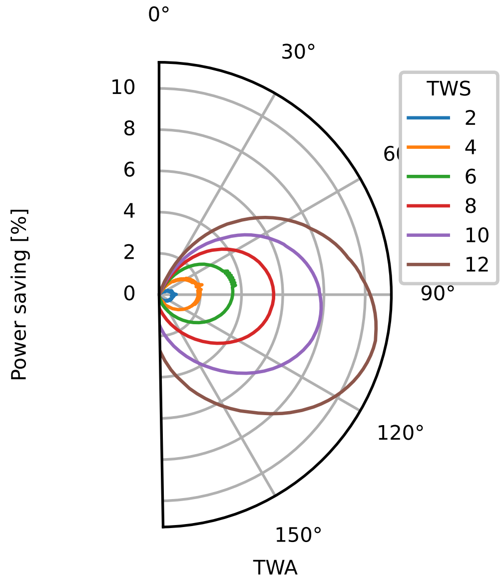
Route analysis report: WPS evaluation

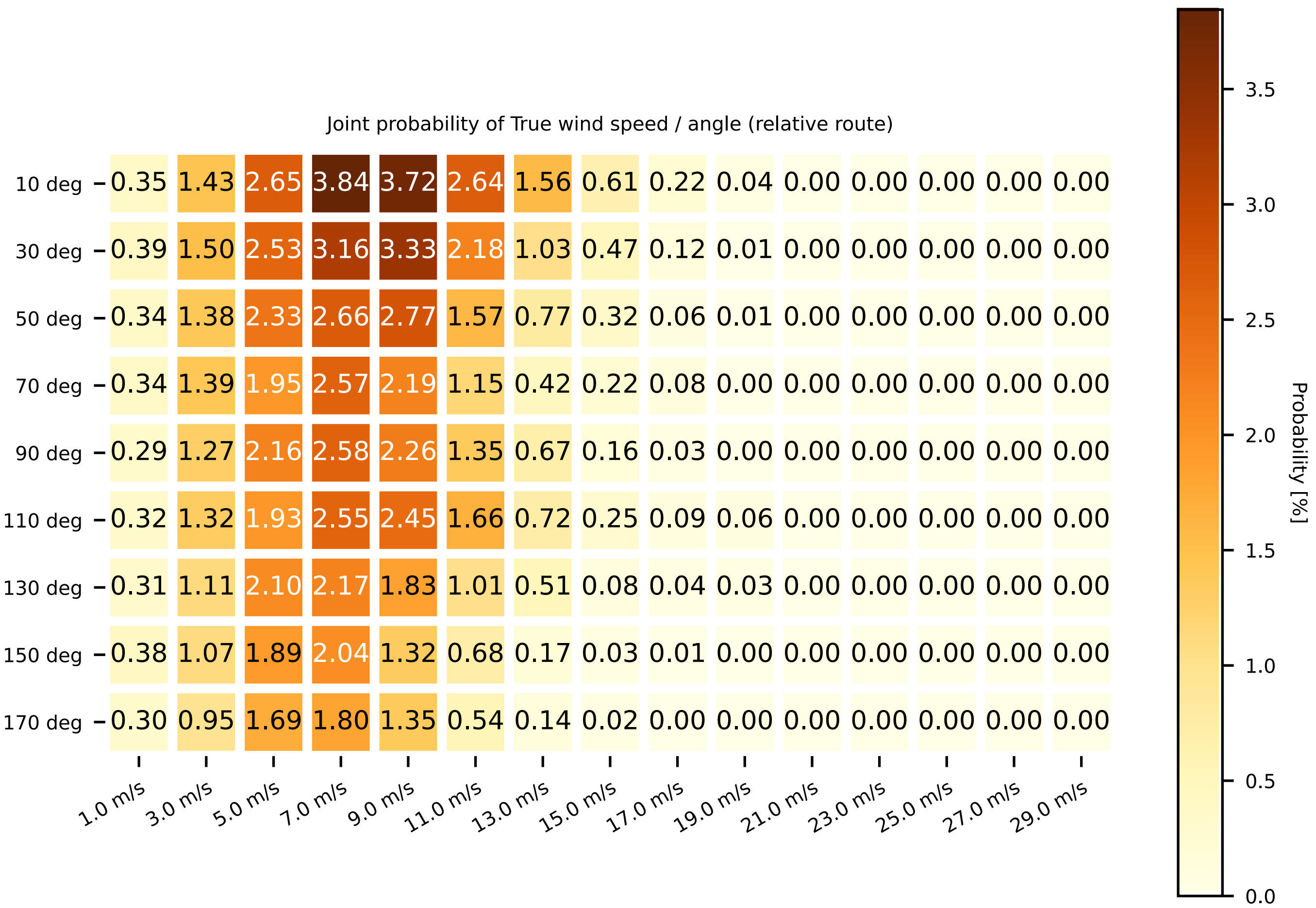
Results for a route analysis for ship: Frisian (ballast) on route: Rotterdam - Riga (inbound) with total distance: 1070.5 nm

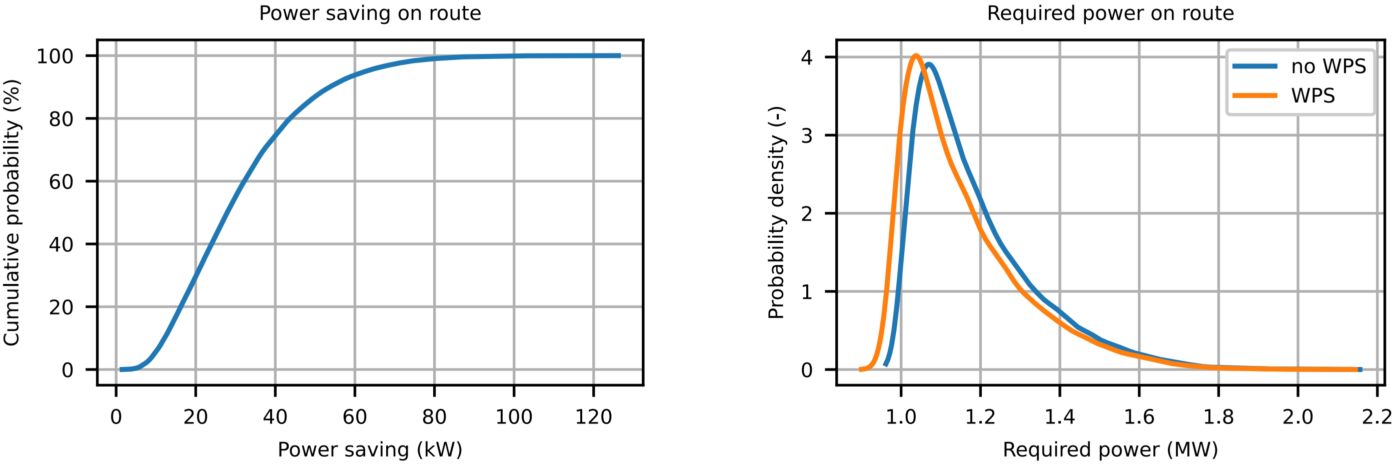
	Average	Min (2.5%)	Max (97.5%)
Power saving (kW)	30.80	7.89	70.61
Energy saving on route (MWh)	3.28	0.84	7.51
Energy saving on route (%)	2.6	0.6	6.0




0°
30°
60°
90°
120°
150°
120
100
80
60
40
20
0
Power saving [kW]
TWA
TWS
2
4
6
8
10
12


0°
30°
60°
90°
120°
150°
10
8
6
4
2
0
Power saving [%]
TWA
TWS
2
4
6
8
10
12

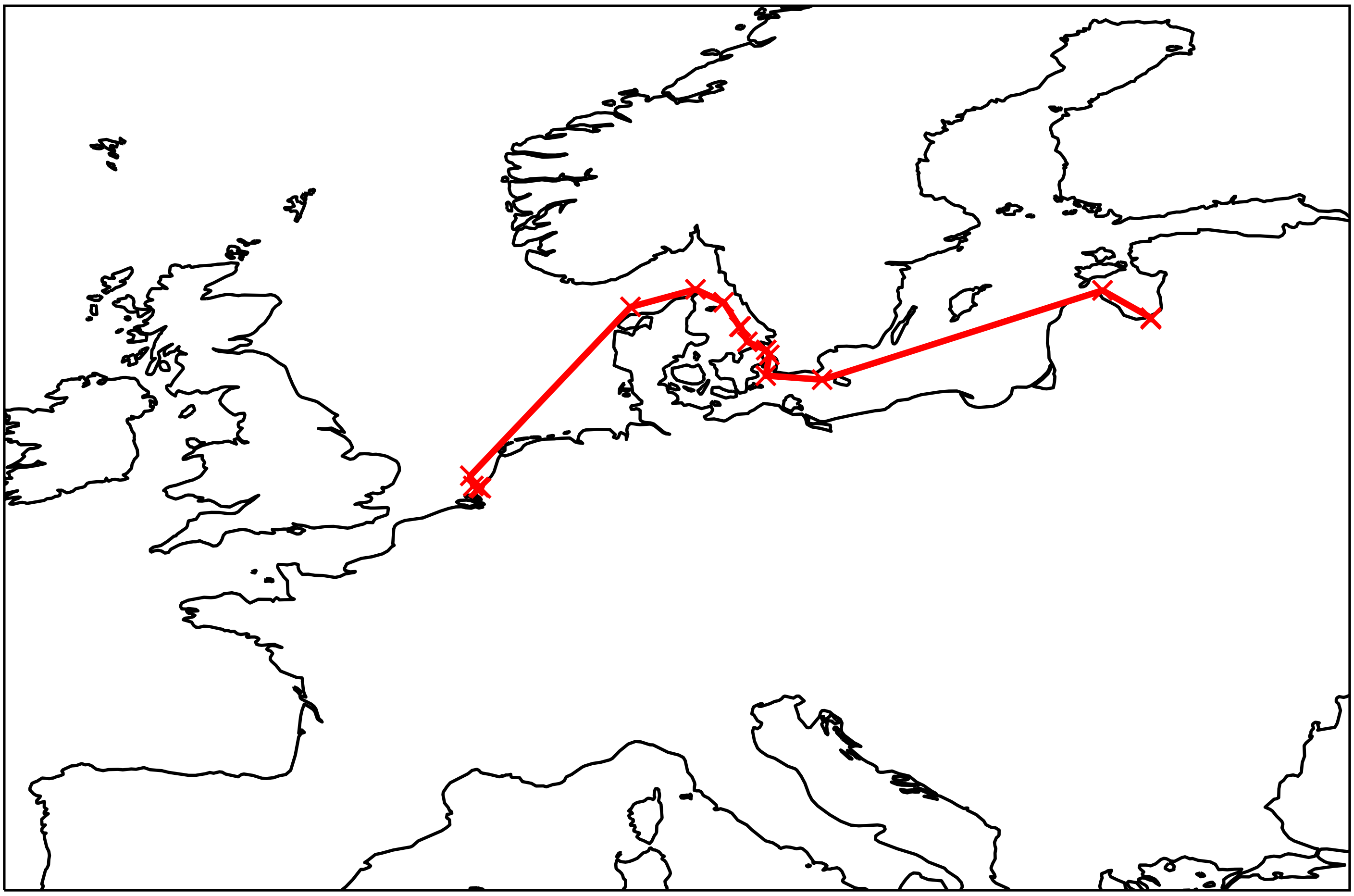

Joint probability of True wind speed / angle (relative route)
10 deg 0.35 1.43 2.65 3.84 3.72 2.64 1.56 0.61 0.22 0.04 0.00 0.00 0.00 0.00 0.00
30 deg 0.39 1.50 2.53 3.16 3.33 2.18 1.03 0.47 0.12 0.01 0.00 0.00 0.00 0.00 0.00
50 deg 0.34 1.38 2.33 2.66 2.77 1.57 0.77 0.32 0.06 0.01 0.00 0.00 0.00 0.00 0.00
70 deg 0.34 1.39 1.95 2.57 2.19 1.15 0.42 0.22 0.08 0.00 0.00 0.00 0.00 0.00 0.00
90 deg 0.29 1.27 2.16 2.58 2.26 1.35 0.67 0.16 0.03 0.00 0.00 0.00 0.00 0.00 0.00
110 deg 0.32 1.32 1.93 2.55 2.45 1.66 0.72 0.25 0.09 0.06 0.00 0.00 0.00 0.00 0.00
130 deg 0.31 1.11 2.10 2.17 1.83 1.01 0.51 0.08 0.04 0.03 0.00 0.00 0.00 0.00 0.00
150 deg 0.38 1.07 1.89 2.04 1.32 0.68 0.17 0.03 0.01 0.00 0.00 0.00 0.00 0.00 0.00
170 deg 0.30 0.95 1.69 1.80 1.35 0.54 0.14 0.02 0.00 0.00 0.00 0.00 0.00 0.00 0.00
1.0 m/s 3.0 m/s 5.0 m/s 7.0 m/s 9.0 m/s 11.0 m/s 13.0 m/s 15.0 m/s 17.0 m/s 19.0 m/s 21.0 m/s 23.0 m/s 25.0 m/s 27.0 m/s 29.0 m/s
Probability [%]
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0

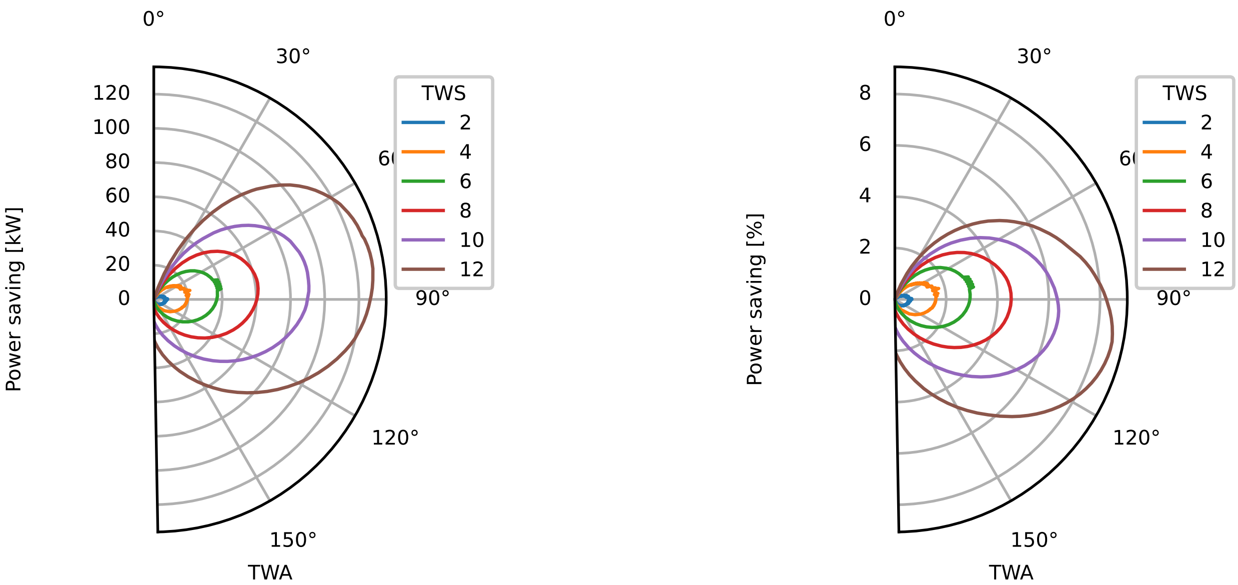

Power saving on route
Cumulative probability (%)
0
20
40
60
80
100
0
20
40
60
80
100
120
Power saving (kW)
Required power on route
Probability density (-)
0
1
2
3
4
1.0
1.2
1.4
1.6
1.8
2.0
2.2
Required power (MW)
no WPS
WPS

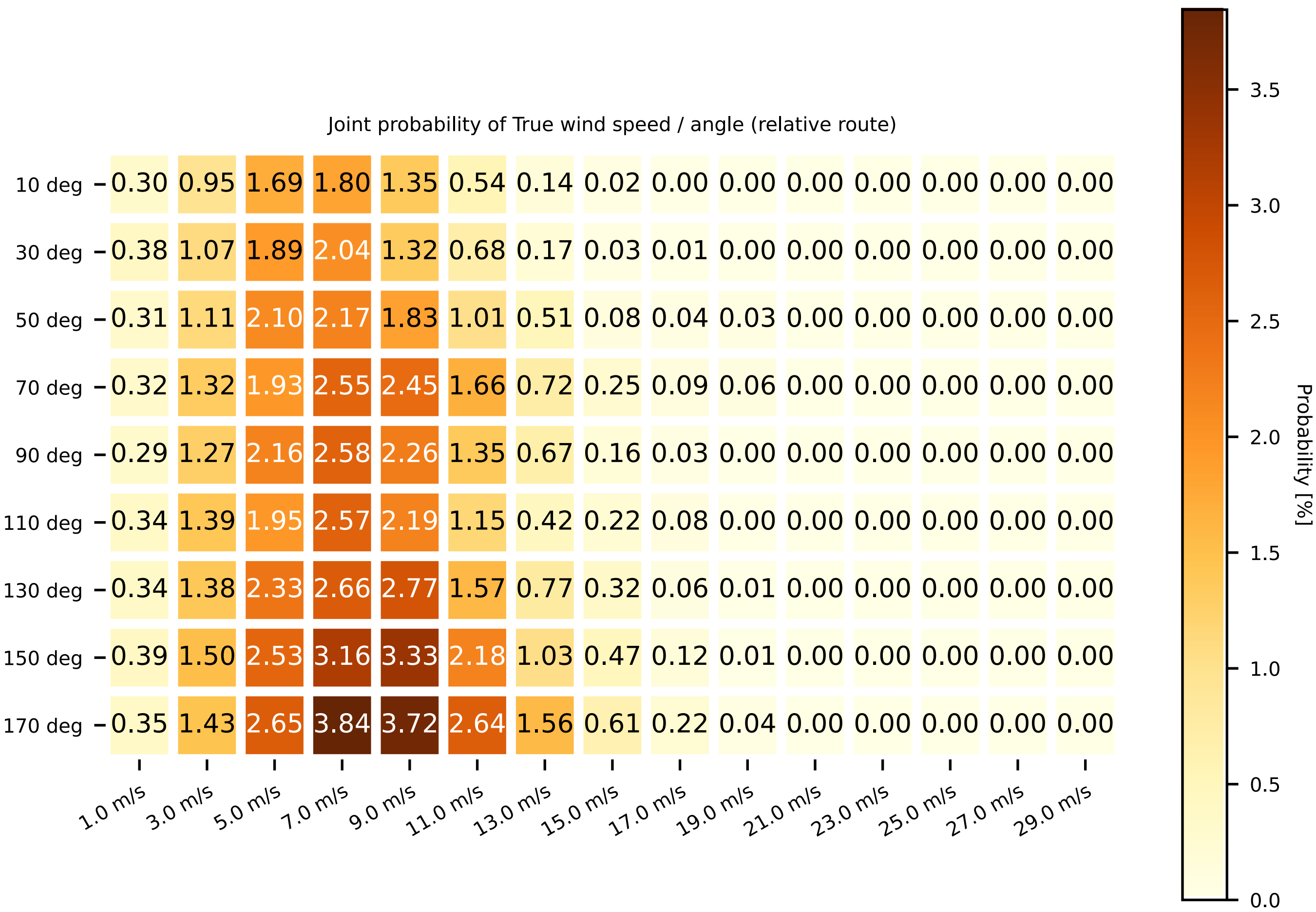
Route analysis report: WPS evaluation

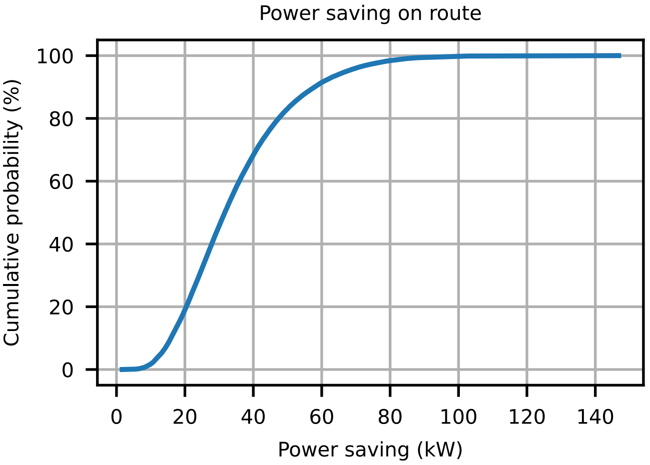
Results for a route analysis for ship: Frisian (laden) on route: Rotterdam - Riga (outbound) with total distance: 1070.5 nm

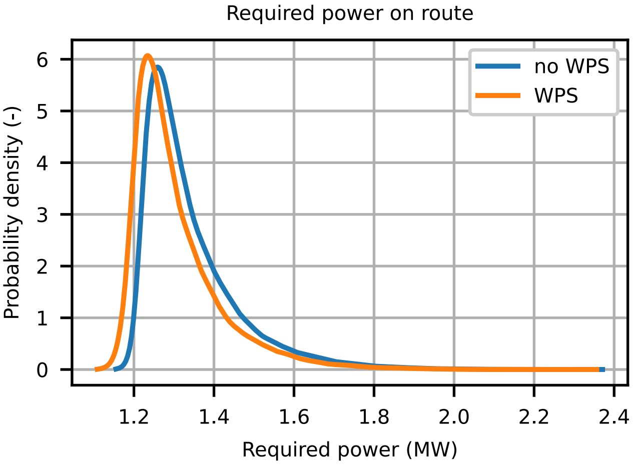
	Average	Min (2.5%)	Max (97.5%)
Power saving (kW)	34.69	10.88	75.20
Energy saving on route (MWh)	3.71	1.16	8.04
Energy saving on route (%)	2.6	0.8	5.2




Power saving [kW]
0 20 40 60 80 100 120
0° 30° 60° 90° 120° 150°
TWA
TWS
2
4
6
8
10
12
Power saving [%]
0 2 4 6 8
0° 30° 60° 90° 120° 150°
TWA
TWS
2
4
6
8
10
12


Joint probability of True wind speed / angle (relative route)
10 deg 0.30 0.95 1.69 1.80 1.35 0.54 0.14 0.02 0.00 0.00 0.00 0.00 0.00 0.00 0.00
30 deg 0.38 1.07 1.89 2.04 1.32 0.68 0.17 0.03 0.01 0.00 0.00 0.00 0.00 0.00 0.00
50 deg 0.31 1.11 2.10 2.17 1.83 1.01 0.51 0.08 0.04 0.03 0.00 0.00 0.00 0.00 0.00
70 deg 0.32 1.32 1.93 2.55 2.45 1.66 0.72 0.25 0.09 0.06 0.00 0.00 0.00 0.00 0.00
90 deg 0.29 1.27 2.16 2.58 2.26 1.35 0.67 0.16 0.03 0.00 0.00 0.00 0.00 0.00 0.00
110 deg 0.34 1.39 1.95 2.57 2.19 1.15 0.42 0.22 0.08 0.00 0.00 0.00 0.00 0.00 0.00
130 deg 0.34 1.38 2.33 2.66 2.77 1.57 0.77 0.32 0.06 0.01 0.00 0.00 0.00 0.00 0.00
150 deg 0.39 1.50 2.53 3.16 3.33 2.18 1.03 0.47 0.12 0.01 0.00 0.00 0.00 0.00 0.00
170 deg 0.35 1.43 2.65 3.84 3.72 2.64 1.56 0.61 0.22 0.04 0.00 0.00 0.00 0.00 0.00
1.0 m/s 3.0 m/s 5.0 m/s 7.0 m/s 9.0 m/s 11.0 m/s 13.0 m/s 15.0 m/s 17.0 m/s 19.0 m/s 21.0 m/s 23.0 m/s 25.0 m/s 27.0 m/s 29.0 m/s
Probability [%]
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5


Power saving on route
Cumulative probability (%)
0
20
40
60
80
100
0
20
40
60
80
100
120
140
Power saving (kW)


Required power on route
Probability density (-)
0
1
2
3
4
5
6
1.2
1.4
1.6
1.8
2.0
2.2
2.4
Required power (MW)
no WPS
WPS